# Nuclear Safeguards
## and Non-Proliferation

### Course Syllabus

This compact course is open to masters degree students (nuclear engineering, physics, chemistry, law, business, international relations etc.) Its primary aim is to complement engineering studies by including nuclear safeguards and non-proliferation in the academic curriculum. For this reason, the course has been attributed 3ECTS (European Credit Transfer System) points in the past. The course also serves the exposure of other students and professionals to this theme of continuing international attention.

The course addresses aspects of the efforts to create a global nuclear non-proliferation system and how this sytem works in practice, including the Treaty on Nonproliferation of Nuclear Weapons (NPT), safeguards systems and technology, and export control. Also regional settings, such as Euratom Treaty, are presented and discussed. The course deals in particular with technical aspects and application of safeguards; i.e. how to implement the safeguards principles and methodology within the different nuclear facilities. The course is complemented with exercises, lab visits and topical lectures on actual issues, the latter not included in this syllabus and not part of the formal examination.

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ESARDA
European Safeguards Research and Development Association

Nuclear Safeguards and Non-Proliferation

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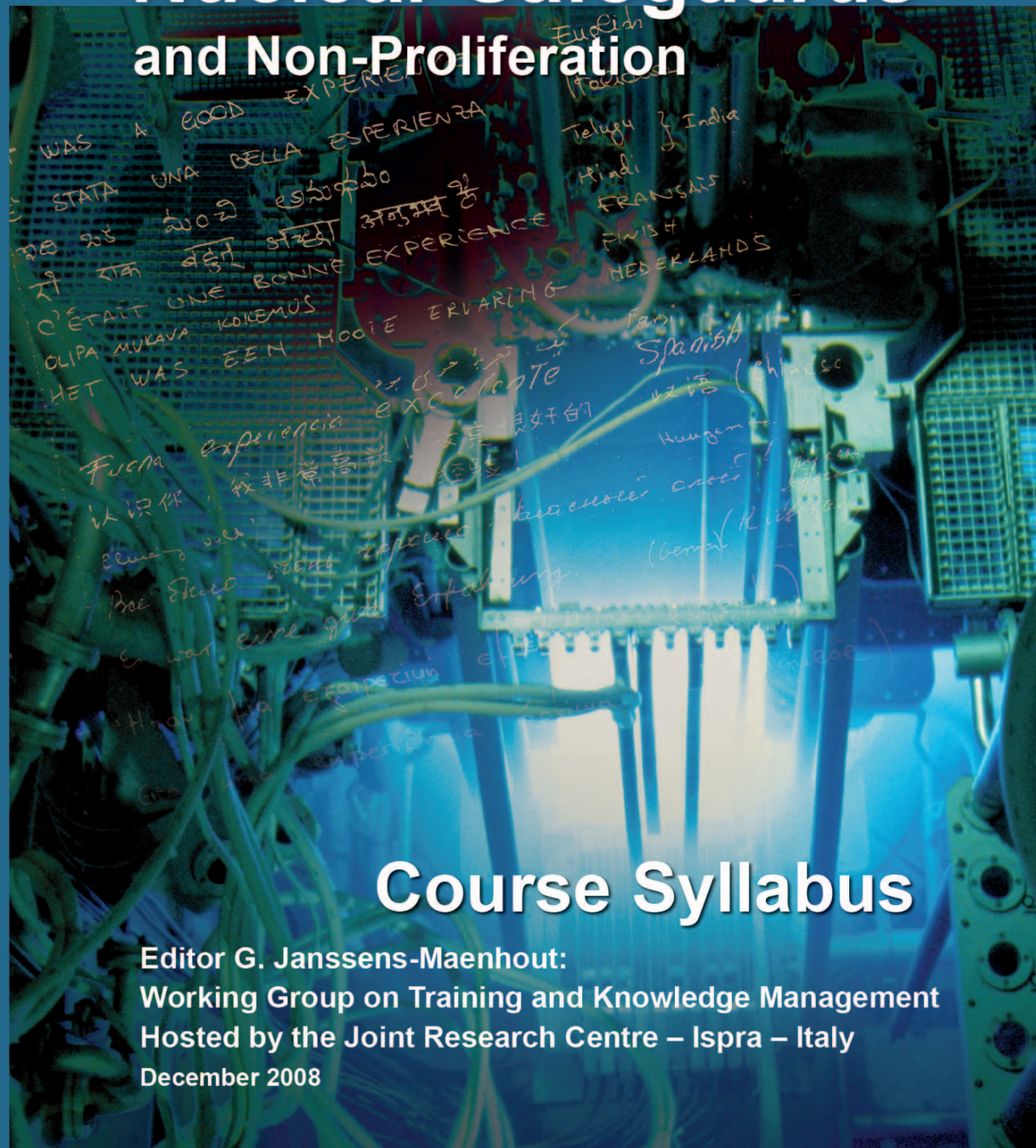


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Editor G. Janssens-Maenhout:
Working Group on Training and Knowledge Management
Hosted by the Joint Research Centre – Ispra – Italy

December 2008

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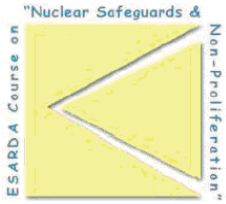


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# Nuclear Safeguards and Non-Proliferation

## Syllabus of the ESARDA Course

http://esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/index.html

December 2008

Editor: G. Janssens-Maenhout
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Hosted by the Nuclear Safeguards Unit,
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## Abstract

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 in collaboration with the Nuclear Safeguards 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. Last but

not least an overview is given on the management and analysis of information, such as collected from open sources. Also the analysis of trade data for import/export control is 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 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 totally complementary aspects: technical and juridical/ political.

# Foreword

The renaissance of nuclear technology 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 etc. 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 nuclear security. The classic nuclear engineering courses in the official program for a European master of science in nuclear engineering (EMSNE) cover well reactor operation and nuclear safety 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 the Nuclear Safeguards fields, 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.

Together with the Joint Research Centre in Ispra a Nuclear Safeguards and Non Proliferation course is organized every spring and is receiving international response of lecturers and students. This five-days course is detailed on http://esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/index.html 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 an accountancy" (the techniques and methodology of verification, statistics for accountancy & 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 with import/export data control).

The standard set of lectures, which represent about two third of the course, are given by representatives from regulatory bodies (IAEA, IRSN, DG-TREN), industry (AREVA, BNG), and research (Stockholm University, Hamburg University, JRC-ITU, and JRC-IPSC). The remaining part is completed with topical lectures addressed by invited lecturers, such as from PNNL and IAEA addressing physical protection, illicit trafficking, the Iraq case study, exercises, including 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 matters 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-labeled 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, as promoted by the IAEA DG in 2007. He called for 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 on safeguards, non-proliferation and security exist. To streamline the educational resources, new synergies with interuniversity collaboration in a first step and interfaculty collaboration in a second step are fostered.

## Acknowledgement

The ESARDA WGTKM is grateful for the effort of the other ESARDA WGs and the devotion of some lecturers in writing these notes. Therefore I would like to thank in name of the WGTKM

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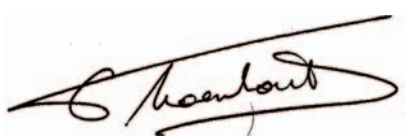

**Greet Janssens-Maenhout**
Chair of the ESARDA WGTKM
Ispra, 15 October 2008

# Nuclear Non-Proliferation – a Brief Historical background

Thomas Jonter

## 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 ([1]).

But in 1911 the atom was discovered for the first time, in an experiment carried out by Ernest Rutherford of New Zealand. Rutherford was inspired by the research on radioactivity conducted by Henri Becquerel and Pierre and Marie Curie ([2]). Discovering the atom was one thing, however, and understanding and exploiting its inherent energy was quite another. 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. Among those involved can be mentioned Niels Bohr, Otto Hahn, Albert Einstein, and Robert Oppenheimer. Indeed, it is probably impossible to establish an exact date. However, if one still wants to attempt finding a date, especially one that signaled 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 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, who was working in New York, was able to establish that two neutrons are released when a neutron that has already been released in the process collides with another (U-235) atom ([3]). These discoveries raised people's expectations. The physicists dreamt of a world where the energy issue had been solved for all time.

However, it was not the civilian use of nuclear energy that the political leaders of Germany, Great Britain, the United States and the Soviet Union first involved themselves in. The world was on the brink of war, a war that became a fact in September 1939, and it was therefore the military possibilities of nuclear power that induced leading politicians to play an active role in the development of

([1]) Richard Rhodes, The Making of the Atomic Bomb. Touchstone Books, New York 1986, p. 30.
([2]) Ibid., p. 42.
([3]) David Fischer, History of the International Atomic Energy Agency: The First Forty Years. IAEA, Vienna 1997, p. 15. et passim.

nuclear energy. This led to a classified and publicly unknown race between the great powers to be the first to reach the goal of developing an atomic bomb. Rumors were running high before and during the Second World War; information was flowing in to the intelligence services of the different great powers about the other states' attempts to acquire nuclear materials and about their plans for producing nuclear weapons. Leading scientists were also engaged in the issue. For example, Albert Einstein, at the request of Leo Szilard among others, wrote a letter on August 2, 1939 to president Roosevelt in which he stated that Germany had begun experiments aimed at producing highly enriched uranium for the development of nuclear weapons. In his letter, the world-famous physicist advised Roosevelt to commit resources to developing nuclear weapons before Nazi Germany would be able to succeed in doing so ([4]).

Aside from enriched uranium, plutonium is the material used in nuclear devices or as an energy-producing source in civilian use of nuclear technology. Unlike uranium, which exists in nature, plutonium is a man-made nuclear material. Toward the end of 1940 Glenn Seaborg and his research team at the University of California succeeded in producing a precipitate of Pu-239. Seaborg named this new material plutonium after the outermost planet of our solar system, Pluto, which is also the name of the God of wealth and the underworld in Roman mythology. Two years later, on 2 December 1942, the Italian physicist Enrico Fermi succeeded in carrying out the first splitting of an atom in the world's first reactor, which had been built under the football stadium at the University of Chicago. This was the first time that plutonium had been artificially produced. A major step toward the possibility of using the released energy had thus been taken. In the same year, Roosevelt launched a gigantic program for the development of U.S. nuclear weapons – the so-called Manhattan Project. Albert Einstein's prayers had finally been heard.

## The Great Race: Who will have nuclear weapons first?

British researchers, who at that time were among the foremost in the world, were invited to join the Manhattan Project together with researchers who had fled from Germany. Although British and American researchers had exchanged information to some degree during the initial war years, there hadn't been any organized cooperation. The British government was kept out of the Manhattan Project, and it wasn't until after protracted negotiations that London won acceptance as a "junior partner," together with Canada, in partially coordinated programs that only gave them limited access the Americans' knowledge. The agreement, the so-called Quebec Treaty which was signed in August 1943, led to the formation of a common high-level organization called the Combined Policy Committee.

Great Britain and the United States had decided to give no mention of the Manhattan Project to the Soviet Union. Although the Soviet Union was an ally in the struggle against Nazi Germany, it was unlikely that the different ideological and economic systems of East and West would live in peaceful coexistence forever. But even France, which was also at the forefront of nuclear research, was excluded from this cooperation during the war years. The Americans did not quite trust that the French government-in-exile would be able to act as a strong and reliable partner; there was concern that secret information might leak out or be exploited politically by the French for national gain. The UK, on the other hand, sought increased cooperation, both political and military, with France's government-in-exile during the period 1940-42. A strong France was seen as a guarantee for keeping a future Germany in check. In addition, there were other reasons for seeking partnership with France: the country itself possessed considerable scientific competence and had access to heavy water, while at the same time French imperial territories possibly held large reserves of uranium and thorium which could be used for both civil and military purposes. The British position changed in 1942-43, when Churchill

([4]) Rhodes, p. 303-314.

in particular realized the importance of forming closer ties to the United States. The earlier policy of striving for independence in the nuclear energy area was jettisoned with the Quebec Treaty. From that point on, the UK was forced to coordinate its nuclear energy policy with the U.S. government. Cooperation and exchange of information with a third party without the consent of Washington were no longer possible. On one matter, however, the British did not yield: they did not give up the possibility of acquiring nuclear weapons after the war. In this regard, one can speak of a concession on the part of the U.S., since it had been Washington's policy to prevent the British from acquiring nuclear weapons ([5]).

Already in 1940-41, U.S. experts estimated that it would be possible to manufacture a nuclear weapon loaded with uranium which would have a decisive impact on the outcome of the war. Civil use of nuclear energy in the form of electricity production was also considered feasible but would take longer to achieve. But since the enemy state Germany, and perhaps the Soviet Union as well, were trying to produce nuclear weapons, it was deemed important to prevent these countries from gaining access to uranium above all. In addition, thorium, which in the long run might be put to use in various nuclear energy programs, should also be controlled, according to American and British officials. Access to large quantities of uranium, or, alternatively, to thorium in combination with a smaller quantity of uranium, constitutes the fundamental prerequisite for starting a nuclear energy program and thus for producing nuclear weapons as well. At that time, knowledge concerning the world's uranium reserves was limited. Geologists up until then had not had cause to conduct any major inventories of the world's uranium reserves. The principal uranium production in the world during the interwar period took place in the Belgian Congo, where large reserves had been found. The Americans and the British knew that Germany had acquired a stock of uranium oxide of Congolese origin when it occupied Belgium and France. The priority now was to prevent the Germans from acquiring uranium from non-occupied areas. The Allied intelligence services had gathered intelligence indicating that Germany had launched a nuclear weapons project. The outcome of the war depended on which of the competing powers won the nuclear race ([6]).

But how far along was Germany in its preparations for nuclear weapons production? This was an uncertain factor. But when the Allies took Strasbourg in November 1944, their worst fears were dissipated. An examination of the documents of German atomic scientists showed that there was scarcely any risk that Nazi Germany would be able to produce nuclear weapons in the immediate future. But it was not only Germany that constituted a threat. The Soviet Union might also want to develop nuclear weapons. On the Anglo-American side, there was scant knowledge of what was happening in the nuclear energy area in the Soviet Union. In fact, the leading Russian nuclear physicist Igor Kurchatov had already in 1939 informed the Soviet government, led by Joseph Stalin, about the possibilities of exploiting fission energy for military purposes ([7]). The year after that, the Russian researchers got started with a laboratory-scale nuclear weapons project ([8]). However, the German invasion temporarily ended these developmental attempts. In addition, the Soviet plans for nuclear weapons were held back by the lack of uranium. At that time, the knowledge about uranium ore reserves in the Soviet Union was very limited. Expeditions had indicated that mining of modest proportions would be possible in Central Asia. It was not until shortly after the end of the war that the Soviet prospecting really got under way. The first cyclotron that was used in the weapons project was not built until

([5]) Gunnar Skogmar, Nuclear Triangle: Relations Between the United States, Great Britain and France in the Atomic Energy Field 1939-1950. Copenhagen Political Studies Press: Copenhagen, 1993, p. 186 et passim.

([6]) Gunnar Skogmar, De nya malmfälten. Det svenska uranet och inledningen till efterkrigstidens neutralitetspolitik. Research program Sweden During the Cold War, Working Paper 3, Stockholm 1997.

([7]) Rhodes, 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.

([8]) Skogmar 1997, p. 17.

September 1944, and the Russians also lacked other important ingredients such as graphite and heavy water ([9]).

Both the UK and the US conducted secret surveys of the world's uranium reserves in order to gain control over these. For example, an American report was put together in 1944 in which eleven states were ranked according to estimated production potential. The category "excellent" contained only the Belgian Congo, which was believed to possess 50 percent or more of the world's reserves. The states of Canada, the United States, Czechoslovakia, Russia, Portugal and Madagascar were listed as "good," whereas Bulgaria and Sweden were categorized as "poor."

In June 1944, the United States and Great Britain entered 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 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 ([10]). The Soviet Union was presumed to have only small quantities at its disposal ([11]). The large uranium assets that were later to be used by the Soviet armed forces in Central Asia, East Germany and Estonia were at this point as yet undiscovered or not fully inventoried ([12]).

## The NPT, its historical roots, development, and current status

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 ([13]). These numbers indicate the explosive force of the world's first nuclear device ([14]). 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 people had died in Nagasaki, and after another five years the number had increased to 140,000 ([15]). 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.

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." ([16])

([9]) David Halloway, Stalin and the Bomb: The Soviet Union and Atomic Energy, 1939-56. New Haven: Yale University Press, 1994, pp. 64, 85, 91, 100-103.
([10]) Holloway, p. 174.
([11]) Skogmar 1997, p. 28 et passim.
([12]) 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.
([13]) Richard Rhodes, The Making of the Atomic Bomb, p. 733 et passim.
([14]) On the explosive force, see Rhodes, p. 561, 643.
([15]) Rhodes, p. 740 et passim.
([16]) Fischer, p. 18.

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, Great Britain 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 Great Britain proposed the setting up 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 maneuverings of the superpowers ([17]).

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 also many were skeptical 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 ([18]).

In September of that year, the Soviet Union performed its first nuclear test. The announcement came as a shock to US officials. They had assumed that it would take the Soviet Union around 20 years to

([17]) Fischer, ibid.
([18]) Ibid., p. 19 et passim.

become the world's second nuclear power ([19]). 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 ([20]).

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. Even Washington's cooperative partners, Great Britain and Canada, were affected by the US export control. The Americans maintained that until a more globally functioning handling of nuclear energy products could be achieved, the flow of materials must be stopped completely. During the immediate post-war years the three states conducted renewed negotiations, and in 1948, a new agreement was entered into, the so-called Modus Vivendi, which replaced the agreement that had been in operation during the war. Although the agreement was concluded, the American attitude was restrictive in practice. It was only the cooperation concerning control of uranium and thorium that was fully operational ([21]). To summarize, we can say that during the period until 1953, US legislation prohibited export of fissile material and equipment that could be used for producing nuclear energy for industrial purposes. The AEC issued licenses for use of these products within the United States and for export to other countries ([22]).

## Launching of the "Atoms for Peace" program

In October 1952, Great Britain became the world's third nuclear power. There was a substantial fear 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

([19]) Ibid., p. 21.
([20]) Gunnar Skogmar, Atompolitik: sambandet mellan militärt och civilt utnyttjande av atomenergin i amerikansk utrikespolitik 1945-73. Lund 1979.
([21]) Skogmar 1997, p. 91 et passim.
([22]) Skogmar 1979, p. 30 et passim.

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 ([23]). Global cooperation is necessary in order to achieve effective global control.

It was against this background that president Eisenhower launched the "Atoms for Peace" program in December 1953, ushering in a new phase in U.S. nuclear energy policy. 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 ([24]).

The "Atoms for Peace" program was a part of the cold war between the superpowers. To begin with, the Soviet Union was skeptical 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 favor 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 part. In the same year, the Soviet Union initiated negotiations concerning participation in the IAEA organization ([25]), 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 ([26]).

## The IAEA is formed: the period 1955-57

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

([23]) Fischer, p. 22 et passim.
([24]) Skogmar 1979, p. 74 et passim.
([25]) Fischer, p. 30 et passim.
([26]) Skogmar 1979, p. 79.

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) ([27]).

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 ([28]).

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 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 ([29]). In cases where states do not fulfill 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, South East 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

([27]) Ibid., p. 35 et passim.
([28]) Ibid., p. 36.
([29]) Ibid., p. 37.

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 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;
5. 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 ([30]).

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 ([31]).

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

([30]) Ibid., p. 43.
([31]) Ibid.

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 ([32]). 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 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 ([33]).

## The NPT is put into effect: the period 1957-1970

The first five years in the history of the organization 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 Sweden, Switzerland, Spain, France, and China 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 15-25 nuclear states in the world if nothing were done to prevent this development. But, of course, ideas existed 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 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 ([34]). The Non-Proliferation Treaty came into force in 1970, and in 2007 has been ratified by 189 states. The NPT can be said to have three purposes:

([32]) Ibid., p. 82.
([33]) Fischer, p. 29.
([34]) Ibid., p. 94 et passim.

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. 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 Nuclear Power Inspectorate (SKI), is a national organization with responsibility for verifying that the treaties are observed. The work of the SKI 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 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. For example, the 1995 conference focused on

the obligation set forth in the NPT 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 ([35]). The 1995 conference raised expectations that the nuclear powers would finally assume their responsibilities and take article VI seriously, and truly strive for effective nuclear disarmament. At the latest conference in 2005, the disarmament issue was not dealt with at all, and this led to a fair amount of disappointment being expressed in the debate concerning the future of the NPT regime. 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.

## 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 political scientist Anver Cohen, for example, has claimed that Israel possesses circa 100 so-called tactical nuclear weapons. Moreover, Israel has not signed the NPT treaty ([36]).

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 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 maneuvering, the newly installed Swedish IAEA general secretary Hans Blix managed to keep both Israel and the United States in the IAEA ([37]).

([35]) George Bunn, "The Nuclear Non-proliferation Treaty: History and Current Problems." Arms Control Today. December 2003.
([36]) Anver Cohen, Israel and the Bomb. New York: Columbia University Press 1998.
([37]) Fischer, p. 106 et passim.

## The Period 1991-2005

The coming into force of the NPT system was seen as a major success in the work to prevent the proliferation of nuclear weapons. A number of states which had theretofore entertained plans for acquiring nuclear-weapons capability – such as Sweden, Switzerland, Spain and West Germany – had now signed and ratified the NPT treaty. True, India and probably Israel too had acquired nuclear weapons of mass destruction, 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. But when 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. In 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").

## International regimes – the views of different schools of thought

How much can and should states trust each other? The prerequisite for effective international cooperation is that the concerned parties, states and organizations, actually trust each other and do what they have promised to do. Pacta sunt veranda (pacts must be respected), in the classical formulation of

([38]) Theodore Hirsch, "The IAEA Additional Protocol. What It Is and Why It Matters." The Nonproliferation Review. Fall-Winter 2004.

Roman law, is the first principle that must apply if a cooperation is to function. The concerned parties must adhere to what they have promised. This may seem obvious. And it probably is when it comes to entering cooperation treaties of a more peaceful and politically less controversial nature, whether they concern commercial or purely infrastructural matters. Most states have agreed on certain international rules governing the sending, for example, of a letter from country X to country Y. This system works pretty well, as we all know, but we also know that letters do not always reach their destination. But when it comes to issues of more decisive importance, such as security and the survival of states, opinions differ on whether or not it is a wise course of action to trust the commitments of other countries and enter into a comprehensive cooperation. States and governments often have different estimations of the possibilities of cooperation.

Within the field of International Relations there are different schools of thought which study the possibilities of cooperation in the international system from different perspectives. The realist school, which to a large degree dominates research in security studies, takes a very critical position with regard to increased cooperation in the domain of security policy. Theoreticians with a realist perspective consider it dangerous to relinquish political independence in exchange for security by forming an alliance with other states or by participating in a supranational system. The reason it is dangerous, according to the realists, is that other states cannot be fully trusted when it comes to serious security issues where the survival of nations may be at stake. When push comes to shove, heads of government may bluff, saying one thing while meaning another. They may exaggerate certain aspects of their defensive capabilities in order to gain the upper hand in negotiations aimed at creating a security alliance, but renege on their commitments once a military conflict is imminent. In addition, governments can be exchanged, which increases the risk of military cooperation treaties being broken. This problem with the difficulty of discerning the other party's true intentions or how it may react in a certain situation has, by some researchers, been termed the *security dilemma* ([39]). If a neighboring state acquires a stronger air force, is this done for reasons of self-defense or is the state in question preparing a military invasion? This is difficult, if not impossible, to determine, most realists would contend. States have a tendency to interpret other states' intentions in a negative light, and more often than not this leads to a situation where the military preparations of one nation provokes neighboring countries into rearming themselves. According to the realist view, international relations are anarchic in nature. There is no and never will be any truly functioning supranational entity, which can act as both judge and policeman in international politics. Even though organizations such as the United Nations and the European Union exist, they do not have the political power required to implement the measures needed to create an effective international order.

But how and by what means can international security be achieved, according to the realists? Even though there are different types of realism, with somewhat different views of the possibilities for international cooperation in the security domain, one can speak of three main elements that run through all realist currents. Firstly, the *state* is the central entity, the actor, which acts and exerts power and influence in the international system. This task cannot be assumed by supranational organizations, according to the realist view. The state maintains order both inwardly and outwardly, and if the state is unable to produce security for its citizens, there is no stable and functioning social order. For security is indeed the primary task in building a functioning society, the realists maintain. Secondly, the principle of survival is common to all realist currents of thought. The primary objective of states is to survive in the anarchic competition between nations in the international system. Realist thinkers differ, however, on whether or not this striving for survival also encompasses, besides security concerns, a drive to maximize one's own power in the international arena. *Offensive realists* claim that such a drive is immanent in all states and that the ultimate goal is to achieve *hegemonic* power (a sovereign

([39]) Kurt Hertz was the scholar who developed the concept in an article titled "Idealist Internationalism and the Security Dilemma" in the review World Politics, 2(2) 1950.

dominant position) in the international system ([40]). Evidently, not all states can achieve a position of hegemony. The competition among states in the international arena, where they act on the basis of their influence in terms of military, political and economic resources, creates a hierarchical order. With a slight simplification, we might say that states achieve the position they deserve in the international system, in the view of the offensive realists. Defensive realists, on the other hand, maintain that states only seek power in order to satisfy their need for security ([41]). The third main element in the basic realist view of international relations is the principle of self-help. The security dilemma produces insecurity and a lack of faith in the possibilities for a widened cooperation with other states, leading states to conclude that ultimately, each state has to rely on its own capacity to guarantee its security. The means for doing this are power and influence, and the national interest is always the fundamental underlying motive behind the actions of governments and countries. The driving force behind foreign and security policy decisions is not idealistic motives, such as the will to protect human rights or promote democracy, although modern states often describe their actions in such terms. And when one party acquires power and influence, it is always at the expense of another. States compete against each other in a game based on the principle of relative gains; cooperation, therefore, cannot produce two or more winners at the same time. To be sure, there are some realists, the so-called *neorealists,* who maintain that cooperation can be worthwhile, within the framework of alliances and international regimes (see below). There are, however, limits to how far a state should go in terms of cooperating with other states. The three principles of realist thinking described above can never be abandoned: namely, the principle of the state being the primary actor in the international arena, the principle of survival and the principle of *self-help.*

In contrast to realist thinkers, liberal schools of thought hold that cooperation entails payoffs. The first variant of this school of thought, *liberal internationalism,* emphasizes the possibility of widening the social contract between individuals, in the form of laws and standards within states, so that it will also encompass relations between states. In the same way that a state governed by law, with its civil society, democratic institutions, police-system, courts and other authorities, creates safety and order for its citizens, so the regulation of international relations can produce security among states. The essence of this liberal perspective is the idea that there is a natural order that produces freedom and security, and that this will come about if only the right conditions are created for people and states. If more and more states decide to create common rules in the form of a system of legal rights and obligations, the world will have become a more secure place. Eventually, a world community can come into being, one in which principles of international law and international treaties and conventions regulate the international system. Liberal internationalism can be said to have grown out of the enlightenment tradition with its strong belief in making use of reason to set things right in the human world. In this case, it is a matter of regulating relations among states so that peace and cooperation can be maintained. The German philosopher Immanuel Kant, who wrote the book, *Eternal Peace,* is one of the seminal figures of this current of thought. In this book, Kant talks about how the lawless barbarism of international relations can be overcome in a new era of enlightened, republican rule, in which principles of constitutionalism, and civic and other rights are made to become the guiding stars of the affairs of nations.

Liberal internationalism had an upswing in the international security debate in the wake of World War I, when a new collective order of peace was to be created, which resulted in the forming of the League of Nations. Realists have criticized, from different angles, what they regard as the liberal internationalists' naïve faith in a natural order and the power of reason to bring about peace and security

([40]) On offensive realism, see John Mearsheimer, "Back to the Future: Instability After the Cold War," International Security, 15:1, pp. 5-56.

([41]) On defensive realism, see e.g. Kenneth N. Waltz, Theory of International Politics. Reading, Mass.: Addison-Wesley, cop. 1979; Man, the State, and War: a Theoretical Analysis. New York: Columbia University Press, 2001.

among nations. They have pointed to the many violent conflicts of the 20th century, including two world wars, and it can be said without exaggeration that the influence of liberal internationalism declined already during the 1930s, when Hitler's power aggrandizement tore apart the collective security arrangements built up around the League of Nations. Since then, the realist school has largely dominated both the actions of states and the academic debate. However, more liberal interpretations of international relations received a boost after the peaceful dissolution of Soviet communism. Liberal pundits maintained that the peaceful disappearance of Soviet communism demonstrated that the basic realist view of the regular occurrence of military conflict was incorrect.

Moreover, liberal pundits and scholars pointed to the long period of peace in Western Europe, which also seemed to go against the realist view of military conflict as a natural part of the human condition. All in all, liberal theories enjoyed an upsurge in the wake of the disappearance of the bipolar Cold War world in the early 1990s. New interpretations of liberal ideas gained more scope in the ongoing discussions of international relations.

In recent years, a theory springing from the tradition of liberal internationalism has become highly influential in the international security debate, viz. the "democratic peace thesis," or "separate peace" as it is also called. In this line of research, political scientists and historians have investigated whether there is any connection between propensity for conflict and type of society ([42]). And according to the studies carried out in this line of research, there is a pronounced connection of this sort which may be summarized in two points:

- Democratic states do not go to war against each other
- The less democratic a regime is, the more serious is its violence against other states

And the self-evident conclusion, according to this perspective, is that we need to increase the number of democratic states in the world. The "democratic peace thesis" has stirred up a lot of debate, and several of its critics have put forward other possible explanations for the "long peace." For example, realists have maintained that the balance of power and nuclear weapons are likelier reasons for the fact that no war has broken out in Europe (with the exception of the wars in former Yugoslavia) since 1945. Others have suggested that the modern world has created an economic and political interdependence between states, regardless of whether or not they are democratic, and that this in and of itself has led to a tendency on the part of states not to use violence as a solution to international conflicts.

Thinkers within the liberal idealist camp are skeptical of the idea of a natural order in the form of principles and standards which may be transferred from the national to the international level. Needless to say, it is desirable to have an order that can bring about peace and security in the international system, but such an order must be actively constructed, and it must be based on historical experience. US president Woodrow Wilson's ideas about a collective security system, which were presented before Congress in 1918, is the most famous example of an attempt to establish such an order. Wilson's idea was carried into effect through the creation of the League of Nations in 1920. The League of Nations was founded on the principle that one nation's security was the concern of every other nation, and that all member states would agree to a collective system of sanctions. This collective arrangement became a great fiasco when the League of Nations proved unable to check the power aggrandizement of Nazi Germany during the 1930s. The organization collapsed in connection with Nazi Germany's reoccupation of the Rhine valley in 1936. A number of states withdrew from the League of Nations in reaction against the organization's failure to uphold the collective security.

([42]) See e.g. Bruce Russet, Grasping the Democratic Peace: Principles for a Post-Cold War World. Princeton: Princeton University Press, 1993.

A modern interpretation of liberal internationalism can be found in David Held's book, *Democracy and the Global Order,* in which he argues for the creation of regional parliaments and a reformed United Nations with expanded powers as a means to create a functioning supranational order ([43]).

A third line of thinking within the liberal school is called *liberal institutionalism,* which may be said to have developed as a reaction against the idealists' failure in creating a powerful League of Nations. To construct an international order by having states join a collective security system is not enough, according to adherents of liberal institutionalism. States must also become integrated with each other at many different levels, economically, politically and culturally, in order for them to become interdependent. Cooperation in one area often leads to cooperation in other areas, and the closer states can be tied together, the less is the risk of war between them, according to this liberal argument. This line of thinking accepts the realist view of the international system as anarchic, but this does not mean that cooperation is not worthwhile. In fact, cooperation can reduce the anarchic element in the international system and create mutual dependence based on common values, and this makes it possible to implement sanctions against states who break these agreed upon rules. Liberal institutionalism is also the current of thought that is most closely associated with the concept of international regimes.

More specifically, what is an international regime? Broadly speaking, it is a new form of cooperation that has evolved at the international and supranational levels since World War II. The purpose of these international regimes, which are based on states' convergent interests on one or more issues, is to create and maintain a common system at the regional or global level, characterized by a common set of norms, rules and values. These systems are upheld by states through different kinds of legal or non-legal agreements aimed at achieving the objectives of the international regime in question. In the nuclear non-proliferation field, we have the NPT treaty and various types of export control regimes, which singly or together constitute established systems designed to prevent the spread of nuclear weapons.

Naturally, there are different definitions of what constitutes an international regime. One definition, starting from a critique of the neorealist view of international cooperation, emphasizes the ability of states and regimes to act beyond the reach and independently of the power and influence of a great power, a so-called hegemon: an international regime "could exert an autonomous influence on the actions of states – even in the absence of a hegemon." ([44])

According to neorealist theory, by contrast, an international regime can only function if a militarily strong state, in the form of a hegemonic force, forms part of the system. There must be a strong state that can guarantee that sanctions of different kinds can be instituted if any party violates the norms and rules of the regime.

Perhaps the most commonly used definition of an international regime is Stephan Krassner's: "Set of implicit principles, norms, rules, and decision making procedures around which actor's expectations converge in a given area of international relations." ([45])

This definition has also been criticized for being too wide and vague ([46]), and also for being applicable only to economic cooperation. One of the neorealists' arguments against liberal institutionalism is that its adherents equate economic cooperation with cooperation in the domain of security policy. This is mistaken, according to the neorealists, for the simple reason that states do not take big risks when it

([43]) David Held, Democracy and the Global Order. From the Modern State to Cosmopolitan Governance. Stanford University Press. Stanford, California 1995.
([44]) J.G. Ruggie, "Multilateralism: The Anatomy of an Institution," in Multilateralism Matters: The Theory and Practice of an Institutional Form. Ruggie (ed.), New York, Columbia University Press, 1993, p. 3.
([45]) Krassner 1983.
([46]) Levy et al., "The Study of International Regimes," p. 270, European Journal of International Relations, 1995.

comes to the survival of societies or nations. History has demonstrated that agreements entered into may not mean much when a conflict escalates into war. And if the international regime is made up of states who are not sufficiently covered by the guarantees of a great power to act against nations who break the common rules, then this system will not function well when inner or outer pressure starts building up, neorealists maintain.

Although neorealists and liberal institutionalists differ in many respects, they can be said to be in agreement on the following principles as applying to an international regime:

States act in an anarchic system;

States are rational and coherent actors;

States are the entities responsible for the setting up of regimes;

Regimes promote order in the international system ([47]).

In current research, one can distinguish three explanations, all with some validitity, for why states establish and maintain international regimes ([48]).

The power-based explanation is put forward by neorealists. These theoreticians claim that the main motive force behind the construction and upkeep of international regimes arises when states are not capable of acting alone and independently and, for this reason, are obliged to cooperate with other nations. The regime is created for the purpose of dividing and prioritizing power between the member states in order to achieve the objectives decided upon by the regime. Since there is not and cannot be any functioning central authority above the states which would regulate transactions in the international system, the states themselves must deal with such matters and assume responsibility for them, according to the neorealists. Therefore, on certain issues, states join forces by forming international regimes in order to achieve certain objectives that have been formulated by the regime in question. Even though there is some evidence to support this hypothesis, subsequent research has found that the power-based explanatory model is becoming less and less relevant in today's world ([49]).

According to the knowledge-based explanation, the driving force behind the creation of international regimes is neither power ambitions nor common interests; rather, these regimes develop in negotiation situations in which both divergent and convergent interests affect the outcome. It is primarily ideas and knowledge that motivate states to act and create international regimes ([50]).

The interest-based explanation is advanced by liberal institutionalists. According to them, it is not the will to maximize one's own power that motivates states to join together in international regimes; instead, these control regimes, in and of themselves, create common rules of the game and norms which result in convergent interests. As a result, certain types of behavior are rewarded. There is one way out of the anarchic international system highlighted by the realists; the solution is to be found in the establishment and maintenance of international regimes which are based on long-term cooperation resulting in an autonomous influence on the actions of states. And this can happen without a hegemonic state being associated with the regime. Most of the research that has been done on international regimes seems to point to the interest-based explanation as the most valid one ([51]).

([47]) Little, R., "International Regimes," in The Globalization of World Politics. An Introduction to International Relations (ed), Baylis, J, Smith, S, New York, Oxford University Press 2001.

([48]) For an extensive discussion of the regime theory and its relation to different forms of cooperation in the export control field, see Ahlström, C, The Status of Multilateral Export Control Regimes. An Examination of Legal and Non-Legal Agreements in International Co-Operation, Uppsala, Iustus, 1999, p. 86 et passim.

([49]) O.R. Young & G. Osherenko, "Testing Theories on Regime Formation," in Regime Theory and International Relations. Rittberger (ed.), Oxford: Clarendon Press, 1993, pp. 223-251.

([50]) Ahlström, pp. 87-88.

([51]) Ahlström, p. 87.

How, then, can one explain the process which, according to liberal institutionalism, results in states' abiding by the principles and norms constituting an international regime? The theory is based on the assumption that the principles, values and norms of the regime can come to represent an independent factor in the international system, which subsists even if the power relations between certain states change. This means that a control regime can function in the absence of supranational control or the maneuverings of a hegemon, and this is because the objectives and purpose of the regime coincide with the rational and utilitarian self-interests of the participant states. This phenomenon, the so-called independent factor in the international system, has also been termed "governing without governance," an expression describing the absence of governance and regulations emanating from a supranational authority ([52]). The participant states abide by the purposes of the international regime since they, quite simply, gain by doing so. Their behavior in this regard can be seen as a form of expanded self-help (to use one of the key realist concepts). A functioning order can thus be constructed and maintained, but it exists between states, not above them. According to the liberal institutionalist perspective, realists look upon the possibilities of cooperation as if it only pertained to a single act in an isolated situation; one party gains power and influence at the expense of another.

Cooperation within the framework of an international regime cannot, however, be understood from this extremely shortsighted perspective, liberal institutionalists assert. It is more a question of a process, consisting of different forms of cooperation, both formal and informal in character, from which all participants can draw advantage since they have convergent interests. Against this background, international regimes may more accurately be seen as a multitude of actions within the framework of a cooperative arrangement in which the parties have abandoned the shortsighted perspective based on the principle of relative gains, and instead adopted a more long-term strategy where the parties give and take and everyone gains in the end. This process results in a binding cooperation between states, which of course means that the members of the regime relinquish some of their independence and potential influence. This partial relinquishment of independence is accepted, however, because the gains are believed to outweigh the losses. The obligations that an international regime entails can either be of a formal or a more confederative character, but in either case they share certain features which are typical of international regimes:

They reduce states' freedom of action, sovereignty, autonomy and room to maneuver;

They increase the cost of withdrawing from the cooperative framework of the regime;

They reduce the likelihood of violations against or defections from the regime ([53]).

When it comes to control regimes concerning weapons of mass destruction, there is no single comprehensive regime today covering all relevant areas. Today there are three main groups: 1) Nuclear weapons; 2) biological and chemical weapons; and 3) missile technology. Each separate main group consists of different arrangements which are all aimed at increasing the control and reducing the spread of the specific materials and equipment itemized within the regime. This is the overarching and coincident interest that binds the regime together. Participating in a regime also entails other coincident interests and advantages, however, namely that the members gain access to "listed" technology and different types of controlled materials for peaceful use. For example, in the nuclear weapons regime member states have a right to conduct trade in classified nuclear materials and the equipment associated with peaceful development of nuclear energy. This exclusive right is accorded participant states since they have promised to abide by the objectives of the regime, i.e., to prevent the spread of nuclear weapons,

([52]) P. Mayer, V. Rittberger, & M. Zürn, "Regime theory: State of the art and the perspectives", in Regime Theory and International Relations. Rittberger (ed). Oxford: Clardon Press, 1993, pp. 391-430; J. N. Rosenau,, "Goverance, order, and change in world politics", in Governance without Government – Order and Change in World Politics. Rosenau & Czempiel (ed), Cambridge: Cambridge University Press, 1992, pp. 1-29.

([53]) K. Weber, "Hierarchy amidst anarchy: A transaction costs approach to International security cooperation", International Studies Quarterly, 41, 1997.

and because this right can be perceived as an incentive for nations to commit themselves to a binding cooperation. These two motives – to prevent proliferation while allowing states access to the controlled materials and equipment – have produced and continue to produce a range of interpretative problems that must be sorted out legally, politically, and practically in order for the control regime to be able to function. All products covered by the nuclear weapons regime are not one-dimensional enough that they can only be used for nuclear weapons production ("single-use"). In fact, the technology, equipment and basic fissile material used can be largely the same in both a military and a civil (peaceful) nuclear energy program. Products and equipment are said to be of "dual use." In order to manage these opposing interests and achieve a functioning practice that both prevents nuclear-weapons proliferation and promotes trade in civil nuclear energy, a number of different regimes have been established. Taken together, these regimes can be viewed as a system that has evolved step by step as new problems have arisen or new discoveries have required specific solutions. In this sense, one can say that new regimes in the nuclear weapons field have been set up to solve problems that the older regimes have not been able to deal with. These different regimes are based on diverse cooperative arrangements. There are three main kinds of agreement underlying international regimes.

**The explicit legal agreement.** In this case, it is a matter of agreements that have been signed and ratified and that are legally binding. The NPT treaty is an example of such a multilateral agreement which is unambiguously binding in a legal sense, and which also has inbuilt sanction instruments that can be applied if any party breaks the agreement. It is important to note that the NPT treaty is not the only legally binding agreement aimed at preventing the spread of nuclear weapons. There are several geographically circumscribed treaties the purpose of which is to create nuclear-weapon free zones: The Treaty for the Prohibition of Nuclear Weapons in Latin America and the Caribbean (Treaty of Tlatelolco); the South Pacific Nuclear Free Zone Treaty (Treaty of Rartonga); the Treaty on the South East Asia Nuclear Weapon-Free Zone (Treaty of Bangkok); the African Nuclear-Weapon Free Zone Treaty (Treaty of Pelindaba). These treaties are designed to prevent the spread and use of nuclear weapons within the regions concerned.

**Explicit non-legal agreements.** Most international regimes do not have the same formal, legal character as the NPT treaty, for example. It is not a matter of legally binding agreements which trigger specific sanctions if the rules of the game agreed upon are broken. These regimes are based on a political cooperation involving a commitment on the part of the participant states to abide by the values, norms and rules established by the regime. By participating in the regime, states have accepted the obligation to reform their national regulatory systems – laws, practices, regulatory bodies – in accordance with the goals and purposes of the regime. But – and this is the crucial difference from the legally based regime – the participant states do not relinquish any decision-making power to the regime. Further, there exists no legally binding agreement in this type of regime that can result in the imposition of international sanctions against a state that violates the rules and values of the regime. It is a political, not a legal, undertaking.

# Nuclear Material Subject to Safeguards

Greet Janssens-Maenhout

## 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 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 A = N + Z. Z and A determine completely the nuclide X, written as ${}^{A}_{Z}X$ or as X-A (because the chemical name X refers unambiguously to Z, e.g. U-235, Pu-241, …). 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. U-233, U-234, U-235, U-236, U-238)
- Isobars: These are nuclides with the same atomic mass number A, but with a different atom number Z (e.g. C-14 and N-14)
- Isotones: These are nuclides with the same neutron number N. (e.g. Np-239 and U-238)

### *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.

- 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 mol C-12 weighs 12 g and 1 u = 1.66043 $10^{-27}$ 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.
- One mole of a nuclide is that quantity as 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 C-12 weighs 12 gram. One mole of a compound material contains also $N_A$ atoms. Example: One mole U-235 weighs 235.044 g and contains 0.6022045 $10^{24}$ atoms U-235.
- 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 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 with 931:478MeV

| | Proton | Neutron | Electron |
|---|---|---|---|
| Mass (u) | 1.00727663 | 1.00866540 | 0.00054897 |
| Charge (e) | +1 | 0 | -1 |

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

In fission reactions mass is converted into energy. Whereas protons and electrons are stable particles, a neutron is only stable as a particle bounded 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 min. 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,

in the 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 $A^{1/3}$ leading to 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 constant. The atomic nucleus shows therefore approximately a constant nucleon density. These observations are similar to those with liquid droplets, that 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 remarkable that some atomic nuclei show a 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 analogeously the existence of proton – proton forces. The very small distances within the nucleus, of the order of $10^{-14}$ m lead to 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 eachother'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 = Zmp + Nmn – m

with mp, mn, and m the mass of a proton, a neutron and the nucleus under consideration. The mass defect corresponds according to Einstein's relation to a certain quantity of energy delta m $c^2$, 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 binding energy B.E. is expressed in MeV and the mass defect delta m in u, then is: 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 U-235 equals: delta m = 92 . 1.007825 + 143 . 1.008665 – 235.0439 = 1.915u and so is B.E. = 1784MeV 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.

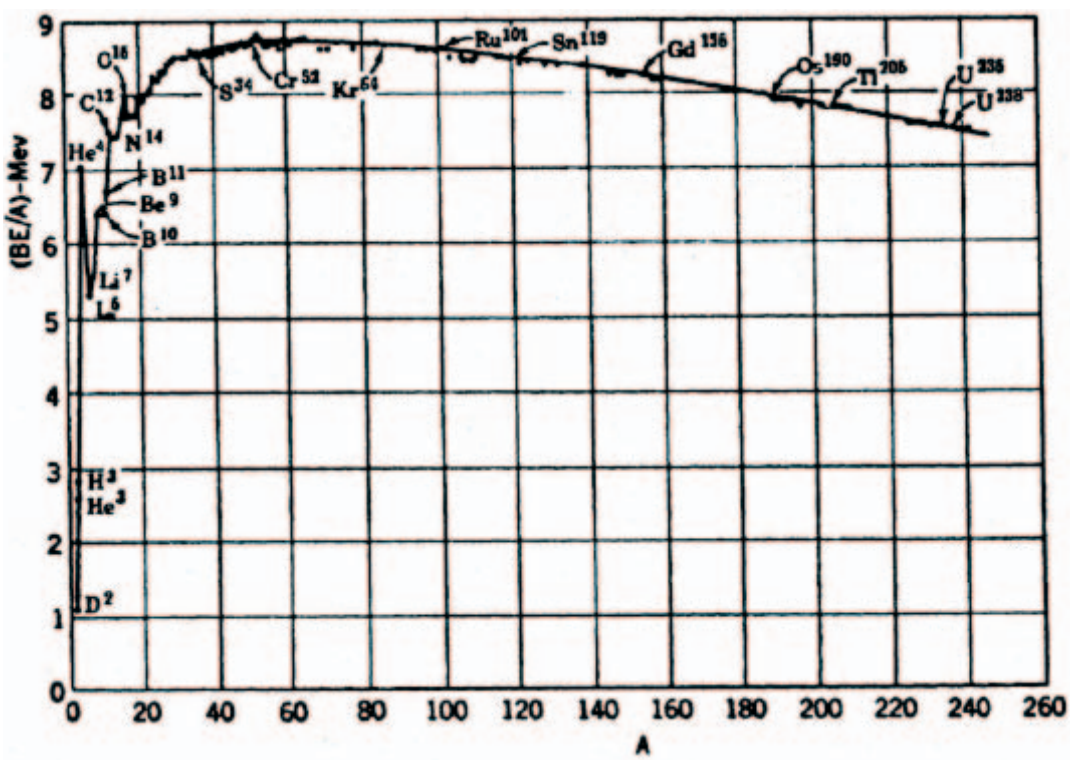


*Figure 1:* Binding energy in MeV per nucleon in function of mass number A

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 bounded more strongly, are energetically of benefit, because the nucleon configuration evolves to a larger stability. In a fission reaction a heavy nucleus (U-235; Pu-239; …) 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 with more strongly bounded nuclei 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 $A(A-1)$ or $A^2$. The binding energy per nucleon would be almost proportional with A, which is clearly contradicted in Fig. 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. An analogon with the droplet model can be considered: the nuclear forces can be compared with the molecular forces of a liquid droplet. The nucleons in a nucleus are bounded 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 experience a surface tension). This needs a correction that is proportional with the number of nucleons that are localised in the boundary zone (surface) of the nucleus (sphere), i.e. proportional with $R^2$ or $A^{2/3}$, which is introduced as 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 and the neutron-neutron nuclear forces. The abundant number of neutrons A-2Z can not 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 can not 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 be also noticed in Fig. 2 that represents the nuclide chart with Z in function of N.

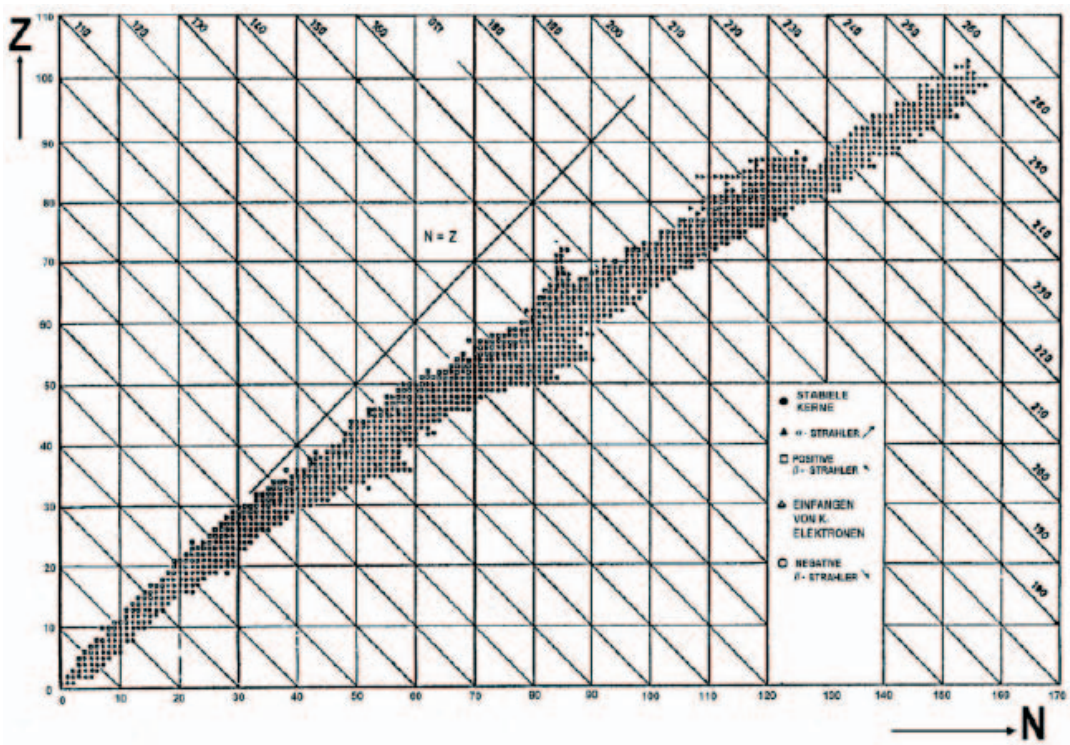


*Figure 2:* Chart of stable and radioactive nuclides

# 3. Excitation and decay of nuclei

## *3.1 Excitation state of a nucleus*

The previous concerned nuclei in their ground state. A nucleus can be also in an excited state, similar as an atom can. In the 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 or 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 an nuclide of different type, called daughter nuclide and is characterised by a decay constant. The decay constant lambda is the mean probability rate of nuclides decaying per second. Experiments demonstrated that lambda 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 have disappeared. Half of the nuclei 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 of this material per second: 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 second. 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 artificial 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 supposition that radioactivity was caused by the capture of neutrons, and so of isotopes of uranium. German radiochemists, O. Hahn, F. Strassmann and L. Meitner proved by chemical analyses in 1939 that the radioactivity was caused by much lighter elements than uranium. This meant that uranium was split under the neutron bombardment. Very fast it was realised that the fission of uranium releases energy and neutrons, with which by means of a chain reaction a new energy source can be generated. 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 → c + d or a(b,c)d. The nuclear reactions are determined by four fundamental conservation law:

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, since 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 $\alpha + \beta \,!\, \chi + \delta$ is this $\mu_\alpha\chi^2 + KE_\alpha + E\xi_\alpha + \mu_\beta\chi^2 + KE_\beta + E\xi_\beta = \mu_\chi\chi^2 + KE_\chi + E\xi_\chi + \mu_\delta\chi^2 + KE_\delta + E\xi_\delta$ with $\mu$ the mass of the particle; KE the kinetic energy of the particle, $E\xi$ the excitation energy of the particle.

The Q-value of a nuclear reaction is defined by $\Theta = (\mu_\alpha + \mu_\beta)\chi^2 - (\mu_\chi + \mu_\delta)\chi^2$

For a fission reaction: ${}^{235}_{92}U + 1\ {}^{1}_{0}n \rightarrow {}^{98}_{42}Mo + {}^{136}_{54}Xe + 2\ {}^{1}_{0}n + 4\ {}^{0}_{-1}B$ the Q-value is determined by delta m = 0.22047u and so Q = 205.4MeV. 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 from about A≅50 onwards decreasing with increasing mass number A (see Fig. 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 bounded. 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 that nuclides with $Z^2/A > 50$ do not (no longer) occur in nature.

The droplet model helps to understand the fission phenomenon. A schematic representation is given in Fig. 3. Starting from a spherical nucleus (Z,A) with radius R (a) fission is induced by deformation and two (spherical) nuclei (Z1, A1) en (Z2, A2) with respectively R1 and R2 as radius (e) are created. Between (a) and (e) the splitting nucleus undergoes various deformation state, as shown in Fig 3. Only if the deformation is large enough the ellipsoid might be tied up and consecutively breaks up in two parts, which fly apart by the repulsive Coulomb forces.

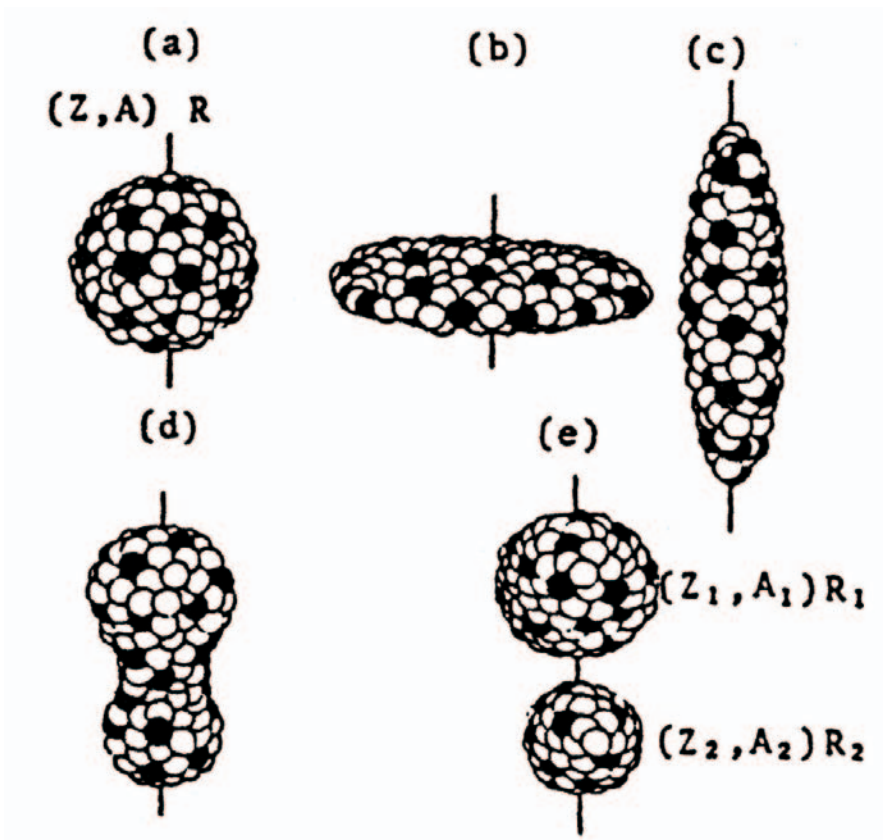


*Figure 3:* Deformation states of a nucleus which induce fission

Three different zones for the energy state of the splitting heavy nucleus can be distinguished during deformation, as shown in Fig. 4.

- Zone 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.
- Zone II: This is the transition zone 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 Fig. 3, where the deformed nucleus becomes tied up.
- Zone III: The energy state in this zone is only determined by the classical Coulomb potential between the charged fission fragments. Nuclear forces do not play any longer a role because of their short range (in the order of $10^{-14}$ m).

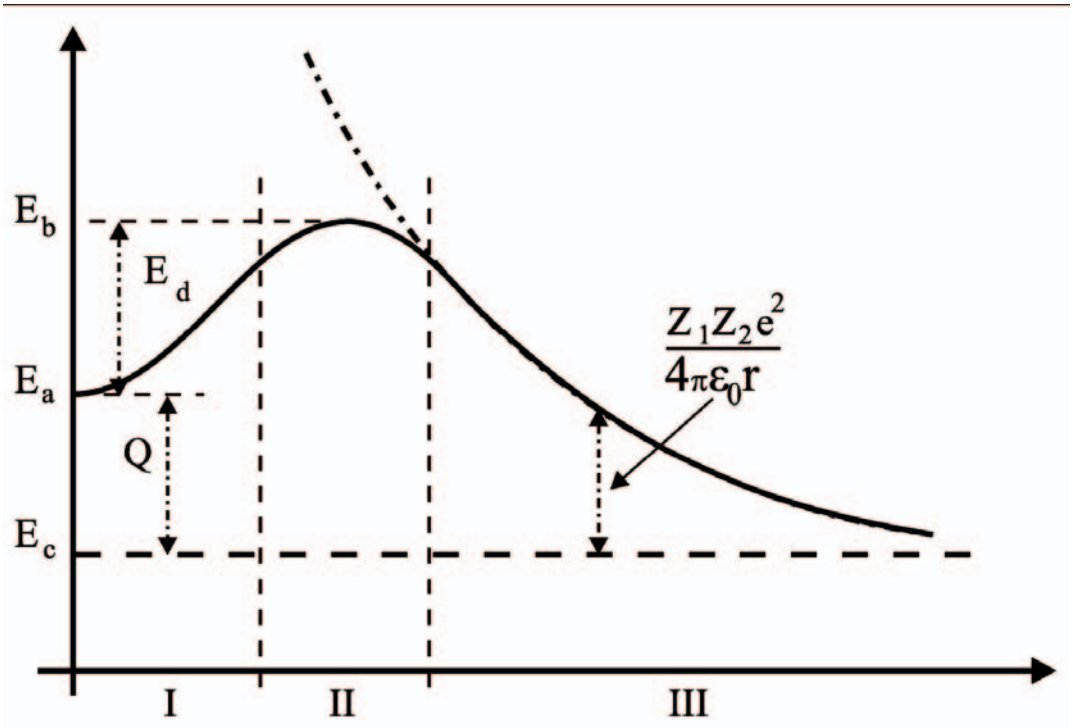


*Figure 4:* Energy state of a nucleus in function of the distance between the two fission fragments

A positive Q-value $\Theta = E_\alpha - E_\chi$ means that the fission is exothermic. However, the fission is therefore not spontaneously initiated. In the case of Fig. 4 and conform to the concept of classical potentials, a minimal excitation energy $E_d$, $E_\delta = E_\beta - E_\alpha$, 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 Ed impedes that heavy nuclei fission spontaneously. 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 be split if it is supplied an excitation energy which is larger than the threshold $E_\delta$. 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 Μες: On the other hand is for uranium the threshold about 6 Μες, so that 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)*. 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 in direct vicinity of the nucleons starts experiencing 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 Ex, which equals the binding energy En of this latest neutron in Μες given by $E_v = 931;48\ (\mu_A + \mu_v - \mu_{A+1})$. 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 ≅ 230 à 240) the binding energy En varies around 6MeV with a variation of about 0.5MeV. 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 En > Ed , 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: U-233; U-235; Pu-239.)
- If $E_n$ < Ed, then the absorption of a thermal neutron does not induce fission. Supplementary 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 $E_x$ > Ed then fission occurs, which is called fast fission. The energy $(E_d - E_n).(A + 1)/A$ is called the kinetic threshold energy of the neutron to induce fission. Nuclides for which this kinetic threshold energy is larger than zero, are not thermally fissionable. (Example: U-238: 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 to classify 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 U-233, U-235, Pu-239, of which only U-235 has a natural abundance.

* The asteriks indicates that the nucleus is in an excited state.

- 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 U-238, Th-232, Pu-240, of which U-238 and Th-232 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 they are by absorption of one or more neutrons transformed directly or indirectly into a fissile nuclide. Examples of fertile nuclides are U-238, Th-232, Pu-240 because the capture of one neutron leads to the formation of the fissile nuclides Pu-239, respectively U-233 and respectively Pu-241.

The most important reactions are presented in Fig. 5.

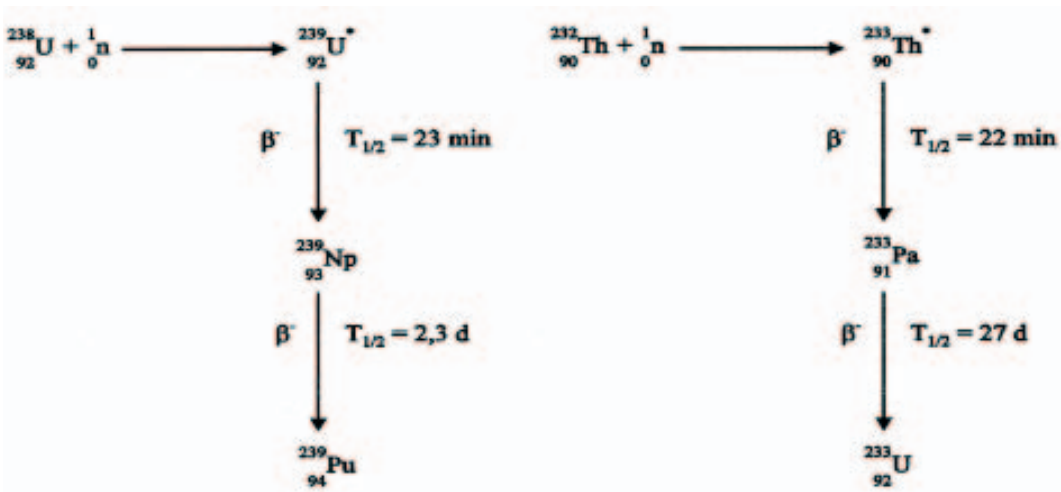


*Figure 5:* Formation of fissile nuclides from fertile nuclides

# 5. Experimental observations of nuclear fission

Experiments on fission induced by neutrons with an 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 broken up into mostly two fragments, the fission fragments. Since the fission is characterised by two fragments, it is called 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 fulfill 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 $\beta^-$-decay to a stable N/Z-ratio. By $\beta^-$-decay a neutron is exchanged for a proton and a electron accompanied with an antineutrino

- About 4/5 of the energy that comes free at the fission is released as kinetic energy of the fission fragments. The quantity of energy released by splitting a U-235 nucleus depends on the way of splitting. In example 2 of section 4.1 the Q-value was 205.4MeV. Although this fission reaction is not at all unique – many possibilities for splitting 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, free 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 from all fission neutrons that are emitted, just one is again inducing one other fission, 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 0.6 %), is emitted with a certain delay in time and are called delayed neutrons.

- The total number of prompt neutrons emitted varies with the way of splitting of the nucleus, and with the excitation energy of the fission fragments and may vary from fission to fission between zero or sometimes five or 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 U-235 split by a thermal neutron is n typically 2.4.) As a consequence of the large diversity of possible fission reactions, the kinetic energy of the prompt neutrons shows a continuous spectrum, the so-called fission spectrum ψ(E). This spectrum is defined such that ψ(E)dE represents the fraction of fission neutrons with an energy between E and E + dE. Experimentally the fission spectrum is very little dependant on the split nuclide and on the energy of the neutron that induced the fission. It shows typically a most probably energy value of 0.72MeV and an averaged energy of 2MeV.
- Although the fraction β of delayed neutrons is small (about 0.0065), 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 $\beta^-$-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 $\beta^-$-decay of the mother nuclide.

## 5.2 The energy production and burn-up

The energy produced by fission that can be recovered is about 200MeV 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 the fission fragments move is very short (about 10-5 m).
- he range the neutrons travel is relatively long (> 0.1 m) but of benefit because they are re-used in a reactor to maintain a chain reaction

- The range the β-rays penetrate is short (in the order of the thickness of an Al foil).
- The range the γ-rays penetrate 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.

| 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*** | 8 MeV | 8 MeV | <0.1cm delayed |
| ***– γ-radiation*** | 7 MeV | 7 MeV | <100cm delayed |
| ***– neutrinos*** | 12 MeV | — | >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*** | 212-217MeV | 195-200 MeV | |

*Table 2:* Generated and recovered energy at the thermal fission of a U-235 nucleus

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

1MWth. The thermal production of 1MWd therefore needs about 1gU-235 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 MWdth. 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/t
- 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/t.

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 U-235). The enrichment in U-235 is determining the burn-up. Typical values are:

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

An exception is a fast reactor, which reaches easily 100.000 MWd/t and which even produces more fissile nuclides than they use. Their enrichment varies up to 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 U-235 there is only one symmetric.)
- For increasing $Z^2/A$ the yield curve remains symmetric 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 to remove 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 1ες 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 2Μες are scattered at the nuclei of the moderator to lose their energy until about 1ες:
- a fast reactor: in this case the fission neutrons are not slowed down and the fissions are mainly induced by neutrons with an energy above 1κες.

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 nowadays 17x17 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, zirconiumalloy, ...) are present in he 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. In the following is focused on a thermal (pressurised water) reactor.

In order to describe the neutron balance in a reactor, the consecutive important steps the neutrons undergo are modelled with different factors, as illustrated in Fig.6. The product of these factors is defining the multiplication factor κ. The different factors are:

1. the production factor ε: 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 abundantly also fertile nuclides. The fertile nuclides can also 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 of one thermal neutron
3. the resonance escape probability π:during the slowing down by scattering at 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 a fast neutron can be slowed down till it reaches a thermal energy. In this way η.ε.π 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 Λϕ: If the fast neutrons are approaching the boundary of the reactor core, they might leak away, which is taken into account for fast neutrons with the factor Λϕ.
5. the thermal non-leakage probability Λτη: Also the thermal neutrons might be localized at the boundary of the reactor core and leak away, which is in a similar way taken in to account by Λτη.
6. the thermal utilization factor ϕ : 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 utilization factor is defined as the probability for absorption of the thermal neutrons in the fuel.

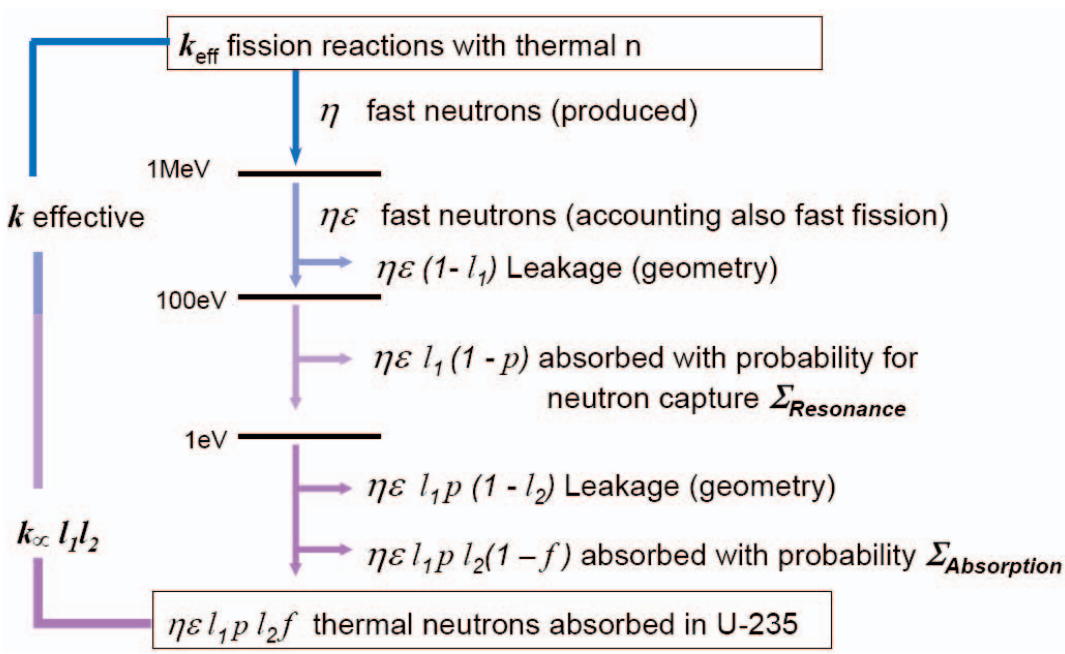


*Figure 6:* Neutron cycle in a thermal reactor (the Σəs are macroscopic cross sections, indicating the probability for being captured)

The total effective multiplication factor κεϕϕ is given by κεϕϕ / η ∀ π ϕΛϕ Λτη and the neutron-kinematics of a reactor can be characterised with κ: If the reactor has:

- κεϕϕ = 1 a stationary behaviour is present, the neutron population remains constant and the reactor is critical (controlled chain reaction)
- κεϕϕϕϕ > 1 the neutron population is increasing and the reactor is overcritical (This is also the case of an atomic bomb)
- κεϕϕ < 1 the neutron population is decreasing and the reactor is subcritical (This is also the case when shutting down a reactor)

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 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 upon: its nuclear properties (e.g. the probability for absorbing a neutron and splitting, which is characterised with the nuclear fission cross-section) and physical properties (in particular the density), its shape and its enrichment. These consider a bare mass of fissile material free in air. Often such critical mass is surrounded with material at which boundary neutrons can reflect. This reduces the amount of fissile material needed for criticality.

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

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

The shape for a critical mass of fissile material with minimum volume is a sphere. The critical mass of this sphere can be typically further reduced with 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 50κγ for Υ-235 and 10κγ for Πυ-239. Bare-sphere critical masses estimated with 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% Υ-235 it is over 400κγ; with 15% Υ-235, it is well over 600κγ. 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 traveled to hit a nucleus is proportional to the density, so 1% more, which compensates that the distance traveled before leaving the system is 1% less. This is something that must be taken into consideration when attempting more precise estimates of critical masses of plutonium isotopes than the rough values given above, because plutonium metal has a large number of different crystal phases which can have widely varying densities.

The calculations need also accurate input on the number of prompt neutrons that are emitted by thermal fission, fast fission or spontaneous fission. In particular for Pu a relative high spontaneous fission probability of Πυ-240 (spontaneous fission rate reaches about 1.6 106 φισσιονσ=γ=ηρ according to Chamberlain et all.(1953)). This explains why weapons-grade Pu is defined in function of the Pu-240 content, i.e. Πυ-240<7% of the Pu-total mass. A too high percentage of Pu-240 impedes an easy accurate control of the initiation of a chain reaction.

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 and implosion. 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) at the other mass (the target). The Hiroshima weapon 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 the most foolproof.

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 Pu-240. 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 kilotons. 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 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. For these safeguards measures have been developed with quantitative goals, which are worked out in the following section.

# 8. Safeguards significant quantities

## 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 ([1]) 0.7% Υ-235) to a low percentage, 3-5%, in Υ-235. Light water reactors (pressurised water reactors, boiling water reactors) can not 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 gas-centrifuges and ultra-centrifuges. The enriching 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 U-235 component from the U-238 component in ΥΦ6 gases. 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 Υ-235 (over 93%), which is of use for 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 grade. For practical inspection the IAEA defined three categories of uranium that are under safeguards:

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

| ***Material*** | ***U-235 in LEU*** | ***U-235 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% | | | | |

*Table 4:* The three IAEA safeguards goals for nuclear material, that occur in the front-end of the fuel cycle

The IAEA safeguards goals for uranium nuclear material are defined underneath and Table 4 shows the restraining measures for higher enrichment of Υ. The significant quantity reflects the order of magnitude calculated to obtain a critical mass in the case of high enriched uranium. These goals aim to impede proliferation of the gun-type method uranium devices by timely and efficient detection of a possible diversion of a significant quantity of uranium material.

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

## *8.2 Significant quantity for the nuclear material of plutonium*

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

- Reactorgrade (RG) Pu is defined by Πυ-240 ≥18% of the Πυ mass
- Fuelgrade (FG) Pu is defined by 7% ≤ Πυ- 240 <18%;
- weaponsgrade (WG) Pu is defined by 3% ≤ Πυ- 240 <7%;
- ivory grade or supergrade is defined by Πυ- 240 <3%.

The introduction of mixed oxide fuel led to a special case of mixture of Πυ oxide with Πυ 20% of the mixture weight. Under the current scientific-political approach of safeguards goals, the isotopic vector of Pu is considered less important, except the presence of the nuclide Πυ-238. If Πυ-238 > 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 underneath in Table 5. Again the significant quantity reflects the order of magnitude calculated to obtain a critical mass in the case of high enriched uranium. 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 bred material.

| ***Material*** | ***U-233*** | ***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% | | | | |

*Table 5:* The 3 IAEA safeguards goals for nuclear materials, that are produced while breeding and are occurring in the back-end of the fuel cycle (supplementary to the ones already present in the front-end – listed in Table 4)

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# The basic principles of nuclear material management

Brian Burrows

## 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 been 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 well being 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 sur-

veillance 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 think 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

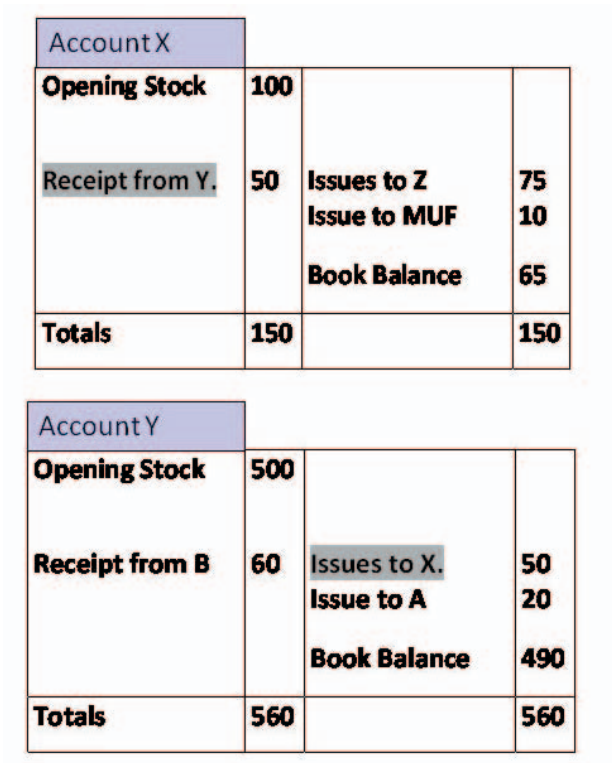
The fundamentals of NMA are that all events and transactions are recorded and that the system of material identifiers and recording allows a full batch tracking capability so that stocks can be derived. All these data have to be resolved into their elemental mass units and all the inventory items must 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 operendi 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.

# International Norms against Nuclear Weapons, an overview: Treaties, Conventions, Agreements and 'Initiatives' regarding non-proliferation of nuclear weapons, disarmament and arms control

Odette Jankowitsch-Prevor

## Introduction

The purpose of this paper is to provide a systematic overview on the relevant international norms, not limited to the subject of non-proliferation of nuclear weapons, but including the wider context.

The three subjects addressed, namely non-proliferation of nuclear weapons, disarmament and arms control, cover three originally discrete subjects that are based on different international norms developed by different fora, with a different history and different scope of application. 'Non-proliferation has maintained its original meaning ([1]) of prevention of the spread of [nuclear] weapons, nuclear weapons material and technology, as well as [the legal norm established to limit rightful possession of nuclear weapons to the five States designated as NWS by the NPT]. The concept of arms-control is now used interchangeably with 'arms limitation' and even with 'disarmament': It first meant, however, in the context of the cold war and the 'bipolar world', to denote the agreed rules established by two superpowers for the objective of limiting the [nuclear, strategic] arms race–essentially between them only.

Disarmament is understood as the [multilateral, or also unilateral] reduction of nuclear weapons, aiming at gradual elimination of all existing arsenals so as to achieve a nuclear-weapons-free world. Today, the three subjects are interlinked.

In essence, these are different approaches to the same issue: how to avoid nuclear catastrophe or, in the terminology of Chapter VII of the UN Charter the "threats to peace …"

The maintenance of peace and security as understood of recent by the international community requires a closer and more coherent examination of the three components of the common issue. Such analysis may be helped by a systematic review of the clusters of underlying norms, i.e. the different binding international treaties and agreements and other relevant understandings.

([1]) The term 'non-proliferation is not defined in the NPT nor in any other legal document. The Oxford Dictionary defines the verb 'to proliferate' as: "Reproduce itself, grow by multiplication of elementary parts.., produce cells" . Dictionnaire Larousse (French) gives a similar definition

# Relevance of the subject today:

Two separate developments taking place presently and upcoming in the near future, draw attention to the existing network of international treaty norms, their implementation, the verification mechanisms and, possibly, the need for added different instruments. These developments are:

(1) The ongoing preparatory work for the 2010 NPT Review Conference-. The First session of the Preparatory Committee for the Review Conference was held 2007,the Second session is scheduled to meet in May 2008:

*What are the major issues?*

Summarizing: Threats to the Non proliferation Regime; Dangers of 'erosion' of the Regime (as stated by the UN High level Panel); Cases in point are the still not fully resolved issues regarding denuclearisation of the DPRK; the non-NPT States with open or assumed NW programmes: India, Israel and Pakistan; the still not fully explained case of Pakistan's individual "proliferator" Q.A.Khan; doubts regarding the exclusively peaceful nature of Iran's nuclear programme; Libya's undetected nuclear programme, later abandoned, as was verified by the IAEA

(2) Expected new major development of civil nuclear power in a large number of States that have no 'nuclear power history' (notably several oil and gas exporting States, States in North Africa, Egypt, and in East Asia. And, also planned expansion of nuclear power installations in China, India, the RF, the UK, possibly the US and other States)

*Reasons for the intended expansion of nuclear power:*

The set of facts that are at the origin of this 'renaissance' of nuclear power are well known: Increased demand for energy worldwide; climate change and the need to reduce carbon emissions from fossil fuel; disputed benefits of bio fuels; need for continued research and development of nuclear technologies in view of its irreplaceable character; continuously expanding applications in medicine, industry, and agriculture…

In this context, the main concerns of the international community are:

- Will the existing norms aimed at prohibiting proliferation and at verifying effectiveness of State's compliance remain sufficient to prevent in the future proliferation by States and, by non-state actors?
- Will the original "Faustian " bargain of the NPT between the Nuclear Weapons States and the Non Nuclear Weapons States remain acceptable to all? Can it realistically continue to be implemented as is?

# Review of international norms

A network of binding international sets of norms?

- A. The Treaty on the Non-Proliferation of Nuclear Weapons, Treaties on Nuclear Weapon free Zones and regarding specific geographical regions. Verification and implementation norms and mechanism.
- B. Agreements aiming at comprehensive or at limited disarmament.
- C. Arms control agreements between individual-or groups of States
- D. Initiatives and Programmes to reduce the threat of proliferation of WMD

# A. Non-Proliferation

The overarching concept of non-proliferation of nuclear weapons has been implemented in different ways: By (i) the mandates given to intergovernmental Institutions, (ii) the Treaty based limitation of the number of NWS, and, (iii) the setting up of nuclear weapon -free regions and areas, as follows:

- "Atoms for peace" also means *no atoms for war*.

First agreements on the concept of non-proliferation were reached in the late 1950'ies: the setting up of Intergovernmental Organisations aimed at promoting-and-controlling the exclusively peaceful nature of uses of nuclear technology. Discouragement of military uses to be achieved by widely promoting research and practical application of "atomic energy" for health and prosperity worldwide.

- No new nuclear weapon States: Treaties NPT:

Late 1960'ies:a clear strong binding international norm to act against proliferation and at the same time limit the number of NWS ("engraved in stone "): multilateral, negotiated disarmament as a Treaty objective

- No further geographically defined space to be open for nuclear military activities:

Expand the regions [Zones] and geographic locations free of nuclear weapons and nuclear military activities: Negotiate and agree on nuclear weapon free Continents and nuclear weapons free areas

## A.I The Intergovernmental Organisations

### *IAEA (1957) The Statue (an international legally binding Treaty)*

Promote peaceful uses worldwide. Ensure that activities undertaken under its supervision, control or assistance are not furthering any military purpose; Control ['safeguard'] the exclusively peaceful nature of all uses of nuclear energy and technology.

***EURATOM (1958)*** Similar mandate on control of non-peaceful uses and contribution to beneficial applications and energy. (Legal title to nuclear material). Regional scope

Both Organisations include among their members Nuclear Weapon and Non Nuclear Weapon States

## A.II The Treaty on the Non Proliferation of Nuclear Weapons [NPT] 1968 (e.i.f. 1970)

Basic principles of non-proliferation: Achieve the objective of a nuclear weapon-free world through implementation of the key provisions of the Treaty:

- ✓ Set number of five NWS only -No new NWS. No legal provisions for recognizing new nuclear weapon States.
- ✓ All States to accept the historic 'bargain': For each NWS: the commitment to non-proliferation, as well as to nuclear disarmament to be negotiated 'in good faith'. For each NNWS: agree o accept through conclusion of a binding agreement with the IAEA (the Safeguards Agreement) specific controls /verification measures of peaceful uses only
- ✓ Civil nuclear development including research to be an 'inalienable right' for all
- ✓ Mechanisms for Treaty review by regular Conferences. Unlimited duration of the Treaty to be agreed by 1995
- ✓ However: no independent Treaty implementation mechanism foreseen; no monitoring by treaty bodies: "institutional deficit" [Role of IAEA]

*The NPT: agreement reached on an asymmetric treaty*

*The unique characteristic of this Treaty is that it recognizes the existence of two distinct categories of States with different rights and different obligations. These States are (a) the Nuclear Weapon States (NWS) and, (b) the Non- Nuclear Weapon States (NNWS).*

*As consequence, all Treaty obligations of the States Parties, their implementation and all ensuing legally binding arrangements and agreements are marked by this asymmetry.*

*The main obligation of each NNWS to conclude a verification ("Safeguards") Agreement with the IAEA, which alone enables the State Party to pursue peaceful nuclear activities and obtain material and technology, transfers from an [NPT] NW State.*

*The Treaty is composed – ab initio – of*

*(1) a fixed, permanent number of States Parties that are the NWS (defined in Article IX 3.) as those States that have manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1.1. 1967): (the three depositary -States, the US; UK; and USSR at entry into force of the Treaty, five States to date (France and China had exploded a device prior to 1970 the e.i.f date of the Treaty, but became Parties to the NPT only in 1992), and*

*(2) an open-ended number of States, the NNWS (37 at the time of entry into force of the NPT, 184 to date).*

***The main legal 'wing' of the NPT edifice** is an unusual trilateral legal construct whereby a multilateral Treaty (the NPT) contains an obligation for some of its Parties (i.e. the NNWS) to conclude a binding bilateral agreement with an intergovernmental organization (the IAEA) for the purpose of allowing verification of fulfillment of their Treaty obligations.*

*Obligations of the States Parties*

- The nuclear non-proliferation undertaking by each NWS *"Not to transfer to any recipient whatsoever nuclear weapons… not in any way to assist, encourage or induce any NNWS to manufacture or acquire … nuclear weapons..."* (Article I),
- The undertaking by each of the NNWS *"not to receive transfer from any transferor whatsoever, of nuclear weapons or other nuclear explosive devices or of control over such weapons or explosive devices directly, or indirectly, nor to manufacture or otherwise acquire nuclear weapons, nor to seek or receive any assistance in the manufacture of nuclear weapons or other nuclear explosive devices "* (Article II),
- The obligation of each NNWS to accept safeguards as set forth *"in an agreement to be negotiated and concluded with the IAEA" for the exclusive purpose of verification* of the fulfillment of its obligations under the Treaty" (Article III),
- The undertaking of *"[E] ach of the parties to the Treaty… to 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"* (Article VI),
- The *"inalienable right"* of all Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with Articles I and II" (Article IV).

  *Note: Despite the apparent clarity of the language defining the obligations incumbent upon NWS and NNWS respectively, it remains open to each Party to place emphasis on one or another aspects of the Treaty: non-proliferation, disarmament or the unconstrained right to develop nuclear energy*

*applications for peaceful purposes. There is a general perception, though not necessarily a universal one, that non-proliferation was accepted as a dominant positive objective per se, even if nuclear disarmament did not occur. This might have reflected a mood of trust rather than fear of the late 1960's.*

*In 1995 despite no noticeable progress in the disarmament talks and despite disclosure of the first serious breaches of (NPT) non-proliferation commitments, a positive outlook prevailed and the NPT Review Conference decides on the indefinite extension of the Treaty (Article X.2.)*

*The 2000 NPT Review Conference closed on the most optimistic note ever by adopting a number of generally accepted principles amounting to a new disarmament agenda. These included:*

- Further efforts by the NWS to reduce their nuclear arsenals unilaterally;
- Increased transparency by the NWS with regard to nuclear weapon capabilities and a voluntary confidence building measure;
- Engaging "as soon as appropriate" all the NWS in the process leading to the total elimination of nuclear weapons, termed an 'unequivocal commitment'

*Five years later, 2005, the NPT Review Conference ended in disagreement and without reaching any conclusions, having failed even to adopt its own agenda.*

*The daunting question has not been answered yet: What has happened during these five years? Like the movement of a kaleidoscope, the picture that emerged after the 2005Conference seemed to have nothing in common with that of 2000.*

## *A.III Regional Non Proliferation Treaties:*

In addition to the NPT aiming at universality, other approaches were pursued with the same objective: a number of Treaties were concluded for continents or large groups of States to remain free of nuclear weapons:

- ✓ The Treaty for the Prohibition of Nuclear weapons in Latin America and the Caribbean [Treaty of Tlateloco], 1967, The "forerunner" (pre NPT):
- ✓ South Pacific Nuclear Free Zone [Treaty of Rarotonga], 1986
- ✓ Treaty on the Southeast Asia Nuclear Weapon Free Zone [Treaty of Bangkok], 1995
- ✓ African Nuclear Weapon-Free Zone Treaty, [Treaty of Pelindaba], 1996 (not yet i.f.)
- ✓ *Bilateral*. Agreement between the Republic of Argentine and the Federative Republic of Brazil for the Exclusively Peaceful Use of Nuclear Energy [ABACC Agreement], 1991.

## *A.IV Specific geographical zones free of nuclear weapons:*

Separately from the NPT regime and the NWFZ (see above) geographical zones were declared by way of international Treaties, to remain free of nuclear weapons:

- ✓ Antarctic Treaty, 1959
  (A recent initiative calls for negotiations to be held urgently on the establishment of a similar treaty for a nuclear weapons-free Arctic)
- ✓ Sea – Bed: Treaty on the Prohibition of the Emplacement of Nuclear Weapons and other Weapons of Mass Destruction on the Sea Bed and the Ocean Floor and in the Subsoil Thereof, 1972
- ✓ Outer Space (Different purpose See A.V. below, test-ban treaties)

## *A.V Implementation and verification of the non-proliferation norm* ([2])*:*

### *1. Resolution 1540 (2004) Adopted by the Security Council of the United Nations on 28 April 2004*

This resolution is the first legally binding call adopted by the UN Security Council ([3]) for all States to carry out their treaty obligations under the NPT and the relevant Treaties regarding Chemical [CWC] and Biological and Toxin Weapons [BTWC]. Res.1540 (2004) is the strongest binding universal norm mandating States to fulfill their non-proliferation commitments.

> *"Affirming that the proliferation of nuclear, chemical and biological weapons, as well as their means of delivery, constitute a threat to international peace and security",*

The new legally relevant feature of this resolution is that it also mandates sovereign States to control possible proliferation to or by "non-State actors". The non-proliferation norm is thereby no longer applicable to States only, but pursuant to what amounts to a new concept in international law, also to threats to peace and security by 'non-State actors'.

The Security Council,

*"Acting under Chapter VII of the Charter of the United Nations"* (this formulation is used to express the binding nature for all Sates Members of the UN of decisions adopted by the Security Council") the SC, decides inter alia: (operative paragraphs)

> *"1. [Decides] that all States shall refrain from providing any form of support to non-State actors that attempt to develop, acquire, manufacture, possess, transport, transfer or use nuclear, chemical or biological weapons and their means of delivery;"*
>
> *2. ["non-State actor" is defined in the resolution as " individual or entity, not acting under the lawful authority of any State in conducting activities, which come under the scope of this resolution"].*
>
> *" 3. [Decides also] that all States shall take and enforce effective measures to establish domestic controls to prevent the proliferation of nuclear, chemical, or biological weapons and their means of delivery, including by establishing appropriate controls over related materials."*

By *"appropriate controls"* the resolution refers as regards the nuclear field to the CPPNM, 1979 ([4]) and its 2005 Amendment

([2]) *Note: the IAEA Safeguards system is not covered by this paper.*

([3]) 1992 the Security Council adopted a resolution regarding non proliferation- however not under Chapter VII.

([4]) Convention on the Physical Protection of Nuclear Material, 1979 which in its substance, obligations of States Parties, technical and legal provisions – notably provisions of criminal law – is linked to non-proliferation and to nuclear security.2005 an Amendment was adopted and opened to ratification, which extends the scope of application of the CPPNM to material in domestic use – and adds 'sabotage' to the list of offences to be prosecuted by the State Parties.

### *2. Verification of the principle of "no nuclear activities for non-peaceful purposes" by NNWS:*

✓ Verification of Treaty based commitments (NPT- IAEA-SG ([5]))

✓ Other measures as e.g. Open Skies Treaty, (e.i.f. 2002)

History of this Treaty goes back to 1955, a US proposal to guard against 'large scale surprise attacks'. 1992 adopted by he CSCE States. Euro-Atlantic Treaty –including Canada and the RF, it establishes a regime of transparency: no off-limits territories for observation flights –only safety considerations to restrict their conduct.

### *3. No trade in materials and technologies to be used for non-peaceful uses: Guidelines for nuclear transfers: Export Control Regimes:*

– The Zangger Committee (1971-,)

– The Nuclear Suppliers Group, (NSG): 1975 (see also INFCIRC/254). Adopts guidelines for Nuclear Related Dual Use Equipment, Material and related Technology.

Security Council resolution 1540 requires States to put in place effective national export and transit controls on nuclear (chemical and biological) weapons, their means of delivery and related materials.

*Note:* these 'regimes' are not based on international treaties but have evolved soon after the entry into force of the NPT as unchallenged consensus arrangements aimed at implementing the non-proliferation norms of the Treaty. They could be considered after being applied for more than 35 years as State practice, that has become customary international law (see also Security Council Resolution 1540)

### *4. No weapons tests: [UN]-Test ban agreements.*

*The objective of the test ban is to prevent further development of nuclear weapons and thereby of nuclear proliferation by prohibiting the testing of weapons.*

- The Treaty Banning Nuclear Weapons Tests in the Atmosphere, in Outer Space and under Water (Partial Test Ban Treaty, 1963) was seen as a transitional agreement opening the way for a comprehensive and permanent test ban. It covers nuclear weapons test explosions in the environment – not under ground (it was however not intended to prohibit or restrict by this ban, the use of nuclear weapons in armed conflicts.).

- [The Treaty on the Limitation of Underground Nuclear Weapons Tests (The Threshold Test Ban Treaty), 1974 concluded between the US and the Soviet Union]

- **The CTBT:** Comprehensive Test Ban Treaty, 1996 (not yet in force) (and the CTBTO, the Provisional Technical Secretariat of contracting States mandated to verify implementation of Treaty obligations. In advance implementation of the Treaty a worldwide monitoring System has been established.

  *Note:* The NPT States have not conducted nuclear tests since the CPBT was opened for signature. (France tested 1996 before adhering to the CTBT – China tested also 1996. non-NPT Parties India and Pakistan conducted their first announced tests in 1998)

([5]) This subject is not covered here, as it is the theme of another presentation at the Course.

# B. Nuclear Disarmament

## B.I Short History of bilateral agreements and the search for general and complete disarmament

***History is relevant, as no new disarmament treaties have been adopted recently*** ([6])**.**

The UN Charter contains a number of references to disarmament. In fact, principles governing disarmament and regulation of armaments have been included among the general principles of international peace and security considered by the UN General Assembly and by the Security Council. A huge number of resolutions have been adopted since the 1950'ies by the General Assembly on the subject of general disarmament (Notably, the first UN GA resolution adopted 24 .01 1946 calling for the elimination of all atomic weapons and *"all other major weapons adaptable to mass destruction."* e.g. also 1959, a plan for 'comprehensive disarmament' was submitted to the GA by the UK.)

It is also recalled in this context, that the origin of the IAEA goes back to the UN Atomic Energy Commission, established by the UN General Assembly and the different plans submitted to it, notably by the US, including later, the seminal address to the GA, 1953, by President Eisenhower *"atoms for peace"*.

The General Assembly also met several times in special sessions on disarmament: notably in 1978, 1982, 1988 with decreasing success ([7]).

Although there have not been any major initiatives towards disarmament (in the meaning of the early 1950'ies) individual NPT nuclear weapon States have undertaken unilaterally a number of measures, which are declared formally as "disarmament measures " ([8]).

## B.II Institutions ([9])

***A number of permanent institutions deal with various aspects of multilateral disarmament of both nuclear (chemical and biological) and conventional weapons. These institutions are usually referred to as- the UN Disarmament machinery:***

- ✓ UN Conference on Disarmament established by the First Special Session on Disarmament, 1978 (HQ. Geneva) The sole multilateral forum for negotiating disarmament. Reports to the GA. 65 States. Scope: arms race and disarmament covering 10 areas (the *"Decalogue"*): nuclear, chemical and other WMD. Conventional forces, disarmament and development, disarmament and security, comprehensive disarmament.
- ✓ UN Disarmament Commission (UNDC), established 1978, open to all UN member States. A deliberative body; makes recommendations on disarmament matters.

([6]) The subject of disarming Iraq after the 1991 Gulf war –Resolution 687, 1991and its implementation by the IAEA and UNSCOM is not covered here.

([7]) A number of more successful initiatives on arms limitations were adopted in the field of conventional weapons.

([8]) In a Document published by the Ministry of Defence and the Ministry of Foreign Affairs of France, distributed to the First Preparatory Committee of the NPT, 2007, France referred to its general principles in accordance with the goals of the NPT, and a number of disarmament measures. including 'progress towards general and complete disarmament'; reducing number of types of nuclear systems.., signature and ratification of the CTBT in 1996, after dismantling its nuclear testing facilities… Other NPT NWS distributed similar documents or statements.

([9]) See also different international disarmament commissions: 2006:"Weapons of Terror. Free the World of nuclear, chemical and biological weapons", Hans Blix, chairman. 1996: Canberra Commission on the elimination of Nuclear Weapons. 1989: Tokyo Forum. 1982: Palme Commission "Common Security".

- ✓ General Assembly of the UN [First Committee].
- ✓ UN Secretariat (UN Department for Disarmament Affairs).
- ✓ UNIDIR- (UN Research and Training Institute) Autonomous body, established by the GA to carry out independent research on disarmament and international security, notably on WMD, missile proliferation, defence and treat implications.

## *B.III International Court of Justice: "Legality of the Threat or Use by a State of Nuclear Weapons in Armed Conflict" Advisory Opinion requested by the UN General Assembly*

In its landmark advisory opinion, the ICJ agreed (unanimously) that: *"There exits an obligation to pursue in good faith and bring to a conclusion negotiations leading to nuclear disarmament in all its aspects under strict and effective international control".*

The Court also agreed that *"There is no comprehensive universal conventional prohibition on " … nor "any specific authorization of ... "the use, threat of use by a State of nuclear weapons..."*

## *B.IV Relation between disarmament and non-proliferation:*

During the early 1990'ies, some positive developments – took place in the field of disarmament linked to successful elimination of proliferation threats.

- ➢ 1991: marks the end of the cold war US–USSR nuclear arms race. Conclusion of bilateral arms control (reduction) agreements.
- ➢ 1991 South Africa accedes to the NPT and concludes a comprehensive Safeguards Agreement with the IAEA .The IAEA verifies that the 'Initial report' (required by the Safeguards agreement) regarding the materials and facilities existing are in accordance with the Safeguards Agreement. 1992 the IAEA reports that it found no evidence that that the Report submitted by SA was incomplete. In–1993-the President of SA disclosed that since 1979 SA had constructed six nuclear warheads and that it had dismantled all six in 1989. The IAEA was invited by the SA Government to verify that the weapons programme had indeed be terminated. The fissile material was placed under IAEA safeguards.
- ➢ 1991,after the end of the Gulf war, the Security Council requested the IAEA to verify the elimination of Iraq's ability to acquire nuclear weapons. IAEA inspectors gradually found out the extent of Iraq's clandestine nuclear weapons programme, which the IAEA had not detected earlier.
- ➢ 1992 the DPRK brought into force its Safeguards agreement with the IAEA. The IAEA was however unable to verify that the 'Initial Report 'submitted had covered all nuclear material in the DPRK. The IAEA reported the discrepancies to the Security Council: the DPRK threatened to withdraw from the NPT – temporarily an agreement concluded 1994 seemed to have convinced the DPRK to limit its nuclear activities to peaceful ones [1994 a multiparty arrangement KEDO – is reached with the US, Europe, Japan South Korea to build a light water reactor in the DPRK-This Project fails. The DPRK resumes and announces production of weapons material later and leaves the NPT [this matter remains however legally unclear]. Present :ongoing negotiations with the DPRK on a verifiable nuclear rollback. Six Party "Talks" led by the US.
- ➢ 1994:warheads are removed from States of the former USSR where they had been stored. (Belarus, Kazakhstan, Ukraine) These States accede to the NPT

# C Arms Control Treaties and Agreements

## C.I Arms limitation Treaties: Summary history

The following sets of agreements were concluded between the USA and the Soviet Union only:

- ✓ 1972: SALT I: Strategic Arms limitation Talks (5 years duration) .Led to the conclusion of the Treaty on the Limitation of Anti-Ballistic Missile Systems-ABM; the Treaty was revised 1992, and later, 1993, the ballistic missile defence system was downgraded. 2002 the US withdrew from the Treaty.
- ✓ 1979: SALT II Agreement (did not enter into force) had provided for a process of reducing US and Russian deployed strategic nuclear warheads.1986 the Treaty was proclaimed invalid.
- ✓ 1987: INF [Intermediate Range Nuclear Forces] Agreement provides for elimination of nuclear delivery vehicles: intermediate range and short-range missiles.
- ✓ 1991 START I (Strategic Arms Reduction Talks) led to the Strategic Arms Reduction Treaty: main purpose was to reduce strategic offensive arms to equal levels; it became the first arms control agreement to reduce significantly strategic nuclear forces. (But did not reach its ambitious goal of a 50% reduction of US and Russian strategic forces.
- ✓ 1993 START II –Treaty was to continue on the same approach of percentage cuts of strategic arsenals, but did not enter into force.
- ✓ The framework for START III negotiations began 1997 – but was not implemented
- ✓ 2002: SORT: "Moscow Treaty" Treaty between the USA and the RF on Strategic Offensive Reductions .To remain in force until 2012: Parties agree to limit their respective nuclear arsenal to [fixed number] of operationally deployed warheads each. Agree that START remains in force.

## C.II Treaties [drafts] regarding nuclear material usable for nuclear weapons:

***Not easily classifiable. Motivation, however, is essentially to facilitate verification of non-proliferation commitments in the context of expected expansion of civil nuclear power***

- ➢ *Fissile Material Cut off Treaty:* Proposals endorsed by the 1995 and 2000 NPT Review Conferences (aiming at ending production of fissile material in order to reduce progressively the fresh supply of plutonium and highly enriched uranium for weapons use.) New proposals made recently in the context of the Conference on Disarmament, but no negotiations ongoing:
- ➢ New proposals ([10]) for multi-or international frameworks for the nuclear fuel cycle (IAEA: to establish a mechanism for assurance of supply of fuel for civil reactors. Multilateral control for enrichment and reprocessing operations. ) Different legal and technical approaches proposed: e.g. by Germany, the Russian Federation

Establishment by States, e.g. by the Russian Federation of international uranium enrichment centres under IAEA Safeguards; International fuel bank. No agreement or treaty established yet:]

([10]) See „New Framework for the Utilization of Nuclear Energy in the 21st Century: Assurances of Supply and Non-Proliferation – The Legal Aspects" Paper submitted to the Nuclear Inter Jura Congress, October 2007, Brussels, by Wolfram Tonhauser, Head Nuclear and Treaty Law Section, Office of Legal Affairs, IAEA.

# Outlook

➢ From strict legal form towards informal, non -treaty initiatives, understandings, and commitments – Enters the 'non-State actor'

At this moment, it is quite difficult to foresee whether these arrangements and initiatives will replace formal international Treaties in the long run or, whether they are preparatory steps for new Treaties. The approach appears to be pragmatic, rapid and directed at specific needs and threats. Such are:

- ✓ G8 Global Partnership Against the Spread of Weapons and Materials of Mass Destruction (G8 Summit June 2002)
- ✓ Proliferation Security Initiative, Statement of Interdiction Principles, Paris 2003
- ✓ (Chairman's conclusions: London 2003; and Lisbon, 2004, Statement Krakow, 2004)
- ✓ Global Threat Reduction Initiative, 2004
- ✓ The G8 Action Plan on Non-proliferation, 2004
- ✓ US Initiative. "Global Threat Reduction Initiative, 2004

➢ *Preparations for the 2010 NPT Review*

The Preparatory Committee for the 2010 NPT Review Conference will meet 2008 and 2009. The outcome may again be poor in light of the failure of the 2005 Review Conference, and the minimal results achieved by the 2007 first session of the Preparatory Committee, or, to the contrary, accomplish unexpected new breakthroughs to overcome the present impasse.

The background of risks and challenges is well known:

- ➢ *The increased dissemination of nuclear technology and know how worldwide: a challenge.*
- ➢ *A number of countries have mastered part or all of the nuclear fuel cycle technology enabling them to enrich uranium, produce fuel for power plants and research reactors and reprocess spent fuel for either re-use or radioactive waste disposal. As stated repeatedly also by the IAEA, it is not illegal under the NPT regime to master enrichment or reprocessing technology. However, it needs to be declared in time and verified.*
- ➢ *Efforts of non-state actors to acquire material for the production of weapons of mass destruction – and potentially nuclear material, in particular [e.g. explosive nuclear devices at a smaller scale] is considered a real danger expressed as the threat of nuclear terrorism: the main threat.*
- ➢ *Concern as to whether the non-proliferation regime and its verification system are strong enough to master the new requirements of an expanding (civil) nuclear power so as to respond to increased energy demand.*
- ➢ *The overriding concern is that there is no clear, perceivable multilateral movement towards nuclear disarmament.*

<u>Sources</u>:


- ❖ *NPT Briefing Book (2005) Mountbatten Center, University of Southampton and Center for Nonproliferation Studies, Monterrey Institute of International Studies*
- ❖ ***"Weapons of Terror": Freeing the World of Nuclear, Biological and Chemical Arms The weapons of mass destruction Commission-2006, Hans Blix Chairman, Stockholm***
- ❖ *UN Office for Disarmament Affairs* http://disarmament.un.org/e-yearbook.html

- *Multilateral Diplomacy and the NPT. An insider's Account. Sipri: Jayantha Dhanapala with Randy Rydell. UNIDIR/2005/3*
- *NTI: Global Security newswire*
- *Arms Control. A Guide to Negotiations and Agreements, Jozef Goldblat, International Peace Research institute, Oslo, 1996*
- *http:/ iaea.org*
- *Papers and documents submitted to the First Session of the Preparatory Committee for the 2010 NPT Review Conference*
- *ICJ:* http://www.icj-cij.org/docket/files/95/7495.pdf

# Safeguards and Nonproliferation: The First Half-Century from a Legal Perspective

Laura Rockwood

## Abstract

This article provides a retrospective of the historical development of safeguards and nonproliferation in "the first half century," ranging from its origins through the statute of the International Atomic Energy Agency to the Model Additional Protocol, and reflections on possible outlooks for the future.

## Introduction

I'd like to invite you to come with me on a journey – a journey through space and time in the development of the legal frame-work of the nuclear nonproliferation regime, and its cornerstone: IAEA safeguards.

What gave rise to this regime? Why has it continued to develop?

In my view, the nuclear nonproliferation regime came about as a function of states' national and collective security needs, and has evolved as a function of their shifting perceptions of the risks to that security. Changes in those perceptions have produced changes in national security policy and, as a consequence, in nuclear nonproliferation policy and the legal framework for that policy.

Along our journey, we will see not only that the law and policies comprising the nonproliferation regime have changed, but that the rate of change has increased exponentially due to fundamental and rapid shifts in the perceptions of the risks.

To demonstrate these changes, and the acceleration in the rate of change, we will look at successive periods: the first twenty-five years, the following twenty years, the next decade, and the recent past, and then turn to speculations about the future of the nonproliferation regime.

## The First Twenty Five Years: 1945–1970

***Perceived risk:*** *Proliferation through the misuse of transferred items*

***Response:*** *Create international verification body; develop system for verifying the use of supplied facilities, equipment, and material*

The dawning of the nuclear era – and the birth of the nuclear nonproliferation regime – was heralded by the most dreadful brilliance: the flash from the explosions of the first – and hopefully the only – nuclear weapons ever used against human beings.

While it was clear, even at the outset, that the atom could be exploited for the benefit of mankind, it was equally clear that the wielding of this mighty double-edged sword required restraint and control.

The first efforts to prevent the spread of nuclear weapons were based on the denial of technology, the assumption being that if the technology holders did not share their knowledge, its pro-liferation would be at least hindered.

In January 1946, the United Nations established a "commission … to deal with the problems raised by the discovery of atomic energy." This commission, the United Nations Atomic Energy Commission (the "UNAEC," consisting of the members of the Security Council and Canada), was tasked with developing proposals for the elimination of atomic weapons and for the control of atomic energy "to the extent necessary to ensure its use only for peaceful purposes."

In June of that year, in an address to his "fellow members of the [UNAEC] and [his] fellow citizens of the world," Bernard Baruch tabled a U.S. proposal for a mechanism designed to ensure that there would be no other nuclear weapons. The Baruch Plan was to create a supranational organization that would have a global monopoly in atomic energy, with the sole and exclusive right to conduct research in the field of atomic explosives. It would not just inspect, but own, control, and manage nuclear material and technology, and license and engage in nuclear activities, in exchange for which the United States gives up its nuclear weapons. It shortly became clear, however, that this proposition had been far too ambitious.

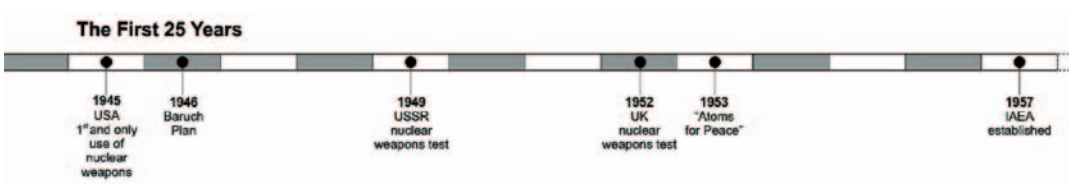
There was business to be had – plenty of demand for that new technology. But if there were to be trade in nuclear technology, there would be a risk that the supplied technology could be misused for the development of nuclear weapons unless there was some oversight. The solution to the problem as it was thus perceived? Restrained and controlled trade. So the technology holders began to sell nuclear material and small research reactors to other countries, pursuant to bilateral supply agreements, many of which invested the supplier with rights to verify that the supplied items would not be used for proscribed (military) uses.

However, clearly neither efforts to ban nuclear weapons, nor bilateral controls on nuclear trade, were going to work to stem the tide of nuclear weapons proliferation: the Soviet Union and the United Kingdom had already developed nuclear weapon programs and other states were working on their own nuclearprograms (such as Belgium, Canada, France, and Italy).

Bilateral agreements were not sufficient to provide assurances to the broader community. To fully address the perceived risk, what was needed was not just bilateral pledges that supplied equipment would not be misused, but internationally binding nonproliferation undertakings by states, verified by an independ-ent international entity.

At the 1953 United Nations General Assembly, U.S. President Dwight D. Eisenhower introduced his Atoms for Peace proposal: to create an international organization that could serve as a repository for nuclear material from the nuclear weapons states from which the non-nuclear weapon states could make withdrawals for peaceful purposes ([1]). The new organization would be responsible for promoting safe and peaceful uses of nuclear energy, and would be entrusted with verifying that nuclear technology was not misused.

This organization was to become the IAEA: an intergovernmental organization, independent from the United Nations, but with a unique relationship permitting direct access to the United Nations Security Council ([2]).




([1]) Bunn, G., 1992. Arms Control by Committee: Managing Negotiations with the Russians. Stanford: Stanford University Press.

([2]) IAEA Statute, Articles III.B.4 and XII.C.

The statute of the IAEA was approved on October 23, 1956, by the Conference on the Statute of the IAEA, held at the United Nations in New York, and opened for signature three days later. It entered into force on July 29, 1957, following the deposit of instruments of ratification by eighteen states (among which, by operation of Article XXI of the statute, were required to be Canada, France, the Soviet Union, the United Kingdom and the United States) with the depositary government, the United States ([3]).

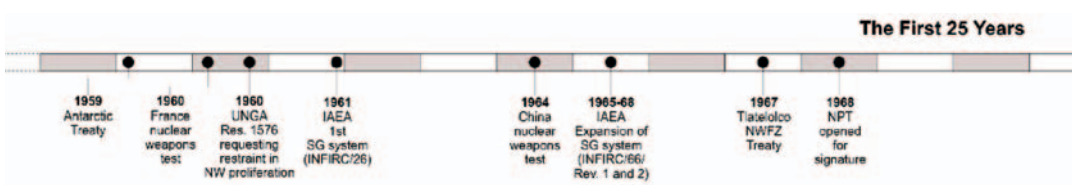
While the original concept of the IAEA as a "nuclear broker" would not gain as much traction as originally foreseen, one very important function of the IAEA that would was its role in safeguarding the peaceful use of nuclear energy.

Article III.A.5 of the IAEA statute authorized the agency:

- To establish and administer safeguards to ensure that nuclear material, services, equipment, facilities, and information made available by the agency are not used to further any military purpose.
- To apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement.
- To apply safeguards at the request of a state to any of that state's nuclear activities.

It is extraordinary that, during the height of the Cold War, consensus could be achieved on such a visionary role for a supra-national inspectorate, and a safeguards system that anticipated measures that were novel and far-reaching, especially for its time: extremely broad rights of access at all times to all places and data and to any person who dealt with items required to be safeguarded; examination and approval by the agency of the design of specialized equipment and facilities to ensure that they would not further any military purpose, that they complied with applicable health and safety standards, and that they would permit effective application of safeguards; reporting and record-keeping by the state; and the possibility of reporting noncompliance to the Security Council ([4]).

In 1961, the agency established the first "safeguards system," published in IAEA document INFCIRC/26, which covered only small research reactors, the technology that was being traded at that time. The system was extended in 1964 to cover large reactors (INFCIRC/26/Add.1). In 1964 and 1965, the agency's system was thoroughly revised (INFCIRC/66), and included procedures for safeguarding principal nuclear facilities ([5]) and nuclear material at other locations. In 1966 and 1968, the agency's safeguards system underwent further revision: first to add special provisions for safeguards at reprocessing plants (INF-CIRC/66/Rev.1), and then to include additional provisions for safeguarded nuclear material in conversion and fuel fabrication plants (INFCIRC/66/Rev.2, the "Safeguards Document"). The Safeguards Document was not a *model* agreement, and its provisions only acquired legally binding force when and to the extent they were incorporated into safeguards agreements.




([3]) IAEA Statute, Article XXI.C; as of April 2007, there were 144 member states of the IAEA.
([4]) IAEA Statute, Article XII.
([5]) A "principal nuclear facility" was defined as a reactor, a plant for processing nuclear material irradiated in a reactor, a plant for separating the isotopes of a nuclear material, a plant for processing or fabricating nuclear material (except a mine or ore processing plant), or a facility or plant of such other type as may be designated by the board, including associated stor-age facilities.

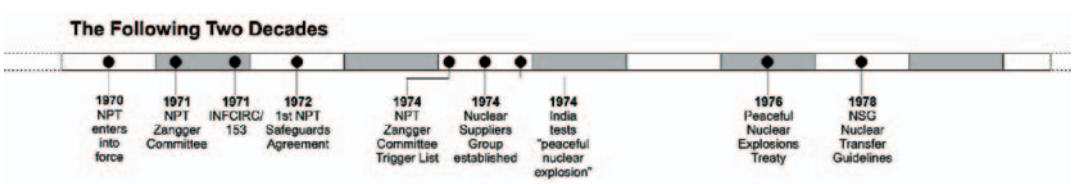
However, since the statute was not crafted in such a way as to make safeguards mandatory by virtue of membership in the IAEA, the implementation of safeguards in a state required the consent of that state. For many years, this consent would be manifested in the form of a safeguards agreement with the IAEA ([6]).

Safeguards agreements are treaties ([7]) that are concluded between the IAEA and a state or states (and, in some instances, regional organizations, such as EURATOM ([8]) and ABACC ([9])). They are drafted by the IAEA Secretariat; negotiated with the other parties to the agreement; approved by the Board of Governors; and signed by the Director General and by the Head of State, Head of Government or Foreign Minister of the state party (or representatives with full powers to do so). Depending on the state's domestic requirements, the agreement enters into force either upon signature or upon receipt by the agency of written notification that the state's requirements for entry into force have been met.

While sharing common safeguards procedures, these INF-CIRC/66-type agreements frequently varied from one to another in form and content. However, the state's undertaking in these agreements – not to use the safeguarded items for any military purpose – tracked the language of Article III.A.5 of the statute.

In terms of scope, the INFCIRC/66-type safeguards agreements evolved to cover the ever-increasing circumstances where safeguards were required (in connection with agency projects for the supply of nuclear material and/or facilities) or requested (in connection with bilateral supply agreements). They also extended beyond nuclear material and facilities to include equipment, non-nuclear material and even a nonnuclear facility (a heavy-water production plant). But they remained limited in scope, requiring the application of safeguards only in connection with the items specified in the agreement (and nuclear material produced, processed or used in connection with those items); hence, the reference to them as "item specific agreements."

As this first part of our journey comes to a close, one can see how the perception of the risks had started to shift. It was becoming increasingly clear that, as a natural consequence of the growing interest in nuclear energy and other applications of nuclear research and development (including nuclear weapons), importing states were beginning to develop their own capacity to produce nuclear material (such as Belgium, Canada, France, and Italy).




([6]) Later, however, such consent would occasionally be expressed through voluntary undertakings (such as those made by South Africa and Libya), and, less frequently, as a conse-quence of prior consent to be bound by action taken by the Security Council under Chapter VII of the United Nations Charter. Article 48 of Chapter VII of the Charter of the United Nations obliges all members of the United Nations to carry out the decisions of the Security Council under Chapter VII for the maintenance of international peace and security.

([7]) A treaty is an international agreement governed by interna-tional law between states concluded in written form between states and/or other entities with juridical personality (such as international organizations).

([8]) IAEA document INFCIRC/193, Agreement between the Kingdom of Belgium, the Kingdom of Denmark, the Federal Republic of Germany, Ireland, the Italian Republic, the Grand Duchy of Luxembourg, the Kingdom of the Netherlands, the European Atomic Energy Community, and the IAEA in Implementation of Article III.(1) and (4) of the NPT.

([9]) IAEA document INFCIRC/435, Agreement between Argentina, Brazil, the Brazil-Argentine Agency for Accounting and Control of Nuclear Material and the IAEA for the Application of Safeguards.

The march toward the possession of nuclear weapons continued unabated. By 1964, two more countries had acquired nuclear weapons. Science being what it is, and people's ingenuity being what it is, neither denial of technology nor restraint in trade alone would work. Nor, clearly, was it enough to try to safeguard individual supply arrangements. What was needed now was legally binding commitments by states not to acquire or develop nuclear weapons, and a mechanism for verifying compliance with those commitments.

This shift fuelled the next major development in the nuclear nonproliferation regime – a development marked by a series of landmark multilateral treaties.

In 1967, the Tlatelolco Treaty was to become the first of these: a treaty prohibiting nuclear weapons within a populated region (Latin America). A year later, the treaty establishing the European Atomic Energy Community (EURATOM), entered into force ([10]).

In 1968, some seven years after the unanimous adoption by the United Nations General Assembly of an Irish draft resolution on the "prevention of the wider dissemination of nuclear weapons," ([11]) and three years of labored negotiations in the Eighteen Nation Committee on Disarmament (ENDC), the text of the Treaty on the Nonproliferation of Nuclear Weapons (NPT) was commended by the General Assembly ([12]) and opened for signature.

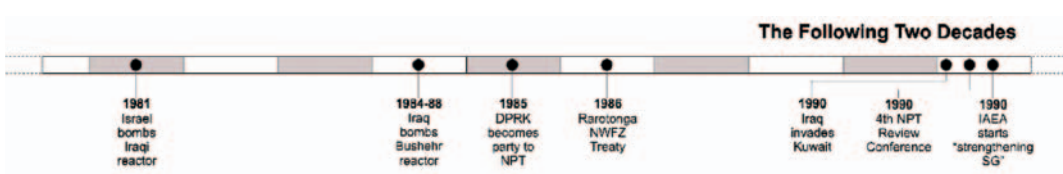
## The Following Two Decades: 1970–1990

***Perceived risk:*** *Proliferation through misuse of indigenous NNWS nuclear fuel cycle*

***Response:*** *Develop a safeguards system for verifying inventories and flows of nuclear material in a state; develop export controls for nuclear material and specialized equipment and material*

If the first twenty-five years can be characterized as a period of controlled supply of nuclear material and nuclear facilities, the next two decades can be characterized as a period of everincreasing indigenous development of nuclear fuel cycle activities.

On March 5, 1970, the world community brought into force the NPT ([13]), the first treaty to include not only a prohibition against the horizontal spread of nuclear weapons by countries which had already exploded a nuclear device ([14]), and a commitment by those who had not yet done so not to develop or acquire nuclear weapons, but a commitment by all parties to the cessation of the nuclear arms race and to disarmament ([15]).




([10]) United Nations Treaty Service, Volume 294, Treaty Number I-4301, registered on 24 April 1958.
([11]) Resolution 1665 (XVI).
([12]) Resolution 2373 (XXII).
([13]) IAEA document INFCIRC/140.
([14]) The People's Republic of China, France, the Russian Federation, the United Kingdom, and the United States.
([15]) An excellent resource for those interested in a more in-depth analysis of the history of the NPT negotiations is the book by George Bunn, former General Counsel of the U.S. Arms Control and Disarmament Agency and one of the U.S. nego-tiators of the NPT cited the references above.

The basic premise of the NPT, insofar as the verification aspects were concerned, was that, without nuclear material, a state could not produce a nuclear weapon. Therefore, if all imports and domestic production of such material were subject to safeguards, the nonproliferation of nuclear weapons could be assured. Thus, Article III.1 of the NPT obliged each non-nuclear-weapon state (NNWS) party to the treaty to "accept safeguards, as set forth in an agreement to be negotiated and concluded with the [IAEA], in accordance with the statute of the [IAEA] and the agency's safeguards system, for the exclusive purpose of verification of the fulfilment by [the state] of its obligations under [the NPT] with a view to preventing diversion of nuclear energy from peaceful uses to *nuclear weapons or other nuclear explosive devices*" (emphasis added).

Under the NPT, safeguards were to "be followed with respect to source or special fissionable material whether it is being produced, processed, or used in any principal nuclear facility or is outside any such facility" and be applied on "*all* source and special fissionable material in all peaceful nuclear activities within the territory of the state, under its jurisdiction, or carried out under its control anywhere" (emphasis added).

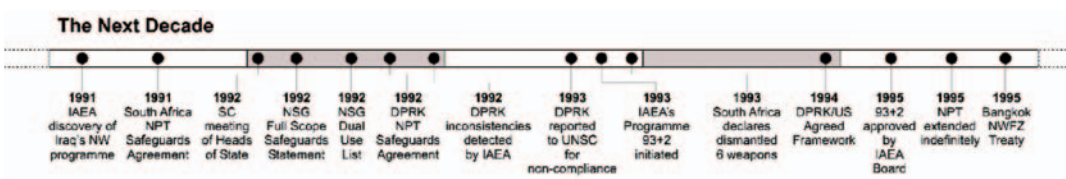
The IAEA's Board of Governors established a Safeguards Committee (Committee 22) to advise it on the contents of these new agreements. Over a period of two years, the committee developed a document entitled "Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Nonproliferation of Nuclear Weapons," which was approved by the Board of Governors in 1972 and published as INFCIRC/153 (Corr.) – the original "blue book."

While not a model agreement per se, INFCIRC/153 spelled out in great detail what such an agreement was to include. As a result, unlike agreements concluded on the basis of INF-CIRC/66, these agreements were to be highly standardized. These new agreements clearly needed to differ from the earlier not only in form, but in undertaking and scope.

In terms of scope, since the purpose was to cover all nuclear material of a state, rather than only items which the state(s) concerned chose to submit to safeguards, these new agreements would become known as *full scope or comprehensive* safeguards agreements (CSAs).

In anticipation of the possibility of non-proscribed military nuclear activities (in particular, nuclear naval propulsion), the basic undertaking of NNWSs under the NPT prohibited the use of nuclear energy for nuclear weapons and nuclear explosive devices. Thus, unlike the earlier safeguards agreements, the NPT agreements would not prohibit all military uses of nuclear material.

Some years later, in 1982, in response to questions raised during a meeting of the Board of Governors, the Secretariat was asked to prepare a study on the compatibility between the undertaking in the NPT safeguards agreements and "the statutory legitimacy of non-explosive military applications of nuclear material subject to the agency's safeguards system" and to inform the Board. In IAEA document GOV/INF/433 (January 21, 1983), the Secretariat submitted the results of its study, in which it concluded that, based on the negotiation history of the statute, and subsequent practice of the Board as the organ which had authority under the statute to determine the safeguards functions of the agency and to approve all safeguards agreements, Article III.A.5 did not require that the undertaking in all safeguards agreements preclude military non-explosive military applications.



The nuclear-weapon states (NWSs) party to the NPT subsequently also concluded safeguards agreements based on INF-CIRC/153, pursuant to voluntary offers to place certain nuclear activities under safeguards ([16]). These so-called voluntary offer agreements (or VOAs) resembled the CSAs, but the scope of these agreements was limited, covering only those facilities and material which the state chose to offer to the IAEA.

One of the provisions in INFCIRC/153 calls for the suspension of the application of safeguards under other safeguards agreements concluded by the state (i.e., the earlier INFCIRC/66-type agreements) ([17]). In time, the application of agency safeguards under most of the item-specific agreements would be suspended in favour of NPT safeguards agreements (today, INFCIRC/66-type agreements are implemented only in India, Israel, and Pakistan). But not before another event occurred, which had a significant impact on the development of safeguards: India's "peaceful nuclear explosion."

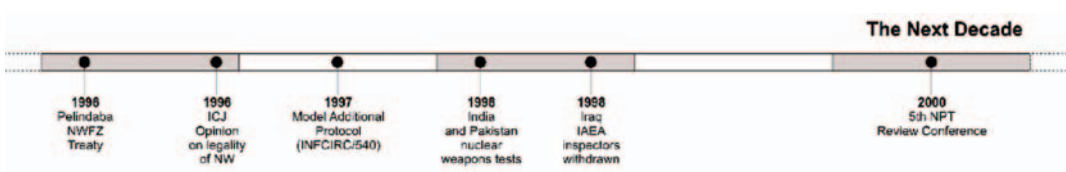
The detonation of India's nuclear device brought about another paradigm shift in the perception of the risk. Clearly, nuclear technology transferred for peaceful purposes could be misused.

This resulted in a revision by the IAEA of a state's basic undertaking in safeguards agreements concluded on the basis of INFCIRC/66. No longer would the proscription be simply against military uses of safeguarded items. The undertaking would thereafter also expressly preclude the use of such items for any nuclear explosive device.

Among the *fallout* from India's test was the strengthening of export controls.

In the early 1970s, nuclear technology had been sufficiently limited that most states were unable to develop nuclear fuel cycles without some external assistance from technology holders in the form of equipment and materials that were especially designed or prepared for nuclear use. To address concerns about the possible misuse of such equipment and material, the drafters of the NPT included in Article III.2 an obligation on the part of all states parties 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 a non-nuclear-weapon state for peaceful purposes, unless the source or special fissionable material shall be subject to the safeguards required by this Article."

While the Board of Governors was engaged in the negotiation of what was to become INFCIRC/153, a group of major nuclear suppliers regularly involved in nuclear trade – the Zangger Committee – convened with a view to reaching common understandings on how to implement Article III.2 of the NPT. In 1974, the Zangger Committee asked the IAEA to publish its so-called "trigger list" of "equipment or material especially designed or prepared for [EDP] the processing, use, or production of special fissionable material," the export of which to NNWSs would *trigger* a requirement for safeguards. In addition to the NPT requirement of safeguards on such transfers, the Zangger Committee also agreed that the supply of "EDP items" should be contingent upon a non-explosive-use assurance by the recipient state and a commitment to insist on the same conditions when retransferring such items ([18]).




([16]) The United Kingdom, INFCIRC/263; the United States, INFCIRC/288; France, INFCIRC/290; the USSR (succeeded to by the Russian Federation), INFCIRC/327; and the People's Republic of China, INFCIRC/369.

([17]) By operation of this provision, it is only the application of safeguards under the other agreements that is suspended. The consequence of this is that the undertaking under an INFCIRC/66-type agreement (no military use) continues to apply with respect to items that had been subject to safe-guards thereunder.

([18]) 18. For a more detailed history of the development of export controls, the Zangger Committee, and the Nuclear Suppliers Group, see IAEA document INFCIRC/539 and the three revisions thereto.

Following India's nuclear test, the Nuclear Suppliers Group, a group consisting of the major nuclear supplier countries who were members of the NPT Zangger Committee and those that were not party to the NPT, was created with a view to improving the conditions of transfers of single use (i.e., nuclear material and other EDP) items for peaceful purposes to help ensure that nuclear cooperation would not be diverted to unsafeguarded nuclear fuel cycles or nuclear explosive activities. The NSG developed its own list of controlled items and agreed on guidelines for the transfer of such items. Among these was agreement on the exercise of particular caution in the transfer of sensitive technologies and materials (i.e., enrichment and reprocessing) because they could lead directly to the creation of material usable for nuclear weapons or other nuclear explosive devices.

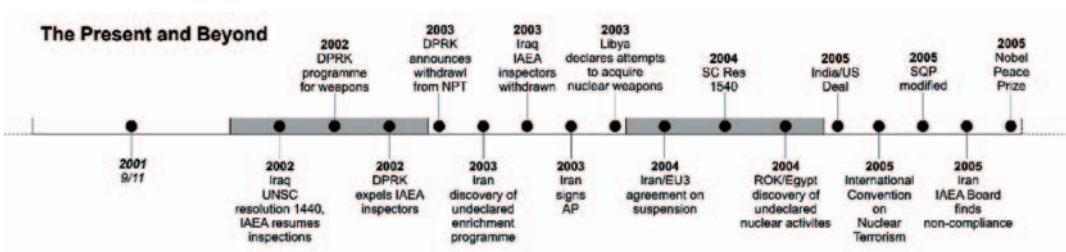
Despite the Indian nuclear explosion, the 1981 bombing by Israel of an Iraqi reactor and, a few years later, the bombing by Iraq of an Iranian reactor, the "nonproliferation mood" at the end of these two decades was pretty upbeat – the Cold War was ending, the Berlin Wall had been brought down, and the United States and the Soviet Union had made substantial progress in arms control and disarmament. As of the end of 1990, 141 states had become party to the NPT, including China and France, the two remaining nuclear-weapon states. And the IAEA had managed to develop a comprehensive safeguards system that permitted the verification of imports and domestic production of nuclear material.

But not all was well in the realm of nuclear nonproliferation. The regime, as it existed at the close of the 1990s, had limitations and drawbacks – as a matter of law and practice – the consequences of which were soon to reverberate throughout the world.

As a matter of law, while safeguards were now in place on the key choke points of the nuclear fuel cycle, the comprehensive safeguards agreements did not cover the entire nuclear fuel cycle. Routine access was limited in terms of frequency and location, and had to be agreed upon with the inspected state. The safeguards agreements included provisions permitting states to exclude nuclear material from safeguards (e.g., exemption, termination). States that informed the IAEA that they had little or no nuclear material and no nuclear material in a facility were allowed to conclude protocols that effectively precluded IAEA verification in those countries.

Most problematic of all, however, was the fact that the safeguards system had developed, as a matter of practice, into verifying only that which was declared to the agency. The combination of member states' frequently reiterated fear of the IAEA carrying out "fishing expeditions," and the Secretariat's cautiousness in pressing the boundaries of its legal authority, had resulted in the implementation of safeguards that were focussed on the verification of declared nuclear material (i.e., the correctness of states' declarations), and not the absence of undeclared nuclear material or activities in the state (i.e., completeness).

In addition, limitations persisted in the export controls of the nonproliferation regime. The Zangger Committee and the NSG (Nuclear Suppliers Group) both operated within the framework of informal, non-legally binding arrangements. And both the trigger list and the guidelines were limited both in scope (insofar as they did not provide for control on dual use items) and in conditions (the safeguards required as a condition of supply were still only of the item-specific type, to be applied only to the



supplied material, facility or other item). There were no procedures for exchanging information on export denials and no sharing of information with the IAEA).

Over the next decade, much of that would change.

## The Next Decade: The 1990s

***Perceived risk:*** *Proliferation through undeclared nuclear material and activities in NNWSs*

***Response:*** *Ensure verification of non-diversion of declared nuclear material and absence of undeclared nuclear material and facilities; expand and improve export controls*

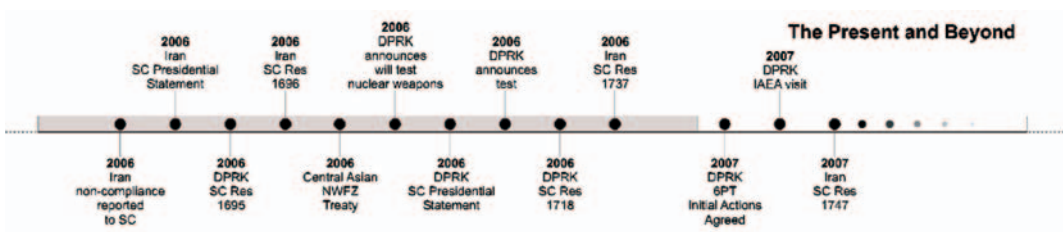
To be fair, the IAEA Secretariat and its member states had already begun to contemplate the need to strengthen IAEA safeguards in 1990. Although no final document was agreed at the 1990 NPT Review Conference in Geneva, the text reported out by Main Committee II (the Safeguards Committee) included language welcoming a study by the IAEA of the possible scope, application, and procedures for special inspections in NPT states where uncertainty existed about whether a state had declared to the IAEA all of the nuclear material required to be subject to safeguards. In addition, in his address to the General Conference in September 1990, immediately following that Review Conference, the Director General also raised the prospect of measures to improve the safeguards system, including the use of unannounced inspections. However, there still remained strong resistance to expanding the IAEA's verification role, whether by practice or by law.

As they say, there's nothing like a crisis to focus one's attention, however.

In April 1991, the IAEA uncovered undeclared nuclear material and activities in Iraq, much of which had been collocated on the site of three safeguarded nuclear facilities just a short ride from Baghdad. Operating under the authority of Chapter VII of the UN Charter, through intrusive inspections and access to all information, people, and locations it deemed necessary, the IAEA was able, by October 1997, to uncover, map out, and dismantle Iraq's program for the production of nuclear weapons. Iraq's clandestine program exposed all too clearly the limitations of a safeguards system focussed exclusively on declared nuclear material.

And that was just the overture for the decade. The years between 1991 and 2000 were characterized by dramatic challenges to the agency's safeguards system, fundamental shifts in states' perceptions of the risks to their individual and collective security, and, as a consequence, fundamental changes in the nonproliferation regime.

Member states of the IAEA, and the world community at large, questioned how it had been possible for Iraq to have developed an undeclared enrichment program, effectively "under the nose of the IAEA." The answer was as simple as it was unfortunate. It was not a question of the lack of legal authority; paragraph 2 of INFCIRC/153 already provided not only for the right, but the obligation, of the agency to ensure that "safeguards will be applied, in accordance with the terms of the Agreement, on *all* source or special fissionable material." However, over the years, the IAEA and its member states had somehow bought into the idea that the agency's authority was limited to verifying declared nuclear material, and that efforts to ensure that there was no undeclared nuclear material in the state would



be rebuffed. Even had the agency been amenable to carrying out inspections to ensure the absence of undeclared nuclear material and activities, however, the Secretariat could not have done so without information, some indicator, giving rise to the need for such inspections, information that it was not able to acquire in the course of routine inspections and was not available from other sources.

It was time for another quantum shift in perception of the risk. The world community had already developed solutions to address the risk to peace and security posed by the possible misuse of supplied nuclear material and technology, and other solutions to address the risk of misuse of declared indigenous nuclear fuel cycles. It was time now to address the clear and present danger attributable to a newly perceived risk: that of a state concealing nuclear material and activities in contravention of its international obligations.

In the same year that Iraq's nuclear weapons program was uncovered, South Africa, a long-time NPT "hold out," became party to the NPT and concluded a comprehensive safeguards agreement. If Iraq had raised member states' awareness of the risk posed by undeclared nuclear material and activities, South Africa provided them with another, somewhat different, but equally clear, case in point. In September 1991, the General Conference of the IAEA adopted a resolution requesting the Secretariat to verify the correctness and completeness of South Africa's initial declaration of nuclear material which, with the openness and transparency on the part of the South African Government, the agency was able to do ([19]).

On January 31, 1992, the Security Council, meeting at the level of heads of state and government, issued a presidential statement (S/23500) in which the Council, *inter alia,* stated that the proliferation of all weapons of mass destruction constituted a threat to international peace and security and, with respect to nuclear nonproliferation, noted "the importance of the decision of many countries to adhere to the [NPT] and to emphasize the integral role in the implementation of that Treaty of fully effective IAEA safeguards, as well as the importance of effective export controls." The Council continued, stating that the members of the Council would "take appropriate measures in the case of violations notified to them by the IAEA."

The safeguards agreement with the Democratic People's Republic of Korea (DPRK) entered into force later that same year. Putting its recently acquired experience to use, the IAEA was able to take advantage of the new tools and practices it had developed in Iraq and South Africa (in particular environmental sampling) to detect inconsistencies in the DPRK's initial declaration about its nuclear material. These inconsistencies gave rise to serious concerns about the possible presence in North Korea of plutonium that had not been declared to the IAEA. The IAEA was also able to make use of intelligence imagery to identify locations not declared to the IAEA, access to which the agency believed would assist it in resolving those inconsistencies.

If, as lawyers are prone to saying, hard cases make bad law, an easy case makes good law. The compelling presentation put by the Secretariat to the Board of Governors, meeting in closed session in February 1993, convinced the Board not only of the need for access to additional information and the undeclared locations, but the agency's right to request such access under the provisions for special inspections ([20]). Unfortunately, the DPRK denied the agency's request. This was reported to the Board of Governors, which, in turn, decided to report the DPRK's non-compliance to the Security Council in April 1993.

([19]) As it turns out, in 1993, South Africa announced to the world that it had in fact had a nuclear weapons program, and that it had dismantled that program, and its six completed nuclear weapons, prior to becoming party to the NPT.

([20]) It is worth noting that board approval is not a precondition for the Secretariat to request access to information or loca-tions pursuant to the provisions in comprehensive safeguards agreements related to special inspections.

This sequence of events clearly put to rest any doubts about the agency's right and obligation under comprehensive safeguards agreements to verify the absence of undeclared nuclear material and activities, and its right to request access to undeclared locations. The objective of safeguards had been redefined in response to states' shifting concerns. These events also gave rise to additional changes in export controls.

In response to the discovery of Iraq's nuclear weapons program, much of which had been developed through the acquisition of dual-use items not covered by the NSG Guidelines, the NSG agreed in 1992: on guidelines for transfers of dual-use equipment, material and technology; on a framework for consultations and exchange of information on the implementation of the guidelines; on procedures for exchanging notifications of denials; and on the need to make full-scope safeguards a condition for the future supply of trigger list items to any NNWS.

Between 1991 and 1995, the IAEA identified a number of measures to "fill the gaps" in the implementation of agency safeguards. Its first efforts were focused on ensuring the early provision of design information on new facilities and modifications to existing facilities, and the voluntary provision of information on exports and imports. In June 1993, responding to the Director General's report of recommendations by the agency's Standing Advisory Group on Safeguards Implementation (SAGSI) for strengthening the effectiveness and efficiency of IAEA safeguards, the Board of Governors requested the Director General to submit to the Board in December 1993 concrete proposals for the assessment, development and testing of measures proposed by SAGSI. These efforts were formalized into "Program 93+2," a coordinated and intensive Secretariat effort, approved by the Board in December 1993 and carried out in continuous consultation with member states. As the name of the program suggests, it was clearly expected that concrete results would be produced in time for the critical 1995 NPT Review and Extension Conference.

By March 1995, the Board had approved the Director General's decision to implement those measures determined to be within the existing authority available to the agency under INF-CIRC/153, and had determined that complementary legal authority should be developed to provide the agency with the broader access to information and locations necessary for the agency to improve the effectiveness and efficiency of safeguards.

The Board also reconfirmed that "… the safeguards system for implementing [comprehensive safeguards agreements] should be designed to provide for verification by the agency of the correctness and completeness of states' declarations, so that there is credible assurance of the non-diversion of nuclear material from declared activities and of the absence of undeclared activities."

The spring of 1995 brought about a critical turning point in the nonproliferation regime: the indefinite extension of the NPT by decision of the states parties at the 1995 NPT Review and Extension Conference. The Conference took two other key decisions, one on a strengthened review process for the Treaty and another on "Principles and Objectives for Nuclear Nonproliferation and Disarmament." ([21])

The "Principles and Objectives" included a statement to the following effect:

"The [IAEA] is the competent authority responsible to verify and assure, in accordance with the statute of the Agency and the Agency's safeguards system, compliance with its safeguards agreements with states parties under-taken in fulfilment of their obligations under article III (1) of the Treaty, with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices. Nothing should be done to undermine the authority of the IAEA in this regard. States parties that have concerns regarding non-compliance with the safeguards agreements of the Treaty by the states parties should direct such concerns, along with sup-porting evidence and

([21]) IAEA document INFCIRC/474, 12 June 1995.

information, to the IAEA to con-sider, investigate, draw conclusions and decide on necessary actions in accordance with its mandate." But the Principles and Objectives were not just about safe-guards. They also contained passages on disarmament and secu-rity assurances, identifying among the relevant principles and objectives: reaffirmation by the nuclear-weapon states of their commitments in Article VI of the NPT; the importance of pur-suing in good faith negotiations on effective measures relating to nuclear disarmament, achieving a universal and internationally verifiable Comprehensive Nuclear Test Ban Treaty (CTBT), negotiating a fissile material cut-off treaty (FMCT), and determined pursuit by the NWSs of systematic and progressive efforts to reduce nuclear weapons, with the ultimate goal of eliminating such weapons. These principles and objectives would come under renewed scrutiny and challenge ten years later.

Within two years, the committee established by the board to negotiate a model text for complementary legal authority completed its task. Based on a first draft prepared by the Secretariat, the committee agreed on a Model Additional Protocol to the Agreement(s) between State(s) and the IAEA for the Application of Safeguards, designed to provide the agency with new tools for achieving the objective of safeguards: verifying the correctness and completeness of states' declarations under comprehensive safeguards agreements. In a special session held in May 1997, the board approved the text, and requested the Director General to use it as the standard for additional protocols to be concluded in connection with comprehensive safeguards agreements. The board also requested the Director General to negotiate additional protocols with other states, incorporating those measures that those states were prepared to accept.

Rounding out this decade, the parties to the NPT convened the sixth quinquennial Review Conference in New York in April 2000. In its Final Document, the Conference reiterated the con-viction of the states parties that the IAEA was the competent authority responsible for verifying compliance with NPT safeguards agreements; reaffirmed that IAEA safeguards should be regularly assessed and evaluated; stated that decisions aimed at strengthening safeguards should be supported and implemented; and endorsed the measures of the Model Additional Protocol. After a hard-fought battle, the Conference also agreed on thirteen steps for the systematic and progressive efforts to implement Article VI of the NPT, which included, *inter alia,* the early entry into force of the CTBT, the negotiation of an FMCT, and specific steps by all NWSs leading to nuclear disarmament in a way that would promote international stability, based on the principle of undiminished security for all.

In 1998, India and Pakistan both openly carried out much publicized nuclear weapons tests, which were roundly condemned by the agency's Board of Governors and General Conference, as well as the Security Council ([22]).

Notwithstanding, by the end of the decade, the prospects offered by a strengthened safeguards system, improved export controls and renewed commitments by the nuclear-weapon states to the "principles and objectives," and in particular to disarmament, made for an optimistic outlook for the nonproliferation regime and IAEA safeguards.

The next few years, however, would dramatically alter that outlook.

## The Present and Beyond: Challenges of the New Millennium

Where are we now? Where are we headed? Iraq – After four years of absence from Iraq, agency inspectors were allowed back into Iraq in November 2002, only to be with-drawn four short months later, just before being able to finalize a report to the Security Council that would have conveyed the agen-

([22]) S/RES/1172 (1998).

cy's conclusion that it had found no indications of the resumption of a nuclear weapons program in Iraq. It is notable, however, that the agency's preliminary findings to this effect were later validated – after almost two years and the expenditure of more than $1 billion U.S. – by the Duelfer Report. The agency has been able to carry out its yearly safeguards inspection of the nuclear material remaining at Tuwaitha, but is still awaiting review by the Security Council of the agency's mandate under the relevant Security Council resolutions.

DPRK – Since 1994, the IAEA had been limited to verifying compliance by the DPRK with the Agreed Framework concluded between the United States and the DPRK. However, following conflicting public reports in mid-2002 about declarations by the DPRK that it had a nuclear-weapons-related enrichment program, and charges by the DPRK that the United States had breached the Agreed Framework, the DPRK expelled the IAEA's inspectors in December of that year and, in early 2003, announced its withdrawal from the NPT. After an extended series of on-again, off-again diplomatic efforts under the so-called Six Party Talks, in September 2005, a Joint Statement on the Korean Peninsula Nuclear Issue was agreed between the DPRK, China, the United States, Japan, the Republic of Korea, and Russia, in which the Six Parties, inter alia, reaffirmed their common goal of the verifiable denuclearization of the Korean Peninsula in a peaceful manner and agreed to take coordinated steps to implement this goal in a phased manner in line with the principle of "commitment for commitment, action for action." In October 2006, the DPRK announced that it had conducted a nuclear weapons test. On February 13, 2007, the Six Parties announced agreement on initial actions for

*Ḥthe implementation of the Joint Statement. Among the steps agreed to was that the DPRK would "shut down and seal for the purpose of eventual abandonment the Yongbyon nuclear facility, including the reprocessing facility and invite back IAEA personnel to conduct all necessary monitoring and verifications as agreed between IAEA and the DPRK." In early March 2007, the Director General, at the invitation of the DPRK, visited the DPRK, where he held exploratory discussions concerning the "initial actions." The DPRK indicated its willingness to invite the agency for further discussions once the issue of financial sanctions had been resolved.

Iran – In the first few months of 2003, the IAEA uncovered in Iran previously undeclared nuclear material and activities associated with conversion, uranium enrichment and reprocessing, much of which had been fueled by a clandestine international market in nuclear technology, equipment, and material. Some of the major events which took place in this context are indicated in the timeline below. In September 2005, the Board of Governors found Iran to be in non-compliance with its safeguards agreement, and, following Iran's announcement of its intention to resume its enrichment related activities, the Board in February 2006 requested the Director General to report the non-compliance to the Security Council. The Security Council has since then adopted a presidential statement, followed by two resolutions: one in December 2006, imposing sanctions on Iran for its non-compliance; and one in February 2007, expanding the sanctions. As of April 2007, the IAEA remained unable to verify the correctness and completeness of Iran's declarations.

Libya – At the end of 2003, Libya publicly announced that it had had a program intended for the production of nuclear weapons, and that it had been engaged for more than a decade in the development of a uranium enrichment capability, including the import of undeclared uranium and centrifuge and conversion equipment and the construction of pilot scale centrifuge facilities. Libya renounced this and its other weapons of mass destruction (WMD) programs, and permitted the IAEA to verify that, henceforth, all of its nuclear activities would be under safeguards and used for exclusively peaceful purposes. The stark awakening? Much of the information, equipment, and materials acquired by Libya for its clandestine nuclear program had been acquired from the same illicit nuclear trade network that had supplied Iran's enrichment program.

The good news? The IAEA's ability to verify the correctness and completeness of states' declarations has been substantially improved and, as a consequence, it was able to uncover instances of small quantities of undeclared nuclear material and activities in the Republic of Korea and Egypt, even though these activities did not rise to the level of those found in Iran or Libya.

NPT – The 2005 NPT Review Conference is described by almost all participants as having been a resounding and dismal failure, with tensions between and among state parties about the spread of sensitive nuclear technologies and those who challenged the lack of progress by the nuclear-weapon states in arms control and disarmament. As of the time of the April 2007 Preparatory Committee meeting in advance of the next Review Conference 2010, these conflicts persist, a situation that does not bode well for the future.

CTBT/FMCT – Ten years after its signature, the CTBT has not yet come into force, despite the fact that 170 countries have signed the Treaty and 135 countries have ratified it. And in the past ten years, it has not been possible even to agree on a mandate to start negotiating the FMCT.

**Perceived Risks?**

Clearly, the events of the last few years have produced, yet again, a shift in the perception of the risks to states' security:

- Illicit nuclear trade networks, and the involvement of non-state actors
- The *breakout* scenario – withdrawal from the NPT, preceded by the development of sensitive technologies and possibly weaponization activities
- Disarmament slowdown – resentment abounds due to the continuing perception that nuclear-weapon-states are not living up to their part of the NPT bargain by achieving progress in disarmament

**Possible Responses?**

Each of these risks could be mitigated through a three-tiered approach to possible solutions:

Strengthening the nonproliferation regime:

- Comprehensive safeguards agreements with an Additional Protocol should be established as the verification standard. As of April 2007, there were 190 states party to the NPT (if one includes the DPRK). Of these, thirty-one NNWSs party to the NPT had not yet concluded comprehensive safeguards agreements, and more than 100 states had yet to bring into force additional protocols.
- Export controls could be further improved, and made binding through international agreements
- More information concerning nuclear trade could be shared with the IAEA
- The regime should be shored up against the risk of non-state actors through effective implementation of Security Council Resolution 1540

Minimizing the risk of breakout:

- Internationalizing key points of the nuclear fuel cycle: A number of proposals for multilateral approaches to the nuclear fuel cycle, in particular as regards the sensitive technologies of enrichment and reprocessing, are currently circulating. In this vein, it is perhaps little appreciated by the international community today that the statute of the IAEA already authorizes the agency to receive nuclear material from member states, to supply such material to its member states, and to establish its own plants, equipment and facilities for the receipt, storage and issue of such material ([23]).
- Ensuring Security Council response to threats of NPT with-drawal

([23]) IAEA statute.

Ensuring the survival of the nonproliferation regime:

- Accelerating disarmament by NWSs
- Addressing over-arching security concerns of NNWSs

## Conclusion

If the initial premise of this paper is correct, that the nonproliferation regime, and IAEA safeguards, have evolved as a function of states' security needs, and states' perceptions of the risks thereto, one must look beyond the day-to-day efforts to fill gaps as they arise and try to resolve the basic issues underlying national and collective insecurity, for the more secure a nation and its people are, surely the less attractive is the appeal of nuclear weapons.

*Laura Rockwood has served in the Office of Legal Affairs of the IAEA since 1985. She has been involved in all aspects of the negotiation, interpretation and implementation of IAEA safeguards agreements for twenty-two years, and was the principal author of the document that became the Model Additional Protocol. She has participated, inter alia, in: the Director General's Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle; three NPT Review Conferences; and the trilateral negotiations between the IAEA, Russia, and the United States to develop an agreement on the verification of materials released from weapons programs. Rockwood is a regular lecturer at the International School of Nuclear Law in Montpellier, France, and the World Nuclear University Summer Institute. She received her bachelor of arts degree from the University of California, Berkeley, in 1973, and her juris doctor degree from the University of California's Hastings College of the Law in San Francisco in 1976. She is a member of the State Bar of California and the Washington, D.C. Bar Association. Prior to working for the IAEA, Rockwood was employed by the U.S. Department of Energy as a trial lawyer, principally in radiation injury cases, and as counsel in general legal matters.*

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# Fifty Years of Safeguards under the Euratom Treaty – A Regulatory Review by the EURATOM inspectorate

Bharat Patel, Peter Chare

## Abstract:

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

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

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

**Keywords:** Euratom treaty; safeguards

## 1. Introduction

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

The tasks entrusted to Euratom were many – to conduct research, to establish uniform safety standards for health protection of workers and the public, to guarantee the equitable supply of ores and nuclear fuels to users, to exercise the right of ownership of special fissile material, to facilitate commerce in the nuclear market, to establish relations with third countries and international organisations promoting civilian uses of nuclear power, and to ensure by appropriate supervision that nuclear materials were not misappropriated from declared uses [1]. From the outset it was recognised that to mitigate the risks of militarisation of the nuclear materials associated with the civil nuclear industry, a safeguards system capable of accounting for the movement and stocks of nuclear material was essential. Thus the dual role of the (Euratom) Commission was created – firstly to promote, but also to apply controls and regulate the holding and transfer of nuclear materials.

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

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

## 2. Background to the founding of the Euratom Treaty

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

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

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

## 3. Implementing Treaty Safeguards (Early Years)

A major task for the Commission following entry into force of the treaty was the enactment of legislation to define the safeguards requirements. In 1959 Euratom issued safeguards regulations (7 and 8). Regulation 7 specified the means for complying with Article 78 on declaration of operating characteristics of the installation for safeguards purposes, although initially debate centred on the application of this to defence establishments [5]. This issue was eventually settled in favour of the member state and gradually a uniform application of the rules was established. Regulation 8 defined the rules for accountancy, reporting of movements, material inventory and of inspection. Mid-1959 saw the start of monthly declarations of material movements by the facility operators. Initial visits to nuclear installations took place in the second half of 1959, and the first Euratom inspection took place at MOL in Belgium in April 1960. Regular inspections by nominated inspectors (initially a team of just 4 persons), followed from May 1960 as required by Regulation 8 [6].

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

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

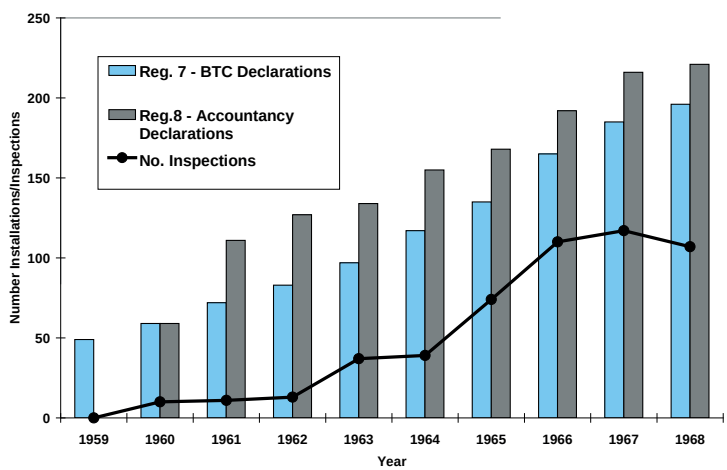


*Figure 1:* No of Installations subject to Regulations 7 and 8, and inspection level (1959-1968*). (* Additional continuous inspections also took place in 1966-68).

In 1962, Euratom began approval of the chemical processing techniques and plant characteristics for three spent fuel reprocessing plants. The first, the Eurochemic project at MOL, Belgium commenced operation four years later [7]. In 1963, the operation of the first full scale industrial power reactor (in France) brought new challenges to safeguards. The expansion from research plants to full scale industrial plants called on new techniques to cope with verification of bulk raw materials and uranium hexafluoride gas rather than just finished fuel elements [8]. Safeguards verification in the early days was mainly based on accountancy declarations, simple mass/volume measurements or sample taking, but research was on-going to develop new instrumentation and measurement techniques. The inspection regime at the reprocessing plant called for continuous inspector presence initially, the control measures requiring US and Canadian authorities' acceptance for material of such origin [9]. The number of inspections in the period 1960-1967 by installation type is shown in table 1.

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

*Table 1:* Inspections by installation type 1960-1967

The quantities of imported material under Euratom safeguards are shown below, illustrating the early dependency on imports of mainly enriched uranium. With the advent of the new power reactors from the mid-1960's the quantities of nuclear material under safeguards control started to rise.

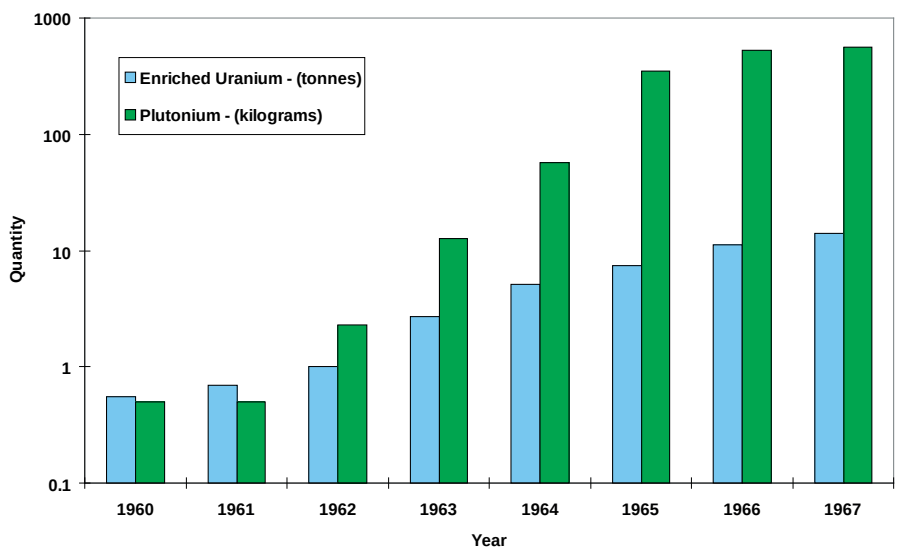


*Figure 2:* Imported Quantities of Material under Euratom Safeguards, 1960-1967 (high- and low-enriched U, and Pu)

# 4. Safeguards Development (Later Years)

The experience gained in these early years was of great importance for the future of Euratom safeguards. The late 1960's and early 1970's brought new challenges to Euratom treaty safeguards due to the negotiations for the Non-Proliferation Treaty (NPT). Euratom's regional safeguards system came under severe challenge and risked being superseded by overriding international non-proliferation concerns. The desire to put global non-proliferation agreements in place put pressure on existing member states to accept IAEA safeguards in substitution for regional Euratom safeguards. Differences of view existed amongst member states, and further complications arose with the presence of the Nuclear Weapons States (NWS) initially France, and later the UK. Compromises had to be accepted that allowed both organisations to pursue their objectives in parallel. The INFCIRC 193 agreement defined the means by which IAEA would obtain independent verification of safeguards in the Non-Nuclear Weapons States (NNWS), whilst Euratom continued its regulatory role in the region. In the event, both NWS entered into voluntary agreements with the IAEA that allowed limited safeguards verification in their territory. The need for more formal agreements between the two organisations over the implementation of safeguards in the European community forced a redefinition of safeguards rules for accountancy, inventory change and material balance reporting. These were elaborated in the Community Regulation 3227/76, which was to remain the mainstay of Euratom safeguards regulation for the following 30 years.

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

## *4.1 Period 1969-1987*

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

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

*Table 2:* Quantities of Material under Euratom Safeguards, 1969-1972

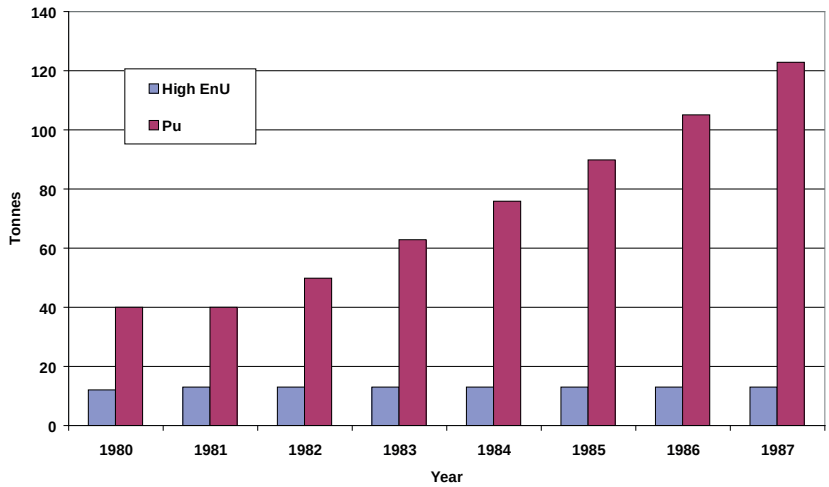


*Figure 3:* Quantities of Material under Euratom Safeguards, 1980-1987

## *4.2 Period 1988-2006*

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

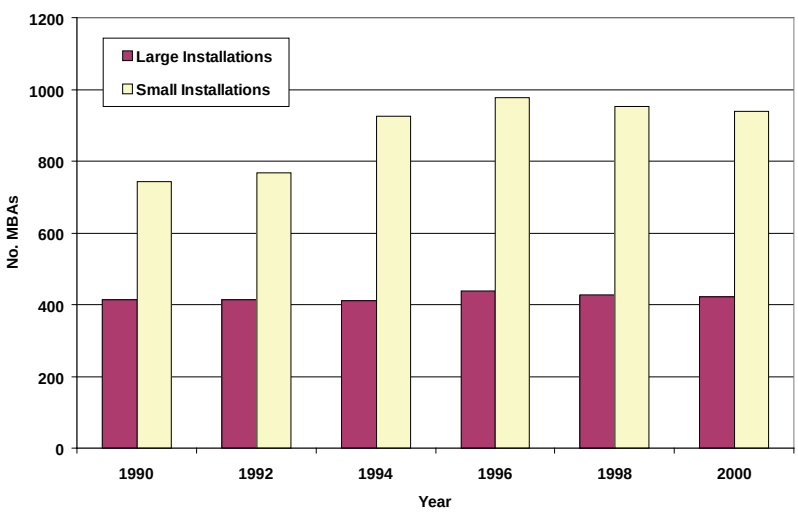


*Figure 4:* Number of Material Balance Areas (MBAs) 1990-2000

The equivalent quantity (as effective kg) under safeguards in the 10-year period from 1988 to 1998 increased by 188%, and in the ten year-period upto 2006, by 56%. This quantity is shown below in Figure 5.

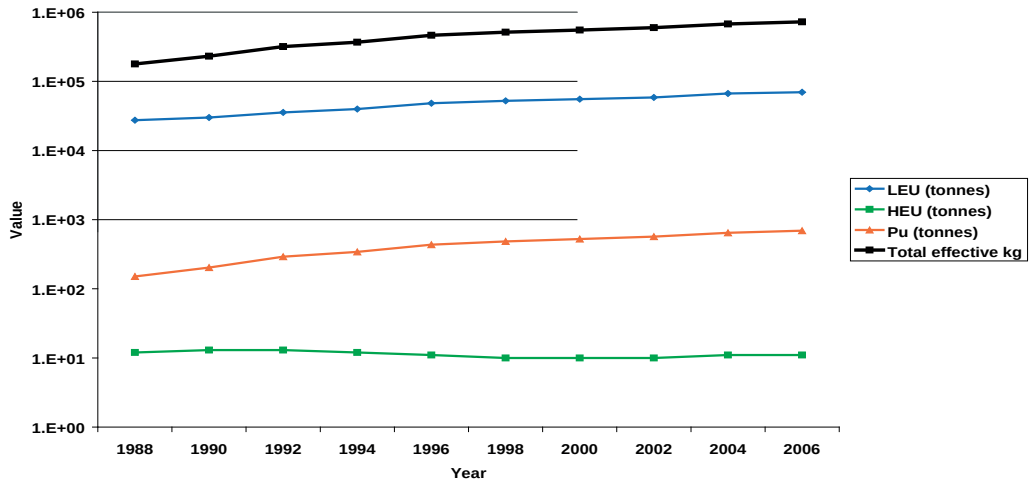


*Figure 5:* Quantity of nuclear materials under Euratom-safeguards between 1988 and 2006

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

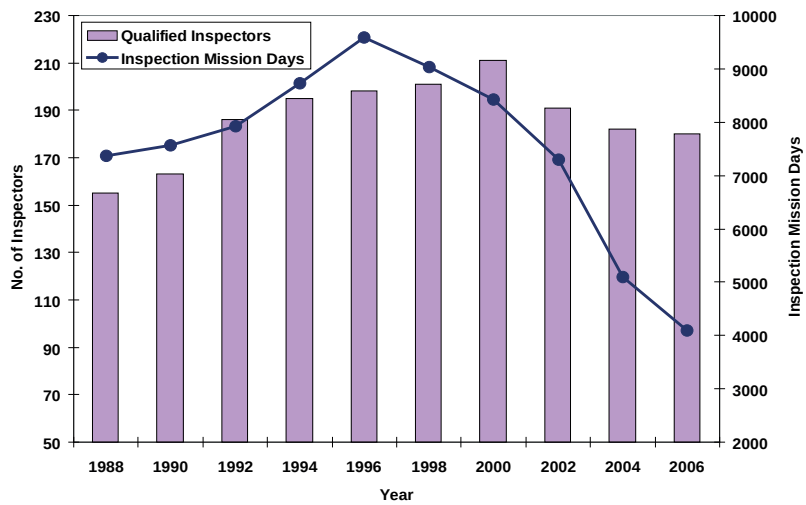


*Figure 6:* Inspection Statistics, 1988-2006

## 5. *Review of Treaty Provisions*

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

all nuclear projects. However, it can be said that this economy of regulation has been one of the reasons for the enduring nature of the regulations. The compromise treaty wording that was found to be politically acceptable at that time, remains in place today and serves its function.

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

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

## 6. Appraisal of Euratom Safeguards

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

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

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

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

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

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

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

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

However, the main success of the treaty lies in the degree of community integration engendered by the safeguards arrangements. The ability of nationals of one country to verify implementation of safeguards in another neighbouring country by accord contributes to the transparency and confidence for establishing security in the region. These principles first enacted in the EC have resonance with the NPT non-proliferation aims and from the post-cold war era the nuclear arms control and disarmament phases in world politics. The experience gained in developing structures, methodology, technical skills and legal apparatus hold lessons for the other areas of arms control. It can be said that European safeguards control and monitoring – despite technical limitations, political interferences, complex relationships between members states, EU institutions, nuclear operators, and the IAEA – have achieved a major advance in international cooperation. The Euratom treaty can claim to have contributed to this achievement.

# 7. Strengthening Safeguards and Future Challenges

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

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

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

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

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

# 8. Conclusion

The origins and development of Euratom's mandate were difficult and at times controversial particularly as it has been and continues to be a heavily politicised issue. It is therefore all the more remarkable that despite political and institutional difficulties in the last 50 years, the original treaty survives and its aims have been met. From very modest beginnings in the late 1950's, with a small core of staff and few facilities, European regional safeguards quickly established itself, and its expertise evolved to cope with one of the most advanced energy industries in the world. The figures show the rise in the quantities of nuclear material in use, representing the growth of the industry, and the large quantities under safeguards control today. The Euratom regional safeguards system continues to play an essential role in its regulation and control. For the demands and concerns of the European citizen, it can claim to be successfully serving its purpose.

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

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

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

**Acknowledgement**

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# An Introduction to Statistical Aspects of NM Accountancy and Auditing

M.T. Franklin

## 1. Background

Every nation State having nuclear activities has legislation designed to ensure that the nuclear material on their territory is protected and that the material is only used for approved purposes. This generally has the consequence that States insist on a high quality of accountancy of all their nuclear materials. The objective of nuclear materials accountancy is to ensure that the ***location*** of all NM is precisely known and in particular to ensure that the ***amount*** of nuclear material in each location is precisely known. As a consequence, each facility must have in place a structure of accountancy procedures whose implementation will ensure good accounting records. Maintaining good accountancy requires ensuring that adequate procedures are effectively implemented. To maintain assurance of high quality, most States have a state agency with responsibility for supervising the quality of accountancy in facilities holding nuclear material. (e.g. SKI ([1]) for Sweden, NRC for USA, GAN for RF, IRSN for France).

In principle both the design of the procedures and their effective implementation, are aspects that can be audited by the State to obtain assurance about the real situation. **Auditing of procedures** can include review of job responsibilities and technical activities as defined in facility documentation. In particular this includes all procedures for creation, transmission and management of data that will be used in creating accounts. **Auditing of implementation** can include verification of conformity between accounts and reality. This can include independently measuring selected material, and comparing the results with the accounting values of the facility. Auditing implementation can also include checking the internal coherence of the accounts as well as auditing the consistency between nuclear accounts and operating records.

While accountancy and State supervision of accountancy are driven by national legislation, they are also motivated by international agreements. The Non-Proliferation Treaty for example – NPT, provides an international framework in which nation States allow international inspectors (IAEA) to audit their accountancy. This is done in order to assure other States that the nuclear material is being used only for the purposes declared under international agreements and is not being diverted for weapons development. Auditing by the IAEA is designed to be able to detect "diversion" of any amount of material that has significance in terms of nuclear weapons development or production. Its purpose is to provide assurance that no such diversion has taken place. In addition, the European Union has its own system of international supervision based on the Euratom Treaty (1957) whose objective is to provide assurance that the real use of the material conforms to the declared use. Under this treaty, the Commission of the EU is allowed to audit accounting records and systems.

([1]) SKI Statens Kärnkraftinspektion, NRC Nuclear Regulatory Commission, GAN Gosatomnadzor, IRSN Institut de Radioprotection et de Sureté Nucléaire.

The existence of these State and international "safeguards" systems for supervision of accountancy, means that the management of nuclear facilities must give a certain priority to accountancy needs. Good accountancy makes for effective management in a technical and economic sense. Facility management however also wishes to have a state of the art accounting process so as to be seen to meet the requirements of the national laws and the international agreements. The difficulty for facility management is to put in place the necessary procedures and technical means for ensuring that a high level of accountancy is achieved.

The statistical problems of nuclear accountancy arise from the fact that the measurement of any quantity of material will incorporate the intrinsic measurement variation of the methods being used to measure the material. Large bulk handling facilities involve extensive chemical processing of nuclear material. Both accounting data and verification data are based on measurements of the uranium and plutonium content of the material products generated in the process. As a result, the assurance of satisfactory control of nuclear materials is an ongoing process of statistical inference.

Over the years, statistical and operations research methods have found their place in such verification work by being concerned with,

- translating general treaty or legal objectives into technical auditing objectives,
- optimizing inspector resource allocation in verification work by deciding what audit approach will be applied to achieve audit goals at reasonable cost,
- elaborating the statistical analysis of accounting and auditing data needed to recognize anomalous situations and to assess accountancy performance.

This note gives an overview of the statistical problems involved in nuclear materials accountancy and auditing. Before starting with statistical problems however, we give a brief introduction to accountancy and auditing as the framework motivating the statistical questions. The sections below describe what are meant by satisfactory accounts, what accounting anomalies are and how the accounting process may be audited.

## 2. Accountancy and Accounting Anomalies

Each facility implements an accountancy system which records all shipments or receipts of material and maintains a record system showing where the material is stored. To be fully useful, each type of record must include the **amount** and **type** of material concerned. This kind of control is applied to specific geographic zones usually described as nuclear 'material balance areas' (MBA).

If the nuclear material in a balance area is in containers that are never opened – merely received or shipped – the recordkeeping of shipments and receipts is in principle adequate to describe the set of material present in the inventory at any time point. All that is needed in addition is information about the *precise* location of storage within the MBA. However in the case where nuclear material is processed, containers will be opened, the chemical form of the material will be changed by the processing, and the new forms of material will be put in new containers. In this situation the shipment and receipt information alone is not sufficient to describe the stock of nuclear material present in the inventory of the MBA. Now there will have to be production records to show which material was transformed during processing, how the newly produced form of material was packed and where the resulting containers are stored. In addition there will be transport records (internal to the facility) every time material is moved form a storage area into a processing zone and vice versa. Depending on how quickly such information is produced and on how well it is organized, it should provide a documentary description of what material is present in the inventory, in what form it is and where exactly it is.

**Criteria for Satisfactory Accounts:** The major objectives of a satisfactory set of accounts are,

- the accounts should **describe** all the material items making up inventories, shipments and receipts. By description here is meant that the items have identities, implicit or explicit, and an associated declared mass.
- all the discrepancies, normally measurement errors, between accounting values and true values should be small enough.
- the accounts should be complete i.e. every object containing nuclear material should be included in the accounts.

**Creating Good Accounts:** Ensuring the quality of the accounting information in the facility database, includes a lot of practical operating aspects such as having,

- a **measurement system** which provides an accurate quantification of stocks and transfers of material.
- **operating records** that document material movements, material locations, identities of items and provide links to related measurement data.
- **accountancy control procedures** whereby information is regularly cross-checked against other information to detect incoherencies.

These are the basic processes that determine the quality of accounting information in any facility. They are designed to ensure measurement quality, to record data and to identify human errors where possible. Each of them is discussed briefly below,

**Measurement System:** The requirement of having small enough discrepancies (normally measurement errors) between accounting values and the true values determines the precision of measurement methods that are required for each accountancy measurement. The precision of the accountancy is ensured by having the appropriate measurement method, by having qualified measurement procedures and by monitoring the correct execution of these procedures. Ensuring the correct execution implies having a 'measurement control program' that monitors the correct functioning of the measurement methods. In addition, it provides estimates of the measurement standard deviations associated with the measurements on which the accountancy is based. Note that it is not necessary to have a complete and accurate quantification of NM masses at all points in time. For auditing purposes it is sufficient to have a complete and accurate description at the moment when auditing is being carried out.

Note also that a measurement method whose use is not respecting the required standard deviations, may create an unexpected frequency of large discrepancies between true value and measured value. This in turn will mean that subsequent estimates of probabilities may be unreliable and hence wrong decisions may be more likely than imagined.

**Operating Records:** Operating records are the documents or computer entries that describe material transfers within the facility (material follow-up), material processing, shipments and receipts, measurement results, etc. Such record keeping usually provides identification of the persons responsible, the locations involved, the container identities as well as measurement results or links to measurement information. Material follow-up often includes a checking of record data as the material is passed from one zone to another when the responsibility for material is transferred from one responsible person to another. The fact that material movements inside an MBA are "followed up" by an internal record keeping, provides the possibility of recognising some human errors and of correcting them before it is too late.

The identification of material items and their exact locations is important since it is what allows an auditor to compare material locations in the information system with the real position of the material. Errors in such information will create needs for time wasting investigations during audits.

**Accountancy Control Procedures:** Up to now, accountancy has been described as a process of recording shipments, receipts, production records and internal transfers. In addition to this however, the process will also include accountancy ***control*** procedures. These are procedures intended to detect incoherencies within the data and incoherencies between data and reality. In particular, an accountancy system will also be validated periodically by physically checking the existence of the inventory. When carried out by facility management, this process of checking the physical inventory is referred to as "Physical Inventory Taking" PIT. The objective of PIT includes identifying the location of all material and assigning an accountancy value to the material in each location or container. To carry out a PIT, all material must be available in measurable (or estimable) form. In any large facility, PIT is a key part of the internal validation of the accountancy and the preparation for any external audit.

The result of a PIT is a total list of inventory items (LII) that have been verified as corresponding to reality. The facility accounting department derives this LII from the database of operating records supplemented by any necessary checking that the list is complete and accurate. How well this list corresponds to reality will depend on the quality of operating records and on the quality of work that has gone into its preparation. This work usually includes some degree of checking that the list is of good quality;

- The first level of *checking* is that of ensuring correspondence as regards item identification and exact location. This will also include ensuring that there is no material that has been overlooked (either for record keeping or for PIT).
- A more rigorous level of *checking* includes verifying that the type of material in each container corresponds to what the accounting records describe and ensuring that the amount of material corresponds to the amount given in the records.

After such a process of checking, it may be necessary to correct some accounting or record information – perhaps with regard to amounts – perhaps with regard to location – perhaps with regard to the nature of the material – or perhaps with regard to items overlooked. After such corrections, if they should be necessary, the facility has a reliable list of the material.

Having such a reliable list of stocks, the facility is then in a position to verify the overall consistency of present stocks with previous history of receipts and shipments. This is the famous material balance equation designed to check "material unaccounted for". The material unaccounted for (MUF), in the interval between two time points of PIT, is computed as,

MUF = Beginning Inventory + Receipts – Shipments - Ending Inventory

In this balance equation, previous stock is compared with present stock taking account of intervening receipts and shipments. Each term on the right hand side is the sum of the measured masses of the corresponding nuclear material. The measurement of any amount however, will incorporate the intrinsic measurement uncertainties of the methods being used to measure the material. If all the procedures related to accounting were carried out correctly, this material balance amount (MUF) should be just an accumulation of legitimate facility measurement errors. This however means that a material balance is not obliged to be zero, even when the accounting has been perfectly carried out. As a result, one important control procedure is to ensure that the MUF for any balance period is acceptably small whilst taking account of the legitimate measurement uncertainties of the NM which have been processed.

Deciding whether MUF is acceptable or not, is a problem of statistical inference. This is done by computing a standard deviation ($\sigma_{MUF}$) for the balance, and then judging the magnitude of MUF value relative to this standard deviation. The standard deviation is usually computed on the hypothesis that discrepancies (between accountancy value and true value) are caused only by legitimate measurement error. Hence, the computation of standard deviation is done using the accountancy information for the balance period and knowledge of the measurement uncertainties of the measurement methods used by the facility.

At this point, we should notice that the possible causes of an unacceptably large MUF value can be that the information used is either incomplete (records for some material are entirely missing from the MUF data-set), or alternatively some accounting information is inaccurate. It is also possible that both of these defects are present. In addition, a MUF which is acceptable in the sense of the MUF test is not necessarily reliable. Inaccuracies could for example cancel out in the MUF equation thereby giving a satisfactorily small value, even though there are serious inaccuracies. Thus if an accountancy dataset were inaccurate or based on incomplete information, it may or may not produce an alarming value of MUF. An apparently acceptable material balance is unfortunately not a demonstration that nothing is wrong. Hence the assurance provided by a small MUF, has to be accompanied by further assurance that the set of accountancy information is complete and that the mass determination for each set of material corresponds sufficiently well to physical reality. Meeting these completeness and accuracy requirements, is addressed by ensuring that the accountancy adequately represents the physical reality.

**Other Control Procedures:** The MUF is a global indicator of the consistency of the accountancy information. Other control procedures can include checking the self-consistency and correct use of the operating records that contribute information to the final accounting balance.

In addition, control procedures normally include careful checking of all data regarding any material entering or leaving the facility.

**Accountancy Conforming to Physical Reality:**

As already mentioned, conformity to physical reality is achieved by completeness and accuracy requirements. Achieving these requirements comes from the quality of design of the accounting procedures as well as ensuring an effective implementation of the design.

As outlined earlier, the essentials of accountancy are incorporated in procedures for measurement and record keeping. These are the primary tasks in the accountancy process. Alongside the primary tasks, accountancy ***control*** procedures are added to provide protection against possible human errors. In addition to these three, further procedures may be applied to ensure the accuracy and completeness of the accounting information. These additional procedures can include,

- procedures to ensure that no movement or processing of nuclear material can occur without an operating record being created. This contributes to completeness and is achieved by having some mechanism of enforcement of the requirement of record creation.
- data management procedures to ensure that the data is preserved and is retrievable as required (completeness).
- procedures to ensure that human errors do not occur in creating the content of accounting and record information and to ensure its correct use (accuracy and completeness). This is usually achieved by some kind of redundancy in data creation and comparison of results.
- procedures to ensure that measurements of nuclear material amounts are sufficiently exact (accuracy). As mentioned earlier this is achieved by qualification of measurement procedures and a measurement control program.

These are ancillary procedures that support the accountancy tasks. If there is a failure of performance in some of the procedures, (primary, control or ancillary), the result will be anomalies of the kind already mentioned while discussing PIT. These were either anomalies about the location of material or anomalies about the amount declared for the material. An anomaly about the amount declared is an unacceptable discrepancy between the declared value and the amount really present. Anomalies can only be detected by verification activities which are the core of auditing the quality of implementation. Before discussing verification requirements however, it is useful to elaborate in more detail the forms that such anomalies can take.

If we consider all the items that physically exist or are mentioned in the LII or are mentioned as contributing to the accounts, we can logically identify all the types of anomalies that can occur in a defective accountancy.

Examination of the anomaly types identifies the tasks that are necessary for checking the accountancy performance. These tasks are,

- check that all LII items really exist (tag-check),
- check that no items exist which are not on the LII (search for undeclared material),
- check that the accountancy information agrees with the LII data both in terms of the items included and the amounts involved for each item,
- check that the accounting and LII values for individual items are not materially misstated (this can only be revealed by confirmatory remeasurement of the item).
- check whether the material balance appears to belong to a physical reality in which no material has been lost or overlooked, i.e. some check that true MUF for the declared reality is zero.

The first three of these tasks are traditional auditing tasks whereas the latter two are auditing tasks that include statistical inference in which the recognition (or not) of an anomaly, must be made while taking account of the uncertainty due to measurement variation. Note that all these tasks are simply questions of taking note that anomalies exist. The auditing activities are aimed at detecting anomalies. They provide the basic data that are an input to subsequent evaluation of the performance of the accountancy system.

The accountancy declarations for a balance period consist of data describing beginning inventory, receipts, shipments and ending inventory. The data describing beginning and ending inventory are generally derived taking account of the results of a PIT as described earlier. Conformity with physical reality is essentially the same concept whether we are speaking about the inventory of some balance time point or about a set of material which has just arrived or a set of material that is about to be shipped. Hence the auditing of shipments or receipts is logically analogously to the auditing of an inventory. For brevity therefore we will speak only of the case of an inventory.

**Quantitative Objectives for Accounting Quality:** Given the existence of intrinsic measurement error, there will always be some small amount of material that could go missing without being detected. The objective of accountancy is to document a control of material ensuring that **no significant amount** of material is missing or lost. What is a significant amount of material is defined by the objectives set by the state or by international agreements. A significant amount of material is an amount which if it were overlooked or lost, the accountancy balance should hopefully be precise enough to identify this fact. If quantitative accounting objectives are defined in terms of some specification of a significant amount, this in turn will generate requirements as regards the required precision of the facility measurement system. It will also generate requirements for the control of human errors affecting accountancy discrepancies.

# 3. Auditing Implementation of the Accountancy Process

The earlier section has described accountancy, the possible types of anomalies and the activities required to detect anomalies. Auditing consists of examining an accountancy process to assess how well it is designed or is performing or both. Such auditing can be carried out by international agencies, by State supervision authorities or by a facility itself. As we will outline in what follows, different auditing agents may have different objectives and hence have different auditing policies. Auditing of the facility procedures consists of ensuring that,

- procedures are complete, methodologically correct and adequately specific,
- appropriate training has been identified for carrying out the procedures,
- the people who must implement the procedures are aware of them and have received the appropriate training.

While these aspects will strongly influence the performance to be expected from the accountancy process, they will not be examined in further detail here. Instead we will focus on the auditing of implementation which can be a major application of statistical sampling theory.

**The Objectives of Auditing Implementation:** The purpose of auditing implementation is to have assurance that the accountancy corresponds to a physical reality in which all nuclear material is properly accounted for. Auditing implementation is carrying out some or all of the tasks described earlier for detecting anomalies. How auditing resources will be allocated will depend on the auditor's perception of the risks of different types of anomaly and their importance relative to the objectives of the audit. Some tasks may be carried out exhaustively (i.e. 100% check) whereas other tasks may be executed for only a random sample of the items. At the moment of auditing,

- all material must be located and an accountancy mass value must be assigned to the material in each location or container,
- all the items should be in a form that would facilitate verification measurement of the item.

What happens in practice is that for every item that the operating records indicate as contributing to the material balance, a physical item of material is made available for verification. In auditing a material balance this will be done for each balance component i.e. inventories, shipments and receipts. These **four sets of declared items** become the "***declared reality***" to which the accounting balance refers. In practice the declaration of sets of material takes the form of providing a list of all items (LII) with their characteristics, containment and locations.

Declared reality refers to specific sets of material that have been made available for verification. This however may not be exactly the same thing as physical reality if we consider "***physical reality***" as denoting all the material that entered the balance zone and its subsequent location. Declared reality implicitly includes the affirmation that the declared reality in question corresponds to the real accounting history of all material that entered the facility. In a situation where material in the facility has been overlooked or is not declared to the auditor for whatever reason, declared reality is different from physical reality. In the situation where material has been illicitly removed from the facility, the declared reality is different from the physical reality.

The LII is a list of items declared to be a complete list of the nuclear material in the facility. When speaking about physical realty, we use the term 'item' to include more generally any item or location containing nuclear material whether or not it is on the LII. Usually an external auditor will verify

the LII by physically checking that a corresponding item exists for each entry in the list. This activity is referred to as the 'tag-check'. A tag-check is the verification of the real existence of the items as declared by the LII.

The reader may be surprised that the LII and the accountancy information are considered as two separate things. In practice they usually are two separate datasets. One is the dataset defining the declared reality including locations and descriptions of items. Under a comprehensive verification régime, such a dataset will exist for each event of shipments, receipts and inventory. These datasets are the basis for the tag-check and usually provide the sampling frame for verification activities. The other is the dataset used to compute the material balance and this includes a contribution for each component of the MUF equation. The creation of information in a large facility is a complex process involving distributed databases with many types of information. There is no standard structure for such databases. To make a logical analysis of the implementation of auditing, all we need is the concept of 'datasets describing declared reality' and the 'dataset for computing the accountancy balance'. We consider that these are separate since they usually are, and this brings with it the requirement that the auditor verify their mutual consistency.

**Measurement System Requirements:** Following our earlier discussion, we can see a number of aspects likely to affect the cost and effectiveness of both accountancy and auditing. Important among these are both the facility's measurement system and the auditor's measurement system. From our discussion of anomalies, we saw that the MUF test is an essential element in any audit. The quality of the facility measurement system will determine the magnitude of the MUF standard deviation. Hence the facility measurement system will determine the ability to recognise the effect of anomalies which are contributing to the value of MUF. Performance may appear satisfactory in the sense that there are no anomalies given the standard deviations associated with the existing measurement systems. This however may be unsatisfactory in the sense that the standard deviations are so big that unacceptable discrepancies may be undetectable. This again emphasizes the idea that there has to be some link between the precision of the facility measurement system and what is considered a significant amount of material from a legislation or treaty point of view.

Recognition of anomalous discrepancies can be achieved by auditor measurement of individual items followed by a statistical test of the difference between the accountancy declared value and the auditor measured value. Obviously the ability to detect an anomaly will depend on the size of that anomaly compared to the standard deviation of the difference. This standard deviation is determined by both the auditor's measurement method and the accountancy measurement method. Hence we see that the required sensitivity of measurement for recognising anomalous discrepancies will also create requirements for both auditor measurement system and for the accountancy measurement system. This is another source of criteria for the accountancy system since it says that the standard deviation of measured quantities have to be small enough to ensure effectiveness in the checking of differences on individual items.

**An Adequate Audit:** The purpose of auditing is to provide assurance that the accounts conform to the declared reality and that the declared reality conforms to an acceptable physical reality. In the last analysis, both of these assurances come from statistical inferences based on the data coming from some audit. Assurance is achieved by carrying out an ***adequate*** audit plan that fails to detect any important anomalies. Saying that an auditing plan is adequate means that if the accountancy were inadequate in any ***important*** way, the audit should be capable of recognizing such a condition. An adequate audit should with good probability be able to identify any important failure of conformity – if it were to exist. The mere fact however of establishing the inadequacy cannot of itself explain how or why the inadequacy has occurred. The audit can only document the inadequacy in terms of the anomalies it has revealed. The characteristics of these anomalies merely raise a list of concomitant hypotheses about the possible causes. This is now discussed in more detail.

**Human Error as a Cause of Discrepancies:**
Discrepancies between accountancy and reality can have a variety of possible causes other than intrinsic measurement errors. Discrepancies that are not legitimate measurement errors, can arise from a variety of types of human error. These are:

- errors in recording or processing information. This includes manual transcription errors, errors in computer data entry, application of computation procedures where not applicable, human computational errors, software errors, etc.;
- failures in carrying out measurement procedures including application of measurement procedures where they are not applicable;
- procedural and technical manufacturing errors which create items whose characteristics are different from design specifications when design specification values are being used as estimated values for accounting.

These examples of human error are all failures of execution of some procedure. Discrepancies can however also be due to errors in defining the procedures themselves. Note also that once we begin to speak about types of errors which can cause anomalies, we have to consider all procedures which generate accounting data and all other procedures which if they were not fully respected, might lead to accounting information being incorrect.

If human errors occur, they will make a contribution to MUF through the discrepancies they cause. In this situation, it may still be reasonable to consider MUF as having a probability distribution. What is less clear however, is how we could get empirical information about this probability distribution. It is clear that if there is a $\boldsymbol{\sigma}_{\mathbf{MUF}}$ that includes the potential contribution of human errors, it is not the same thing as the $\boldsymbol{\sigma}_{\mathbf{MUF}}$ described earlier which included only intrinsic measurement errors. We thus realise that the $\boldsymbol{\sigma}_{\mathbf{MUF}}$ estimate based only on the propagation of legitimate measurement error, is only an oversimple model of the accountancy uncertainty. Already however we can note that quality assurance in any accountancy system must include some concern to reduce the incidence of such human errors.

**Measurement Problems as a Cause of Discrepancies:** It can happen that existing measurement methods or procedures for these methods may give inadequate results for some new type of material. This problem may take sometime to reveal itself. Undetected however it can be the cause of small measurement biases which accumulate in the material balance. This can give an unacceptable MUF that is apparently inexplicable.

**Falsification as a Cause of Discrepancies:** In its implementation of the NPT, the IAEA must take account of the hypothesis that discrepancies could be caused by falsifications aimed at disguising the removal of material. The need to consider this hypothesis comes from the NPT objective of providing assurance that material capable of producing a nuclear weapon has not gone unaccounted for. At the level of the ***analysis*** for designing IAEA verification approaches, the State is treated as a potential adversary. The NPT safeguards inspector must employ verification procedures that can lead to valid conclusions even if discrepancies have been created by a falsification strategy. As a result, IAEA planning of verification leads to an extensive consideration of hypothetical falsification strategies.

The case of NPT safeguards is not the only scenario in which falsification strategies need to be considered. Under national legislation, the facility and the State are concerned to prevent theft of material. In a scenario of theft, an individual or subgroup, within or outside the operator's organisation, steals nuclear material and perhaps introduces falsified accounting data to reduce the risk of detection.

**The Effect of Human Errors:** We recognise the possibility that human errors may occur and that they could be a source of alarm in the MUF test or in the tests of verification differences. These alarms can only be resolved by investigation to identify the cause if possible. This is useful if we are using the auditing to detect human errors with a view to quantifying performance and eliminating the causes of

mistakes. This is the perspective of facility management. If however we are an international authority, interested in obtaining assurance that there is no falsification strategy being implemented, the situation is different. Anomalies could be human mistakes or they could be consequences of a falsification strategy. They will be costly to investigate and sometimes the investigation may lead to inconclusive results. The less human mistakes occur, the less likely it is that such unsatisfactory ambiguities will occur. It is a fact that having good accountancy will greatly reduce the work of auditing. It will reduce both the intrusiveness to the facility and the cost for the auditor.

**State Perspective on Accountancy Implementation:** In all States, the national legislation requires facilities to protect nuclear material and to maintain a reliable accountancy. The objectives of NMA&C include maintaining accurate, up to date and reliable information regarding the quantities and locations of material as well as regular reporting of this information, including any anomalies. This is particularly important for material in transit where detailed procedures will exist for ensuring continuity of knowledge during transport.

As well as documenting the storage, transport and processing of nuclear material, the facility accountancy and protection system (FAPS) should incorporate checks that are sufficient to detect falsification of data and reports by a single individual including an employee in any position, or involving collusion between individuals one or more of whom have authorized access to nuclear material.

As mentioned in the introduction, many States have a national agency that supervises the implementation of national legislative requirements for accountancy and protection. Such agencies may be involved in auditing accountancy information and verifying the conformity of accounts with reality. In most States, the legislation and the related guidelines for implementation, also include prescriptions regarding job responsibilities for accountancy and control, for measurement quality and for measurement quality control.

**Consistency of Operating Records:** The goal of an audit is to be sure that the accountancy process is documented in sufficient detail and that it is effectively implemented. Up to now we have spoken mainly about the MUF test and checking agreement with reality. Usually the audit of accountancy will also include checking the self-consistency and correctness of use of the operating records. As was mentioned earlier, such records will describe follow-up of material, storage locations, container identities, measurement results and results of measurement control activities. This additional checking of the consistency and correct use of operating records (from data creation through data processing, up to the accountancy reports), provides an additional input for assessing the ultimate reliability of accountancy declarations. It provides an additional source of information since it is possible for data processing errors to produce anomalies (affecting MUF value or item discrepancies) that are small and not detectable with the given measurement error uncertainty. Absence of such data processing errors suggests that anomalies caused by error are infrequent and hence increases the credibility of the accountancy system.

This enhancement of credibility is valid if anomalies are considered as caused by human errors and if the hypothesis of falsification is excluded. However even when the hypothesis of falsification is not being excluded, checking the consistency of operating records has the advantage that it increases the probability of detecting some falsifications if they exist.

**Other Factors Affecting Accountancy Performance:**
Discussing systems of protection of nuclear material is not the subject of this note. There can however be links between accountancy performance and the performance of some elements of the security control system for protection of nuclear material. A brief look at this aspect clarifies what is meant by the earlier reference to facility procedures having an influence on accountancy performance. The design of such control procedures can influence the incidence of human errors and render falsification extremely difficult.

Under national legislation, the protection of nuclear material is the responsibility of the facility in partnership with the security forces. In this framework the security system will contribute to,

- deterrence of theft or falsification by making them inherently difficult,
- high probability of speedy detection of illicit activities (e.g. accountancy anomaly or other procedural anomaly),
- high probability of identification of malefactor.

A variety of security procedures contribute to effectiveness in this regard. Such procedures include control and monitoring of access by personnel to nuclear material, to measurement equipment and software and to the creation of data records that will determine accountancy information. These are security control procedures whose effectiveness will limit the possibilities for error, theft or falsification and hence contribute to ensuring that all NM are properly accounted for.

Apart from the question of security procedures denying unjustified access to sensitive information or material, other control procedures can be designed to ensure the correct implementation of accountancy procedures. They can do this by playing a role in the enforcement of primary accountancy procedures (i.e. enforcement of correct record creation, of correct measurement procedure and verification of material transfer). This kind of enforcement control procedures can include 'multi person rules' or automated verification of compliance in order to reduce risk of error and to inhibit falsification. In the event of illicit activities such enforcement procedures may send an alarm to the security system.

Because of such potential links between accountancy procedures and some kinds of security related procedures, accountancy effectiveness can be supported by the design of the system of protection and conversely some requirements of physical control procedures are supported by the design of the accountancy system.

These kinds of considerations can also have implications for the design of an auditing plan. It may for example be preferable to orient auditing resources to aspects where vulnerability is highest (whether for falsification or for inadvertent errors). Vulnerability can be inversely related to the degree of protection offered by some enforcement or security procedures.

**The IAEA Auditing Criteria**

IAEA auditing criteria are determined by the desire to detect with a reasonable probability any accounting anomaly considered significant in terms of the amount of nuclear material capable of producing a nuclear weapon. A concomitant of the adversarial hypothesis is the need for an audit that is independent of the facility. Verifying that a nation state is not reneging on its NPT obligations implies use of a verification approach whose effectiveness cannot be deflected by any strategy of falsification the state could employ. Another feature of NPT safeguards is the way in which the IAEA determines the amount and frequency of auditing. This is done only in terms of the characteristics of the facility, the amount of material necessary to develop a weapon and the time that this development would require. The concept is that auditing activities would be determined only by such purely technical criteria. The auditing burden on a State would not be determined by subjective variables such as political perception of motivation to default. One consequence of adopting such technical criteria is that an extensive verification of reality is required.

**Facility Management Perspective:**

The perspective of facility management is different from that of external auditors such as an international safeguards authority. Facility management knows that it is not trying to falsify its accounts. The objective of facility management is to have good accountancy and this is achieved by the design of the accountancy process and by monitoring its performance through time.

Facility management is pleased to have auditing of accountancy performance, which for facility management is a way of monitoring the rate of occurrence of human errors or procedural deficiencies. The risk of occurrence of such anomalies is of course related to management's role in creating job specifications, procedures for technical methods and training for all kinds of personnel whether they are involved in production, measurement or in record keeping. For facility management, identifying anomalous discrepancies and trying to find the cause can be a mechanism for improving techniques, procedures and training.

Some program of audit is necessary if management wishes to know what is being achieved and whether anything needs to be improved. Audits provide some data collection for quantifying accountancy performance. Definitions of performance can be made and standards can be set for performance. After an audit, the achieved performance can be estimated and the difference between the desired performance and the achieved performance can be recorded. In this way, management can have internal monitoring of the quality of accountancy being achieved. For a facility that is subject to external audit (either by the state or by an international authority), internal monitoring of performance reduces the risk that the external audit will produce embarrassing surprises.

In some States, organisations operating large facilities may have internal audit departments and in this situation many of the functions of auditing and supervision of accountancy can be the object of collaboration between the facility audit department and the State agency for supervision.

**The Perspective of the Euratom Treaty**

Under the Euratom treaty the facility must ensure that nuclear material is employed only for its declared use. The facility is obliged to have accountancy systems in place and to regularly report its accountancy to the Commission of the European Union. The role of the Commission services is to ensure the correctness of the operator's declarations on their use of nuclear material. The Commission's task is aimed at controlling conformity between declarations and reality. Under the treaty, the Commission has a direct relationship with each facility. It has the right both to make inspections and to impose sanctions in case of non-respect of obligations. The Euratom treaty does not contain any reference to nuclear weapons nor the risk of their proliferation. The safeguards approach of the Commission is based on audit of the material accounting and control systems, with appropriate random checks of procedures, records and of the physical reality. The emphasis in auditing strategy is linked to monitoring indicators of accountancy performance and on initiatives to improve performance if these should be required. The adaptive auditing approach takes into account the historical experience of the reliability and effectiveness of the operator's system. Assurance of conformity can also be provided by access to information acquired by other monitoring organizations such as the IAEA or the State agency for supervision.

Using accounting declarations, audits and other sources of information, the Commission services can provide assurance that the terms of the Treaty are being respected. This will contribute to ensuring that the facility has a credible system of accountancy in line with the most recent international standards.

# 4. An Overview of NPT Safeguards Methodology

This section gives a brief overview of the methodology used for determining safeguards implementation under the NPT. In this methodology, risk analysis defines performance criteria for the design of the safeguards system and then the implemented safeguards system has to meet these criteria. The IAEA safeguards criteria are expressed in terms of the concepts of **significant quantity, detection probability** and **timeliness**. Giving values to these three elements, for each specific category of material, specifies a requirement for detection sensitivity. For example we could say, if **8 kg** of Pu is missing, the safeguards system has to have **.95** probability of raising an alarm within **10** days.

Figure 1 illustrates the relationship between risk analysis, detection sensitivity criteria, safeguards system design and the cost of the safeguards system. It also brings into the picture the nature of the facility (process flow sheet) and its accountancy system.

The basic message of Figure 1 is three ideas,

- detection sensitivity is used to denote a series of performance criteria which must be achieved by the safeguards system. It represents the time duration within which the safeguards system is required to produce an alarm with a required probability when a specific "diversion event" has occurred.
- The performance criteria for detection sensitivity are chosen taking account of a number of factors which may include the two measures which are "Proliferation time" and "Fissile material quality".
- the third idea is that the safeguards system is designed to achieve the criteria. To do this, the safeguards system has to be designed around the process flow sheet using safeguards techniques to achieve the required detection sensitivity. Once the design is specified so as to achieve this requirement, the implemented design determines the resources needed for its implementation, i.e. determines the cost of setting up the safeguards system and its subsequent running costs. In other words, required detection sensitivity has a determining influence on the design needs and thereby on the related measure detection resources i.e. costs.

**Determination of required detection sensitivity**

Fissile material category is the degree to which the characteristics of the material affect its utility for use in fabricating a nuclear weapon. This consideration results in a categorization of material types (i.e. Pu, HEU, etc).

In analyzing hypothetical proliferation scenarios the category and amount of material and when it will be removed from accountancy, are referred to as a "diversion scenario". The diversion scenario considers diversion objectives as being the category and quantity of material as well as the time over which it is planned to complete the removal from the accountancy. The removal of the material can be a single event or a series of successive removals.

The analysis of hypothetical proliferation scenarios also goes on to consider the time a state might need to process the material and fabricate a weapon. Once **reference times** for acquisition, processing and fabrication of a weapon have been identified for each specific material, the non-proliferation analyst can specify within what time the safeguards system must be able to detect an anomaly (i.e. provide an alarm) revealing the diversion strategy in action. Roughly speaking this should reflect the desire to have an alarm before the state can acquire the material or do much with it.

In IAEA methodology the criteria (significant quantity, timeliness and probability) are related to some analysis of possible conversion and fabrication times but the details of this reasoning are not spelt out. The required detection time, significant quantity and detection probability are simply specified for each category of material and are the same for all states possessing that material type. This is related to the NPT non-discrimination concept whereby safeguards system criteria should be determined by purely objective characteristics of the fuel cycle and not by any a priori judgment about whether the state is likely to divert.

In IAEA methodology, the diversion scenario is used to identify the patterns of anomalies that could be encountered in such a scenario. When this is applied to the scenarios referred to in safeguards criteria, it provides reference situations for judging the performance of any proposed safeguards system. Because of the nature of accountancy and the rules for presenting declared material for verification, the identification of the anomaly patterns that are characteristic of a diversion scenario is relatively straightforward.

In this note we are essentially interested in the fact that detection sensitivity criteria are given in terms of **significant quantity, detection probability** and **timeliness** and that the detection sensitivity requirement is broken down by material type. This specification of the **required detection sensitivities** provides the design objectives for the safeguards system which then has to be designed in detail. Once a criterion (significant quantity, timeliness and probability) is given for a specific material type, the analysis of the related anomaly patterns allows the safeguards analyst to establish detailed safeguards activities for detecting any emerging scenario. This is discussed in more detail in the next section.

In Figure 1, the process of determining detection sensitivity criteria is represented as a box whose inputs are f**issile material category** and **proliferation times.** We do not attempt here to discuss the how the output values for desired sensitivity are determined inside this box.

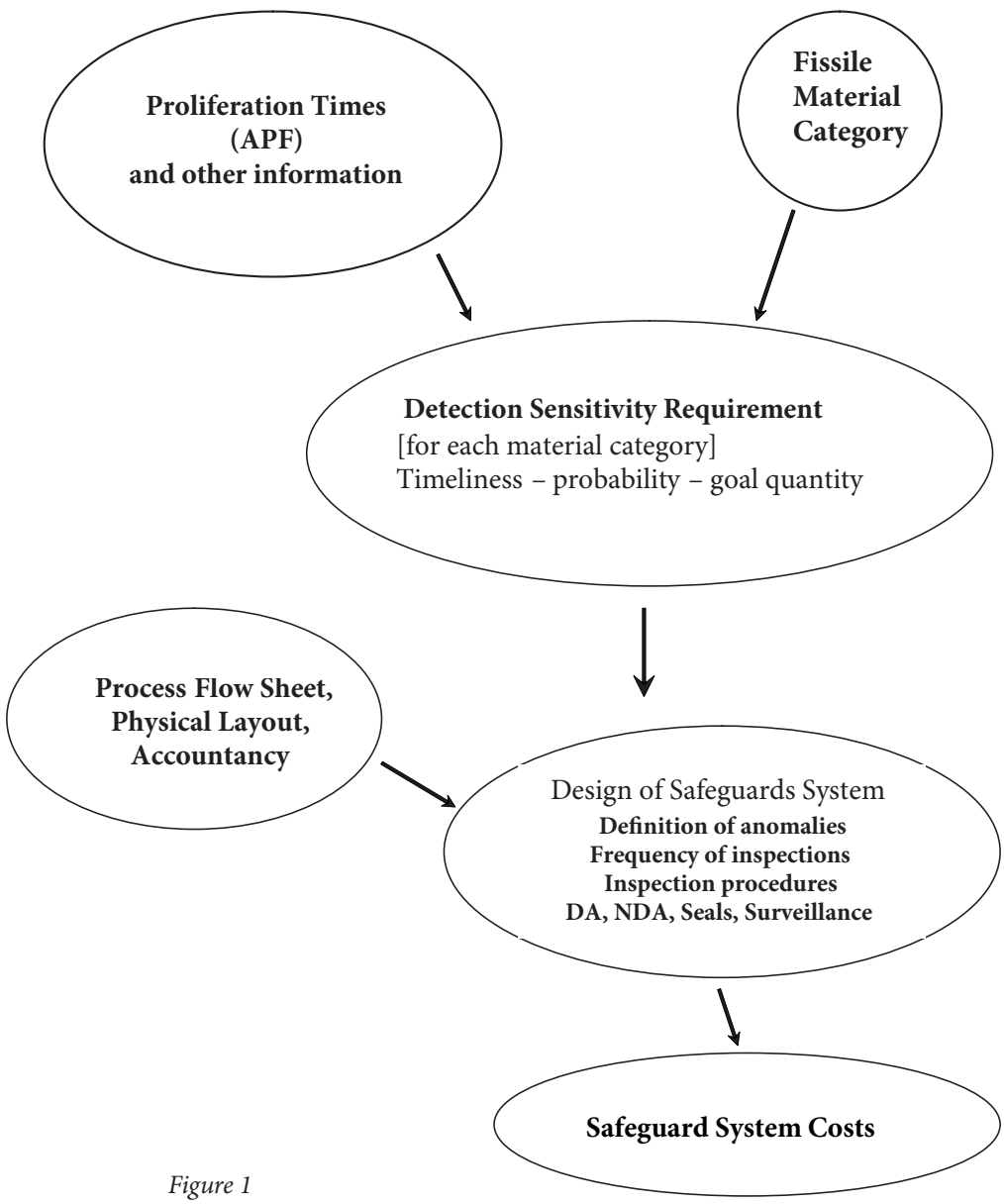


*Figure 1*

**Specification of the Design of the Safeguards System (PR).**
In the NPT approach, the safeguards system must be designed to ensure detection of any breach of accountancy requirements. The accountancy requirement is that the accountancy be complete and that the location of all material and its amount should be as described in the accounts. The design of the safeguards system is aimed at being able to recognize any pattern of accountancy anomalies that is the consequence of a diversion of a significant amount of NM. A satisfactory system must be able to recognize an anomaly in time to meet the timeliness requirements for each different category of material. The design methodology (for safeguards systems) uses the safeguards criteria to identify **'anomaly patterns'** which need to be recognized with a desired probability. In what follows we elaborate on these elements in more detail

**General discussions of proliferation** looks at a number of distinct themes including (i) how the material might be removed, (ii) how the accounts might be falsified (anomalies) and (iii) what strategy of disguise might be used to foil the verification of material whose amount has been falsely declared. For NPT safeguards methodology, the first of these (how the NM is removed) is largely irrelevant in that the methodology makes no assumptions about it or the possibility of knowing it. For a diversion made by the state, the state can remove the material as it pleases. The second is highly relevant and is discussed at length below. The third (the disguising of an anomaly) is treated by the methodology as part of the design of item verification activities and is also discussed briefly below.

The methodology for designing an NPT safeguards system is based on the fact that if material is removed (i.e. removed from the set of NM made available to the inspector for verification), then there must be accountancy anomalies corresponding to that diverted quantity. Accountancy anomalies are of two distinct kinds. The first kind is called a difference anomaly and is an anomalous **discrepancy between the declared accountancy value for an item and the real content of that item.** The second is an anomalous discrepancy at the level of closing the operator's material balance (**MUF anomaly**).

The set of discrepancies in the accounts are objective facts and they always indicate the amount of material diverted ([2]). This fact is embodied in the accountancy identity,

$MUF = MUF_{TRUE} + L_{MUF}$

where $MUF_{TRUE}$ is the true material balance and $L_{MUF}$ is the accumulation of all discrepancies in the accounts. This equation is of fundamental importance since it says that if $MUF_{TRUE}$ is non-zero, then

$MUF - L_{MUF}$ is non-zero and equals the true material balance.

If on the other hand, $MUF_{TRUE}$ is zero, the MUF is just an accumulation of discrepancies. Note that even when no falsification or diversion has taken place, discrepancies always exist because of legitimate facility measurement error.

The accountancy equation however, says that if $MUF_{TRUE}$ is equal to a goal quantity, either the material balance will be an anomaly or there must exist discrepancies whose magnitudes are anomalous. Anomalies of a total magnitude of $MUF_{TRUE}$ are there waiting to be found. This forms the basis for identifying the patterns of anomalies that could accompany a specific diversion scenario. The discrepancies of course are themselves not observables and hence use of this equation in verification theory involves linking it to measurement of the discrepancies.

To design an effective safeguards system for a specific significant quantity, all that is needed is to have procedures that have the desired probability of detecting at least a **single anomaly** when $MUF_{TRUE}$ is a significant quantity. The detection of at least a single anomaly has to be achieved for whatever pattern of anomalies may have been created by the states diversion of a significant quantity. A single anomaly

([2]) This is one of the basic identities of NM accountancy.

acts as an **alarm** and is followed by verification of further items. The state may falsify its accountancy so as to leave a pattern of anomalies that it hopes will have the smallest probability of detection. This is called the **least favorable anomaly scenario** (for the inspector). The verification procedures are defined with all of this in mind. They aim to ensure the desired detection probability even for the least favorable anomaly scenario. The statistical theory of accountancy and auditing developed over the last 35 years is the methodology for designing the safeguards inspection activities with exactly this objective in mind ([3]). The only characteristics of diversion scenario that play a role in this approach are

– the time points at which material is removed from the accountancy
– the amount of material removed at each time point and
– the pattern of accountancy anomalies (material balance or item differences) that could exist at each point in time.

In addition, the methodology assumes that if an item is verified, the verification method has known probabilities of failing to recognize any specific size of anomaly however it may be disguised. The work of designing verification methods is aimed at increasing these detection probabilities for whatever anomaly – however it may be disguised.

As a result of this theory, the implemented safeguards system consists of inspection procedures that look for hypothetical anomalies. This is achieved by verifying at appropriate time intervals (timeliness), that the accounts balance (MUF) and that the physical reality is in agreement with the accounts. The procedures usually involve verification measurement of randomly selected material. At each visit the auditing intensity is such as to achieve the desired detection probabilities **if** anomalies corresponding to a goal quantity were to exist. The inspector workload is reduced by the use of **tamper indicating sealing and surveillance of material** ([4]) that has been previously verified. This is usually applied to material which probably will not be used by the facility before the next inspection and is referred to as maintaining '**continuity of knowledge**'. Tamper proof sealing is also used to 'freeze' material which is waiting for verification.

**Final Remark:** The global approach to characterizing the implementation of NPT safeguards is built on four subordinate elements. These are,

(a) deciding **detection sensitivity requirements**,
(b) identifying the **patterns of accountancy anomalies** which in the particular facility could correspond to the goal quantities in the detection sensitivity requirements,
(c) **designing the safeguards system** to meet detection requirements,
(d) determining the **safeguards system costs** required for the proposed safeguards system design.

([3]) The statistical methodology determines how many items (chosen at random) must be verified and with what measurement precision different subsets of them need to be measured.
([4]) **Tamper indicating** refers to the idea that the state cannot falsify the fact that material has been accessed.

# Random Sampling in Nuclear Material Safeguards

Rudolf Avenhaus, Morton Canty

## 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 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. Two kinds of sampling procedures will be considered. With the help of the *variables sampling* |1| procedure, which takes into account measurement errors, the expected differences between the operators' reported data and the inspectors' findings are quantitatively evaluated. The *attribute sampling* |2| procedure permits only qualitative statements about the reported data. In addition, *variables sampling in the attribute mode* will be sketched, since it has raised some discussion over the years |3, 4, 5|.

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 at the end of the verification procedure a decision has to be taken whether or not 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 |6|; 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 represents a *game theoretical problem*. Here, we will only treat the test, not the estimation problem |6|; as a result of the game theoretical analysis it is assumed that the operator – if at all – will falsify data in such a way that he minimizes the probability of detection 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 they can be found in the literature given at the end of this paper.

# 2. Attribute Sampling

According to general understanding |2| "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 somebody 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 pair of data – reported and verified – it can be stated, without committing any error whether or not these two data are consistent. It should be mentioned that the reported data may be seals: 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 how large the number n of observations has to be if in case that 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 it is determined by the hypergeometric distribution, see e.g. |7|, and is given by

$$1-\beta = 1-\frac{\binom{r}{0}\cdot\binom{N-r}{n-0}}{\binom{N}{n}} = 1-\frac{\binom{N-r}{n}}{\binom{N}{n}}; \tag{2-1}$$

this can also be written as

$$1-\beta = 1-\prod_{i=0}^{r-1}\left(1-\frac{n}{N-i}\right). \tag{2-2}$$

If the number of falsified data is small compared to the total number, i.e. if $r << N$, then we get

$$1-\beta \approx 1-\prod_{i=0}^{r-1}\left(1-\frac{n}{N}\right) = 1-\left(1-\frac{n}{N}\right)^{r} =: 1-\beta_1. \tag{2-3}$$

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

$$1-\beta_2 := 1-\left(1-\frac{r}{N}\right)^{n}. \tag{2-4}$$

Since the difference between drawing with and without replacement should be negligible in case of a small sample size (n<<N), one should get this formula also from (2-1). In fact, since this formula is symmetric in n and r we can write it also as

$$1-\beta = 1-\prod_{j=0}^{n-1}\left(1-\frac{r}{N-j}\right)$$

which gives for n<<N just formula (2-4).

Let us answer the question posed at the beginning of this section: For n<<N we get from (2-3)

$$n_1 = N \cdot \left(1 - \sqrt[r]{\beta_1}\right) \tag{2-5}$$

whereas we get for n<<N from (2-4)

$$n_2 = \frac{\ln \beta_2}{1n\left(1 - r/N\right)}. \tag{2-6}$$

For a given value of $\beta_2$ 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 this ratio f, then $n_1$ can be written as

$$n_1 = N \cdot \left(1 - \sqrt[N \cdot f]{\beta_1}\right) \tag{2-7}$$

For fixed values of $f$ and $\beta$ we obtain, using the rule of L'Hospital twice, the following asymptotic value of $n_1$ :

$$n_1^{\infty} := \lim_{N \to \infty} n_1 = -\frac{\ln \beta_1}{f}. \tag{2-8}$$

Furthermore, because of $\ln\left(1 - f\right) \approx -f$ for $f << 1$ we get from (6) and (8), and with $\beta_1 = \beta_2$

$$n_2 = n_1^{\infty} \text{ for } f << 1. \tag{2-9}$$

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 items have been falsified by large amounts (*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 Sanborn |3| and Jaech |4|. More recently, interest in the problem has been renewed, with Lu et al |5| 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.

If the inspector verifies $n_1$ data with the accurate 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 non-detection probability $\beta$ for sampling with replacement is given by

$$\beta = \left(1 - \frac{r_1 + r_2}{N}\right)^{n_1} \cdot \left(1 - \frac{r_2}{N}\right)^{n_2} \tag{2-10}$$

if we ignore statistical errors of the first and second kind.

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 discussion to sampling with replacement.

Now we shall assume that the operator falsifies his data by a total amount $\mu$, his goal quantity. Let $\mu_1$ and $\mu_2$ be the small and large individual falsifications respectively. Then obviously we have

$$\mu_1 \cdot r_1 + \mu_2 \cdot r_2 = \mu;\ \mu_1 << \mu_2. \tag{2-11}$$

Similarly we assume that the total amount of time available to the inspector for his measurements is $\varepsilon$, and that $\varepsilon_i$ is the time required for the verification of a single datum with the $i$ th method, $i = 1,2,$

$$\varepsilon_1 \cdot n_1 + \varepsilon_2 \cdot n_2 = \varepsilon;\quad \varepsilon_1 >> \varepsilon_2. \tag{2-12}$$

A rational solution to this problem involves the determination of a saddle point $\left(\underline{n}^*, \underline{r}^*\right) = \left(n_1^*, n_2^* : r_1^*, r_2^*\right)$ of the non-detection probability $\beta$ in the strategy space $\left(\underline{n}, \underline{r}\right) = \left(n_1, n_2; r_1, r_2\right)$ of the two players defined by

$$\beta\left(\underline{r}, \underline{n}^*\right) \le \beta\left(\underline{r}^*, \underline{n}^*\right) \le \beta\left(\underline{r}^*, \underline{n}\right) \quad \text{for all } \underline{n}, \underline{r} \tag{2-13}$$

whereby the boundary conditions (11) and (12) for given $\mu$ and $\varepsilon$ are to be met. Formally, the solution of this problem is given by

*Theorem 1* |8|
Let the sets of pure strategies $X_\varepsilon^1$ and $Y_\mu^1$ of the inspector and of the operator be given by

$$\begin{aligned} X_\varepsilon^1 &= \left\{\left(n_1, n_2\right) : \varepsilon_1 \cdot n_1 + \varepsilon_2 \cdot n_2 = \varepsilon\right\} \\ Y_\mu^1 &= \left\{\left(r_1, r_2\right) : \mu_1 \cdot r_1 + \mu_2 \cdot r_2 = \mu\right\} \end{aligned} \tag{2-14}$$

and let the payoff to the inspector be given by (2-10). Under the assumption that the sample sizes $n_i$ and $r_i$ can be considered as continuous variables, the solution of the zero-sum game $\left(X_\varepsilon^1, Y_\mu^1, 1 - \beta\right)$ is given by

$$n_1^* = \frac{\varepsilon}{D} \cdot \mu_1 \cdot \exp\left(-\varepsilon_1 \cdot C\right), \tag{2-15a}$$

$$\begin{aligned} n_2^* &= \frac{\varepsilon}{D} \cdot \left(\mu_2 - \mu_1\right) \cdot \exp\left(-\varepsilon_2 \cdot C\right), \\ r_1^* &= N \cdot \left(\exp\left(-\varepsilon_2 \cdot C\right) - \exp\left(-\varepsilon_1 \cdot C\right)\right), \\ r_2^* &= N \cdot \left(1 - \exp\left(-\varepsilon_2 \cdot C\right)\right) \end{aligned} \tag{2-15b}$$

$$1 - \beta^* = 1 - \exp\left(-\varepsilon \cdot C\right), \tag{2-15c}$$

where the parameters C and D are given by

$$\mu_2 - \frac{\mu}{N} = (\mu_2 - \mu_1)\cdot\exp(-\varepsilon_2\cdot C) + \mu_1\cdot\exp(-\varepsilon_1\cdot C)$$
$$D = \varepsilon_1\cdot\mu_1\cdot\exp(-\varepsilon_1\cdot C) + \varepsilon_2\cdot(\mu_2-\mu_1)\cdot\exp(-\varepsilon_2\cdot C).$$

For $\varepsilon_i \cdot C << 1$ for i = 1, 2, the forms (2-15a) reduce to

$$n_1^* = \tfrac{\varepsilon}{M}\cdot\mu_1$$
$$n_2^* = \tfrac{\varepsilon}{M}\cdot(\mu_2-\mu_1) \qquad (2\text{-}16)$$
$$M = \varepsilon_1\cdot\mu_1 + \varepsilon_2\cdot(\mu_2-\mu_1);$$

here the sample sizes $n_1^*$ and $n_2^*$ are independent of the total falsification $\mu$.

## 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…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 $\varepsilon_i$ of the inspector for verifying one datum with an independent measurement method. Furthermore, let us assume that the inspector has the total inspection effort $\varepsilon$ at his disposal in order to verify $n_1$ data in the i-th class, i = 1…K, which means

$$\sum_{i=1}^{K}\varepsilon_i\cdot n_i = \varepsilon. \qquad (2\text{-}17)$$

Finally, we assume in which way the operator will – if at all – falsify the reported data:

*Definition 2*
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 $\mu_i \le \mu_{i\max}, i = 1...K$, which are supposed to be known to the inspector such that the data are falsified by the total amount $\mu$ of material,

$$\sum_{i=1}^{K}\mu_i\cdot r_i = \mu. \qquad (2\text{-}18)$$

The problem to be solved is to determine that distribution of the total inspection effort $\varepsilon$ 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. Formally, the solution of this problem is in case of drawing with replacement given by

*Theorem 3* |9|
Let the sets of pure strategies $X_\varepsilon^2$ and $Y_\mu^1$ of the inspector and of the operator be defined by

$$X_\varepsilon^2 := \left\{(n_1...n_K): \sum_i \varepsilon_i\cdot n_i = \varepsilon\right\} \qquad (2\text{-}19a)$$

$$Y_\mu^2 := \left\{(r_1...r_K): \sum_i \mu_i\cdot r_i = \mu\right\}, \qquad (2\text{-}19b)$$

and let the payoff to the inspector be the probability

$$1-\beta = 1-\prod_{i=1}^{K}\left(1-\frac{r_i}{N_i}\right)^{n_i}. \tag{2-20}$$

Let us consider the zero-sum game $\left(X_\varepsilon^2, Y_\mu^2, 1-\beta\right)$, where the values of the parameters $\varepsilon, \mu, \varepsilon_i, \mu_i, i = 1...K$ are known to both "players". Under the assumption that the sample sizes $n_i$ and $r_i$ can be considered as continuous variables, the solution of this game is

$$n_i^* = \frac{\varepsilon}{\sum_i \mu_j \cdot \varepsilon_j \cdot N_j \exp\left(-K \cdot \varepsilon_j\right)} \cdot \mu_i \cdot N_i \cdot \exp\left(-x \cdot \varepsilon_i\right), \tag{2-21a}$$

$$r_i^* = N_i \cdot \left(1-\exp\left(-x \cdot \varepsilon_i\right)\right), i = 1...K, \tag{2-21b}$$

$$1-\beta^* = 1-\exp\left(-x \cdot \varepsilon\right), \tag{2-21c}$$

where the parameter x is uniquely determined by

$$\sum_i \mu_i \cdot N_i \exp\left(-x \cdot \varepsilon_i\right) = \sum_i \mu_i \cdot N_i - \mu. \tag{2-21d}$$

It can be seen by implicit differentiation of x with respect to $u_i$ that $1-\beta^*$ is a monotonically decreasing function of $u_i$. This means that the operator will take as large as possible values of $u_i$ i = 1…K.

If all of the class-specific verification efforts are equal, $\varepsilon_i = \varepsilon_1$ for $i = 1...K$, we get with

$$n = \frac{\varepsilon}{\varepsilon_1}, N = \sum_i N_i, r^* = \sum_i r_i^* = \frac{\mu \cdot N}{\sum_i \mu_i N_i} \tag{2 –22a}$$

from (2-21a) to (2-21d)

$$n_i^* = \frac{n \cdot r^*}{N \cdot \mu} \cdot \mu_i \cdot N_i \tag{2-22b}$$

$$r_i^* = \frac{r^*}{N} \cdot N_i \text{ for } i = 1...K \tag{2-22c}$$

$$\beta^* = \left(1-\frac{r^*}{N}\right)^n, \tag{2-22d}$$

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.

For $\max_i K \cdot \varepsilon_i << 1$ one gets from (2-21)

$$n_i^* = \frac{\varepsilon}{\sum_j \mu_j \cdot \varepsilon_j \cdot N_j} \cdot \mu_i \cdot N_i \tag{2-23a}$$

$$r_i^* = \frac{\mu}{\sum_j \mu_j \cdot \varepsilon_j \cdot N_j} \cdot \varepsilon_i \cdot N_i, i = 1...K \tag{2-23b}$$

$$1 - \beta^* = \frac{\mu \cdot \varepsilon}{\sum_j \mu_j \cdot \varepsilon_j \cdot N_j}. \tag{2-23c}$$

This solution which was obtained long time ago |10| 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 sample sizes $r_i$* 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

If we use instead of the probability of detection (2-14), that based on (2-2),

$$1 - \beta = 1 - \prod_{i=0} \left(1 - \frac{n_i}{N_i}\right)^{r_i}, \tag{2-24}$$

then we arrive at a different sampling distribution:

*Theorem 4* |11|
Let the sets of pure strategies of inspector and operator again be given by (2-19), the values of $\varepsilon$ and $\mu$ as well as $\varepsilon_i, \mu_i$ for $i = 1...K$ be given and known to both sides, and the overall probability of detection by (2-24). Under the assumption that $n_i$ and $r_i$ may be treated as continuous variables, and that

$$n = \sum_i n_i \le \min_i N_i, \mu \le \min_i \mu_i N_i, \tag{2-25a}$$

the unique solution of the game $\left(X_\varepsilon^2, Y_\mu^2, 1 - \beta\right)$ is

$$n_i^* = N_i \cdot \left(1 - \beta^* \frac{\mu_i}{\mu}\right) \text{ for } i = 1...K, \tag{2-25b}$$

$$\underset{-}{r}^* = \left(\frac{\mu}{\mu_1}, 0, ..., 0\right) \text{or } \ldots \text{ or } 0, ..., \frac{\mu}{\mu_K} \tag{2-25c}$$

with the guaranteed probability of detection $\beta^*$ given implicitely by

$$\varepsilon = \sum_i \varepsilon_i N_i \cdot \left(1 - \beta^{*\mu_i/\mu}\right). \tag{2-25d}$$

For uniform falsification across all classes,

$$\mu_i = \mu_1 \text{ for } i = 1...K$$

$$\frac{\mu_i}{\mu} = \frac{1}{\sum_i r_1^*} = \frac{1}{r^*} \text{ for } i = 1...K \tag{2-26a}$$

we get from (2-25b)

$$n^* = \sum_i n_i^* = \sum_i N_i \cdot \left(1 - \beta^{*\frac{1}{r^*}}\right) \tag{2-26b}$$

and hence, with $N = \sum_i N_i$

$$\beta^* = \left(1 - \frac{n^*}{N}\right)^{r^*} \tag{2-26c}$$

This solution can again be considered as the 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, e.g. $\varepsilon_i = \varepsilon_1, i = 1...K$, Theorem 2.2 reduces to a solution to the attribute sampling problem which has come to be known as the "IAEA Formula", documented by the IAEA |12|. It is used extensively by the International Atomic Energy Agency 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. Let each item of the $i$ th class of reported data have magnitude $u_i$ (rather than $\mu \max_i$). Then the operator has to falsify $r_i = \mu / \mu_i$ data of the $i$ th class should he wish to confine his falsification to one class. Recalling equation (2-3) the class-specific non-detection probabilities are

$$\beta_i = (1 - n_i / N_i)^{r_i}, i = 1...K. \tag{2-27}$$

Should the operator, on the other hand, wish to distribute his activities over the $K$ classes such that

$$\mu = \sum_{i=1}^{K} \tilde{\mu}_i \tag{2-28}$$

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

$$\tilde{r}_i = \tilde{\mu}_i / \mu_i, i = 1...K. \tag{2-29}$$

The non-detection probability for the i-th class is

$$\tilde{\beta}_i = (1 - n_i / N_i)^{\tilde{r}_i}, i = 1...K \tag{2-30}$$

or, with (2-29) and $\mu_i = \mu / r_i$,

$$\tilde{\beta}_i = (1 - n_i / N_i)^{\left(\tilde{\mu}_i r_i\right)/\mu} = \beta_i^{\tilde{\mu}_i/\mu}. \tag{2-31}$$

If the inspector now determines his class sample sizes $n_i$ so as to obtain, for each class, a non-detection probability $\beta$ under the assumption that the total amount is falsified in *one* stratum, i.e. $\beta_i = \beta$, then according to (2-31) this non-detection probability is still guaranteed if the falsification had actually been distributed in some arbitrary way over the K classes:

$$\prod_{i=1}^{K} \tilde{\beta}_i = \prod_{i=1}^{K} \beta^{\tilde{\mu}_i/\mu} = \mu \cdot \sum_i \tilde{\mu}_i / \mu = \beta. \tag{2-32}$$

This heuristic result, applied as we have said extensively by the IAEA, is nothing other than formula (2-30) of *Theorem 3*, as can be seen by solving the right hand equality in (2-49) for $n_i$ and replacing $\beta_i$ by $\beta^*$ and $\tilde{\mu}_i$ by $\mu_i$.

# 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 is |1| "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".

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 observations, and that for each pair of data in general it cannot be decided without committing errors whether or not 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 $X_i$, i = 1…N, have been reported by an operator, and that $n(\leq N)$ data are verified by an inspector with the help of independent observations $Y_i$, i = 1…n, on a random sampling basis. 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 generated data, he will construct his test procedure with the differences of these corresponding data:

*Definition 5*
The differences $Z_i$, i = 1…n, between the operator's reported data $X_i$ and the independent findings $Y_i$ of the inspector are assumed to be independently and identically normally distributed random variables with variances

$$\mathrm{var}(Z_i) = \mathrm{var}(X_i) + \mathrm{var}(Y_i) =: \sigma^2, i = 1...n, \tag{3-1}$$

and with expected values

$$E(Z_i) = \begin{cases} 0 & under\ H_0 \\ \mu_i > 0, i = 1...n, & under\ H_1 \end{cases} \tag{3-2}$$

where $H_0$ is the null hypothesis (no data falsification) and $H_1$ is the alternative hypothesis (data falsification). □

According to standard practice we are again looking for that test procedure which maximizes the probability of detection $1-\beta$, i.e., the probability of accepting $H_1$ if it is true. For a fixed value of

the false alarm probability, 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 u in such a way that the probability of detection is minimized.

If one ignores systematic measurement errors, then the optimal test procedure for the *maximum* sample size n = N is given by

*Theorem 6*
Let the sets of pure strategies $\Delta_\alpha$ and $Y_\mu^3$ of the inspector and of the operator be defined by the sets $\Delta_\alpha$ of all test procedures with given false alarm probability $\alpha$, and

$$Y_M^3 := \left\{ (\mu_1 ... \mu_N) \mid \sum_{i=1}^{N} \mu_i = \mu, 0 \le \mu_i, i = 1...N \right\} \tag{3-3}$$

and let the payoff to the inspector be the detection probability $1-\beta$. Then the solution of the game $(\Delta_\alpha, Y_\mu^3, 1-\beta)$ is given by the test $\delta^*$ the critical region of which is

$$\left\{ (Z_1,...,Z_N) : \sum_i Z_i > \sqrt{N} \cdot \sigma \cdot U(1-\alpha) \right\}, \tag{3-4}$$

where Uis the inverse of the standard distribution, and by the equally distributed falsification $\mu^* = (\mu / N),..., \mu / N$. The guaranteed probability of detection is

$$1-\beta^* = \phi\left( \frac{1}{\sqrt{N}} \cdot \frac{\mu}{\sigma} - U(1-\alpha) \right), \tag{3-5}$$

where $\phi$ is the standard normal distribution. □

If one ignores systematic measurement errors, then the optimal test procedure for the *minimum* sample size n = 1 is given by

*Theorem 7* |13|
Let the sets of pure strategies $\Delta_\alpha$ and $Y_\mu^3$ of the inspector and of the operator be defined by the set $\Delta_\alpha$ of all test procedures with given false alarm probability $\alpha$, (3-3) and let the payoff to the inspector be the detection probability $1-\beta$. Let us consider the zero-sum game $(\Delta_\alpha, Y_\mu^3, 1-\beta)$, where the values of $\mu, \alpha$ and $\sigma$ are known to both "players". Let $\mu^*(N)$ be the unique zero point of the function $F(\mu)$, defined by

$$F(\mu) = \phi\left( U(1-\alpha)\frac{1}{N} \cdot \frac{\mu}{\sigma} \right) - \frac{1}{N} \cdot \left( \phi\left( U(1-\alpha) - \frac{\mu}{\sigma} \right) + (N-1) \cdot (1-\alpha) \right), \tag{3-6}$$

where $\phi$ and U are defined as above. For $\mu \le \mu^*(N)$ the strategy of the operator is $(\mu / N,..., \mu / N)$, whereas for $\mu \ge \mu^*(N)$ it is $(\mu,0,...,0)..(0,...,0,\mu)$. The solution for the inspector is the test given by the critical region $\{z : z > \sigma \cdot U(1-\alpha)\}$, it is independent of the strategy of the operator. The guaranteed optimal probability of detection, is

$$1-\beta^{*}=\begin{cases}\phi\left(\frac{1}{N}\cdot\frac{\mu}{\sigma}-U(1-\alpha)\right) & \mu\le\mu^{*}(N)\\ \text{for} & \\ \frac{1}{N}\cdot\phi\left(\frac{\mu}{\sigma}-U(1-\alpha)\right)+\left(1-\frac{1}{N}\right)\cdot\alpha & \mu\ge\mu^{*}(N).\end{cases} \tag{3-7}$$

The sequence $\{\mu^{*}(N)\}$ of critical falsifications is strictly monotonically increasing in N; it starts with $u^{*}(2)=2\cdot\sigma\cdot U(1-\alpha)$ and converges to a limiting value u* which is implicitely given by

$$\frac{1}{\sqrt{2\pi}}\cdot\exp\left(-\frac{1}{2}\cdot U^{2}(1-\alpha)\right)\cdot\frac{\mu^{*}}{\sigma}+\phi\left(U(1-\alpha)-\frac{\mu^{*}}{\sigma}\right)-1+\alpha=0. \tag{3-8}$$

□

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.

Further results for intermediate sample sizes, r < n < N, have been obtained for very small and for very large total falsifications u: Whereas in the former case again the D-statistic is optimal, in the latter one the problem turns into an attribute sampling one which means that the single differences $Z_i$, i = 1…n, are evaluated separately. Analytical solutions for given values of $\sigma, n$ and $\mu$ are not feasible as the case N = 3, n = 2, the most simple one not covered by *theorems 6 and 7*, indicates.

Since it turns out that essentially only the equally distributed and the one-point falsification count, for practical applications one may proceed as follows: One compares the probabilities of detection for the D-test and the two falsification strategies just mentioned. If one defines u* as that falsification where the two probabilities of detection are the same, then for $\mu<\mu^{*}$ one applies the D-test, and for $\mu>\mu^{*}$ that test where the single differences are evaluated, which in fact results in an attribute sampling procedure.

## *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. Thus, we consider N data, $n_1$ of which are verified with a device with variance 1, and $n_2$ of which are verified with a device with variance $\sigma^{2}<1$, i.e., according to (3-2)

$$\operatorname{var}(Z_i)=\begin{cases}1\ for & i=1\ldots n_1\\ \sigma^{2}\ for & i=n_1+1\ldots n_1+n_2.\end{cases} \tag{3-9}$$

Just in order to demonstrate the complexity of this problem, let us assume *a priori* that – if at all – all the $N$ data are equally falsified,

$$E(Z_i) = \mu_i = \frac{\mu}{N} \text{ for } i = 1...N \text{ under } H_1 \tag{3-10}$$

and furthermore that all data are verified, one of them with to precise method. In this case the Neyman Pearson Lemma, see, e.g. |14|, leads to the test statistic

$$D = \sum_{i=1}^{N-1} Z_i + \frac{Z_N}{\sigma^2},$$

thus, the detection probability for *any* falsification

$$\left( \mu_1,...,\mu_N \mid \sum_{i=1}^{N} \mu_i = \mu \right) \tag{3-11}$$

is given by

$$1 - \beta(\mu_1...\mu_N) = \frac{1}{N} - \sum_{i=1}^{N} \phi \left( \frac{\mu - \mu_i \cdot \left(1 - \frac{1}{\sigma^2}\right)}{\sqrt{N - 1 + \frac{1}{\sigma^2}}} - U(1-\alpha) \right). \tag{3-12}$$

The problem therefore, consists in showing for which values of u the form (3-12) is maximized with respect to the falsification strategies (3-11). So far, this has been shown up to N = 4, and the supposition is that for any N and for

$$\mu < U(1-\alpha) \cdot \sigma^2 \cdot \sqrt{N - 1 + \frac{1}{\sigma^2}} \tag{3-13}$$

in fact the D-test and the falsification (3-10) are saddlepoint strategies.

## 3.3 Several Classes of Material

Like in section 2.2 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

$$X_{ij} = \mu_{ij} + E_{0ij} + F_{0i}, i = 1...K, j = 1...N_i, \tag{3-14}$$

where $u_{ij}$ is the true value of the j-th class, $E_{0ij}$ is the random and $F_{0i}$ the systematic error. The errors are assumed to be independently and normally distributed with zero expectation values and known variances,

$$\begin{aligned} &E(E_{0ij}) = E(F_{0i}) = 0 \\ &\text{var}(E_{0ij}) = \sigma^2_{0ri}, \text{var}(F_{0i}) = \sigma^2_{0si}, i = 1...K, j = 1...N_i. \end{aligned} \tag{3-15}$$

The inspector verifies $n_i$ of the $N_i$ batch data in the i-th class with the help of independent measurements. His findings can be written as

$$Y_{ij} = \mu_{ij} + E_{Iij} + F_{Ii}, i = 1...K, j = 1...n_i, \tag{3-16}$$

where the random errors $E_{Iij}$ and the systematic errors $F_{Ij}$ are again independently and normally distributed with zero expectation values and known variances:

$$E(E_{Iij}) = E(F_{Ii}) = 0$$
$$\text{var}(E_{Iij}) = \sigma^2_{Iri}, \text{var}(F_{Ii}) = \sigma^2_{Isi}, i = 1...K, j = 1...n_i. \quad (3\text{-}17)$$

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 observed data, he will construct his test procedure with the help of the differences between these data:

*Definition 8*
The differences

$$Z_{ij} := X_{ij} - Y_{ij}, i = 1...K, j \in A_i^Y \quad (3\text{-}18)$$

between the operator's reported data and the independent observations $Y_{ij}$ of the inspector are assumed to be normally distributed with expectation values

$$E(Z_{ij}) = 0 \text{ under } H_0 \text{ (no falsification)} \quad (3\text{-}19a)$$

and with variances and covariances

$$\text{var}(Z_{ij}) = \sigma^2_{ri} + \sigma^2_{si} = \sigma^2_{0ri} + \sigma^2_{Iri} + \sigma^2_{0si} + \sigma^2_{Isi} \quad (3\text{-}19b)$$

$$\text{cov}(Z_{ij}, Z_{i'j'}) = \begin{cases} 0 & for \quad i \neq i' \\ \sigma^2_{si} & for \quad i = i', j \neq j' \end{cases}. \quad (3\text{-}19c)$$

□

Like in the attribute sampling case, we define $\varepsilon_i$ 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 $\varepsilon$ 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. First,

*Definition 9*
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 amounts $\mu_i \leq \mu_{i\max}, i = 1...K$, which means

$$E(Z_{ij}) = \mu_i \ for \ i = 1...K, j \in A_i^\gamma \ under \ H_1, \quad (3\text{-}20)$$

such that the data are falsified by the total amount u of material, i.e., such that

$$\sum_{i=1}^{K} \mu_i \cdot N_i = \mu. \quad (3\text{-}21)$$

□

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.

*Theorem 10* |9|
Let the sets of pure strategies $\Delta_\alpha \otimes X_\varepsilon^2 and\, Y_\mu^4$ of the inspector and of the operator be defined by the set $\Delta_\alpha$ or tests for the two hypotheses $H_0$ and $H_1$ for the random variables $Z_{ij}$, given by *Definitions 8 and 9*, and by (2-19a) and

$$Y_\mu^4 := \left\{ (\mu_1 ... \mu_K) : \sum_i \mu_i \cdot N_i = \mu \right\}, \tag{3-22}$$

and let the payoff to the inspector be the detection probability. Let us consider the zero-sum game $\left(\Delta_\alpha \otimes X_\varepsilon^2, Y_\mu^4, 1-\beta\right)$, where the values of $\alpha, \varepsilon, \mu, \sigma_{ri}, \sigma_{si}$ and $\varepsilon_i, i = 1...K$ are given and known to both "players". Under the assumption that the sample sizes $n_i$ , i = 1…K, can be considered as continuous variables, the solution of this game is given by a test, characterized by the statistic

$$D^* = \sum_{i=1}^{K} \frac{N_i}{n_i^*} \cdot \sum_{j=1}^{n_i^*} Z_{ij}, \tag{3-23a}$$

and, furthermore, by

$$n_i^* = \frac{\varepsilon}{\sum_k N_k \cdot \sigma_{rk} \cdot \sqrt{\varepsilon_k}} \cdot \frac{N_i \cdot \sigma_{ri}}{\sqrt{\varepsilon_i}}, \tag{3-23b}$$

$$\mu_i^* = \frac{\mu}{\mathrm{var}(D)} \cdot \left( \frac{1}{\varepsilon} \cdot \sum_k N_k \cdot \sigma_{rk} \cdot \sqrt{\varepsilon_k} \cdot \sigma_{ri} \cdot \sqrt{\varepsilon_i} + N_i \cdot \sigma_{si}^2 \right), i = 1...K, \tag{3-23c}$$

where the variance of D* is

$$\mathrm{var}(D^*) = \frac{1}{\varepsilon} \cdot \left( \sum_i N_i \cdot \sigma_{ri} \cdot \sqrt{\varepsilon_i} \right)^2 + \sum_i N_i^2 \cdot \sigma_{si}^2. \tag{3-23d}$$

The guaranteed optimal probability of detection is

$$1 - \beta_A^* = \phi\left( \frac{\mu}{\sqrt{\mathrm{var}(D^*)}} - U(1-\alpha) \right). \tag{3-23e}$$

□

The D-statistic for K classes of material, as given by (3-23a), was proposed the first time in 1971 |15| for the use in nuclear material safeguards, then it was justified by heuristic arguments. *Theorem 10* shows under which conditions it can be derived from first statistical principles. In fact, we would have obtained the sampling distribution (3-23b) if we would have minimized the variance of the D-statistic (3-23a) with respect to the $n_1 \ldots n_k$ under the boundary condition (2-16).

If all systematic errors vanish, and all class specific efforts are equal, then with

$$\frac{\varepsilon}{\varepsilon_1} = \sum_i n_i = n, \sum_i N_i = N, \frac{\sum_i N_i \sigma_{ri}}{\sum_i N_i} = \sigma_r$$

we obtain from *Theorem 10*

$$n_i^* = \frac{n}{N \cdot \sigma_r} \cdot N_i \sigma_{ri},$$

$$\mu_i^* = \frac{n}{N\sigma_r} \cdot \sigma_{ri}, i = 1...K,$$

$$\mathrm{var}\left(D^*\right) = \frac{N^2}{n} \cdot \sigma_r^2$$

$$1 - \beta_k^* = \phi\left(\frac{\sqrt{n}}{\sigma_r} \cdot \frac{\mu}{N} - U\left(1-\alpha\right)\right).$$

The guaranteed 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 $\mu / N$ and $n$ of which are verified. We saw the same in *Theorems 3 and 4*, and recognize it now to be a general feature of optimal stratified sampling strategies.

Let us consider *model B*, given by *Definition 2*. Since it is not possible to determine the optimal test procedure for this model, we use the D-statistic

$$D = \sum_{i=1}^{K} \frac{N_i}{n_i} \cdot \sum_{j=1}^{n_i} Z_{ij}. \tag{3-24}$$

However, since we still have problems in view of its complicated distribution function, we use a normal distribution approximation:

$$D \sim \begin{cases} N\left(0, \mathrm{var}_0\left(D\right)\right) & for\ H_0 \\ N\left(\mu, \mathrm{var}_1\left(D\right)\right) & for\ H_1 \end{cases}, \tag{3-25}$$

with variances given by

$$\mathrm{var}\left(D\right) = \begin{cases} \sigma_{D0}^2 := \sum_i N_i^2 \cdot \left(\frac{\sigma_{ri}^2}{n_i} + \sigma_{si}^2\right) \\ \sigma_{D1}^2 := \sigma_{D0}^2 + \sum_i \left(\mu_i^2 \cdot r_i \cdot \left(N_i - r_i\right) + N_i^2 \cdot \sigma_{si}^2\right) \end{cases} \tag{3-26}$$

for the sampling with replacement scheme. This way, the probability of detection is given by

$$1 - \beta_B = \phi\left(\frac{\mu}{\sigma_{D1}} - \frac{\sigma_{D0}}{\sigma_{D1}} \cdot U\left(1-\alpha\right)\right). \tag{3-27}$$

If we consider the special case

$$\mu >> \sigma_{D0} \cdot U\left(1-\alpha\right), \tag{3-28}$$

then (3-27) is given by

$$1 - \beta_B = \phi\left(\frac{\mu}{\sigma_{D1}} - U\left(1-\alpha\right)\right), \tag{3-29}$$

thus, we can use the variance $\sigma_{D1}^2$ as optimization criterion:

*Theorem 11* |11|
Let the pure strategy sets $X_\varepsilon$ and $Y_\mu^4$ of the inspector and of the operator be defined by (2-18) and

$$Y_\mu^4 := \left\{ (r_1 \ldots r_K, \mu_1 \ldots \mu_K) \mid \sum_i \mu_i \cdot r_i = \mu \right\}, \tag{3-30}$$

and let the payoff to the inspector be the negative variance – $\sigma_{D1}^2$ as given by (3-26). Under the assumptions that the sample sizes $n_i$ and $r_i$ can be considered as continuous variables, and furthermore, if

$$\frac{1}{2} \cdot \sum_i \mu_i^{\max} \cdot N_i - \mu \geq 0$$

$$\mu_i^{\max} \geq \frac{2\sigma_{ri}}{\sqrt{\chi \cdot \varepsilon_i}} \quad (\chi \text{ defined below) for i = 1…K,} \tag{3-31}$$

a solution of the game $\left(X_\varepsilon, Y_\mu^5, -\sigma_{D1}^2\right)$ is given by

$$n_i^* = \frac{\varepsilon}{\sum_k N_k \varepsilon_k S_k} \cdot N_i \cdot S_i \tag{3-32a}$$

$$r_i^* = \frac{N_i}{2} \cdot \left( 1 - \frac{2}{\mu_i^{\max}} \cdot S_i \right) \tag{3-32b}$$

$$\mu_i = \mu_i^{\max}, i = 1 \ldots K \tag{3-32c}$$

$$\sigma_{D1}^{*2} = \frac{\chi}{\varepsilon} \cdot \left( \sum_k N_k \varepsilon_k S_k \right)^2 + \sum_k N_k^2 \cdot \sigma_{sk}^2 \tag{3-32d}$$

where the constants $S_i$ are defined by

$$S_i^2 = \frac{\sigma_{ri}^2 + \left(\mu_i^{\max}\right)^2 / 4}{1 + \chi \cdot \varepsilon_i} \; for \; i = 1 \ldots K, \tag{3-32e}$$

and where $\chi$ is uniquely determined by

$$\sum_k N_k \cdot S_k = \frac{1}{2} \cdot \sum_k \mu_k^{\max} \cdot N_k - \mu \tag{3-32f}$$

□

If the total falsification u is half the maximum falsification, we get from (3-32f)

$$\sum_k N_k S_k = 0 \tag{3-33a}$$

and therefore with (3-32e) $\chi \to \infty$. Thus we get explicit expressions for $n_i^*$ and $r_i^*$ and furthermore

$$\sigma_{D1}^{*2} = \frac{1}{\varepsilon} \cdot \left( \sum_i N_i \cdot \sqrt{\varepsilon_i \left( \sigma_{ri}^2 + \mu_i^{\max 2} / 4 \right)^2} \right) + \sum_i N_i^2 \sigma_{si}^2. \tag{3-34}$$

Comparing this variance with that given by (3-23d), we see that it is larger and therefore, leads to a smaller detection probability. On the other hand if we take u to be close to zero, then the variance $\sigma_{D1}^2$ under $H_1$ approaches the variance $\sigma_{D0}^2$ under $H_0$, and we get from (3-27)

$$1 - \beta_B \approx \phi\left( \frac{\mu}{\sigma_{D0}} - U(1-\alpha) \right),$$

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 (3-23b) as given by *Theorem 10*.

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 10* or that of *Theorem 11*. If the inspector thinks that the size of the falsification, relative to the standard deviation $\sigma_D^*$, is small, he can assume an equally distributed falsification and apply the sampling procedure of *Theorem 10*. Otherwise he should act according to *Theorem 11*. Note the similarity of this prescription and that of *Theorem 7*.

# 4. Variable Sampling in the Attribute Mode

Variables inspection presupposes the existence of a variable measuring instrument or a variable tester |12|. 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 so as 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*

Let us assume again that N data have been reported, and that n data are verified. To use the variable tester in the attribute mode means that one chooses for one single comparison of a reported and an independently generated datum a significance threshold s and decides that there is no significant difference, if the observed difference between reported and independently measured data is smaller than s. The single false alarm probability $\alpha'$ and the single probability of detection $1-\beta'$ then are

$$\alpha' = \phi\left( \frac{s}{\sigma} \right), 1 - \beta' = \phi\left( \frac{\mu_1}{\sigma} - U(1-\alpha') \right), \tag{4-1}$$

if we assume that the observed differences are normally distributed with variance $\sigma^2$ and expected values zero or $u_1$ in case of no falsification or falsification, respectively.

Now let us assume that n independently generated pairs of data are drawn *without* replacement. The overall probability $\beta$ of not detecting a falsified datum is composed of all probabilities of

finding l falsified data without recognizing them as such and n – l unfalsified ones recognizing them as such. The probability of finding among n data l falsified ones, if in total r data are falsified, is determined by the hypergeometric distribution. Therefore, according to the *Theorem of the Total Probability*, $\beta$ is given by

$$\beta = \sum_{l} \beta'^{l} \cdot (1-\alpha')^{n-l} \cdot \frac{\binom{r}{l} \cdot \binom{N-r}{n-l}}{\binom{N}{n}}. \tag{4-2}$$

Here, the single false alarm probability $\alpha'$ is replaced by the overall false alarm probability $\alpha$ via

$$(1-\alpha')^{n} = 1-\alpha. \tag{4-3}$$

In the case that the sample size n is small compared to the total number N of data, which is equivalent to the drawing *with* replacement case, one can replace the hypergeometric by the binomial distribution and obtains by use of the binomial expansion formula

$$\beta = \left( \beta' \cdot \frac{r}{N} + (1-\alpha') \cdot \left( 1 - \frac{r}{N} \right) \right)^{n}; \tag{4-4}$$

this expression could also have been obtained directly.

In order to use (4-2) or (4-4) for the determination of the sample size n for a given value of $\beta$ one has to make assumptions about $u_1$ and r. As earlier, it is assumed that – if at all – r data are falsified by the single amounts $u_1$ such that

$$\mu = \mu_1 \cdot r, \tag{4-5}$$

and that for given value of u, those of $u_1$ and r are chosen in such a way that the overall detection probability is minimized. In the following we will only consider the drawing with replacement scheme, expressed by (4-4).

An analytical investigation shows that
for $\mu < \sigma \cdot U(1-\alpha)$ the optimal falsification strategy is $r = N, \mu_1 = \mu / N,$ which leads to the overall probability of no detection

$$\beta_N = \left( \phi\left( U(1-\alpha') - \frac{1}{N} \cdot \frac{\mu}{\sigma} \right) \right)^{n}; \tag{4-6}$$

for $\mu > N \cdot \sigma \cdot U(1-\alpha)$ the optimal falsification strategy is $r = r_{\min}, \mu_1 = \mu_{\max}$; *for* $r_{\min} = 1$ one gets the probability of no detection

$$\beta_1 = \left( \phi\left( U(1-\alpha') - \frac{\mu}{\sigma} \right) \cdot \frac{1}{N} + (1-\alpha') \cdot \left( 1 - \frac{1}{N} \right) \right)^{n}. \tag{4-7}$$

Furthermore, it can be shown that only one of these two extremes represents an optimal choice from the falsification point of view, thus, it remains to be seen which of the two is the better. For simplicity we assume $r_{\min} = 1$.

If one wants to compare the two probabilities of detection $\beta_1$ and $\beta_N$, then it suffices to analyze

$$\sqrt[n]{\beta_N} - \sqrt[n]{\beta_1}\,.$$

At first sight, it is surprising that this leads exactly to the form given by (3-4) if one replaces $1-\alpha$ by $1-\alpha'$; at the second sight this is clear since variables sampling in the attribute mode with drawing with replacement represents an experiment which consists of independent repetitions of the same single experiment which we discussed in section 3.1. Thus, *Theorem 7* tells us that there exists a critical amount $\mu^*(N)$, given by the unique zero point of (3-4), with the property

$$\beta_N > \beta_1 \text{ for } \mu < \mu^*(N) \text{ and } \beta_N < \beta_1 \text{ for } \mu > \mu^*(N)$$

furthermore, as we saw this Theorem gives some interesting properties of this critical amount.

## 4.2 Several Classes of Material

Just to give an idea what still can be achieved, we consider *model A* as given by *Definition 9* and assume furthermore, that the class specific efforts for verifying one datum are the same for all classes. Then the effort boundary condition (2-16) can be written as $\sum_i n_i = n, where\, n$ is the total number of verified data.

*Theorem 12* |9|
Let the sets of pure strategies $X_n$ and $Y_\mu^4$ of the inspector and of the operator be defined by

$$X_n := \left\{ (n_1 \ldots n_K) : \sum_i n_i = n \right\}$$

and by (3-22) and let the payoff to the inspector be the overall probability of detection, given by

$$1-\beta = 1 - \prod_{i=1}^{K} \phi\left( U\left( \sqrt[n]{1-\alpha} \right) - \frac{\mu_i}{\sigma_i} \right)^{n_i}$$

where the values of $n, \mu$ and $\sigma_i, i = 1 \ldots K$, are given and known to both "players". Under the assumption that the variables $u_l$ and $n_i$ can be considered to be continuous, a solution of the zero sum-game $\left(X_n, Y_\mu^4, 1-\beta\right)$ is given by

$$n_i^* = \frac{n}{\sum_j N_j \cdot \sigma_j} \cdot N_i \cdot \sigma_i$$

$$\mu_i^* = \frac{\mu}{\sum_j N_j \cdot \sigma_j} \cdot \sigma_i, \; i = 1 \ldots K$$

$$\beta^* = \phi\left( U\left( \sqrt[n]{1-\alpha} \right) - \frac{\mu}{\sum_i N_i \cdot \sigma_i} \right)^n .$$

□

The most interesting aspect of this solution is that the optimal sample size distribution of the inspector is exactly the same as that given by *Theorem 10*, for $\varepsilon_i = \varepsilon_1, i = 1...K$. Furthermore, the optimal guaranteed probability of detection $1-\beta^*$ 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 amounts $\bar{\mu}_1$, with standard deviation $\bar{\sigma}$ of one single inspector operator measurement difference, given by

$$\bar{\mu}_1 = \frac{\mu}{N}, \bar{\sigma} = \frac{1}{N} \cdot \sum_i N_i \cdot \sigma_i, N = \sum_i N_i.$$

Similar results one gets, as we saw, as special cases from the Theorems given above.

# 5. Concluding Remarks

So far, we have only considered nonsequential 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 others, on 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 this 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 |11|. If one assumes, however, that more than one falsification may be intended, then one has to deal with sequential games *without recursive structure* and everything gets 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, i.e. a technical quantity, as payoff function. 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 |16| and poses another serious challenge – a challenge which, however, is more of an administrative-political than of a scientific nature.

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# Destructive Sample Analysis for Nuclear Safeguards

Yetunde Aregbe, Klaus Mayer, Magnus Hedberg

## Abstract

The analysis of samples taken by safeguards inspectors for verification purposes can be carried out in different ways; various measurement techniques are available for carrying out these analyses. The different sample types arising from different categories of nuclear plants are presented. According to the material type and the analytical or the safeguards requirements, the measurement techniques have to be selected. A number of measurement techniques being applied for verification measurements and the most common analytical measurement techniques to detect traces of nuclear materials in samples collected in or/and around of a known or suspected facility are discussed. The importance of quality control tools is emphasized from the point of view of providing traceability and comparability of measurement results in fissile material accountancy and environmental sampling. Verification sample analysis activities are illustrated and examples of the use of reference materials and on measurement capabilities of laboratories performing safeguards analytical measurements are given.

## 1. Introduction

By signing the Nuclear Non-Proliferation Treaty (NPT) non-nuclear weapon states officially declare to abandon all efforts to develop nuclear weapons and to conclude the safeguards agreements [1]. Through unannounced inspections and nuclear material balances, safeguards inspectors are able to verify that no nuclear material is diverted from its intended peaceful use. Safeguards arrangements exist on international level under the protocols of the International Atomic Energy Agency (IAEA) on European Union level under the Euratom Treaty [2] and on regional levels. In 1991 inspectors detected evidence of a clandestine uranium enrichment programme in Iraq. This led to the implementation of strengthened safeguards systems and the publication of INFCIRC/540 [3], also referred to as the Additional Protocol (AP) with the aim to move from an exclusively quantitative system focused on accounting for known quantities of fissile material towards a more qualitative system that is able to provide a comprehensive picture of a state's nuclear activities. At that time efforts were made to identify those analytical measurement techniques that are sufficiently selective and sensitive to detect traces of nuclear materials in environmental samples in or around a known or suspected facility. The collection of these techniques was given the name 'environmental sampling' by the IAEA.

Safeguards aims at the verification of the non-diversion of fissile material from its intended and declared (peaceful) use. Therefore a reliable nuclear material accountancy system has to be established by the plant operator. A reliable system of verification is the responsibility of the safeguards authority in charge. Safeguarding nuclear material involves the quantitative verification of the accountancy of fissile material by independent measurements. These measurements consist of a bulk measurement, hence a combination of mass and/or volume determination and the analysis samples taken from this bulk. The sampling procedure should guarantee that the sample is indeed representative for the bulk. It has furthermore to be ensured that the sample is not tampered on its way from the sampling station to the measurement laboratory [4]. Environmental sampling is a supplementary safeguards tool aiming at correctness and completeness of plant operators' declarations.

*Effective IAEA safeguards remains the cornerstone of the world's nuclear non-proliferation regime aimed at stemming the spread of nuclear weapons and moving towards nuclear disarmament."* – Olli Heinonen: IAEA Deputy Director General and Head of the Department of Safeguards

A number of analysis strategies are applied in parallel:

**On-line analysis** is limited to the monitoring of typically a single parameter by a non-destructive measurement method. This technique is applicable for checking material flows.

**In-field analysis** requires the transport of mobile measurement equipment to the facility and the analysis of samples on the spot. This technique is only applicable to Uranium samples, as the transportation of Pu-contaminated instrumentation poses practical problems. In another modification, in-field analysis uses equipment which is permanently installed at a certain facility, but is used and operated only by the inspectorate. This requires analysts to travel frequentlyto the facility to carry out the measurements.

**Off-site analysis** is the 'classical' way of performing verification measurements. Samples taken by an inspector are dispatched to an analytical laboratory which will then perform the measurements on request of the inspectorate. This enables the laboratory to operate under optimal conditions and with instrumentation permanently installed.

**On-site laboratories** represent a concept which is based on the operation of a specialized laboratory working under the responsibility of the safeguards authority at the site of the facility to be inspected and analyzing material exclusively for safeguards purposes. Its independence and the confidentiality of the results produced have to be guaranteed by appropriate measures.

Depending on the plant size, material throughput and material type, an efficient measurement scheme has to be established, making use of one or more of the above mentioned possibilities. The last three analysis strategies rely on the measurement of samples taken by an inspector. The system of measurements applied in nuclear safeguards is requested to be conform to the latest standards or being equivalent in quality to such standards. Reliable measurements of the highest quality are indispensable to comply with this request. Destructive 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. This paper focuses therefore on measurements of the nuclear material element or isotopic concentration or content involving measurement techniques which are carried out in such a way that the sample being measured is not returned to the batch it was taken from, hence introducing a significant change.

# 2. Plant and Sample Types

Depending on the nature of the plant, different types of samples are obtained. 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.

## *2.1 Enrichment*

Uranium Hexafluoride is the material which is exclusively handled in commercial enrichment plants, operated for the production of low enriched uranium (LEU) as needed 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.

## 2.2 Fuel fabrication

There are two major categories of fuel in the civil nuclear fuel cycle: uranium oxide and U/Pu mixed oxide fuel (MOX).

After conversion of the $UF_6$ to $UO_2$ the material is first handled in the form of 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 analyzed 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 be in a position to correct for this effect.

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 plant as this is already done at the reprocessing plant. In contrast to that the products, i.e. the MOX pellets are intensively verified. These samples have to be analyzed for uranium and plutonium element content as well as for their isotopic composition. The $^{241}Am$ content provides useful information on the last plutonium purification.

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 [5]. 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.

## 2.3 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. The most widely used technique is the so called PUREX process. 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. These 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 analyze.

The separation of uranium, plutonium and the fission products at the nuclear reprocessing plant results in concentrated, rather pure solutions of U and Pu. The element and isotopic content are measured on samples from these 'product' solution.

The product solutions are used as base material for oxide powder production. The fissile isotope and element content of these $UO_2$ and $PuO_2$ 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 analyzed. The information requested usually focuses on the one hand on the uranium isotopic composition, where the $^{235}U$ isotope abundance is the most relevant information for safeguards purposes. The uranium content in a sample also needs to be determined. The combination of the latter with 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 the sample analysis results with the information on the bulk results in 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.

The plant types, material types and analysis types typically encountered in the fuel cycle are summarised in Tab. 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 [6]. It has to be emphasized that the amount of material actually required for a measurement can be considerably lower (compare **Table 3**).

| Plant Type | Material | Sample Size [6] | Analysis |
|---|---|---|---|
| Enrichment | $UF_6$ | 4-8 g | Uconc., U iso. |
| Fuel Fabrication | Solution: $UO_2^{2+}$ | 10 g | Uconc., U iso. |
| | Pu | 1-5 g | Pu conc., Pu iso. |
| | Powder: $UO_2$ | 10 g | Uconc., U iso. |
| | $PuO_2$ | 2 x 0.5 g | Pu conc., Pu iso., Am |
| | Pellets: $UO_2$ | 7-20 g | Uconc., U iso. |
| | MOX | 2 x (5-10) g | Uconc., U iso.<br>Pu conc., Pu iso., Am |
| Reprocessing | Solution: Spent Fuel | 1-5 g | Uconc., (U iso.)<br>Pu conc., Pu iso. |
| | $UO_2^{2+}$ Nitrate Soln. | 10 g | Uconc., (U iso.) |
| | Pu Nitrate Soln. | 1-5 g | Pu conc., Pu iso. |

*Table 1:* Simplified overview of plant categories, material types, desirable sample sizes and analyses

# 4. Sample Analysis Methodology

For any of the quantities to be determined as mentioned in Table 1, a selection of analytical techniques is available: each or several of them could be applied to attain the desired goal. The choice of the measurement method to be applied for the determination of a certain parameter depends on a number of criteria, such as:

- sample composition
- available amount of material, which may be limited due to:
  - activity or dose rate restrictions
  - sample transport regulations
  - sampling procedures at the plant

- desired measurement uncertainty
- instrumentation and manpower available
- tolerable measurement delay
- creation of (secondary) waste

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 content of uranium and/or plutonium is of key importance for establishing the material balance in a plant for accountancy purposes and also for its verification. It is therefore essential to have a method at hand that allows the respective element concentrations to be measured in samples taken at some place in the plant. 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 [7]. 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.

(1) $UO_2^{++} + 2Fe^{++} + H^+ \rightarrow U^{4+} + 2Fe^{3+} + 2H_2O$

(2) $3Fe^{++} + NO_3\text{-} + 4H^+ \rightarrow 3Fe^{3+} + NO + 2H_2O$

(3) $Fe^{++} + NO_3\text{-} + 2H^+ \rightarrow Fe^{3+} + NO_2 + H_2O$

(4) $HNO_2 + NH_2SO_3H \rightarrow N_2 + H_2SO_4 + H_2O$

(5) $Cr_2O_7\text{--} + 3U^{4+} + 2H^+ \rightarrow 2\ Cr^{3+} + 3UO^{2++} + H_2O$

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 [8]. 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. 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 sulfuric 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 sulfuric 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. 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 (pure, solid, oxide) sample of either element will lead to a (stable) compound of defined stoichiometry. 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 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. This method is therefore of growing interest to safeguards laboratories.

Uranium is heated in air or oxygen at 950°C in order to obtain $U_3O_8$. If prepared under these conditions, no deviations from stoichiometry are expected.

Similarly, Plutonium is heated in air or oxygen at 1250°C in order to obtain $PuO_2$. If prepared under these conditions, the latter compound has been demonstrated to be stable and stoichiometric.

### *4.1.4 K-Edge Densitometry*

Uranium or plutonium can be determined in a sample by K-Edge Densitometry (KED). The method [9] uses a highly collimated X-ray beam passing through a solution sample 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-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 as can be seen from Figure 1. The K-edge instrument requires a series of carefully characterized solutions of uranium and/or plutonium for establishing a calibration curve.

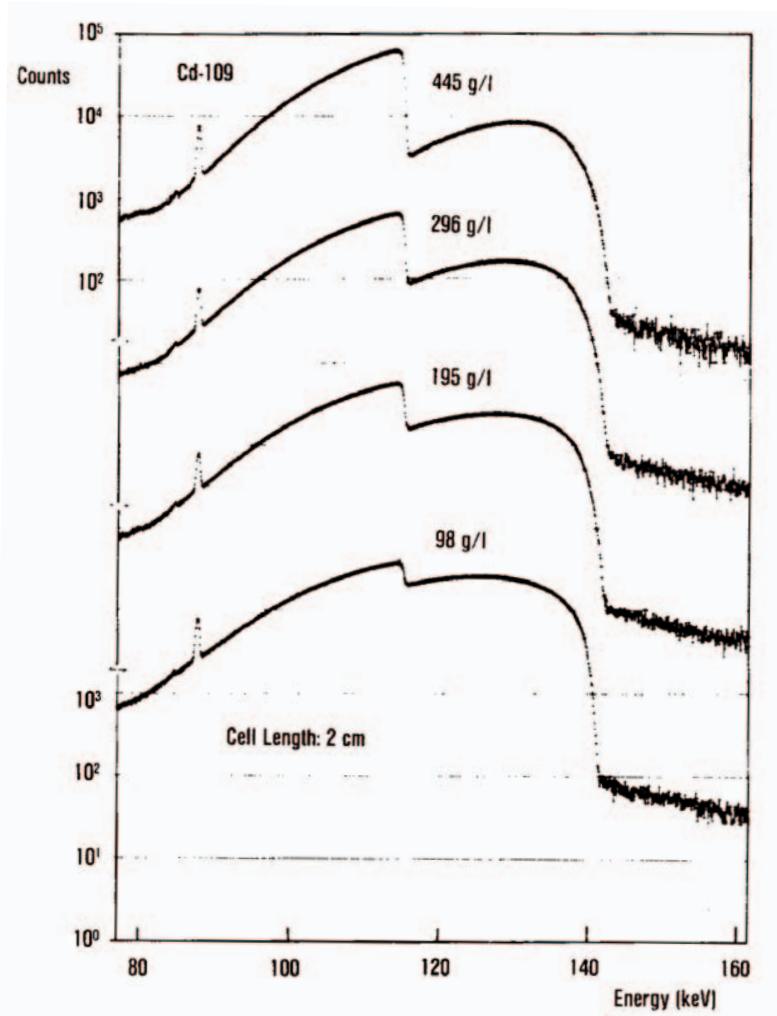


*Figure 1:* K-Edge jump for different uranium concentrations

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.

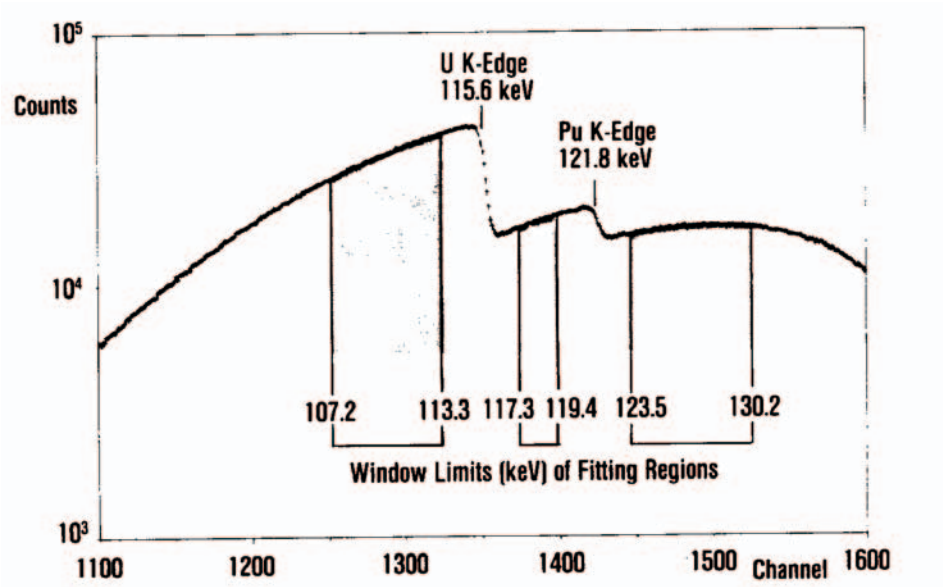


*Figure 2:* X-ray transmission spectrum for a solutions with a U/Pu ratio of about 3

K-Edge Densitometry delivers measurement results as volume concentration, i.e. in milligrams per millilitres or grams per liter. Most other techniques deliver results in mass concentration, 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 appropriate calibration, for the absolute determination of the respective amounts of element. In the first case the U/Pu ratio is derived from the net peak areas of the UK$\alpha_1$ and the PuK$\alpha_1$ 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 γ lines of similar energy. Furthermore the self-absorption in the sample has to be taken into account. Measurement uncertainties of about 0.7% have been demonstrated.

### *4.1.6 Isotope Dilution Mass Spectrometry*

Isotope dilution mass spectrometry (IDMS) is based on the addition of a known amount of an enriched isotope (called the "spike") to a sample [10, 11 ]. After equilibration of the spike with the sample, mass spectrometry is used to measure the altered isotopic ratio(s). The concentration of the element under investigation can be derived from the change(s) in isotope ratio(s). Consequently, only weighings (of sample and spike mass) and measurements of ratios (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 ionization 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 concentration and the isotopic composition of the sample to be simultaneously determined. Also enriched $^{235}$U or $^{236}$U may be 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 is spiked with enriched $^{242}$Pu. The application of $^{239}$Pu or $^{240}$Pu as spikes has been demonstrated successfully [12].

IDMS is a highly selective method. It has the potential for high accuracy and precision. Also IDMS is a "primary method" of measurement. Thermal Ionization Mass Spectrometry (see section 4.2.1) is mostly applied as isotope ratio measurement technique. ICP-MS is also used, however resulting in somewhat higher uncertainty on the measurement results. IDMS has found wide application in safeguards measurements.

### *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 techniques 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.

## *4.2 Isotope Assay*

Besides the determination of the element concentration, 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 fissile *per se,* but rather the 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.

However, 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 Ionization Mass Spectrometry*

Mass spectrometry is the most commonly used destructive analysis (DA) technique in nuclear safeguards, see also section 4.1.6., for measuring the isotopic composition and isotopic amount content (concentration) of uranium, plutonium and other actinides in a sample [13]. Thermal Ionization Mass Spectrometry (TIMS) is widely applied for isotopic measurements. 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 in the mass spectrometer. These sample vapour

is then atomized and at the hot (>1600 $^{0}$C) filament surface ionized, from which the name "thermal ionization" is derived. The species U+ -ions are accelerated by applying a high voltage, and and subsequently mass separated (e.g. $^{234}$U+, $^{235}$U+, $^{236}$U+, $^{238}$U+) by means of a magnetic field, an electrostatic field or a quadrupole.

An appropriate detection system allows the measurement of ratios of 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. This method is widely applied in nuclear analytical laboratories.

### *4.2.2 Gas Source Mass Spectrometry*

Samples in the form of UF6 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 ionization 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 enrichment plants for accountancy purposes; only few applications for safeguards verification measurements are known.

### *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 (planar, coaxial, dwell) and prepared from different materials (NaI(Tl), Si(Li), Ge(Li), high purity silicon, high purity germanium, CdTe) are in use. The type of detector to be used is selected dependent 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.

One of the codes used is the so called MGA code, developed at Lawrence Livermore Laboratory [14]. The Multiple Group Analysis (MGA) allows the isotopic composition of plutonium samples to be determined without external efficiency calibration. Its major drawback arises from the fact that $^{242}$Pu does not show useful gamma rays. This isotope abundance has therefore to be estimated using isotope correlation techniques [15]. However, it is a non-destructive technique which has proven its capability in field application as well as under laboratory conditions.

The determination of the $^{235}$U enrichment is typically done by measuring the intensity of the 186 keV line of this isotope. A particular geometry and calibration is required as the other isotopes can only be insufficiently determined. One of the major advantages is the possibility to use cheap NaI(Tl) detectors of relatively low resolution. A more sophisticated approach is the application of the MGAU code. Again, no external calibration is required.

Gamma spectrometric methods have considerably improved in performance over the last years. They are widely applied for accountancy and verification measurements.

### 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 analyte. The resulting α-spectrum allows the activity ratio of the α-active isotopes present in the sample to b e measured. The isotope abundance ratios can be derived from that. Its application in safeguards is limited to the determination of the $^{238}Pu/(^{239}Pu+^{240}Pu)$ ratio. This information is complimentary to the mass spectrometrically obtained information on the $^{238}Pu/^{239}Pu$ ratio which sometimes suffers from isobaric interference of $^{238}U$.

## 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.

### 4.3.1 COMPUCEA

The combined product uranium concentration and enrichment assay (COMPUCEA) calls upon a combination of gamma ray spectrometry for measuring the $^{235}U$ abundance and K-edge Densitometry for the uranium element concentration measurement. The methods involved have been discussed in some detail in the sections above. Applications of the instrument are in verification measurements at enrichment plants, at fuel production plants and for the uranium product streams of reprocessing plants.

### 4.3.2 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.

The number of such instruments in use and being installed is increasing, as the experience with existing instrumentation demonstrates the reliability of the results.

### 4.3.3 Neutron-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 $^{242}Pu$)
- 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 [16, 17].

# 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 (α, β,) 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.

Table 2 lists Q.T.P. for material under safeguards verification:

| | **Material type** | | | | | |
|---|---|---|---|---|---|---|
| | U235 in LEU | U235 in HEU | $U_N$ $U_D$ | Pu-fresh | Pu(irr) | 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 | $\alpha \leq 0{,}05$ and $\beta \leq 0{,}1$ | | | | | |

*Table 2:* Euratom Q.T.P.

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 that are fit for purpose within the required measurement uncertainties in compliance with the international target values (ITVs). The international target values 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 [6].

The vast majority of EURATOM safeguards verification samples are analyzed under the responsibility of the Institute for Transuranium Elements (ITU) [18]. These analyses are carried out during in-field measurement campaigns at the site being inspected and in two On-Site Laboratories (Sellafield, La Hague). Off-site analysis is carried out at the laboratories at ITU.

## 5.1 In-Field Measurements

In-field measurement campaigns are carried out exclusively on uranium samples to avoid the transport of Pu-contaminated equipment. In-field analysis comprises titration, COMPUCEA, thermal ionization mass spectrometry and gas source mass spectrometry. This spectrum of analytical techniques covers the needs arising in uranium handling facilities. It is perfectly 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.

Safeguarding the large reprocessing plants undoubtedly poses a challenge to the Safeguards Authorities. The size of the plants 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 analyzes 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 at 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 site of the two large European reprocessing plants, namely the 'On Site Laboratory (OSL)' at Sellafield (UK) and the 'Laboratoire sur Site (LSS)', La Hague (France) [19]. Measurements at the on-site laboratories are carried out using hybrid K-edge, COMPUCEA, TIMS and neutron-gamma counting. 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, 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. The quality control concept implemented in the on-site laboratories forms an integral part of the laboratories' measurement strategy, see also 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.

### 5.2.1 Measurement Techniques and Instrumentation

In the laboratories at ITU the following measurement techniques and instrumentation are routinely applied for verification sample analysis:

- potentiometric titration
  ⇒ several Radiometer Autotitrators are available for this purpose
- thermal ionization mass spectrometry
  ⇒ three Finnigan MAT sector field mass spectrometers are available
- isotope dilution mass spectrometry
  ⇒ sample preparation is performed in a glove-box by two laboratory robots (Zymark)

- neutron coincidence counting combined with gamma spectrometry
  ⇒ a specially developed instrument is used
- K-Edge Densitometry
  ⇒ several instruments are available ([1])
- Hybrid K-Edge
  ⇒ instrument attached to the hot cells
- alpha spectrometry
  ⇒ several devices from Canberra and Ortec, some of them modified for use by the robot in a glove-box, are available

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.

### *5.2.2 Verification Sample Analysis*

Reprocessing input samples are typically analyzed for isotopic compostion and uranium and plutonium element concentration. This is achieved by thermal ionization mass spectrometry and by isotope dilution mass spectrometry, respectively.

The concentration of uranyl and plutonium nitrate solutions are 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 isotope dilution mass spectrometry. The isotopic composition is determined by thermal ionization mass spectrometry.

Powder samples of uranium oxide ($UO_2$, $UO_3$ or $U_3O_8$) are first checked for sample mass, in order to be in a position to correct for possible weight changes due to moisture uptake during transport. Then these samples are dissolved and subjected to potentiometric titration. The isotopic composition is measured using thermal ionization mass spectrometry.

$PuO_2$ powder samples are treated similarly. As a supplementary technique the combined neutron/gamma counter 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. After dissolution, aliquots are taken for titrimetric determination of the uranium and plutonium. Further aliquots are used for isotopic measurements of U and Pu by TIMS.

**Table 3** summarizes the amounts of material typically for a particular technique, required to carry out a measurement.

([1]) Instrument developed at Forschungszentrum Karlsruhe, commercially available from Canberra.

| Method | Typical amount of element required for a single measurement (excluding sample preparation) [a] | | | Unit |
|---|---|---|---|---|
| | U | Th | Pu | |
| Titrimetry | 20 - 100 | 50 - 100 | 5 - 50 | mg |
| Coulometry | 2 - 20 | - | 2 - 10 | mg |
| Gravimetry | 2 - 20 | 0.5 - 1 | 0.2 - 3 | g |
| X-ray fluorenscence | 0.1 - 30 | 0.1 - 30 | 0.1 - 30 | mg |
| Isotope dilution mass spectrometry | 10 - 1000 | 10 - 1000 | 1 - 1000 | µg |
| Spectrophotometry | 20 - 500 | 5 - 250 | [b] | µg |
| Fluorimetry | 2 - 500 | - | - | ng |
| Alpha counting | 2 - 250 | - | 0.1 - 1 | µg |
| K - edge | 0.3 - 1 | - | 0.3 - 1 | g |
| Gas mass spectrometry | 20 | - | - | mg |
| Thermal ionization mass spectrometry | 1 - 1000 | 10 - 1000 | 1 - 1000 | µg |
| Gamma spectrometry | 0.1 - 1 | - | - | |
| Alpha spectrometry | - | - | 0.1 - 1 | µg |

*Table 3* Typical amounts of sample needed to perform a measurement
a) The sample preparation is not considered except for the spiking and chemical treatment in isotope dilution analysis
b) Spectrophotometry direct measurement at 830 nm Pu(VI): 0.1-10 mg

# 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 assay, the isotopic composition and the impurities of such special samples. Impurity analysis can confirm the coherence between materials and their consistency with declared processes giving evidence that only declared materials are present at a facility.

Analysis of environmental samples is carried out to detect (unavoidable) traces in the environment originating from technological activities. The Additional Protocol (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 plants, 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 10 years and is recognised as a sensitive and reliable tool for the verification of the absence of undeclared nuclear activities. Samples are taken by inspectors wiping over surfaces inside nuclear facilities, mainly enrichment and reprocessing plants.

These so-called swipe samples are shipped for analysis to the IAEA's Seibersdorf Analytical Laboratory (SAL) in Austria and the Network of Analytical Laboratories (NWAL) [20]. Upon arrival the swipe samples are screened for uranium, plutonium or other actinides using gamma spectrometry and 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 and homogeneous dispersion of those particles on a pyrolitic graphite planchet. Once the particles of interest are found isotopic measurements are performed on particles of a few micrometer sizes. To determine the isotopic composition the following instrumental techniques can be applied [21]:

| Sample Type | Measurand | Instrument Type |
|---|---|---|
| U-oxide particles | Elemental composition<br>Particle morphology | Scanning electron microscopy + X-ray spectrometry |
| U or U-oxide particles | Isotopic composition | SIMS (directly)<br>FT-TIMS (fission track)<br>TIMS (if loaded on filament)<br>ICP-MS (using LASER ablation) |

## 6.1 Secondary Ion Mass Spectrometry (SIMS)

The majority of particles originating from swipe samples are measured by secondary-ion mass spectrometry [22, 23]. SIMS uses an energetic primary ion beam to sputter the surface of the sample, generating secondary ions that are used for material characterization. The primary ions are typically produced by a duoplasmatron source ($O_2^+$, $O_2^-$, $N_2^+$,$Ar^+$, $SF_5^+$), surface ionization ($Cs^+$, $Rb^+$) or by liquid metal field ion emission ($Ga^+$, $In^+$). The sputtering of the sample with a primary ion beam produces mono- and polyatomic particles that emerge back through the sample surface. A small fraction of these particles are positively or negatively charged secondary ions and can be separated according to their mass-to-charge ratios, thus are measured with a mass spectrometer to determine the elemental, isotopic, or molecular composition of the surface. SIMS is a very sensitive surface analysis technique and widely applied in particle analysis.

## 6.2 Thermal Ionisation Mass Spectrometry on single particles

Thermal Ionisation Mass Spectrometry measurements on individual particles offer the advantage of superior accuracy on the uranium isotope ratios. However, the sample preparation is more complex as 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 of and the elemental composi-

tion of uranium particles found in dust sampled at nuclear facilities [21] 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 [24, 25].

## 6.3 Fission Track Thermal Ionisation Mass Spectrometry (FT-TIMS)

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. Subsequently the selected particles are transferred onto a filament for TIMS measurements for isotopic composition analysis [25].

## 6.4 Laser ablation inductive coupled plasma mass spectrometry (LA-ICP-MS)

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) has only been applied quite recently for the analysis of particles from environmental sampling. 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 ionized and its isotopic composition measured, most commonly by applying an ICP-MS with a multi-collector detector system [26].

Environmental and special samples pose inspectors and analysts often 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, are of major concern to draw relevant safeguards conclusions. All the mass spectrometry techniques mentioned in chapter 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). 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 [3].

Quality assurance (QA) and quality control (QC) in destructive sample analysis for nuclear safeguards measurements are means to the end of complying with the requirements to provide reliable measurement results for the nuclear safeguards system. 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). Such a reference material shall consist of "a material or substance which is homogeneous and for which one or more values are well established" [27]. 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 [28]. 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 amount and amount content and mostly applied for isotope dilution mass spectrometry measurements (IDMS), particularly large sized dried spikes of uranium and plutonium are applied for verification of input solutions. An exhaustive list of reference materials for destructive analysis in nuclear safeguards can be found in [28]. Reference materials certified for isotopic amount content and/or isotopic abundance ratios can be obtained from laboratories specialised in their certification, including the IRMM [29], NBL [30] or CETAMA [31]. 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. Any deviation from the reference values is an indication of (systematic) errors and needs to be looked at. Special attention has been given recently to the development of reference materials and quality control samples for the analysis of special samples and for environmental samples. To meet these future needs IRMM has produced a number of reference materials certified also for minor uranium isotope ratios and is developing uranium reference particles for nuclear safeguards and non-proliferation control [32]. The development of reference materials for age determination of nuclear materials is under discussion.

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) 2000 for Meas-

urement Uncertainties in Safeguarding Nuclear Materials represent estimates of achievable uncertainties under routine measurement conditions. They are intended to be used by plant operators and safeguards organizations [6].

External control of the quality of the measurements of the nuclear fuel cycle materials is indispensable to demonstrate international measurement capabilities. Participation of analytical laboratories 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 IRMM has organised the Regular European Interlaboratory Measurement Evaluation Programme (REIMEP) [29]. 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 UF6 , MOX pellets, U, Pu oxides to U, Pu nitrate solutions. 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 [29]. 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. Individual measurement results of participants are compared to the certified reference value provided by IRMM. 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 [31] and NBL [30].

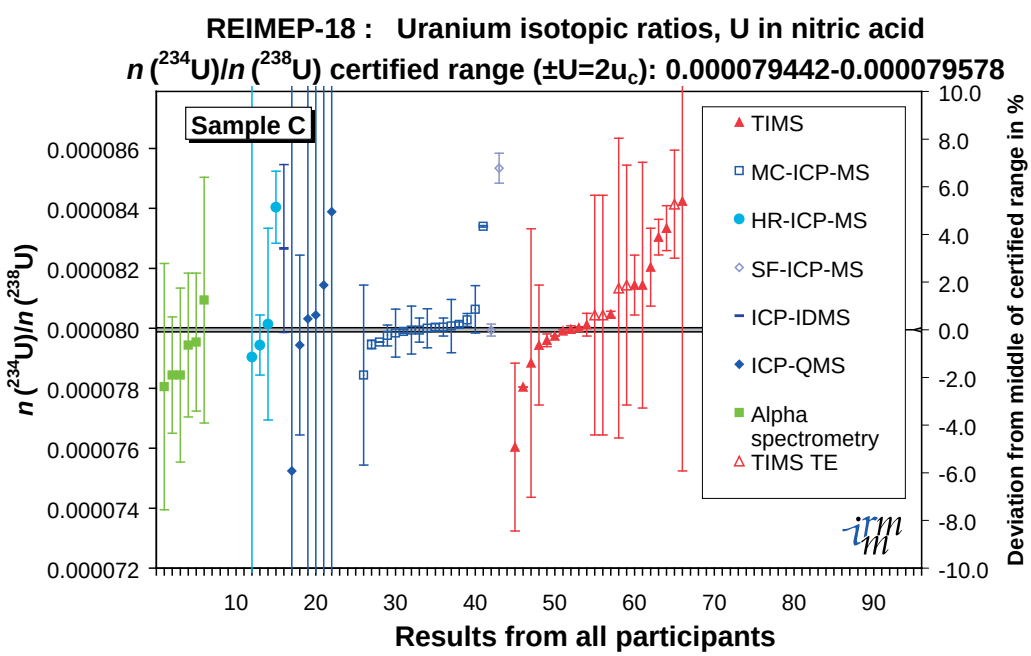


*Figure 3:* Participant results from REIMEP-18
*'Isotopic abundances of low-enriched uranium in nitrate solutions'*

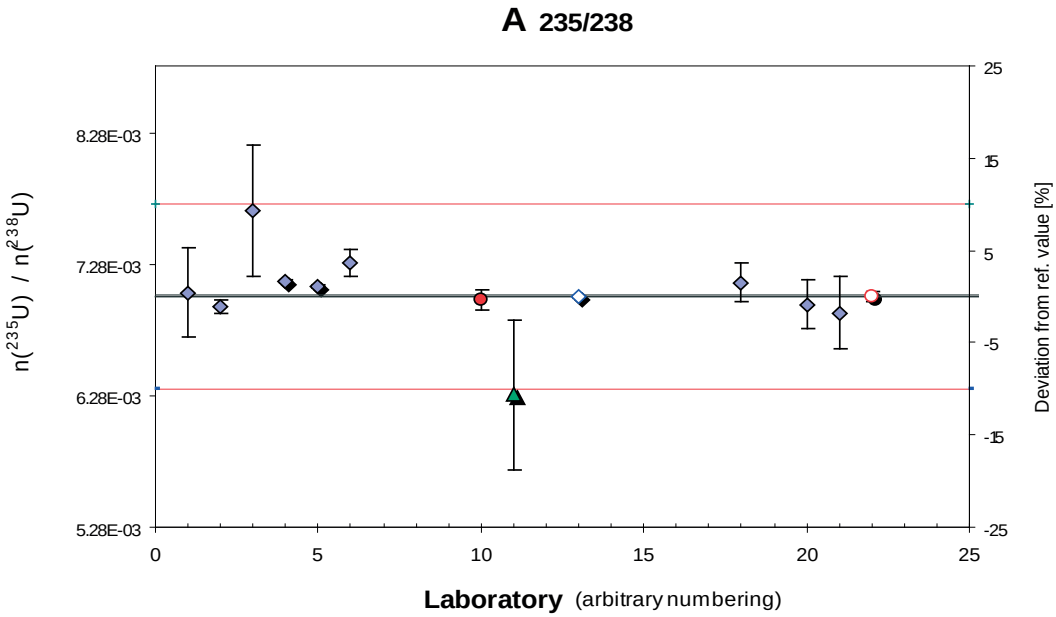


*Figure 4:* Participant results on $n(^{235}U)/n(^{238}U)$ in sample A (5 ng/g U) from NUSIMEP-4 *'Uranium isotopic abundances in simulated urine'*

Inter-laboratory comparisons on isotope ratio measurements in nuclear material are also organized on the level of national metrology institutes and invited expert laboratories as part of the activities of the Consultative Committee for Amount of Substance – Metrology in Chemistry (CCQM) of the Bureau International des Poids et Mesures [33]. National metrology institutes do not only need to demonstrate that their measurement results are reliable and comparable, they also have to be in compliance with legislation, international standards and international recognition arrangements that support the free trade goal "measured once, accepted everywhere". RMM assists the CIPM (International Committee for Weights & Measures) to support the CIPM-MRA (Mutual Recognition Arrangement) by making available the same samples as used in NUSIMEP for inter-laboratory comparisons in chemistry among national metrology institutes and expert laboratories. For the pilot study CCQM-P48 (Uranium isotope ratio measurements in simulated biological/environmental materials) material representative for a large range of biological and environmental samples was chosen to produce test samples, among those also NUSIMEP-4 samples [34].. Measurement claims and demonstrated measurement capabilities can therefore be compared in a transparent way on all levels of the international measurement infrastructure from normal field laboratories to network laboratories to reference laboratories to national metrology institutes involved in measurements for nuclear safeguards.

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. Some laboratories involved in measurements on nuclear materials or in environmental sampling already have or are striving for accreditation, mainly according to the ISO/IEC guide 17025:2005 [35], in order to have an external attestation by an accreditation body with regard to their technical abilities [36, 37]. 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.

## 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 for the verification of the non diversion of fissile material from its intended and declared (peaceful) use. 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 the 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 concentrations. 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 future convergence of nuclear forensics, environmental sampling and classical safeguards analysis.

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# Non Destructive Assay

Montserrat Marin-Ferrer, Paolo Peerani

## Introduction to Non-destructive Assay

Both for accountancy and control purposes, mass and composition of nuclear material are mainly determined by measurements performed by destructive and non-destructive methods (namely **Destructive Analysis,** or **DA,** and **Non Destructive Assay,** or **NDA** methods).

DA involves measurements on samples taken from a larger quantity or batch; typically samples are altered by their preparation such that the sample is not returned to the batch. The main DA techniques are Isotope Dilution Mass, Spectrometry, Secondary Ion Mass Spectrometry, Inductively Coupled Plasma Mass Spectrometry …

NDA techniques are not intrusive and are characterized as passive or active depending on whether they measure radiation from spontaneous decay of the nuclear material or radiation induced by an external source. The main NDA techniques are classified as gamma-ray assay, neutron assay, and calorimetry

The measurements are non-destructive in that they do not alter the physical or chemical state of the nuclear material. In some cases, the emitted radiation is unique to the isotope(s) of interest and the radiation intensity can often be related to the mass of the isotope(s). NDA obviates the need for sampling, reduces operator exposure, and is much faster and cheaper than chemical assay; unfortunately NDA is usually less accurate than chemical assay. The development of NDA reflects a trend toward 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.

## 1. Calorimetry

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.

The principal 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 needed.
- ✓ Theassay is comparable to chemical assay in precision and accuracy if the isotopic composition is well known.
- ✓ Theassay is applicable to a wide range of material forms. Plutonium can be measured in the presence of Uranium.

## 1.1 Objective of the technique

Radioactive decay of any radioactive material produces heat. Calorimetry may be used to measure the thermal power of Plutonium samples. 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 Pu isotopic mass ratios. Calorimetry provides a convenient, accurate and non-destructive measure of the total Plutonium mass in samples of unknown composition.

## 1.2 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: 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, this is not a routine technique for safeguards. Nevertheless, in the US Calorimetry is used for routine measurements for nuclear materials accountability and shipper-receiver confirmatory measurements for Pu.

## 1.3 Principle of Measurement

Plutonium isotopes decay emitting α,β, and γ particles, of which the α,β particles are responsible for the heat generated in the surrounding sample matrix. The calorimetric Plutonium assay needs information on the content of $^{241}$Am in the measured item, which also contributes to the measured thermal power 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 Pu isotopes (and of $^{241}$Am and $^{3}$H) are recorded.

*Table 1:* Specific thermal power values (from ref [1,2]

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

## 1.4 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 Peff (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 calorimeter 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 (Fig 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 (Fig. 2). The difference between the old (baseline) and new inner cylinder applied electrical powers being equal to the sample power.

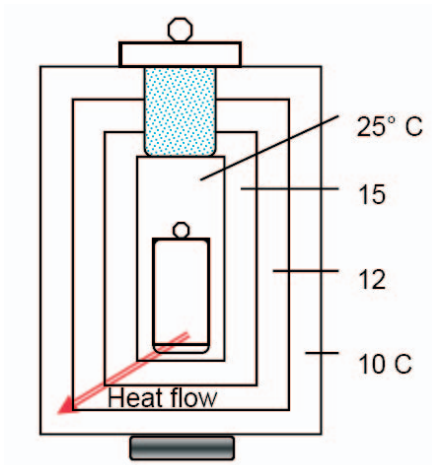


*Figure 1:* Schematic view of an isothermal air-flow calorimeter

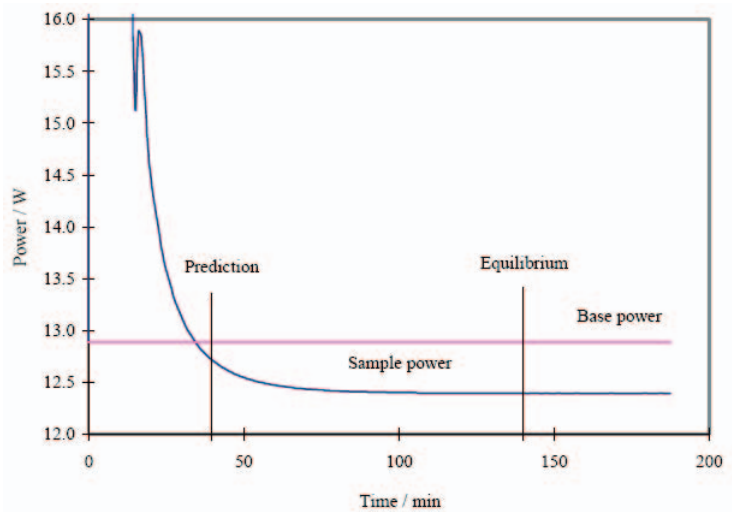


*Figure 2:* Servo-controlled electrical power applied to calorimeter

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.

## 1.5 Performance Values

The performance of a calorimetric Plutonium assay depends on the thermal power W as determined by the calorimeter and on the quantity Peff 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. (from [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 Peff 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 spectrometry).

*Figure 3:* Plutonium air–flow calorimeter

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## 2. Gamma Spectrometry

Most radioactive decays are associated to the emission of gamma rays, where the photon energy is characteristics of each individual isotope. Gamma detectors allow not only to reveal and count photons, but also to discriminate the photon energy, giving so a detailed information on isotopic composition.

The most commonly used gamma detectors are scintillators (plastics, NaI, $LaBr_3$) or semiconductors (HPGe, CdTe, CZT). Unfortunately the relatively low penetration of photons in high-Z materials produces a strong self-absorption phenomenon in fissile samples. This limits the applicability of gamma techniques for quantitative measurements to a restricted number of cases: small samples or low-density (for instance liquid) samples.

Nevertheless gamma spectrometry is extremely important for the qualitative information about the isotopic composition. In fact all the 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.

## 2.1 Objective of the technique

Gamma spectroscopy is the most commonly used Non-destructive Assay (NDA) technique in nuclear safeguards to measure Uranium enrichment and Plutonium isotopic composition [1]. Another important field of application are measurements on spent fuel to confirm characteristics, cooling time, initial enrichment or burn-up of fuel assemblies.

## 2.2 Principle of measurement / Definition of the physical principle

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

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

- inorganicscintillators, mostly NaI(Tl), and recently the new lanthanum halide scintillation detector (e.g. $LaBr_3$ [3]).
- semiconductor detectors, such as high-purity germanium (HPGe) or cadmium-zinc-telluride (CZT).

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

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

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

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

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

## 2.3 Measurement technique / Description of the implemented technique

### 2.3.1 Acquisition of gamma spectra

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 lines, such as Plutonium. The use of NaI detectors in nuclear safeguards, often referred to as **Low Resolution Gamma Spectrometry (LRGS),** is therefore limited to the measurement of $^{235}U$ enrichment in Uranium samples.

**High Resolution Gamma Spectrometry (HRGS)** is the preferred technique for Plutonium isotopic determination, although it can also be applied to measure Uranium enrichment. HPGe detectors provide good energy resolution (better technologies are in preparation but not yet ready for use). 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 photos at the end of this chapter).

For applications where portability or accessibility is an important requirement, other types of crystals have been introduced, such as Cadmium-Zinc-Telluride (CZT) which provides reasonable energy resolution at room temperature. 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). Figure 4 shows a comparison of typical spectra as generated from different types of photon detectors.

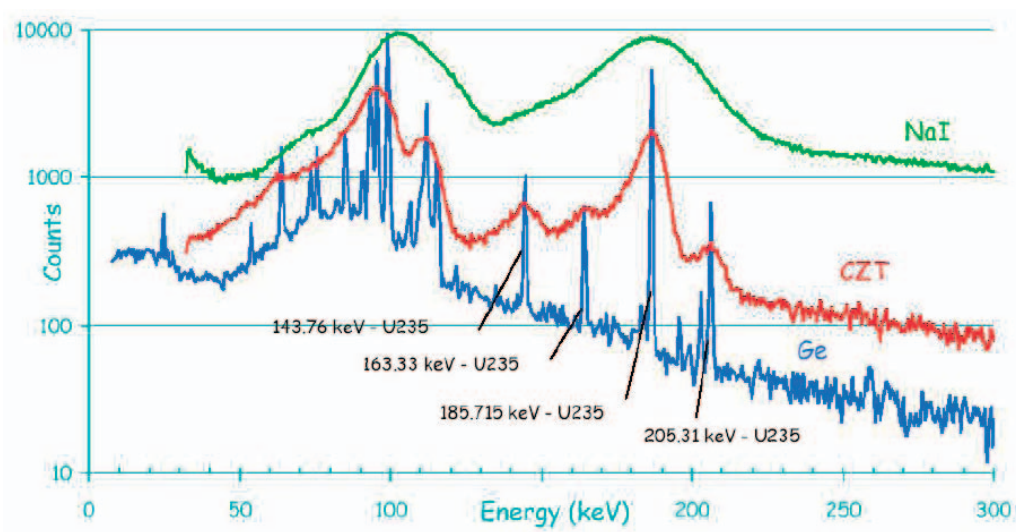


*Figure 4:* Comparison of Uranium spectra from different detector types [from 4]

## 2.3.2 Analysis of gamma spectra

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

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

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

Measurements based on **the intrinsic calibration method** avoid the need for calibration with physical standards. Here, the isotopic ratios are determined from the measured gamma spectrum using corresponding gamma and X-rays from the decay of all isotopes, taking into account physical phenomena such as the energy dependence of detector efficiency, self-absorption in the sample and attenuation in the container and filters.

For Plutonium spectrum analysis, a major advancement for the measurement technique was achieved with the development of the Multi-Group Analysis (MGA) code, which successfully exploits the complex XKα region (94-104 keV) of a Plutonium gamma spectrum for the isotope analysis [5]. Since this spectral region contains the most abundant Plutonium gamma and X-rays detectable in a gamma spectrum from Plutonium in the presence of Am, the use of MGA code enables relatively precise isotope abundance determinations from gamma spectra accumulated in relatively short counting times (15-30 min).

For Uranium spectra, the method again uses analysis of the 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 to freshly separated Uranium materials.

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

*Table 3:* Some gamma Radiation Detectors and their applications [from 4].

| Detector type | Resolution | Efficiency | Application | Codes | Remarks |
|---|---|---|---|---|---|
| NaI | Low | Very high | U enrichment | U235 | Calibration requires **2** standards<br>Wall thickness correction **not** allowed |
| | | | | NaIGEM | Calibration with 1 standard<br>Wall thickness correction allowed |
| | | | Attribute test | SPEC, MCA | |
| Ge – Planar | Very high | Low | U enrichment | UF6 | Calibration with at least 1 standard |
| | | | | MGAU | **No calibration required** |
| | | | Up isotopic composition | MGA | **No calibration** |
| Ge – Coaxial | High | High | Attribute test | SPEC, MCA | |
| CdZnTe | Medium or high | Very low | U enrichment | UF6 | Calibration with at least 1 standard |
| | | | U enrichment | U235 | Calibration requires 2 standards.<br>Wall thickness correction not allowed |
| | | | | MGAU | **No calibration required** |
| | | | Attribute test on spent fuel | FP | |

## 2.4. Performance Values for gamma spectrometry

For Uranium enrichment measurement there is a variety of methodological possibilities according to the choice of the detector (NaI, HPGe or CZT) and of the analysis method (enrichment meter or intrinsic calibration). Table 4 compares typical performance values of the possible combinations [6] as a function of the enrichment range. In this table CT stands for counting time in seconds, and "r" and "s" stand for the contributions to the measurement uncertainty derived from the statistical (random) and systematic components respectively.

For Plutonium isotopic composition the choice of HPGe in combination with intrinsic calibration is the only NDA option practically applied. Table 5 shows typical performance values for HRGS technique for different Plutonium compositions. The random component of the uncertainty is based on the assumption of a typical counting time of 10 to 20 minutes. The systematic uncertainty is estimated based on the use of a well-known isotopic ratio of $^{242}$Pu. If this value is not known, and has to be computed from isotopic correlations, the systematic uncertainty can increase significantly, being dominated by the uncertainty of the $^{242}$Pu content.

*Table 4:* Performance values for gamma-spectrometric enrichment measurements on low-enriched Uranium oxide materials (CT= counting time) [from 6]

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

*Table 5:* Performance values for Pu isotope assay in PuO2 and MOX [from 6]

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

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http://www.ortec-online.com/detectors/photon/b2_3.htm
http://www.ortec-online.com/papers/reprints.htm#Nuclear
http://www.canberra.com/products/465.asp
http://www.canberra.com/literature/
http://www.gbs-elektronik.de/
http://www.bsi.lv/


*Figure 5:* Germanium detectors with dewars for liquid nitrogen cooling

*Figure 6:* Gamma spectrometer with liquid nitrogen-cooled germanium detector, Mini Multi-channel Analyser, and Hewlett Packard LX200 palmtop computer

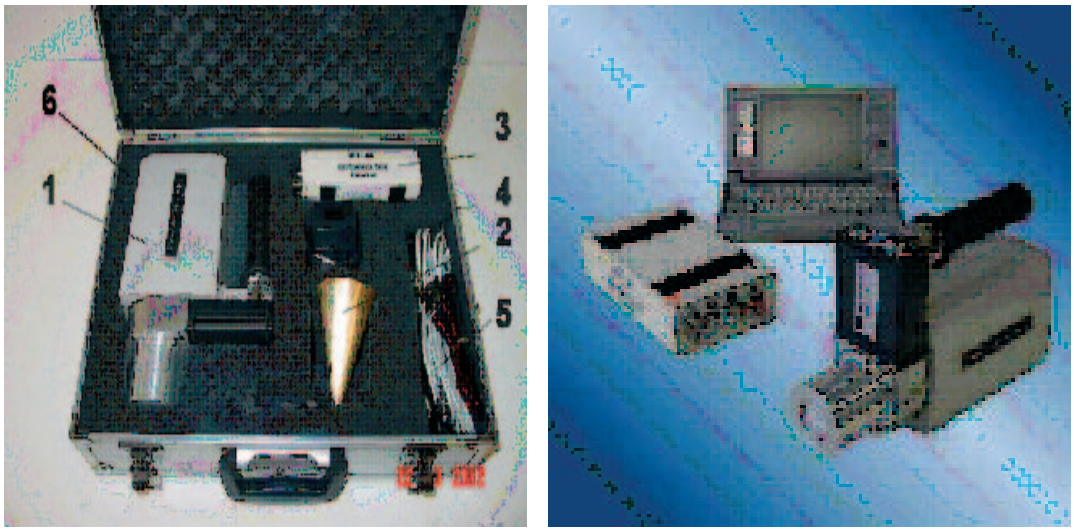



*Figure 7:* HP(Ge) Hand Held Detector (BSI Ltd.)

*Figure 8:* The latest advance in the portable germanium detector area is the Cryo3, developed by 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.

# 3. Neutron Assay

## *3.1 The Origin of the Neutron Radiation.*

The nuclear materials that are accounted for in the nuclear fuel cycle often emit neutrons as well as gamma rays. For most isotopes, the neutron emission rate is very low compared to the gamma-ray emission rate. For other isotopes, the neutron emission rate is high enough to provide an easily measurable signal. If the sample of interest is too dense to allow the leak of gamma rays from its inside, then an assay by passive or active neutron detection may be the preferred technique.

Neutrons are emitted from nuclear materials with a wide energy spectrum. As they travel through matter, they interact and exchange their energy in a complex way. However, neutrons detectors do not usually preserve information about the energy of the detected neutrons. Consequently, neutron assay consists of counting the number of emitted neutrons without knowing their specific energy.

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.

### *3.1.1 Spontaneous and Induced Nuclear Fission*

The spontaneous fission of Uranium, Plutonium or other heavy elements is an important source of neutrons. The graph of binding energy per nucleon suggests that nuclides with a mass larger than about 130 amu should spontaneously split apart to form lighter, more stable, nuclides. The actual mass of an atomic nucleus is always a little smaller than the sum of the present masses of all its nucleons (protons and neutrons). This is because some of the masses of the nucleons were changed into energy needed to form the nucleus. This energy is called **binding energy.** The higher the binding energy, the more stable the nucleus is. A graph of binding energies vs. mass numbers shows that the binding energy increases as the mass number gets higher until approximately the mass number 60 (Figure 9), then it starts to decline from that point on. A region of greatest stability is on the peak of the curve, around mass number 55 to 80.

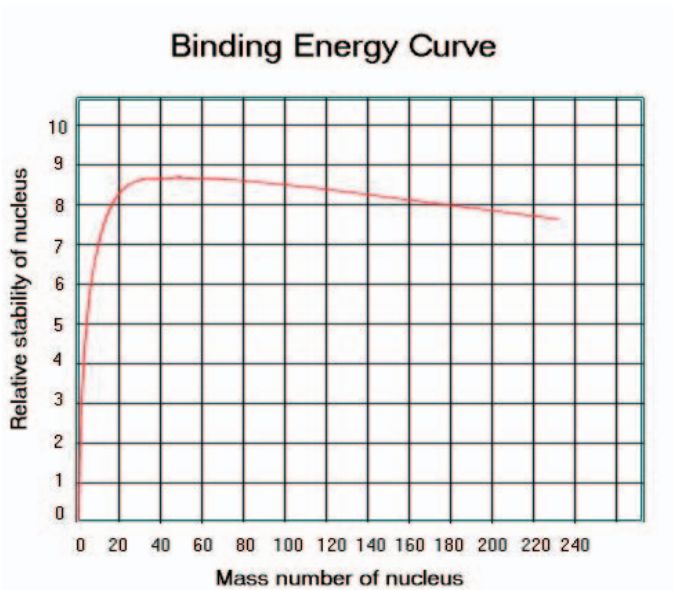



*Figure 9:* Binding energies vs. mass numbers.

Unstable elements with a mass number lower than the ones in the region tend to undergo **fusion** (the combination of nuclei) to reach the region. Unstable elements with a mass number greater than the ones in the region tend to undergo **fission** (the splitting of nuclei) to reach the region. Experimentally, we find that spontaneous fission reactions occur for only the very heaviest nuclides those with mass numbers equal or higher than 230. Even when they do occur, these reactions are often very slow. The half-life for the spontaneous fission of 238U, for example, is $10^{16}$ years, about two million times bigger than the age of our planet!

We don't have to wait, however, for slow 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 10).

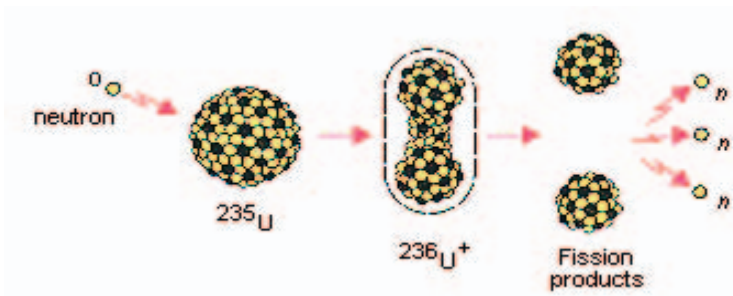



*Figure 10:* Induced fission process

The absorption of a neutron by $^{235}$U induces oscillations in the nucleus that deform it until it splits into fragments, the same way a drop of liquid might break into smaller droplets. Within $10^{-13}$ s of scission, each of the two fragments emits a number of prompt neutrons and gamma rays. The fragments are usually unequal in size, with mass distributions centred near atomic numbers 100 and 140. These fission fragments carry away the majority of the energy released in fission (typically 170 MeV) in the form of kinetic energy. Also, within milliseconds or seconds, many of the fragments decay by beta-particle emission into other isotopes that may emit delayed neutrons or gamma rays.

Spontaneous fission is a quantum mechanical process involving penetration of a potential barrier. The height of the barrier, and hence the fission rate, is a very sensitive function of atomic number Z and atomic mass A. For Thorium, Uranium, and Plutonium the fission rate is low compared to the rate of decay by alpha-particle emission, which dominates the total half-life. For Californium and even heavier elements, the fission rate can approach the alpha decay rate. The fission n-yield of $^{240}$Pu, 1020 n/s-g, is the most important single yield for passive neutron assay because $^{240}$Pu is usually the major neutron-emitting Plutonium isotope present.

The strong dependence of spontaneous fission rates on the number of protons and neutrons is important for assay considerations. The fission rate for odd-even (odd neutron (or proton) number and even proton (or neutron) number) isotopes is typically $10^3$ times lower than the rate for even-even isotopes, and the fission rate for odd-odd isotopes is typically $10^5$ times lower. These large differences are due to nuclear spin effects [1].

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 may be far enough below the Coulomb barrier that spontaneous fission is not observed, but absorption of a relatively small amount of energy, such as from a low-energy neutron or photon, forms an intermediate state (perhaps a compound nuclear

state) at or above the barrier, so that induced fission occurs readily, competing successfully with other modes of decay of the compound nucleus. Among the even-odd isotopes that can be fissioned by neutrons there are $^{233}$U, $^{235}$U and $^{239}$Pu. These isotopes are called fissile. Even-even isotopes, such as $^{238}$U and $^{240}$Pu, that are not easily fissioned by low-energy neutrons, are called **fertile.** This term comes from reactor theory and refers to the fact that through neutron capture theses isotopes are fertile sources of fissile isotopes.

The ability of a nucleus to undergo induced fission will depend critically on the energy of the intermediate system: for some nuclei, absorption of thermal neutrons may be sufficient to push them over the barrier, while for others, fast (MeV) neutrons may be required.

### *3.1.2 Neutrons from (α,n) reactions.*

Nuclei can decay spontaneously by alpha- or beta-ray emission as well as by fission. Alpha particles are helium nuclei with two protons and two neutrons, and beta particles are energetic free electrons. In principle, all nuclei of atomic mass grater than 150 are unstable towards alpha decay. However, alpha decay is a quantum mechanical barrier penetration process like spontaneous fission, and the Coulomb barrier is high enough to make alpha decay unlikely for all but heaviest elements.

The alpha decay process leads to the emission of gamma rays from unstable daughters. 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.

The alpha particle is emitted from Uranium or Plutonium with energies in the range of 4 to 6 MeV. Because $^{234}$U is the dominant alpha emitter in enriched Uranium, the average energy for alpha particles emitted from Uranium is 4.7 MeV. For Plutonium, an average energy of 5.2 MeV is typical. In air, the range of alpha particles from Uranium is 3.2 cm and the range of alpha particles from Plutonium is 3.7 cm. The range in other materials can be estimated from the Bragg-Kleeman rule [2]:

$$\text{Range} = 0.00032 \frac{\sqrt{\text{A}}}{\text{density}\,(\text{g/cm}^3)} x \quad \textit{range in air} \qquad \text{(Eq. 3)}$$

where A is the atomic weight of the material. The range in Uranium and Plutonium oxide is roughly 0.006 cm and 0.007 cm, respectively. Thus the alpha particles lose energy very rapidly when travelling through matter. In many cases this short range means that the alpha particle can never reach nearby materials in which (α,n) reactions could take place. If, however, elements such as oxygen or fluorine are intimately mixed with the alpha emitting nuclear material, an (α,n) reaction may take place because the alpha particle can reach these elements before it loses all its energy.

Reactions with 5.2 MeV alpha particles are possible in low-Z elements. In all elements with atomic number greater than the one of chlorine, the reaction is energetically not allowed [3]. 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. The neutron yield will depend very sensitively on the alpha activity of nuclear isotopes, the alpha particle energy, the reaction Q-values (that is the difference in binding energies between the two initial nuclei and the two final reaction products), the impurity concentrations, and the degree of mixing (because of the short range of the alpha particle).

The energy of the neutron emitted in an (α,n) reaction depends on the energy that the alpha particle has at the time of the reaction and on the Q-value of the reaction in the isotope. Another 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.

### *3.1.3 Neutrons from other Nuclear Reactions.*

Spontaneous fission, induced fission and (α,n) reactions are the primary sources of neutrons observed in passive measurements. However, other reactions such as (γ,n), (n,n') and (n,2n) may take place in the sample or detector assembly and contribute slightly to the observed count rate. These reactions are more important in active non-destructive assay measurements.

The **(γ,n)** reaction can produce neutrons in any element if the gamma-ray energy is high enough. The typical minimum threshold energy (8 MeV) is much higher than the energies of gamma rays emitted from radioactive nuclides. However, the (γ,n) threshold energies for **beryllium** (1.66 MeV) and **deuterium** (2.22 MeV) are anomalously low. For passive assay applications it is only necessary to keep in mind that prompt fission gamma rays or gamma rays from some (α,n) reactions can produce extra neutrons if the detector assembly contains beryllium or deuterium. Or, conversely, neutrons can be captured in hydrogen to produce deuterium and 2.22 MeV gamma rays.

Inelastic neutron scattering **(n,n')** can occur in heavy nuclei with neutron energies of roughly 0.1 to 1.0 MeV or higher. This reaction is possible if the target nucleus has energy levels low enough to be excited by the neutron. The probability of this reaction is not high, and the number of neutrons present is not altered. However, the average energy of neutrons in the material will decline somewhat faster than would be expected from elastic scattering alone.

The **(n,2n)** reaction can increase the number of neutrons present, but the threshold energy in most elements is in the range of 10 MeV. For deuterium, beryllium and tungsten the thresholds are lower, but the number of extra neutrons produced is likely to be small.

### *3.1.4 Isotopic Neutron Sources.*

**Californium-252** is the most commonly used 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 60 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.

### *3.1.5 Neutrons from Fission.*

Prompt neutrons and gamma rays emitted at the time of scission are the most useful for passive assay because of their intensity and penetrability. Many passive assay instruments, such as coincidence and multiplicity counters, are designed to detect prompt fission neutrons and are often also sensitive to gamma rays.

The number of neutrons emitted in spontaneous or induced fission is called the neutron multiplicity. For neutron-induced fission the multiplicity increases slowly and linearly with the energy of the incoming neutron. From one fission to another the neutron multiplicity may vary from 0 to 6 or more, depending on the distribution of excitation energy among the fission fragments. Terrell [4] has shown that the multiplicity distributions for both spontaneous and thermal-neutron-induced fission can be approximated by a Gaussian distribution centred at $\overline{\nu}$, the mean prompt multiplicity:

$$P(\nu) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(\nu-\overline{\nu})^2/2\sigma^2} \qquad \text{(Eq.4)}$$

A distribution width σ of 1.08 can be used as an approximation for all isotopes except $^{252}$Cf where 1.21 should be used.

Information about the neutron multiplicity distribution in fission is used in the analysis of coincidence and multiplicity counting. One question that has arisen in this regard is whether the neutron multiplicity and the mean neutron energy are correlated. In other words, if the number of neutrons emitted in a fission is above average, will the mean neutron energy be below average? The available experimental evidence indicates that the mean neutron emission energy is approximately constant and that the number of neutrons emitted increases with the amount of available energy. Thus the mean energy may be approximately independent of the multiplicity.

In passive assay systems the delayed neutrons and gamma rays are usually masked by the stronger prompt emissions. The time delay, however, is often used by active assay systems to discriminate between the interrogation source and the induced fission signal. Delayed neutrons can be arbitrarily categorized into six groups with decay half-lives ranging from 200 ms to 55 s [5]. The neutron yield of each group is different for each Uranium or Plutonium isotope. Delayed neutrons energy spectra are highly structured, as opposed to the smooth Maxwellian distributions of prompt neutrons. Also, the average energy of delayed neutrons is only 300 to 600 keV, as opposed to the 2 MeV average of prompt neutrons. Most important, the number of delayed neutrons is typically only ~ 1% of the number of prompt neutrons. Thus, delayed neutrons contribute to passive neutron measurements, but their effect is not large and may be treated as random.

## *3.2 Neutron interaction with matter [6].*

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. 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 utilize 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).

### 3.2.1 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. Elastic collisions tend to be very probable, and often serve to bring the slow neutron into thermal equilibrium with the absorber medium before a different type of interaction takes place. Much of the population in the slow neutron energy range will therefore be found among these **thermal neutrons,** which, at room temperature, have an average energy of about **0.025 eV**.

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 [or (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.

### 3.2.2 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. At each scattering site, the neutron loses energy and is thereby moderated or slowed down towards lower energies. The most efficient moderator is hydrogen because the neutron can lose up to all its energy in a single collision with a hydrogen nucleus. For heavier nuclei, only a partial energy transfer is possible.

If the energy of the fast neutron is sufficiently high, inelastic scattering with nuclei can take place. In this reaction the recoil nucleus is elevated to one of its excited states during the collision. The nucleus quickly de-excites, emitting a gamma ray, and the neutron loses a greater fraction of its energy than it would do in an equivalent elastic collision. Inelastic scattering and the subsequent secondary gamma rays play an important role in the shielding of high-energy neutrons but are an unwanted complication in the response of most fast neutron detectors based on elastic scattering.

### 3.2.3 Neutron Cross Sections.

For neutrons with fixed energy, the probability per unit path length is constant for any interaction mechanism. This probability is called the cross section per nucleus for each type of interaction. The cross section has units of an area and is traditionally measured in barn ($10^{-28}$ $m^2$). For example, each nuclear species has an elastic scattering cross section, a radioactive capture cross section, and so on, each of which is a function of the neutron energy.

When multiplied by the number of nuclei N per unit volume, the cross section is converted into the macroscopic cross section Σ:

$$\Sigma = N\,\sigma \qquad \text{(Eq. 5)}$$

which has dimensions of inverse length.  can be interpreted as the probability per unit path length for the specific process described by the "microscopic" cross section $\sigma$. When all processes are combined by adding together all cross sections for each individual interaction:

$$\Sigma_{tot} = \Sigma_{scatter} + \Sigma_{rad.\ capture} + \ldots \quad \text{(Eq. 6)}$$

the resulting $\Sigma_{tot}$ is the probability per unit path length that any type of interaction will occur. If a narrow beam attenuation experiment is carried out for neutrons, the number of detected neutrons will fall off exponentially with the absorber thickness. In this case the attenuation relation is written:

$$\frac{I}{I_o} = e^{-\Sigma_{tot} t} \quad \text{(Eq. 7)}$$

The neutron mean free path λ is given by $1/\Sigma_{tot}$. In solid materials, λ for slow neutrons may be in the order of magnitude of a centimetre or less, whereas for fast neutrons it is normally tens of centimetres.

When discussing the reactions rate induced by neutrons, it is convenient to introduce the concept of neutron flux. If we first consider neutrons with a single energy or fixed velocity v, the product vΣ gives the interaction frequency for the process for which Σ is the macroscopic cross section. The reaction rate density (reactions per unit of time and volume) is then given by **n(r)vΣ,** where n(r) is the neutron density number at the position vector r, and n(r)v is defined as the **neutron flux φ(r)** with dimensions of length$^{-2}$ time$^{-1}$. Thus, the reaction rate density is given by the product of the neutron flux and the macroscopic cross section for the reaction of interest:

$$\text{Reaction rate density} = \varphi\,(r)\,\Sigma \quad \text{(Eq. 8)}$$

This relation can be generalized to include an energy-dependent neutron flux φ (r, E) and cross section Σ (E):

$$\text{Reaction rate density} = \int_0^\infty \varphi(r, E)\Sigma(E)dE \quad \text{(Eq. 9)}$$

## 3.3 Neutron Detection

### 3.3.1 Gas-Filled Detectors.

Mechanisms for detecting neutrons in matter are based on indirect methods because of their neutral nature. The process of neutron detection begins when neutrons, interacting with various nuclei, initiate the release of one or more charged particles. The electrical signals produced by the charged particles can then be processed by the detection system. The energy recorded by the detector is the reaction energy (plus, perhaps, some of the remaining initial neutron energy). Thus, in general, neutron detectors provide information only on the number of neutrons detected and not on their energy.

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). Detectors' walls are about 0.5 mm thick and are manufactured from either stainless steel or aluminium. Steel walls absorb about 3% of the neutrons; aluminium walls, about 0,5%. Thus, aluminium tubes are usually preferred because of their higher detection efficiency. However, steel tubes have some small advantages over aluminium tubes for certain applications: they require less careful handing during assembly, the connecting threads are less susceptible to galling, and impurities can be kept lower. In addition, in very low count-rate applications, a background of about 1 count/min has been observed and attributed to radium impurity in aluminium.

The central wire is typically 0.03-mm-thick gold-plated tungsten. Tungsten provides tensile strength for the thin wire, and the gold plating offers improved electrical conductivity. The wire is held in place by ceramic insulators.

Sometimes the interior walls are coated with **activated charcoal.** This coating is used in $^{3}$He-filled tubes operated in high neutron fluxes. The activated charcoal serves to absorb electronegative gases that build up during neutron irradiation.

As described before, 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. In a gas-filled detector, approximately 30 eV is required to create an ion pair.

If little or no voltage is applied to the tube, most of the ions will recombine and no electrical output signal is produced. If a positive voltage is applied to the central wire (anode), the electrons will move toward it and the positively charged ions will move toward the tube wall (cathode). An electrical output signal will be produced whose magnitude depends on the applied voltage, the geometry of the counter, and the fill gas. These parameters determine whether the detector operates in the ionisation region, the **proportional region,** or the **Geiger-Mueller region.**

### *3.3.2 Proportional Counters.*

In the proportional region the electric field strength is large enough so that 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 ionize 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.** When a total of "A" ion pairs result from a single primary pair, the process has a gas amplification factor of A. "A" will be unity in an ionisation chamber where no secondary ions are formed and as high as $10^3$ to $10^5$ in a well-designed proportional counter. Note that in the proportional region the charge collected is also linearly proportional to the energy deposited in the gas.

At the same time that the electrons are drifting toward the anode, the positive ions are drifting toward the cathode. In a proportional counter, the **drift velocity** of the electrons is approximately 3 orders of magnitude larger than the drift velocity of the positive ions. Because the avalanche is formed near the anode wire, the electrons with a larger drift velocity are collected in an extremely short time interval (within $10^{-8}$ s); the slower drifting positive ions are collected on the cathode over a much longer time interval.

For a large tube, nearly all the reactions occur sufficiently far from the walls of the detector to deposit the full energy of the products within the proportional gas. Once the size of the tube is no longer large compared with the range of the reaction products, some events no longer deposit the full reaction energy in the gas. If either particle strikes the chamber wall, a smaller pulse is produced. The accumulative effect of this type of process is known as the **wall effect** in gas counter. Consequently, consideration is often given in the design of the gas-filled detectors to minimize the wall effect. One obvious step is to build the counter with a diameter as large as possible so that most neutron interactions occur far away from the wall. Another one is to increase the pressure of the $^{3}$He gas to reduce the range of the charged particle reaction products. Because of the low atomic mass of $^{3}$He, reaction products ranges are unusually long and the wall effect is considerably more significant than for a $BF_3$ tube of the same size and fill gas pressure.

One method of reducing the charged particle ranges is to add a small amount of a heavier gas to the $^{3}$He to provide an enhanced stopping power. For example, **a heavy gas such as argon** can be used to

reduce the range of the reaction products so that more of their kinetic energy is deposited within the gas and, thereby, the output pulse-height resolution is improved. Adding a heavy gas also speeds up the charge collection time, but has the adverse effect of increasing the gamma-ray sensitivity.

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. Compared with $BF_3$ tubes, $^{3}He$ counters can be operated at much higher pressures with acceptable gas multiplication behaviour and are therefore preferred for those applications in which maximum detection efficiency is important. The lower Q-value of the $^{3}He$ reaction, however, makes gamma-ray discrimination more difficult than for an equivalent $BF_3$ tube.

A polyatomic gas may also be added to proportional counters to serve as **quench gas.** The rotational degrees of freedom available to polyatomic gas molecules serve to limit the energy gained by electrons from the electric potential, thus helping to dampen and shorten the avalanche process and improve the pulse-height resolution. Gases as $BF_3$ or $CH_4$ are already polyatomic gases and require no additional quench gas. Tubes filled with $^{3}He$ and $^{4}He$ often have a small quantity of $CO_2$ or $CH_4$ added. Because $BF_3$ or $CH_4$ gases are polyatomic, detectors filled with these gases require higher operating voltages. Also, the relatively large quantity of polyatomic gas restricts the intercollisional energy gain so that these detectors are usually not operated at fill pressures as high as those used for detectors filled with monatomic gases.

### *3.3.3 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 $\mathbf{Q_{value} = 0.764\ MeV}$. For reactions induced by slow neutrons, the $Q_{value}$ of 0.764 MeV leads to oppositely directed reaction products with energies $\mathbf{E_p = 0.573\ MeV}$ and $\mathbf{E_{H\text{-}3} = 0.191\ MeV}$.

The thermal neutron cross section for this reaction is 5330 barns, significantly higher than that for the boron reaction, 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 $^{3}H$ detectors in approximately 10 cm of polyethylene or other moderating materials to maximize their counting efficiency. Although $^{3}He$ is commercially available, its relatively high cost is a factor in some applications.

$$n + {}^{3}He \rightarrow p + {}^{3}H + 764\ keV$$

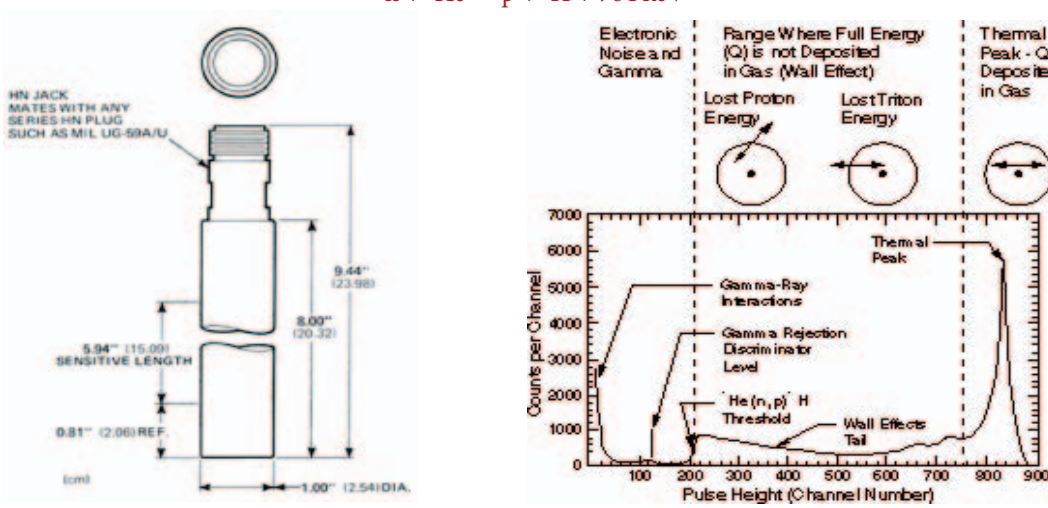



*Figure 11:* The $^{3}He$ Proportional Counter: structure and typical spectrum.

## 3.4 Neutron Detection Electronics [7].

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, 0.025 eV, by about 27 collisions in hydrogen. The capture reaction is:

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

Typically the multiplicity counter will have 80 to 130 $^3$He detectors at 4-atm. pressure and 1-in. diameter, with the effective length varied to suit the size of the counter. The reaction energy of 765 keV appears as the kinematic 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. The applied high voltage is typically 1500 to 1680 V so that the 3He tubes are operated in the proportional mode, where the initial ionization charge is amplified by a factor of $10^2$ to $10^3$. The $^3$He tubes will produce a broad distribution of electrical output pulses depending on the location of the neutron capture in the tube and the direction of the outgoing reaction products. The pulses will have a fast rise time of about 0.1 μs due to collection of electrons at the anode, but collection of positive ions at the outer tube wall, the cathode, may take up to 200μs. The recovery time of a $^3$He tube, the time before it can provide another output pulse, which may overlap a previous pulse, is typically 1 to 2 μs.

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. Each of them will be mounted on a small circuit board that gives an output pulse to the data acquisition electronics and also provides an output pulse to drive one light-emitting diode (LED) that flashes whenever a neutron is detected.

### 3.4.1 The Neutron Pulse Stream and Rossi-α Distribution.

Logic signals from the amplifiers are passively summed (or-ed) or actively mixed using a derandomizer 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. The mathematical basis for defining correlated and uncorrelated neutrons is given in Multiplicity Mathematics section below. In this section it is just necessary to distinguish their time dependence to understand the operation of the shift register coincidence circuits.

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 12 is a histogram of the Rossi-α distribution.

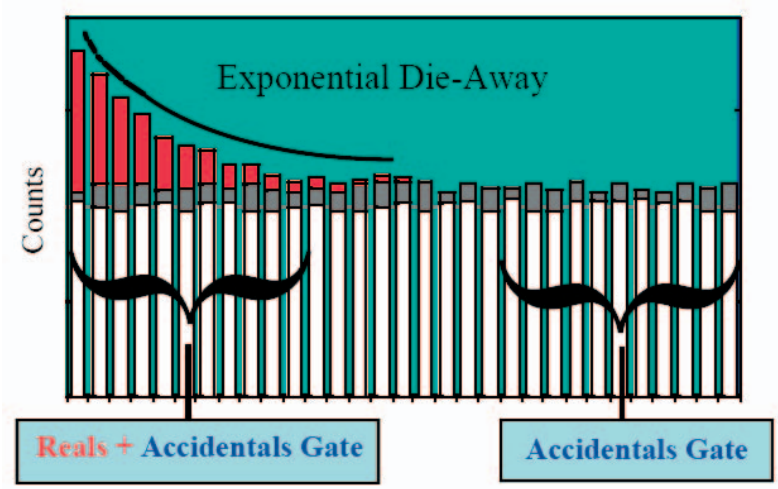



*Figure 12:* Histogram of a Rossi-α distribution. An actual measured distribution with exponential die-away time is superimposed above the histogram, and the (Reals + Accidentals) and (Accidentals) coincidence counting gates are superimposed at the bottom of the histogram (from [7]).

The initial trigger events at t=0 can be either correlated or uncorrelated events. The dark bars represent fission neutrons correlated to the initial pulse (Reals). The striped 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 components.

Figure 12 also shows two coincidence counting intervals superimposed, the R + A (Reals plus Accidentals) and A (Accidentals only).

### *3.4.2 Pre-delay Circuit.*

The most important cause of pulse pileup is usually amplifier baseline displacement following a pulse. Any closely following pulses that fall on the displaced bipolar baseline of the amplifier before it is fully restored to zero may have a higher or lower probability of triggering the discriminator. Bias resulting from **pulse pileup** is proportional to the square of the count rate and may become noticeable at high count rates.

To reduce the dead-time and pileup effects, a short shift register called the "pre-delay" is located at the input to the coincidence or multiplicity shift register circuits (see figure 13). This circuit delays the start of the coincidence counting interval for the R+A gate until a short time interval PD (the pre-delay) has passed. The length of the pre-delay is **typically 1.5 to 4.5 µs**. If it were not present, the effective length of the R+A gate would be reduced by some poorly determined time of 1 to 2 µs or more depending on the count rate. Then the R+A gate would be shorter that the A gate, and a counting imbalance would result. "Bias" is defined as the difference between the R+A and A counting rates when a random source such as AmLi is used. For a random source the difference should be zero. If it is not, the percent bias is 100 R/A.

It is important to select the length of the pre-delay based on the speed of the amplifier, the storage capacity of any derandomizer that is used, and the expected count rate.

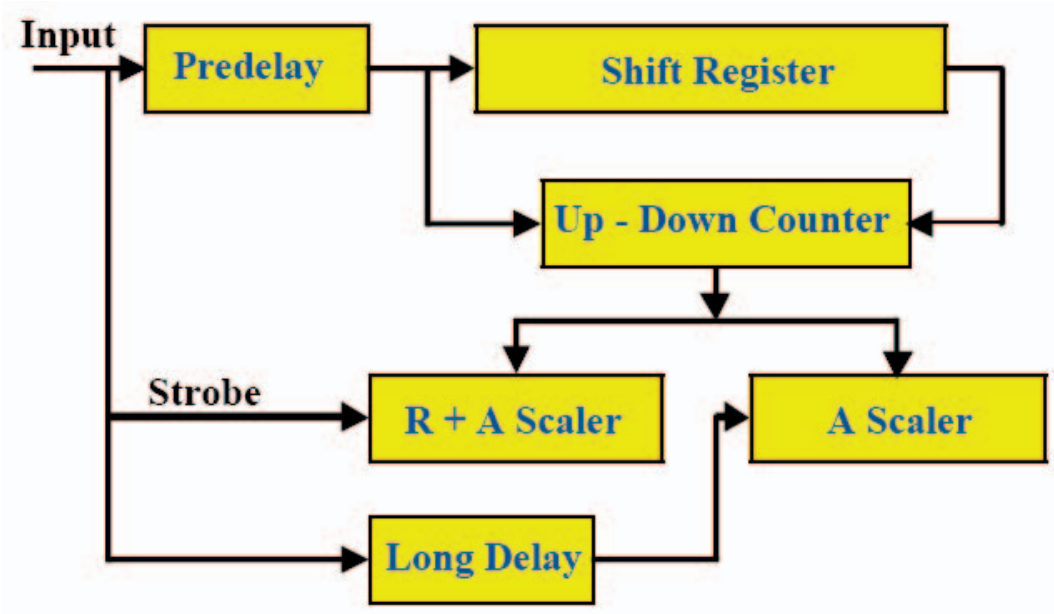



*Figure 13:* Conventional Shift Register Circuit (from [7]).

### *3.4.3 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 visualized in terms of the Rossi-α distribution shown in Figure 12. This figure 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).

The shift register collects the counts in the R+A and A gates without explicitly measuring the entire Rossi-α distribution. Every input event passes through the PD and then passes into and through the R+A gate. Figure 14 compares this process to an escalator. Every event that gets on the escalator increments an up-down counter, and every event that gets off decrements the up-down counter, so that this counter keeps a running tally of the total counts in the shift register. Every input pulse, before it enters the PD and the shift register, also provides a strobe pulse that transfers the current contents of the up-down counter to an accumulator that serves as the R+A scaler.

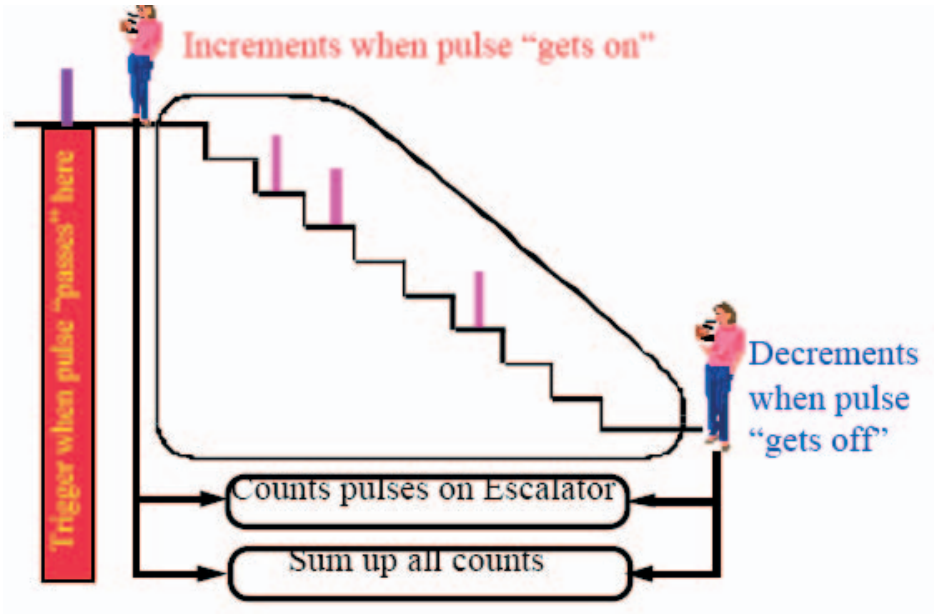



*Figure 14*: Comparison of the shift register circuit to an escalator in time (from [7]).

This counting algorithm records all possible pairs of coincidences between events. An example is given in figure 15 as four pulses pass through the shift register, the number on the escalators is 0, 1, 2 and finally 3 counts. The accumulator count rises from 0 to 1, then 3, then 6. Figure 16 shows that 6 is the total number of possible coincidences between 4 events, and that in general the number of coincidences recorded for n closely following events is **n(n-1)/2**. This equation is the **reduced second factorial moment of the distribution P(n) of incoming neutrons.** Note that the possible permutations in counting two-fold coincidences can exceed the number of events.

The coincidence events in the R+A gate can represent two or more neutrons from a real fission event, or just the random overlap of background neutrons or neutrons from different fissions, as illustrated in the Rossi-α distribution in Figure 12. To separate out the accidental coincidences, a second accumulator is introduced, but the strobe that triggers this accumulator is delayed by a few thousands of μs. because this delay is much longer than the neutron die-away time in the detector, it's extremely unlikely that any correlated events will be collected. Hence this second scaler collects only accidental pairs of events. The number of accidental events collected in the A scaler will be the same as those in the R+A scaler within counting statistics, so that the difference between the R+A and A scalers is R. The accidental count rate A is related to the singles count rate S by the equation:

$$\mathbf{A = GS^2} \qquad \text{(Eq. 12)}$$

This non-linear relationship shows that A will exceed S when the singles count rate is greater than 1/G. Because Eq. 12 must hold within counting statistics, unless the background is fluctuating tremendously, it provides an excellent diagnostic check on the operation of shift register circuitry.

### *3.4.4 Multiplicity Shift Register Basics.*

There is more information in a neutron pulse stream that just single and double neutron events. In multiplicity counting the distribution of 0's, 1's, 2's, 3's, etc. in the coincidence gates to deduce the multiplicity distribution of the neutrons 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. For example, if seven neutron pulses are in a coincidence gate when another neutron arrives, then "1" is added to the counter that tallies multiplicities of seven. Figure 17 is a simplified circuit diagram for a multiplicity shift register.

Separate multiplicity distributions are measured for the R+A and A coincidence gates. Table 5 shows typical R+A and A multiplicity distributions measured with a 60g Plutonium oxide sample measured in a multiplicity counter with roughly 56% neutron detection efficiency. Each distribution contains the number of times each multiplicity occurred in the corresponding gate. As an example from this table, seven neutron pulses were found 183 times in the R+A coincidence gate, and 42 times in the A coincidence gate.

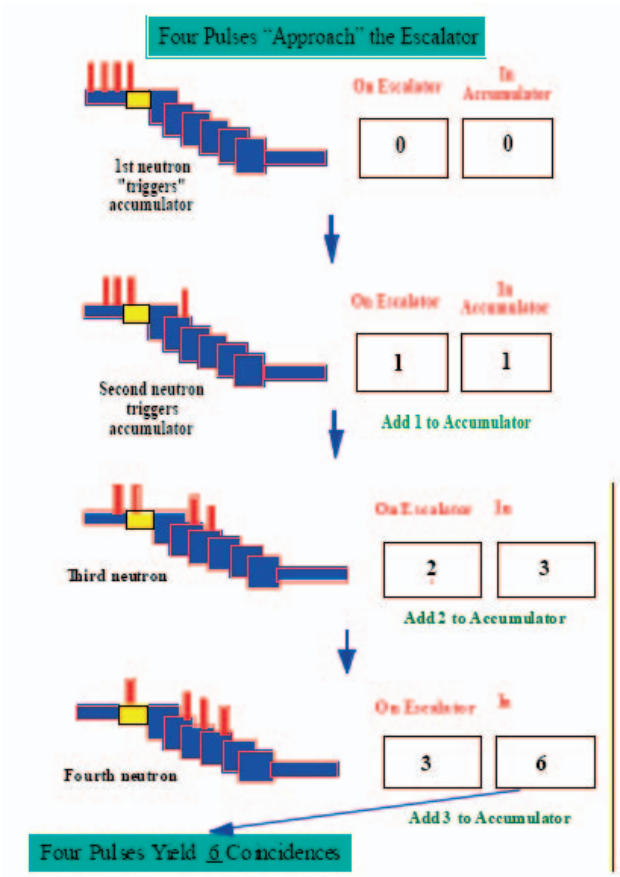



*Figure 15:* Example of shift register operation as four neutron pulses pass through the shift register (from [7]).

The sum of all the multiplicities in the A distribution (37,153,097) is the total number of triggers, because the singles scaler is situated at the output of the A scaler. The sum of all the multiplicities in the R+A distribution (37,153,123) is not always equal to the total number of triggers [the R+A gate interval is shifted, in this case, by about 4 ms from that of the A gate]. For a purely random pulse stream, the two distributions are the same within statistical errors. For a correlated pulse stream, the R+A distribution has more high-multiplicity events, and the A distribution has more events with multiplicity 0 (i.e., a trigger with no following events).


*Figure 16:* Illustration of the total number of possible coincidence pairs between 1, 2, 3, or 4 neutron pulses (from [7]).

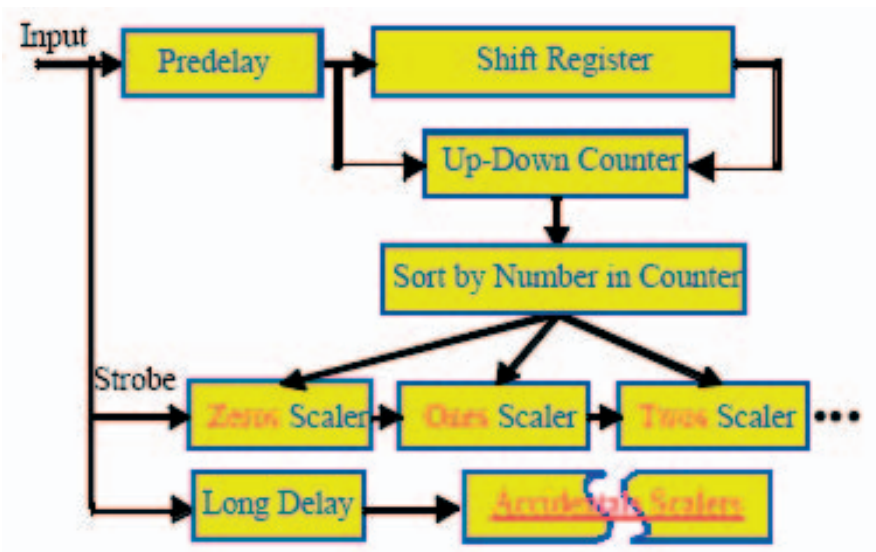



*Figure 17*: Multiplicity shift register circuit (from [7]).

The two distributions in Table 6 can be analyzed to obtain the number of single, double and triple neutron pulses. But note that the number of 1's, 2's, and 3's in Table 6 is not what we call the singles, doubles, and triples! Instead, the singles rate is the sum of all the triggers divided by the count time. The doubles rate is the sum of all the triggers divided by the count time, times the mean of the R+A distribution minus the mean of the A distribution. The doubles is "the same" as the conventional shift register output. The triples is a more complex unfolding of the R+A and A distributions, Of course, a conventional shift register cannot determine the triples because it does not measure the multiplicity distributions.

*Table 6* – Multiplicity distribution for 60g Plutonium Oxide Sample (efficiency ~56%) (from [7]).

| Multiplicity | Counts (R+A Gate) | Counts (A Gate) |
|---|---|---|
| 0 | 26 804 360 | 29 731 130 |
| 1 | 8 187 530 | 6 222 207 |
| 2 | 1 772 831 | 1 016 603 |
| 3 | 325 270 | 157 224 |
| 4 | 53 449 | 22 387 |
| 5 | 8 231 | 3 093 |
| 6 | 1 237 | 402 |
| 7 | 183 | 42 |
| 8 | 30 | 8 |
| 9 | 2 | 1 |
| 10 | 0 | 0 |

The reason that we have to measure very high multiplicities, 8's, 9's, 10's, etc., is that the average number of events inside the gate width of the shift register is the singles count rate times the gate width. For example, if the singles rate is 100,000 counts/s, and the gate width is 64 μs, the average number of events in either the R+A or the A gate at any given time is 6.4. So even for a purely random neutron source, we will record two R+A and A multiplicity distributions that range from 0's to 15's or 20's, with their peak around 6 or 7.

## 3.5 Dead time corrections for the shift register. [3]

The coincidence gate length G does not introduce dead times into the shift register circuit, which permits operation at count rates above 100 kHz. At such high rates, however, a number of smaller dead times associated with the analogue and digital parts of the circuitry become apparent. These include:

- detector charge collection time
- amplifier pulse-shaping time
- Amplifier baseline restoration time
- losses in the discriminator OR gate
- shift register input synchronization losses

These dead time effects can, be studied with time-correlated californium neutron sources, with uncorrelated AmLi neutron sources, and with new digital random pulsers. Even though the dead times can often be studied singly or 'together, the total effect is difficult to understand exactly because each dead time perturbs the pulse train and alters the effect of the dead times that follow. This section summarizes what is presently known about these dead times. Overall empirical correction factors are given, and several electronic improvements that reduce dead time are described.

### 3.5.1 Detector and Amplifier Dead times

For most shift register systems in use today, the analogue electronic components consist of (a) gas-filled proportional counters, (b) charge-sensitive preamplifiers, (c) amplifiers, and (d) discriminators. A charge signal can be obtained from the gas counter within an average time of 1 to 2 μs after the neutron interaction.

This time dispersion is limited by variations in the spatial position of the interaction site, and is not actually a dead time. However, the ability of the detector to resolve two separate pulses will be comparable to the time dispersion. The preamplifier output pulse has a rise-time of about 0.1 $\mu$s, and the amplifier time constant is usually 0.15 or 0.5 $\mu$s. If all of the electrical components listed above are linked so that one preamplifier and one amplifier with 0.5-$\mu$s time constant serve seven gas counters, a total dead time of about 5 $\mu$s is observed. In practice this dead time is reduced by using multiple preamplifier-amplifier chains, as described in Section 3.5.4.

The amplifier output enters a discriminator that consists of a level detector and a short one-shot. The one-shot output is 50 to 150 ns long.

### *3.5.2 Bias Resulting from Pulse Pileup*

In addition to actual dead times, the electrical components can produce a bias in the shift register output. Bias is defined as the difference between the R+A and A counting rates when a random source such as AmLi is used. For a random source the difference (R+A) – A should be zero if it is not, the percent bias is 100 R/A. Possible sources of bias include electronic noise uncompensated amplifier pole zero shift register input capacitance, a dead time longer than the pre-delay P, or amplifier baseline displacement following a pulse, which is the most important source of bias if the electronic components are properly adjusted to minimize the other sources. Any closely following pulses that fall on the displaced baseline before it is fully restored to zero have a different probability of triggering the discriminator. Bias resulting horn pulse pileup is proportional to the square of the count rate and may become noticeable at high count rates. If the baseline is not filly restored in a time less than the pre-delay time, the effect will extend into the R+A gate and a bias will result.

Figure 18 illustrates a bias measurement as a function of pre-delay. The measurement used a coincidence counter with six amplifier charnels. The observed bias was reduced to an acceptable value of 0.01% or less for pre-delay settings of 4.5$\mu$s or more. These results are typical for well-adjusted electronics. For some high-efficiency and long die-away-time counters that operate at rates above 100 kHz, a conservative pre-delay setting of 6 to 8 $\mu$s may be warranted, but in general 4.5$\mu$s sufficient. At high count rates, R is typically on the order of 1% of A, a pulse pileup bias of 0.01% in R/A implies a relative bias of 1%in R, a bias that is only barely acceptable.

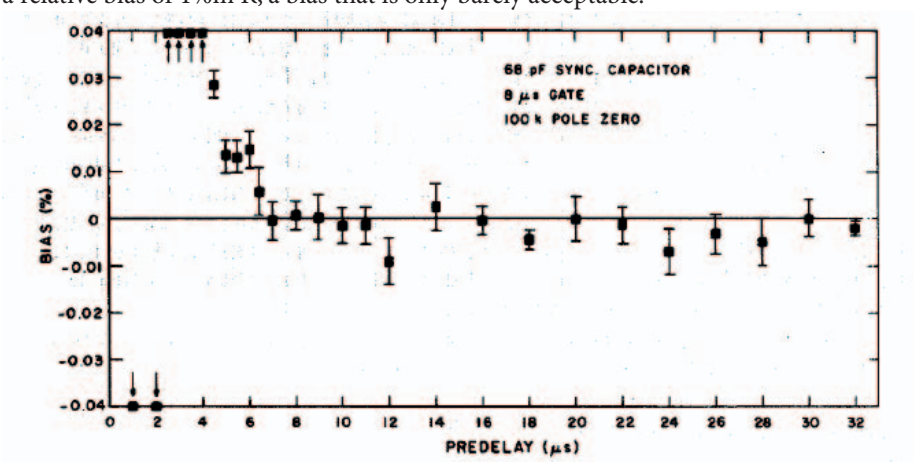



*Figure 18:* Shift register coincidence bias R/A as a function of pre-delay P for electronics with 0.5$\mu$s time constant, as measured with a strong random AmLi neutron source. For this measurement, bias was minimized by using optimum values of 100k$\Omega$ for the amplifier pole-zero resistance and 68 pF for the shift register input synchronizer capacitor. Sensitivity to any remaining bias was maximized by using an 8-$\mu$s coincidence gate G for the measurements (from [3]).

### 3.5.3 Digital Dead times

Because of the dead time in the amplifier-discriminator chain, it is customary to

divide the detector outputs of a coincidence counter among at least four to six amplifiers. Each amplifier channel may serve three to seven detectors. The discriminator outputs of each channel are then "ORed" together before they enter the shift register (autocorrelation mode). Now the dead time after the OR gate is much less than before provided the two events are from different channels. The dead time contribution of the OR gate itself can be calculated under the assumptions that (a) no losses occur within a channel because of the longer preceding amplifier dead time and (b) losses between channels are due to pulse overlap.

$$\text{OR gate overlap rate} = [n(n-1)*2(\text{disc. output Width})(T/n)^2]/2! \quad \text{(Eq. 13)}$$

where n is the number of channels and T is the total count rate. The ideal dead time for an OR gate accepting 50-ns-wide pulses is then

$$\text{OR gate dead time} = [(n-1)/n]^* (50\ \text{ns}) \quad \text{(Eq. 14)}$$

This dead time is for total events; the coincidence dead time has not been calculated but would be larger.

The output of the OR gate is a digital pulse stream that enters the shift register. At this point the 50-ns-wide pulses must be synchronized with the 500-ns-wide shift register stages. The limit of one pulse per stage means that some closely following pulses will be lost unless a derandomizing buffer is used. These losses have been measured with a digital random pulser, as illustrated in Figure 19. The shape of this curve is given by:

$$\text{measured totals} = (1 - e^{-pT})/p \quad \text{(Eq. 15)}$$

where p is the shift register clock period (500 ns in this case) and T is the total input rate. At low rate% Equation 16-19 yields a non updating dead time of p/Z at high rates, the dead time approaches p. The coincidence dead time is on the order of 2p. In general, the synchronizer dead time is small compared to the amplifier dead time, but it can be appreciable at high count rates. For example, at 256 kHz the totals losses will be 6% and the corresponding coincidence losses will be larger.

### 3.5.4 Empirical Dead time Correction Formulas

The total effect of the analogue and digital dead times described above has not been calculated, but can be determined empirically with californium and AmLi neutron sources. The coincidence dead time $\delta_c$ can be determined by placing a californium source

in a fixed location inside a well counter and measuring the coincidence response as stronger and stronger AmLi sources are introduced. During these measurements it is important (1) to center the sources so that all detector channels observe equal count rates and (2) to keep the sources well separated so that scattering effects are minimized. The result of such a measurement is shown in Figure 20.The totals dead time $\delta_t$ can be measured by the source addition technique, where two californium or AmLi sources are measured in the counter, first separately and, then together. An updating dead time equation also works well for, the total count rate correction. Bias can be measured by placing only random AmLi sources in the counter.

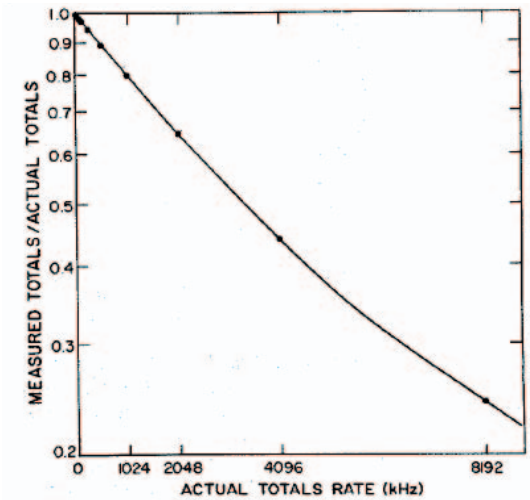



*Figure 19:* Shift register synchronizer dead time as measured with a digital random pulser attached directly to the synchronizer input. The shift register clock period is 500 ns and the digital random pulser has a pulse-pair resolution of 60 ns (from [3]).

Under the assumption that the electronic components have been adjusted so that bias is negligible, the overall empirical dead time correction equations are

$$T(\text{corrected}) = T_m \exp(\delta_t T_m) \quad \text{(Eq. 16)}$$

$$R(\text{corrected}) = R_m \exp(\delta_c T_m) \quad \text{(Eq. 17)}$$

where $T_m$ is the measured totals rate and $R_m$ is the measured coincidence rate, (R+A) scaler – (A) scaler. Note that in Equations 16 and 17 the argument of the exponential contains $T_m$ instead of the corrected rate T. The use of $T_m$ is a convenient approximation at rates up to about 100kHz, but at higher rates this approximation forces $\delta_t$ and $\delta_c$ to become functions of the count rate rather than constants. Values of $\delta_t$ and $\delta_c$ appropriate for the amplifier chains and 2-MHz-clock shift registers most commonly used today are summarized in Table 6. For example, six channels of O.15-$\mu$s time-constant amplifiers will have $\delta_c$ = 0.62 $\mu$s and will exhibit an overall coincidence dead time of about 6% at 1O-kHz counting rates.

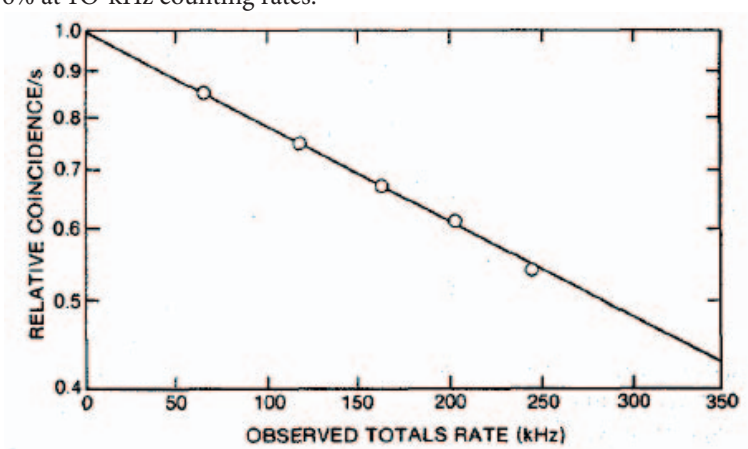



*Figure 20:* Semi logarithmic plot of relative coincidence response from a californium source as a function of Increasing totals count rate resulting from additional AmLi sources. The points are measured values; the line is a least-squares fit to an exponential with dead time coefficient $\delta_c$ = 2.4 $\mu$s (from [3])

From Table 7 it is apparent that the dead time coefficient depends weakly on the detector gas mixture and strongly on the number of amplifier channels available. The number of detector tubes per amplifier channel has no measurable effect on the coefficient although this situation may change if the detector tubes are subject to count rates in excess of about 20 kHz per tube.' Note that all of the coincidence dead time coefficients in Table 7 were measured with a californium source (v = 3.757) whereas the isotope usually assayed is $^{240}Pu$ (v = 2.16). The effect of this difference is not yet known.

*Table 7:* Compilation of empirical dead time coefficient for shift-register-based coincidence counters [from 3]

| $^{3}He$ Detector Gas Additive | Number of Detectors/ Channel | Number of Amplifier Channels | Amplifier Time Constant (μs) | Deadtime (μs) | | |
|---|---|---|---|---|---|---|
| | | | | Totals, $\delta_t$ | Coincidence, $\delta_c$ 0-100kHz | Coincidence, $\delta_c$ 0-500kHz |
| $Ar + CH_4$ | 7 | 6 | 0.5[a] | 0.6 | 2.4 | $2.3 + 1.6 \times 10^{-6}T_m$ |
| $Ar + CH_4$ | 7 | 4 | 0.5 | 0.87 | 3.0 | $2.8 + 2.7 \times 10^{-6}T_m$ |
| $Ar + CH_4$ | 7 | 2 | 0.5 | 2.9 | 4.7 | |
| $Ar + CH_4$ | 7 | 1 | 0.5 | 4.9 | 12.6 | |
| 5% $CO_2$ | 7 | 6 | 0.5 | 0.9 | 3.1 | |
| $Ar + CH_4$ | 3 | 6 | 0.15[b] | 0.16 | 0.62 | $0.62 + 0.20 \times 10^{-6}T_m$ |

[a] Los Alamos-designed 0.5-μs time-constant amplifier chain (Refs. 22, 23).
[b] AMPTEK A-111 integrated circuit with approximately 0.15-μs time constant in conjunction with a derandomizing buffer on the shift register input (see Section 16.6.5).

### *3.5.5 AMPTEK Electronics and Derandomizing Buffer*

Recent improvements in the analogue and digital electronics include faster amplifiers, shorter discriminator outputs, and a derandomizing buffer at the shift register input. The faster amplifier, which has an effective time constant of about 0.15 $\mu$s, consists of a Model A-111 hybrid charge-sensitive preamplifier, discriminator, and pulse shaper manufactured by AMPTEK, Inc., of Bedford Massachusetts. This unit provides sufficient gain and signal/noise ratio if the $^{3}He$ detector tubes are operated at +1700 V.

The Model A-111, has been incorporated with other electronics on a printed circuit board mounted in a small shielded enclosure. Each enclosure contains an amplifier insensitive to external noise, an LED output monitor, a discriminator output shortened to 50 ns, and connections for "ORing" multiple channels together. Six channels ofA-111 units can be operated with a reduced pre-delay of 3 $\mu$s with less than 0.01% bias.

The derandomizing buffer holds pulses that are waiting to enter the shift register, thus eliminating the input synchronization losses. Input pulses separated by less than 0.5 $\mu$s —the shift register clock period- are stored in a 16-count buffer until the shift register can accept them. This circuit eliminates the coincidence dead time of roughly 1.0 $\mu$s associated with the shift register input and permits counting at rates approaching 2 MHz with virtually no synchronizer counting losses. However, as the derandomizing buffer stretches pulse strings out in time, it may create strings longer than the predelay and thereby produce a bias. Because the AMPTEK A-111 amplifier requires a predelay of only 3 $\mu$s, the maximum recommended totals rate for less than 0.01% bias is 500 kHz.

With the AMPTEK electronics and the derandomizing buffer, the coincidence dead time is reduced by a factor of 4 to about 0.6 $\mu$s, as noted in Table 16-1. This combination permits passive assays of almost any Plutonium samples, with criticality safety of the sample in the wellbeing the only limit.

## *3.6 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.
- ✓ Analysisprocedures are well documented and internationally recognised. Modern software packages guide the user through the process of calibration, data acquisition, data analysis and interpretation.
- ✓ Accuracybelow 1 % are achieved when the reference samples are representative of the samples to be verified in terms of mass, chemical form, shape and containment.
- ✓ Shortmeasurement times of typically 5 to 10 minutes are sufficient to achieve a precision below 1 %.

### *3.6.1 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.

#### *3.6.1.1 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.

The primary quantity, that is commonly determined in passive neutron coincidence counting, is an effective amount of $^{240}$Pu, $m_{240eff}$, representing a weighted sum of the 3 even isotopes 238, 240 and 242:

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

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 $^{240}Pu$. 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

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

The total amount of Pu is then evaluated as:

$$m_{Pu} = \frac{m_{240eff}}{^{240}Pu_{eff}}. \quad \text{(Eq. 20)}$$

*Table 8:* Spontaneous fission neutron yields

| Isotope | Spontaneous fission yield (neutrons /s.g) |
|---|---|
| $^{238}Pu$ | $2.59\ 10^{3}$ |
| $^{239}Pu$ | $2.18\ 10^{-2}$ |
| $^{240}Pu$ | $1.02\ 10^{3}$ |
| $^{241}Pu$ | $5.\ 10^{-2}$ |
| $^{242}Pu$ | $1.72\ 10^{3}$ |

### *3.6.1.2 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 [8] 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 [7, 9], 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.

The research and development work for improved PNCC and PNMC techniques is still continuing. Some recent advances which have been achieved in the areas of interpretation of measurement results, detector technology, fundamental nuclear data, have resulted in notable improvements in measurement performance for certain applications.

### *3.6.2. Performance Values for Passive Neutron Measurements*

PNCC is applicable to practically all kinds of Pu-bearing materials, but the majority of the measurements for Safeguards are carried out on relatively pure and well characterized 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.

Table 9 gives typical random (r) and systematic (s) error components for passive neutron counting of the most significant nuclear materials [10]. Table 10 gives the corresponding performance values for "impure" materials [10]

*Table 9:* Performance values for m240eff measured in thermal passive neutron coincidence counters with shift registers [from 10]

| **Nuclear Material Category** | **Pu Mass (g)** | **r (%)** | **s (%)** |
|---|---|---|---|
| Pu Metal | $10^2 \sim 10^3$ | 0.5 | 1 – 2 |
| $PuO_2$ | $10^2 \sim 10^3$ | 0.3 | 1 – 3 |
| MOX Powders | $10^2 \sim 10^3$ | 0.3 | 3 – 5 |
| LWR-MOX & FBR Fuel Elements | | 1 | 1 – 3 |

*Table 10:* Performance values for m240eff measuredin thermal neutron multiplicity counting mode [from 10]

| Material Category | SNM Mass (g) | (α,n) /SF rate | Counting Time (s) | r (%) | s (%) |
|---|---|---|---|---|---|
| Pu-Scrap | 100<br>100-1200 | 5<br>1-6 | 1000<br>3600 | 12<br>4.5 | 1 – 5 |
| Plutonium Residues | 120<br>300<br>20-100<br>100 | 13-29<br>7-34<br>8-30<br>5-9 | 3000<br>3600<br>3600<br>3600 | 20<br>18.9<br>7<br>8.7 | 2 – 10 |
| Plutonium Waste (estimated) | 1<br>1<br>1 | 1<br>5<br>20 | 1000<br>1000<br>1000 | 2<br>10<br>50 | 1 – 2<br>2 – 5<br>5 – 10 |

*Figure 21:* Model 2203 – Very High Efficiency Neutron Counter (VHEnC) – Antech

The VHEnC has a modular construction based on the well proven 'decagon' design for the neutron counting of 200 liter waste drums. This drum monitor can be operated with multiple neutron measurement methods include: neutron totals counting mode for very low level measurements, neutron coincidence counting to reach lower level detection thresholds, and neutron multiplicity counting to perform matrix correction where sufficient Pu mass is present in the chamber (unloading Lower Limit of Detection of between 1.3 – 15mg 240Pueffective in totals mode equivalentto between ~20 and 250mg total Pu (military grade)). The system can also be operated as an absolute neutron multiplicity system, independent of calibration for intermediate level waste. The removable internal cadmium filters allows detection efficiency to be varied in accordance with the measurement requirement: Very high detection efficiency, typically 36% with Cd filters deployed and between 41% and 45% with the internal Cd liner removed.

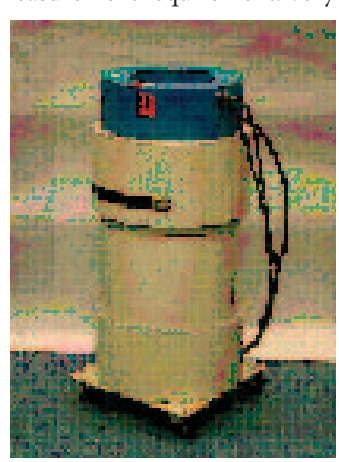


*Figure 22:* "Los Alamos" High Level Neutron Coincidence Counter (HLNCC)

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. 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 aluminum 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 3He tubes.

## 3.7 Neutron multiplicity counting

This method is an extension to the conventional coincidence counting method. In addition to the neutron count rate and the Reals rate (correlated pair rate) also the triples 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.
- ✓ Themethod does not rely on operator declarations of, for example, isotopic composition, chemical form, or container and matrix materials.
- ✓ Themethod 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.

### 3.7.1 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 240Pu * m240, where m240 = effective 240Pu mass,

$\nu_{s1}$, $\nu_{s2}$, $\nu_{s3}$ = first, second and third moments of the spontaneous fission neutron multiplicity distribution,

$\nu_{i1}$, $\nu_{i2}$,$\nu_{i3}$ = 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, ft = 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 solution for M is obtained first by solving the following cubic equation:

$$a + bM + cM^2 + M^3 = 0 \qquad \text{(Eq. 22)}$$

Where the coefficients are functions of S, D and T:

$$a = \frac{-6T\nu_{s2}(\nu_{i1}-1)}{\varepsilon^2 f_t S(\nu_{s2}\nu_{i3}-\nu_{s3}\nu_{i2})}$$

$$b = \frac{2D[\nu_{s3}(\nu_{i1}-1)-3\nu_{s2}\nu_{i2}]}{\varepsilon f_d S(\nu_{s2}\nu_{i3}-\nu_{s3}\nu_{i2})} \qquad \text{(Eq. 23a/b/c)}$$

$$c = \frac{6D\nu_{s2}\nu_{i2}}{\varepsilon f_d S(\nu_{s2}\nu_{i3}-\nu_{s3}\nu_{i2})} - 1$$

Once M is determined, then the sample fission rate F is given by;

$$F = \frac{\left[\frac{2D}{\varepsilon f_d} - \frac{M(M-1)\nu_{i2}S}{\nu_{i1}-1}\right]}{\varepsilon M^2 \nu_{s2}} \qquad \text{(Eq. 24)}$$

The second term in the numerator of Eq. 24 represents the effect of sample self-interrogation due to induced fission, which must be subtracted from the emitted doubles to obtain the spontaneous fission rate. Once F is obtained, the sample's $^{240}$Pu effective mass $m_{240}$ is given by;

$$m_{240} = \frac{F}{(473\ fission/s-gm)} \qquad \text{(Eq.25)}$$

Also the sample's (α,n) reaction rate α is given by;

$$\alpha = \frac{S}{F\varepsilon\nu_{s1}M} - 1 \qquad \text{(Eq.26)}$$

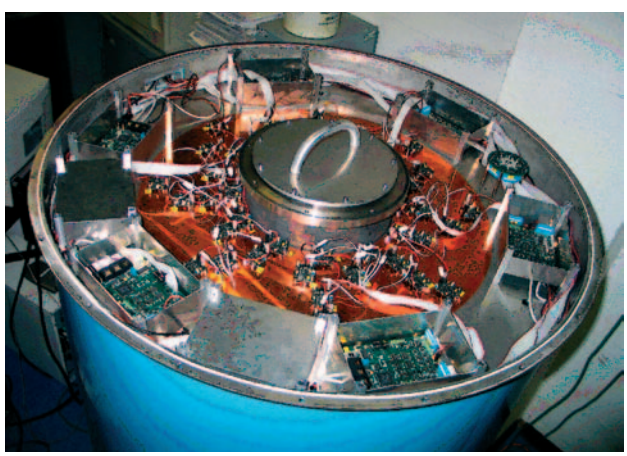
To implement this procedure it is necessary to supply the NCC code with several parameters that appear in the above-mentioned equations:

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

Nevertheless, the complete characterisation process of a passive neutron counter consists also in the determination of the following instrumental parameters:

- ✓ Optimum operating high voltage.
- ✓ Neutron decay time for a Cfpoint source.
- ✓ Gate width and pre-delay.
- ✓ The dead time parameters.

Initial determination of the detector and electronic parameters needed for multiplicity assay can be done with a $^{252}$Cf source alone. However, multiplicity assays of Plutonium based on the parameters determined from $^{252}$Cf alone can be biased because of differences in detection efficiency between $^{252}$Cf and Plutonium fission neutrons, and differences between the actual samples to be assayed and the assumptions of the "point model". These uncertainties limit the accuracy of a calibration based only on californium and nuclear data to about 2% [11].



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. 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 23:* "Ispra" New Scrap Neutron Multiplicity Counter (SNMC)

## *3.8 Active Neutron Coincidence Counting*

### *3.8.1 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.

#### *3.8.1.1 Principle of measurement / Definition of the physical principle*

Due to the very low spontaneous fission yields of all the Uranium isotopes, passive neutron coincidence techniques are generally not suitable for the assay of Uranium bearing samples (an exception is the use of (alpha,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 (<ν>=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.

### *3.8.1.2 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;
- 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. It can be operated either with or without a cadmium liner (fast or thermal mode).

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.

### *3.8.2 Performance Values for Passive Neutron Measurements*

Performance values for the assay of the fissile Uranium content obtained with two common instruments (NCC and AWCC) from different materials are given in Tables 11 and 12, essentially based on field experiences [12, 13]. 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 systematic uncertainty for the fast mode assay is generally higher than for the thermal mode, due to the range of matrix effects, although the potential for gross assay underestimation is greatly reduced in fast mode.

Active neutron interrogation techniques can also be used for other purposes, for instance waste characterisation.

*Table 11:* Performance values for the determination of the $^{235}U$ mass loading in fresh LEU fuel elements (1000 s counting time).

| Technique | Objects | Enrichm. | r (%) | s (%) |
|---|---|---|---|---|
| NCC (active mode) | UO2 Fuel Elements for LWR | Up to 3% | 1 | 1 – 2 |
| | UO2 Fuel Elements for LWR | 3 – 5 % | 1 | 2 – 4 |
| | LWR fuels with burnable poisons | any | 1 | 3 – 5 |

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

*Table 12:* Performance values for the determination of the fissile content in U samples.

| Technique | Objects | r (%) | s (%) |
|---|---|---|---|
| AWCC | HEU Metal | 2 | 3 |
| | HEU Powder (fast mode) | 2 | 10 |
| | HEU Powder (thermal mode) | 2 | 5 |
| | $UF_4$ Salt | 5 | 2 |
| | HEU/Th/C Pebbles | 2 | 4 |
| | HEU/Al MTR | 1 | 3 |
| | LEU Powder (fast mode) | 2 | 5 |

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 U-235 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 U-235. Using this method the mass of Uranium is readily determined.

Two Action Modes are available depending on the size of the U-235 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 1gm of U-235.
- **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 23gm of U-235.

In **Passive Mode** the Am-Li neutron sources are removed and the AWCC can function either as a neutron coincidence counter or a neutron multiplicity counter. The detector measurement chamber can be enlarged by removing the two internal polyethylene disks and the nickel reflector. It can also be operated in the horizontal position with the end plugs removed and with a material test reactor (MTR) holder in position for the measurement of Uranium in MTR measurements.

The **Uranium Neutron Coincidence Collar (UNCC)** has been developed for measurement of the $^{235}U$ content in fresh fuel assemblies. The method employs an AmLi neutron source to induce fission reactions in the fuel assembly and coincidence counting of the resulting fission reaction neutrons. Coincidence counting eliminates the undesired neutron counts from the random AmLi interrogation source and room background. When no interrogation source is present, the passive neutron coincidence rate gives a measure of the $^{238}U$ through the spontaneous fission reactions. When the interrogation source is added, the increase in the coincidence rate gives a measure of $^{235}U$. The Uranium Neutron Coincidence Collar (UNCC) system can be applied to the fissile content determination in boiling-water-reactor (BWR), pressurized-water-reactor (PWR), and other type fuel assemblies for accountability, criticality control and safeguards purposes.

The **Under Water Coincidence Counters (UWCC)** that has been designed for the measurement of Plutonium in mixed oxide (MOX) fuel assemblies prior to irradiation. 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 analyzed for singles, doubles, and triples time correlations to determine the $^{240}Pu_{effective}$ mass per unit length of the fuel assembly.

*Figure 24:* Active Well Coincidence Counter (AWCC)

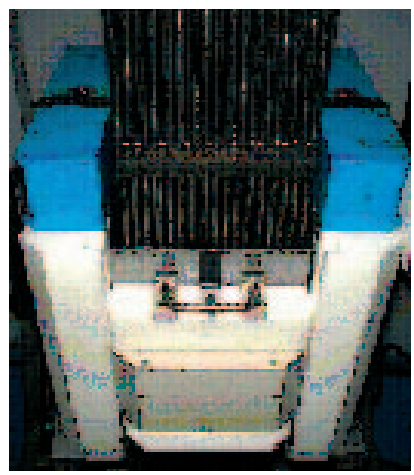


*Figure 25:* Uranium Neutron Coincidence Collar (UNCC)

*Figure 26:* Under Water Coincidence Counters – Model 2106 (UWCC)

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 TREN (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 238U, 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. So 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 characterized 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%. Two new detection systems for the DG TREN (Euratom Safeguards) inspectors at the Dessel (Germany) and Juzbado (Spain) fuel fabrication plants were commissioned in 2003.

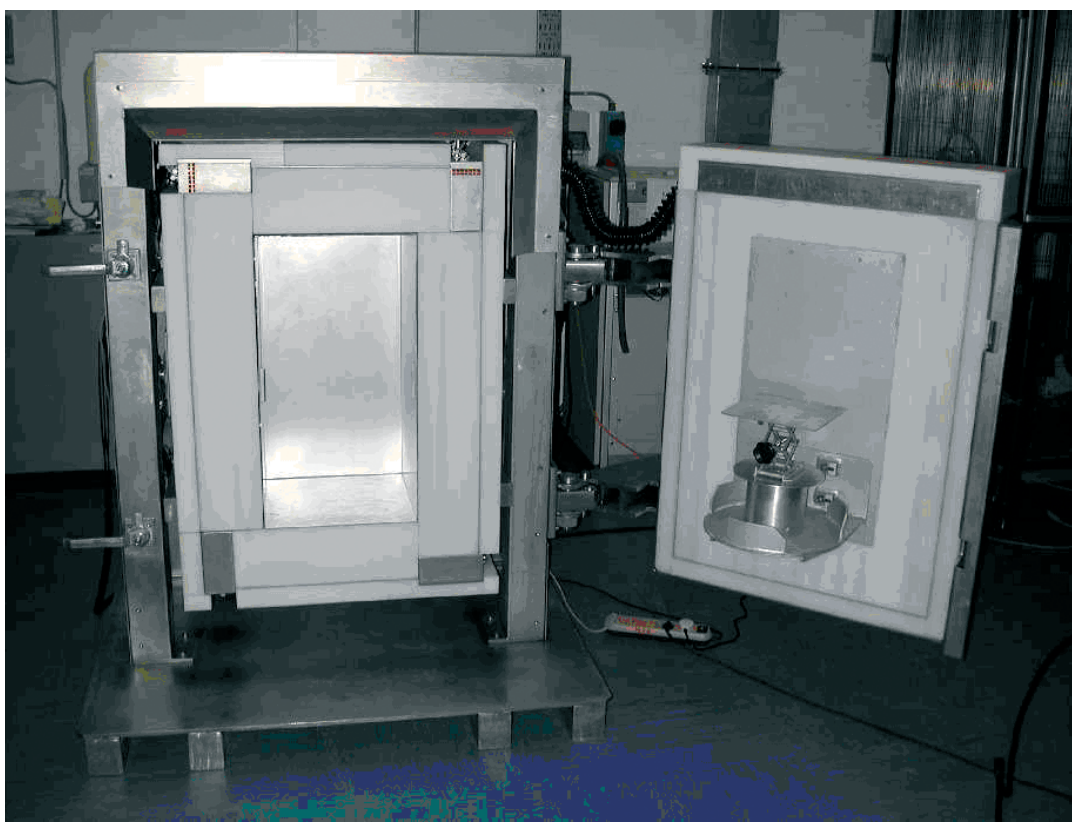


*Figure 27:* The High Efficiency Passive Counter (HEPC).

Web sites:

www.canberra.com/products/1062.asp

www.ortec-online.com/nda/awcc.htm

www.antech-inc.com

## 3.8 Multiplicity counting versus conventional neutron coincidence counting.

One important question for safeguards personnel is when to use multiplicity counting versus when to use conventional neutron coincidence counting or calorimetry. This is a complex question because multiplicity counting lies between conventional coincidence counting and calorimetry in terms of accuracy and count time requirements. Also, there are many conventional coincidence alternatives, including non-linear calibration curves, the known-α approach, and the known-M approach, which work well on some material types.

More experience is required to determine the accuracy of multiplicity counting for some samples types, but some general conclusions are as follows:

1. If samples are known to be **pure Plutonium oxide or metal,** then **conventional coincidence counting** will give better assays than multiplicity counting because the (α,n) yield can be calculated and does not need to be measured.
2. If **samples are thought to be pure, but not with certainty, then multiplicity counting can be used to check the conventional assay.** If conventional and multiplicity results are in statistical agreement, then the conventional result can be used; if they are in disagreement, then the multiplicity result can be used.
3. For **impure materials with high (α,n)** reaction rates, the overall performance of **multiplicity counting is significantly better** than conventional coincidence counting even though the precision is significantly degraded as the (α,n) reaction rate goes up. **If the (α,n) reaction rate is very high,** the counting time required for multiplicity will approach or exceed that required for calorimetry. **Then calorimetry should be used, if available**.
4. Multiplicity counting provides a higher level of verification than is possible with conventional coincidence counting because less information about the sample is needed. In general, when multiplicity hardware and software are available, the multiplicity information should be collected, either to improve assay accuracy or to provide additional diagnostic information.
5. **Calorimetry is inherently a more matrix-insensitive NDA technique than multiplicity counting.** Where calorimeters are available with large enough wells to accommodate the samples, and longer count times are acceptable, they will usually provide more accurate results.

# 4. Techniques for Spent Fuel [14].

## 4.1 Neutron emission and detection

Spontaneous fissions in the $^{242}$Cm and $^{244}$Cm isotopes are the major source of neutrons emanating from spent fuel. These isotopes are produced through multiple neutron capture events when a fuel assembly is exposed to high neutron fluxes in a nuclear reactor. Fission products in the irradiated fuel produce an extremely high radiation background in which the neutrons must be detected. The high radiation environment influences the type of techniques that can be deployed for spent fuel verification. One approach is to choose a detector which is basically insensitive to gamma rays. Another approach is to shield against the gamma rays while allowing neutrons to pass through the shield into the neutron detector. Spent fuel verification methods include not only neutron detection but also gamma ray and ultraviolet light (Cerenkov radiation) detection.

Table 13 lists the spent fuel measurement systems in use by the IAEA. The Fork Detector (FDET) incorporates both neutron and gamma ray detectors for gross defect verification of fuel assembly

characteristics such as irradiation history, initial fuel content and number of reactor cycles of exposure. Detector systems are available to measure the gamma ray energy spectra from irradiated fuel (SFAT and IRAT), and gamma ray intensity as a function of fuel bundle storage position (CBVB and CBVS). Cerenkov glow viewing devices (ICVD and eventually a digital device, DCVD) examine the ultraviolet light that appears in the water surrounding spent fuel. The various measurement systems are described in more detail below.

## *4.2 Gross neutron and gamma ray detection FDET.*

The Fork Detector Irradiated Fuel Measuring System shown in Fig. 28 and 29 includes the detector head, a several metre long extension pipe (not shown), a Gamma Ray and Neutron Detector electronics unit (currently the GRAND3 but eventually to be replaced by the MiniGRAND) and a portable computer. The detector head incorporates gamma ray insensitive neutron detectors (four gas filled fission chamber proportional counters) and gamma ray detectors suitable for measuring extremely high gamma ray intensities (two gas filled ionization chambers). The neutron and gamma ray signatures measured by the detectors are used to verify the highly radioactive spent fuel assemblies stored underwater in spent fuel ponds. The FDET is positioned about 1 m above the tops of neighboring assemblies. The irradiated fuel assembly being measured is lifted so that the tines of the detector straddle the fuel portion of the assembly in order to collect the neutron and gross gamma data.

The ratio of the neutron to gamma ray data, when combined with other, complementary information, is used to characterize a particular type of fuel assembly, giving information related to its neutron exposure in the reactor, its initial fissile fuel content and its irradiation history (e.g. the number of cycles for which the assembly was in the reactor).

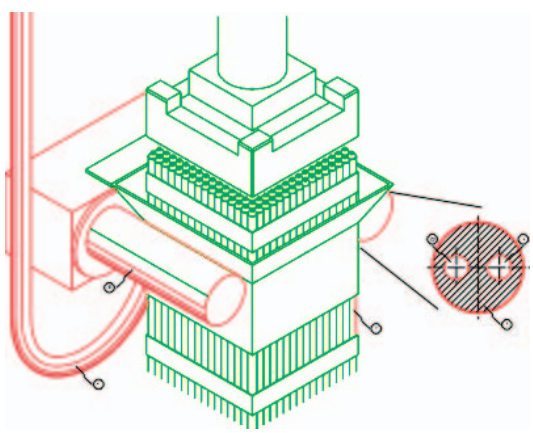


*Figure 28:* Drawing of the FORK detector during safeguards inspection measurements. In red: the FORK detector, in green: the fuel assembly to be measured [from 14].

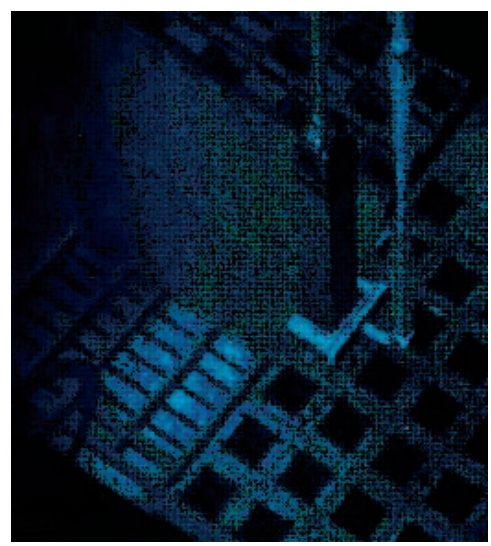


*Figure 29:* Fork detector during safeguards inspection measurement [from 14].

The Sellafield Thermal Oxide Reprocessing Plant (THORP), has two identical spent fuel instruments called the Feed Pond Fuel Monitors (FPFM) shown in Figures 30-31 [15]. These operate in parallel in order to meet the throughput requirements and measure a number of fuel parameters to ensure that only those fuel assemblies within prescribed limits are reprocessed. Thus the instrument provides a go/no-go signal indicating if the fuel is within the plant's acceptance envelope. The limiting

parameters relate to the minimum cooling time and maximum burnup and final enrichment U-235 equivalent (originally initial enrichment) for both light water reactor (LWR) and advanced gas cooled reactor (AGR) fuel. The change from an initial enrichment parameter to final enrichment took place this year in conjunction with a reduction in neutron gadolinium poisoning of the dissolver vessel. The reduction was made possible by the adoption of a burnup credit fuel management regime. The vessel was originally poisoned on the assumption that the dissolved fuel was enriched to its initial enrichment rather than its final enrichment as recognized under the burnup credit revision. As a result the Gd usage has been reduced by approximately 50% giving considerable cost savings and benefits to the vitrified waste stream product quality.

The FPFMs each use a 15% efficiency HPGe detector, and five fission chamber neutron detectors that are split into two modules arranged at 90° to each other. A neutron source transfer system, controlled by the FPFM, moves a $^{252}$Cf source between exposed and shielded positions to allow active and passive neutron measurements. Prior to each assay, measurement control is implemented by an automated standardization routine. Once the fuel assembly has been transferred to the measurement position, assays are performed at four measurement heights as the fuel rotates. A combination of three techniques are used to characterize the fuel. Cooling time is determined by HRGS using fission product gamma activity ratios. Burnup is determined using a diverse combination of HRGS and passive neutron data. Initial enrichment is calculated from a combination of the final enrichment and measured burnup. Final enrichment is determined by a combination of the measured burnup and a neutron multiplication parameter determined from the active neutron measurements using the external $^{252}$Cf neutron interrogation source. The only operator declared input that is required is the fuel type e.g *PWR, BWR or Advanced Gas Cooled Reactor (AGR).*

*Figure 30:* Feed Pond Fuel Monitor – A fully plant integrated system for the determination of the key parameters of spent fuel assemblies including final enrichment, irradiation and cooling time [from 14].

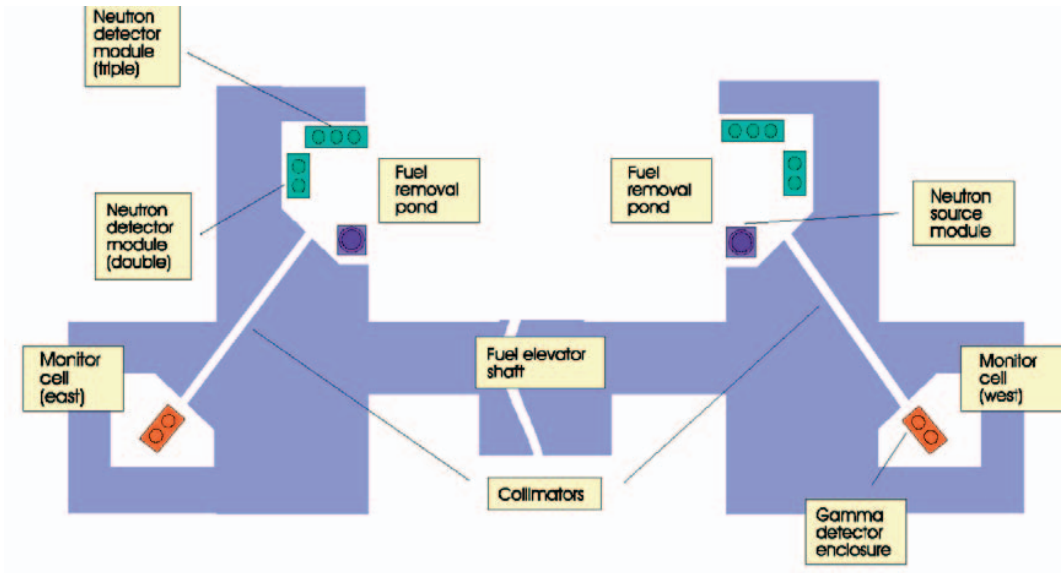



*Figure 31:* THORP Feed Pond Fuel Monitors [from 14].

## 4.3 Gamma ray energy spectral analysis

### 4.3.1 SFAT.

The Spent Fuel Attribute Tester (Fig. 32), consisting of a multichannel analyser electronics unit and a NaI or CdZnTe detector, is used for taking measurements from the top of a fuel assembly as it sits in the storage rack [16] [17].

The SFAT provides a qualitative verification of the presence of spent fuel through detection of particular fission product gamma rays – either from 137Cs (662 keV) for fuel that has cooled for longer than four years or from short lived fission products such as 144Pr (2182 keV) for fuel with short cooling times.

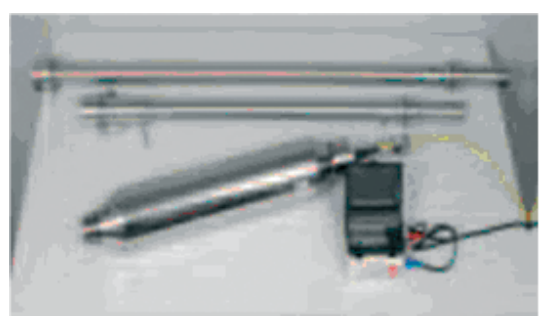


*Figure 32:* SFAT- Spent Fuel Attribute Tester [from 14].

Activation products such as $^{60}$Co are also identifiable. The SFAT is particularly helpful in situations where Cerenkov viewing cannot provide verification, e.g. when Cerenkov radiation is weak because the spent fuel has low burnup and/or a long cooling time, or when water in the storage pond is insufficiently clear. The SFAT and its lead shielding are housed in a stainless steel watertight container which is submerged in a storage pond and positioned over the item to be examined.

A watertight collimator pipe is attached below the detector housing to permit only radiation from the principal assembly rather than from adjacent assemblies to reach the detector. A multichannel analyser provides for acquisition, recording and analysis of data, as well as supplying power to the detector.

The intensity of the selected gamma rays from a specific fuel assembly is compared with the spectrum from the gap separating the assembly from its neighbors to confirm the presence of fission or activation products in the measured assembly.

### *4.3.2 IRAT.*

The Irradiated Fuel Attribute Tester (Fig. 33) is a small, lightweight CdZnTe based detector that can be suspended from a spent fuel pond bridge and used to measure a fission product spectrum from a spent fuel assembly partially raised from a storage rack. The detector is housed in a stainless steel cylinder that includes shielding and a collimator. A multichannel analyzer collects and analyses spectral information from a spent fuel assembly. The presence of fission product isotopes such as $^{137}$Cs, $^{134}$Cs, $^{144}$Pr, $^{154}$Eu and others is used to confirm the irradiated fuel characteristics.

*Figure 33:* IRAT- Irradiated Fuel Attribute Tester [from 14].

## *4.4 Gamma ray intensity scanning*

**CBVB, CBVS.** The CANDU Bundle Verifier, suspended on an automatic winch whose speed can be set for scanning either storage baskets or storage stacks, includes a highly collimated and shielded CdTe detector. The verifier is attached to an amplifier and a portable computer. The computer can be used either with an external analyzer for high count rate conditions or with an internal multichannel analyzer card for moderate count rate applications. The 662 keV gamma ray line from $^{137}$Cs generally dominates a spectrum for spent fuel that has cooled longer than two years and provides a useful signature for verifying the spent fuel. For shorter cooling times the 757 keV line from $^{95}$Nb/$^{95}$Zr is used to verify the presence of spent fuel. The particular gamma ray line to be used is selected in the SCANDU program. The detector head is moved at a selected speed vertically across the face of the stacked fuel and a scan sequence is initiated in the computer. The gamma ray intensity is measured as a function of the vertical position. The high intensity peaks, indicating irradiated fuel bundles, are counted and compared with the declared information on the number of stored fuel bundles.

## *4.5 Cerenkov radiation detection*

**ICVD, DCVD.** The Cerenkov Viewing Device (ICVD) and Digital Cerenkov Viewing Device (DCVD) are image intensifier viewing devices sensitive to the ultraviolet radiation in the water surrounding spent fuel assemblies. The hand-held ICVD is shown in Fig. 34. The viewing device is capable of operating with facility lights turned on in the spent fuel pond area.

The ICVD is optimized for ultraviolet radiation by filtering away most of the visible light and by having an image intensifier tube primarily sensitive to the ultraviolet light frequencies. Cerenkov radiation is derived from the intense gamma radiation emanating from spent fuel, which when absorbed in the water produces high energy recoil electrons. In many cases these electrons exceed the speed of light and therefore must lose energy by emitting radiation (Cerenkov radiation). Spent fuel also emits b particles (which are also energetic electrons), adding to the Cerenkov radiation. Spent fuel assemblies are characterized by Cerenkov glow patterns that are bright in the regions immediately adjacent to the fuel rods. The variation in light intensity is apparent when viewed from a position aligned directly above the fuel rods. With careful alignment and appropriate assessment of the object being viewed, an irradiated fuel assembly can be distinguished from a non-fuel item that may look the same to the naked eye. Typically, a row of fuel assemblies is viewed vertically from the bridge while the facility operator slowly runs the bridge down the row. One inspector views the items in the row through the ICVD and verbally declares each item as spent fuel, as a void or as some other object, while a second inspector compares the observed results with the facility declarations. The DCVD is currently being developed for use in verifying assembles with long cooling times and/or low burnups which have weak Cerenkov signals that cannot be seen with a standard ICVD.

*Table 13:* Spent Fuel Measurement Systems

| Code | Equipment name | Description and applications |
|---|---|---|
| FDET | Fork Detector Irradiated Fuel Measuring System | Detector system that straddles LWR fuel assemblies with pairs of neutron and γ ray detectors. Gross γ ray and neutron intensities and ratios of intensities can give specific information on the fuel assembly. |
| SFAT | Spent Fuel Attribute Tester | Gross defect device used for verifying the presence of fission product or activation product at the top of the irradiated fuel assembly. |
| IRAT | Irradiated Fuel Attribute Tester | Gross defect device used for verifying fission product presence in an irradiated fuel assembly. |
| ICVD | Cerenkov Vieiwing Device | Hand-held light intensifying device optimized to view Cerenkov light (near ultraviolet) in a spent fuel storage pond. System can be used in a lighted area. Primarily used to identify irradiatred LWR fuel assemblies. |
| DCVD | Digital Cerenkov Viewing Device | Highly sensitive digital device for viewing Cerenkov light from long cooled, low burnup fuel. |
| CBVB<br><br>CBVS | CANDU Bundle Verifier for Baskets<br><br>CANDU Bundle Verifier for Stacks | Attended radiation monitoring systems that scan storage baskets or stacks of CANDU fuel bundles and record gamma intensity as a function of detector position. |
| CBUV | Gamma Burnup Verifier | Facility specific system used to make high resolution γ ray measurements of spend fuel assemblies. Collimator in front of the Ge detector is built into the facility. |

*Figure 34:* Cerenkov Viewing Device (ICVD) [from 14].

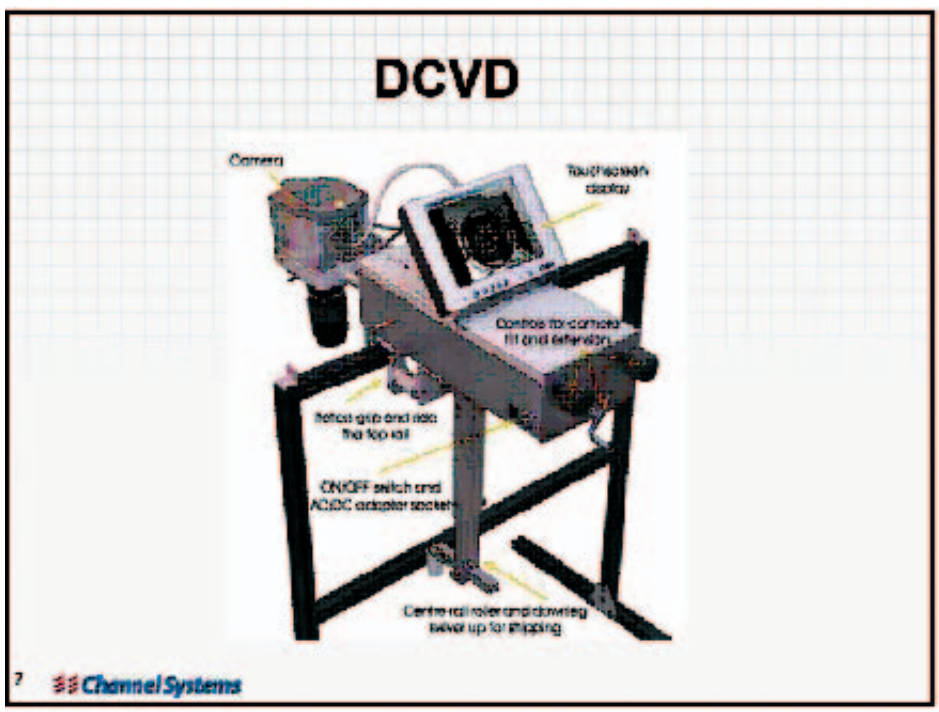



*Figure 35:* Digital Cerenkov Viewing Device (DCVD) [from xxx].

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# Containment and Surveillance – Status and Perspectives

Bernd Richter

## 1. Introduction

Containment and surveillance (C/S) measures can only provide indications for possible diversions of nuclear materials or misuse of nuclear facilities, and their rôle is considered complementary to nuclear materials accountancy. However, present generation nuclear facilities such as commercial reprocessing and mixed-oxide 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 rôle of C/S. This article begins by discussing the rôle of C/S on the basis of the nuclear treaties. Practical experience has led to a list of design and functional requirements for C/S techniques which are basically determined by the necessity for unattended use of the equipment. Then, examples for the application of C/S are given, followed by an outline of the evolution of C/S devices. Furthermore, there is a discussion of techniques which are in current use by the International Atomic Energy Agency (IAEA). Finally, the article discusses development projects of C/S techniques which are currently under way. The article basically draws upon literature which is listed at the end under References.

## 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 non-nuclear 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 Agency 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.

As the non-nuclear weapons 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 concluded the Verification Agreement (VA) known as INFCIRC/193 derived from INFCIRC/153. In the VA, C/S measures are mentioned several times. This will be discussed below in detail.

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 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 interpreted that C/S are not assigned fundamental but rather auxiliary functions. 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 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 rôle of C/S was legally spelt out at a time when the impacts of bulk handling facilities with large throughputs and of long term storage facilities with difficult-to-access or even inaccessible material were not really considered. Instead, safeguards focused on reactor facilities, fuel fabrication and enrichment plants where the material is still accessible for item verification, sampling, and measurements. Nowadays, a large part of the nuclear material is enclosed in heavily shielded process piping and emplaced in thick-walled casks which will be stored over long terms with no intent to be opened for periodical physical inventory taking.

The VA constitutes nuclear material accounting as a fundamentally important safeguards measure. Therefore, the IAEA used to aim at a quantitative statement on the detection probability of diversion. However, this is only possible for facilities where nuclear material inventories and flows are periodically measured to the end of determining the material-unaccounted-for. Consequently, no detection probability can be determined for facilities in which only qualitative or no measurements are made. Moreover, as the detection probability decreases with increasing nuclear material inventory and flow, also in large commercial processing facilities the significance of a detection probability must be questioned. Hence, the importance of C/S measures and inspection activities is enhanced.

Based on many years of practical experience, the IAEA in its Glossary tried to arrive at a comprehensive list of functions assigned to C/S /4/. The most important aspects 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.

## 3. Safeguards Requirements

The safeguards inspectorates, developers from a number of countries as well as international advisory and working groups, such as the ESARDA Working Group on C/S, have extensively dealt with the requirements for C/S techniques. 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. In the following the principal criteria are discussed.

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 three 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 safeguards 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 or radiation monitoring.

Optical surveillance requires consideration of some additional criteria influenced by the recording capacity of the data carrier but ultimately by the inspector's reviewing effort. The application of external triggering, e.g., using scene change detection, restricts both recording and reviewing requirements to only those scenes which show possible movements of nuclear material. Practical experience shows that the reduction factor may be as large as 20 compared to constant time-interval triggered recording. Another method is to use data compression algorithms reducing the recording capacity needed per scene.

As the optical information has to be evaluated by the inspector automatic reviewing and data processing techniques can significantly reduce the inspector's evaluation time to reviewing those scenes which are of safeguards relevance. This requires, of course, that both the optical surveillance system and the automatic review station are designed and operated appropriately. It should be realized that an automatic technical review, i.e., evaluation regarding the system performance, became possible only after deployment of video techniques.

Furthermore, remote transmission and interrogation of safeguards data may also help to reduce inspection effort, especially in large countries where the nuclear material is located at many different places. The implications of remote transmission should also be investigated for highly industrialized small countries with good infrastructures. In this connection, encryption of video data will be important. Standardization and compatibility between devices as well as exploitation of the consumer market could increase the flexibility of integrated C/S system designs and reduce equipment costs when designing facility-specific C/S systems.

# 4. Application Examples

The following table I shows a list of safeguards relevant features for both operator activities and facility components with respect to most of the commercial stations of the nuclear fuel cycle. These safeguards relevant features do not represent a complete list but have to do with C/S measures, which are indicated in the very right column. However, the question of their application has to be answered on a case-by-case basis taking into account specific sets of criteria. These include above all the timeliness of detection and the assumed diversion strategies. More detailed information will be given in chapter 7 below.

*Table I:* Potential C/S Instrumentation for Different Facility Types and Activities

| Facility Type / Operator Activity/ Facility Component | LWR[1] reactor | CANDU[2] reactor | Pu fuelled reactor | MOX[3] fuel fabrication | enrich-ment plant | reprocess-ing plant | storage facility[4] | Potential C&S Instrument |
|---|---|---|---|---|---|---|---|---|
| handling of fresh fuel containers | X | X | X | | | | | camera |
| fresh fuel in store | X | X | X | X | | | | seal, camera |
| handling of fresh fuel | X | X | X | X | | | | camera, bundle counter |
| reactor core | X | X | X | | | | | camera, seal |
| handling of spent fuel | X | X | X | | | X | X | camera, bundle counter |
| handling of spent fuel containers | X | X | X | | | X | X | camera |
| spent fuel in store | X | X | X | | | X | | camera, seal, SCD[5] |
| shipping containers with spent fuel | X | X | X | | | X | X | camera, seal |
| handling of UF6 containers | | | | X | X | | | seal |
| UF6 containers in store | | | | X | X | | | seal |
| store for SNM[6] in bulk form | | | | X | X | X | X | camera, SCD[5], seal |
| filling/emptying of SNM[6] containers | X | X | X | X | X | X | | seal, camera |
| SNM[6] process containment | | | | | | X | | camera, SCD[5] |
| Pu cans | | | | X | | X | X | weld seam |
| fuel assemblies | X | X | X | X | | X | | seal |
| process sampling | | | | X | X | X | | seal, portal monitor |

(1) Light Water Reactor.
(2) Canadian Deuterium Uranium Reactor.
(3) Mixed Plutonium Uranium Oxide.
(4) E.g., dry intermediate storage of spent fuel assemblies.
(5) Scene Change Detection.
(6) Special nuclear material, i.e., fissile nuclear material.

# 5. Evolution of Containment and Surveillance – The first four decades 1957-1997 /5/

The IAEA was established in 1957 as a functional organization, including the commencement of inspections at nuclear facilities in member states. The first inspections began in the early 1960s at small research reactors, and expanded in 1962 to power reactors. Although there was little C/S equipment available for use, it was in this time frame that the first use of C/S began. Several commercially available seals were placed in use, initially on a trial basis. In the fall of 1966, the IAEA was using the US Internal Revenue Service (IRS) seal. Brookhaven National Laboratory (BNL) in the US later developed solder techniques designed to strengthen the tamper resistance of these seals. When implemented for IAEA Safeguards on a routine basis, the IRS seal became known as the "Type E" seal. Even after 40 years, it is still in use. No optical surveillance or monitors were in use in the first decade of the IAEA.

Starting in the second decade after 1967, a variety of equipment was introduced. In the area of seals, the backbone became the aforementioned Type E metallic seal. Today, after several modifications, it remains the most widely used seal. Adhesive (paper) seals were introduced, principally for short term sealing applications. The first fibre optic seal, termed Fiber Lock, was developed and offered for evaluation by the US Arms Control and Disarmament Agency (ACDA). Also, the development of electronic seals began at Forschungszentrum Jülich in Germany, and Sandia National Laboratories (SNL) in the US.

By early 1976, the IAEA had about 60 optical surveillance systems in use, including several types of single frame 35mm, 16mm, 8mm, Super 8mm cameras, and a few custom made video units. This came about as a result of the rapidly expanding commercial market for industrial and home use of film-based movie photography. These systems included:

Film Systems – One of the first optical surveillance devices used was the 35mm Robot Camera, custom made for the IAEA by a German vendor. This system was mains powered and had an 8,000 frame capacity, with time recorded on each frame from a battery operated 24 hour clock. It produced excellent picture quality, and was evaluated in several nuclear facilities in Europe and South America.

Throughout this decade, numerous commercial film cameras were developed and appeared on the market. A number of these systems were evaluated by the IAEA, and to a limited degree, used in field applications. These systems included:

- Zeiss 35mm Contarex camera
- Flight Research 35mm camera
- Bolex 16mm camera
- 8mm Minolta D-4 camera (first 8mm system)
- Minolta D-6 camera
- Minolta D-10 camera
- KodakAnalyst Super 8mm camera
- Minolta XL-400 and XL-401 Super 8mm cameras

The first models of the Minolta XL-400 camera system used a French mechanical timer, were battery operated, with constant or random picture taking time-intervals, and had a 3,600 frame capacity. Later models had an electronic built-in timer, a 7,200 frame capacity, and used Kodak MFX film. By 1978, the Twin Minolta XL-401 camera system, after a number of timer modifications, became the primary IAEA optical surveillance system, and was in worldwide use for well over two decades, until it was replaced by video systems.

In some cases, inspectors had to develop the film in the bathtubs/sinks of their hotel rooms, producing a variety of inconveniences and results. The inspectors later used the Porto-PAC dry process Kodak developer for processing the film. Use of this developer eliminated the hotel room-bathtub-film developing routine.

Video Systems – As video emerged on the market, the IAEA was quick to realize the potential benefits that could be derived, most notably of which were vastly increased scene capacity, and, with an appropriate monitor, rapid scene review. On an Agency contract, Psychotronic Elektronische Geräte, an Austrian vendor, produced the first IAEA video system, the Psychotronic System. This system used a time lapse recorder operating in pulse mode. It was designed in the early years of video technology, and used a reel-to-reel recorder having a capacity of 180,000 frames. Ultimately, some 30 systems were purchased, many of which were placed in safeguards use. The maintenance level was quite high. In time, the system was modified to use tape cartridge recorders.

Review of Optical Surveillance Data – The purpose of optical surveillance is to record the events that occur during the inspector's absence. This results in the need to review the collected data. Even with the use of film cameras, this is recognized as a very laborious job. The review process was performed with rather basic equipment which could be set to run the film at a relatively slow speed, or, if the inspector chose, a particular frame could be stopped for more detailed viewing. While this was very useful, it was found that, with some review equipment, leaving the film stopped for a period of time resulted in burning the particular frame being examined. The Recordak Motormatic Reader was one of the systems used at IAEA Headquarters.

Monitors and Other Devices – In the second decade of the IAEA (1967-1976), the use of monitors and sensors was introduced, albeit not on a wide-scale basis. While it is debated whether such devices can be categorized C/S equipment, it is interesting to take notice of them. Some of these devices are briefly described below:

*Reactor Thermal Power Monitor* – This unit, developed in South Africa, was donated to the IAEA in 1969. The second power monitor, developed in Denmark, was installed in the Danish DR-2 reactor. Its first use was in the 1968-1969 time frame.

*Reactor Electrical Power Monitor* – This system was developed in the former Czechoslovakian Socialist Republic.

*Track Etch Monitor* – This unit was sponsored by the US-ACDA and developed by the General Electric firm. It provided a means of monitoring neutron flux level related to power level, and was used in a number of facilities.

*Bundle Counter* – This system, sponsored by the US-ACDA and developed by SNL, was designed for application in on-load fuelled power reactors. It provided a count of the number of irradiated bundles moved from reactor core to the storage pond and vice versa. It was installed in a Canadian Deuterium Uranium (CANDU) reactor in 1975 and operated for years without failure. A second bundle counter system, designed to perform a similar function as the one above, was developed in Canada, by Atomic Energy of Canada, Ltd. (AECL).

*Glass Dosimeters* – Radio Photo Luminescence (RPL) dosimeters of fluoro-glass were introduced as yes/no monitors to measure exposure to radiation. They were used to detect flow of irradiated material through unauthorized routes. They easily fit inside the Type E Seal, and were used in several facilities such as on-load fuelled power reactors.

In the third decade of the IAEA (1977-1986), there were many technology advances, and the level of C/S equipment activities increased. Equally important, a number of IAEA member states established R&D programmes in support of the IAEA, and several of these programmes had significant

activities in the area of C/S. In this decade, as in the previous one, to many, C/S meant "cameras" and "seals". Considerable effort was devoted to the development of film camera systems with increased film capacity, video systems utilizing video cassettes and discs, electronic seals, and a variety of other C/S equipment. Some of these systems are listed below.

In Canada, AECL developed the first multiplexed video system for use in CANDU power reactors. This system used video discs as the storage medium. It was configured to store data from multiple cameras, eliminating the need for a storage device for each camera. The maintenance required for this system was found to be excessive, and it was ultimately replaced.

Also the IAEA developed a multiplexed video system. In addition, the IAEA pursued the development of the Laser Scanning System (LASSY) for use principally at spent fuel storage pools to detect objects being retrieved from the storage pool. LASSY was designed to scan a layer immediately above the water level.

Within the Commission of the European Communities (CEC), the Joint Research Centre at Ispra (JRC Ispra) developed an ultrasonic sealing system for Boiling Water Reactor (BWR) fuel assemblies. Concurrently, in the US, SNL developed the Fuel Assembly Identification Device (FAID)/Seal Pattern Reader (SPAR) ultrasonic sealing system, also for BWR fuel assemblies. These two systems were simultaneously tested at the Kahl experimental power reactor in Germany, with successful results. The EURATOM Safeguards Office developed a dual recorder video system.

In Germany, several types of systems were developed. Forschungszentrum Karlsruhe developed an 8mm film camera system using the ELMO camera, which had a film capacity of twice the one of the Minolta System. The Inaccessible Inventory Instrumentation System (IIIS) was developed which was an integrated C/S system designed for monitoring the handling of the fuel at the Kalkar sodium-cooled fast breeder reactor. This system and the SNL Integrated Monitoring System mentioned below, were among the first integrated C/S systems. Forschungszentrum Jülich developed the Variable Coding Sealing System (VACOSS), an electronic seal which was implemented by the IAEA and EURATOM after 1990. This seal provided the capability of in situ verification, recording of multiple opening and closing, and a high level of tamper indication. The IAEA started to take it out of service in 2006.

In Hungary, underwater optical instruments were developed to enable underwater reading of nuclear fuel assembly serial numbers. Similar efforts were conducted in the US.

In Japan, the Japan Atomic Energy Research Institute (JAERI) developed a large capacity 8mm film camera system, a semi-automatic verifier for the Cobra Seal System, and a portal and penetration monitoring system for the Fast Critical Assembly (FCA) Facility. The Power Reactor and Nuclear Fuel Development Corporation (PNC) developed a spent fuel monitoring system for use at the Tokai Reprocessing Facility. In addition, the Nuclear Material Control Center (NMCC) and others developed an electronic seal and a remote monitoring system.

In the US, ACDA developed the RECOVER System, designed to remotely, via commercial telephone lines, monitor the operational status of C/S devices. This system was extensively tested, on a worldwide scale, and served to demonstrate the basic feasibility of remote monitoring. Concurrent with the RECOVER activities, in Germany, Forschungszentrum Jülich developed and tested the LOVER (Local Verification) System intended for use within facilities in the same local area. Following the tests of the RECOVER and LOVER systems, in Japan, JAERI continued development of remote monitoring equipment. Los Alamos National Laboratory (LANL) developed the Reactor Power Monitor which was implemented in several facilities. SNL developed the Surveillance Television And Recording (STAR) System, the MINISTAR System, the Passive Environmental Monitor (PASEM), and the

Cobra Seal System (fibre optic). Also, the Integrated Monitoring System was developed, which combined radiation detectors, crane monitors, and a data collection module, and provided a trigger for optical surveillance devices.

In a cooperative effort between AECL and SNL, the AECL Random Coil (ARC) Seal/SNL SPAR System was developed, tested, and approved for routine safeguards use. This ultrasonic seal system is used to seal spent fuel storage racks in CANDU on-load fuelled reactors.

In a cooperative effort between JRC Ispra and SNL, development of the MOX Fuel Assembly Ultrasonic Seal System was commenced. This project was an extension of the earlier mentioned JRC Ispra/SNL ultrasonic seal systems for BWR fuel assemblies.

The first attempt at easing the film review process came in about 1981, with the development of a film scanner. This equipment, developed by SNL, was based on early scene change detection technology. The film was projected, and with a change of the scene, the scene was transferred to a video disc. This technique proved to be useful when there was hardly any operational activity the area under surveillance. In the cases where there was activity, many scenes were stored – in fact, so many, that frequently the disc was filled to capacity, stopping the review process.

In the late 1980s, it became evident that the film camera technology would be replaced by video technology, and that steps were necessary to insure that, when that time came, the IAEA would be prepared to replace some 200 Twin Minolta Film Camera Systems that were deployed. Both Japan and the US addressed this problem – JAERI with the Compact Surveillance Monitoring System (COSMOS), and SNL with the Modular Integrated Video System (MIVS) which was placed in routine safeguards use in early 1991.

The age of video surveillance was bringing with it a tremendous increase in the amount of recorded data. While the increased amount of surveillance was very desirable from the standpoint of determining what has occurred in the inspector's absence, it also brought along a burden to inspectors who had to review all the data. A drawback, however, was the loss of colour as compared to film cameras. In recognition of the large amount of data that resulted from the transition from (colour) film camera to (black and white) video systems, EURATOM and the US commenced development of video review systems: at JRC/Ispra, the Polyline System; at SNL, the MIVS Image Processing System (MIPS); and at a commercial firm in the US, Aquila Technologies Group (ATG), the Mk V Review Station. In the early 1990s, the Multi-system Optical Review Station MORE was developed under the German Support Programme by Dr. Neumann Consultants (DNC). MORE was designed to select images with scene changes and, thus, increased the efficiency of the inspector's image review process. This semi-automated optical surveillance review process of "back end data reduction" was implemented for routine use by IAEA and EURATOM, and has proven to be extremely effective.

In another approach to review aids, the European Commission, France, and Germany pursued development of video "front end" processing of surveillance data, i.e., scene change detection at the camera level. This and other optical surveillance developments are described below:

- In Canada,the AECL Improved Multiplex System using time lapse video recorders.
- AtEURATOM, a video system coupled with video motion detection circuitry, and a fully digital video system (EMOS) with multiple storage modes.
- At JRC Ispra and EURATOM,the Computer Aided Video Surveillance System (CAVIS).
- In France,at CEA, digital video systems.
- In Germany,at DNC, the Multi-Camera Optical Surveillance System (MOS).
- In the US,the SNL Portable Surveillance Unit (PSU).

Other significant C/S development activities included:

- In Australia,a remote monitoring system capable of transmitting video data over commercial telephone networks.
- AtJRC Ispra, a semi-automatic verification system for Type E seals, and an improved Laser Scanning System (LASSY).
- InFrance, the CEA Spent Fuel Transfer Monitoring System (CONSULHA), and the CLTO Fibre Optic Seal System.
- InGermany, at Dornier company an improved VACOSS Seal, and at DNC a Tamper Resistant Video Link.
- InJapan, an improved JAERI FCA Portal/Penetration Monitoring System, the PNC Plutonium Fuel Production Facility (PFPF) Advanced C/S System, the PNC video systems at the Tokai Reprocessing Plant, and the Fuel Number Reader activities at Japan Nuclear Fuel Services, Hitachi, and Toshiba.
- Inthe US, the SNL Modified Cobra Seal System, video and data link authentication systems, the Authenticated Item Monitoring System (AIMS), the Item Identification System, the Re-usable In-situ Verifiable Authenticated (RIVA) Seal System, Valve Monitors, a Secure Container for Glove Boxes, and Sample Vial Containment. In addition, ATG manufactured a lightweight version of the Modified Cobra Seal.
- Ina cooperative effort between AECL, LANL, and the IAEA, a Core Discharge Monitoring System for use in CANDU stations.
- Ina cooperative effort between EURATOM, British Nuclear Fuels Ltd. (BNFL), LANL and SNL, the Thermal Oxide Reprocessing Plant (THORP) Skip Monitoring System, integrating radiation detectors and video surveillance.
- Ina cooperative effort between Canada, JRC Ispra, and the US, the In situ Readable Ultrasonic Seal System (IRUSS) for ARC, VAK, and other ultrasonic seals.
- Ina cooperative effort between France and EURATOM, a small general purpose ultrasonic seal/transducer combination system (TITUS), and associated equipment for remote transmission of the TITUS data.
- Ina cooperative effort between JRC Ispra and BNFL, the Advanced Sealing and Item Identification Multi Element Bottle (MEB) Bolt Seals, ultrasonic seals for spent fuel casks. In the early stages of this effort, a similar cooperative effort between BNFL and SNL was conducted.
- In a cooperative effort between Forschungszentrum Jülich, Dornier company and SNL, the VACOSS/MIVS Interface System.

## 6. Introduction of Digital Systems /6/

For more than 25 years the nuclear safeguards system had been based on states' declarations and IAEA's ([7]) verification /7/. The world community, in response to the violation of the Treaty on the Non-proliferation of Nuclear Weapons (NPT), strengthened the safeguards system, i.e., NPT compliance verification system, by establishing the Additional Protocol (AP) /8/. Under the AP, the IAEA's mission is not only to verify the correctness and completeness of states' declarations but also to detect undeclared nuclear facilities, materials and activities,. While continuing to use material accountancy to detect diversion of nuclear material, the IAEA has to execute extended access rights within the nuclear facilities as well as on the states' territories. Furthermore, the IAEA has to handle more comprehensive information to be provided by the states as well as information acquired by the IAEA from

([7]) IAEA = International Atomic Energy Agency, Vienna, Austria.

open sources about states' nuclear activities. To this end, the IAEA has acquired new competence in open source information analysis including satellite imagery analysis and is re-engineering its safeguards information system. In Eastern Europe and Asia new states have come under safeguards, and nuclear programmes in Asia and elsewhere are being expanded. Finally, in the course of nuclear disarmament in nuclear weapons states the IAEA will have to safeguard excess fissile materials transferred from former military use.

In order to cope with these challenges, the IAEA, in cooperation with member states, is developing approaches to increase its efficiency and effectiveness in using its resources. The IAEA will focus more on qualitative safeguards measures concerning the nuclear fuel cycle in a state as a whole and on key activities like enrichment and reprocessing. Inspection effort related to routine activities at declared nuclear sites that are less sensitive will be reduced enabling the IAEA to re-allocate its staff. In 1992, the ESARDA ([8]) Working Group on Containment & Surveillance had proposed the concept of substituting on-site inspection effort by unattended and remote monitoring techniques with data evaluation at IAEA headquarters, as this may not only improve the cost effectiveness of routine safeguards but also reduce the interference with plant operations. In addition, nuclear radiation exposure of IAEA inspectors and technicians as well as of plant operators' staff will be reduced. Also, the European Commission, especially in designing new safeguards approaches in a regional union of, now, 27 member states, has started to consider this concept. Another aspect of unattended and remote monitoring is improving the data collection and analysis by acquiring safeguards data in a timely manner at random or programmable time intervals. Given the ever increasing amount of safeguards data it is also important to develop appropriate data review methods.

The whole concept requires the use of state-of-the-art technologies. In autumn 2004, after in-depth discussions, the two ESARDA Working Groups on C/S and on Techniques and Standards for Non Destructive Analysis (NDA) issued guidelines for developing unattended and remote monitoring and measurement systems /9/. In this context, the ESARDA Working Group on C/S has also started to revisit the issue of how to determine the performance and assurance of containment & surveillance equipment, an issue which the working group already addressed in the late 1980's.

This chapter highlights trends in the area of image surveillance, radiation monitoring, and electronic sealing. The example techniques presented will meet the requirement of system integration into sensor networks which will become more and more important in nuclear safeguards. Also, it should not be overseen that, in the future, some activities up till now carried out by the safeguards inspectors may be carried out by the nuclear facility operators provided the performance and assurance of the safeguards equipment will find the operators' acceptance.

The large variety of nuclear facilities to be safeguarded requires a great flexibility on the part of the IAEA in designing facility-specific safeguards instrumentation. The use of digital techniques (hardware, firmware, software) and modular hardware and software solutions for automated on-site instrumentation enables to design equipment systems integrating different sensor techniques such as cameras, radiation monitors, and seals. It has to be taken into account though, that electronic components have short times to obsoleteness requiring short-term replacement. Examples for rapidly changing technologies are microprocessors and data carriers. Also, technical progress leads to new concepts and requires periodical replacement of safeguards equipment.

For cost reasons (procurement, training, repair and servicing) it is desirable to use commercial-off-the-shelf (COTS) components to the greatest extent possible. However, it is necessary and expensive to adapt COTS components to nuclear safeguards applications. From the IAEA's point of view the critical component of a safeguards system is the sensor head with digital data generator module. Here,

([8]) ESARDA = European Safeguards Research & Development Association.

loss-free data acquisition and local storage as well as a high data security including authentication are required. Normally, this is realised with customised solutions for hardware and firmware, which, by nature, are expensive, as the nuclear safeguards market is very small, and these requirements are not requested in other verification systems. Therefore, IAEA member states support the IAEA in developing customised equipment, in order to keep the IAEA's procurement costs free from the development costs.

In a remote monitoring scheme the IAEA must be able to evaluate the safeguards data at IAEA headquarters. For the reason of safeguards confidentiality only encrypted safeguards data will be transmitted. The implementation of remote monitoring systems requires cost-benefit analyses on a case-by-case basis. Costs depend on country-specific factors such as the number of facilities involved, availability and quality of a communication infrastructure, and communication tariff, and on other factors such as licensing of encryption algorithms and archiving requirements.

For software upgrading and trouble shooting, the IAEA may wish to have remote system access to its remote monitoring systems. This will only be granted under the provision that the plant operator's security concerns can be sufficiently met, as there is always a non-negligible security risk of unauthorised access. Furthermore, the plant operator may be concerned about the unaltered status of the data transmission scheme, if, for instance, delayed transmission of surveillance data has been implemented.

The amount of data to be handled must be kept as low as possible, i.e., only relevant data should be transmitted, archived and evaluated. Otherwise, transmission times may become unacceptably long, archiving capacities extremely large, and data management and evaluation very laborious, when considering a whole country. For example, the remote transmission of optical surveillance data involves large data files. Applicable data reduction methods are: (1) mathematical compression to reduce the file size; and (2) front end scene change detection to transmit only relevant images. To further reduce the amount of transmitted data, it is possible to correlate different types of data, e.g., images are relevant only if radiation is detected.

The remote retrieval of state-of-health data allows to monitor the performance of the safeguards systems and to initiate timely repair and maintenance. While highly reliable sensor head/data module units with uninterrupted power and loss-free data storage provide the assurance of continuity of knowledge, temporary outages of COTS components can be tolerated.

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

## *6.1 Digital Safeguards Instrumentation*

Unattended integrated remote monitoring and measurement systems will play a major rôle. They consist of sensor heads, associated electronics, digital data generators, a data collection system, and network interfacing equipment for remote data retrieval. The majority of such systems is computer-based, as compared to customized solutions.

Sensors with their signal processing electronics as well as digital data generators are security relevant components, as they are the sources of the safeguards data. Any unauthorised physical access must be inhibited. Data authentication takes place in the data generator. Ideally, the components are mounted in a common tamper-indicating enclosure (TIE). Servicing, repair and replacement must be restricted to the IAEA's staff.

This concept is realised in two equipment categories used by the IAEA: (1) Digital image surveillance and (2) electronic sealing. The IAEA's standard digital camera unit has a low power OEM ([9]) CCD ([10]) camera and the digital data module DCM 14 mounted in the sealable IAEA standard camera housing. Also, the VACOSS electronic seal has many features of the concept.

In contrast, for radiation sensors development efforts have to be directed towards authentication of NDA data and tamper protection. The development of the digital unattended multi channel analyser DIUM is a first step in this direction (see below). It is worth mentioning that radiation detectors usually need to be physically separated from their data generators. In this case, the principle of tamper-indication must be separately maintained for (1) the sensor, (2) the signal line, and (3) the data generator module.

Within a nuclear facility the data collection system receives data from the sensors used. It stores the data until retrieved on site by an inspector or remotely transmitted to IAEA headquarters.

For on-site retrieval the data must be available on an exchangeable storage medium. Contemporary standards are digital linear tape (DLT), magneto-optical (MO) disk, recordable compact disc (CD-R), and DVD. In addition to the exchangeable storage medium, data collection systems may have other internal storage devices.

If a data collection system is interfaced to a public communication network, the data can be directly transmitted over the network to IAEA's headquarters. In this case, the confidentiality of the data must be guaranteed at all times by means of an appropriate encryption scheme. If the data are retrieved on site, confidentiality is the responsibility of the IAEA staff all the way from the facility to the headquarters. The inspector may want to transport encrypted data only, in order to ensure confidentiality in case of loss of the data carrier.

The reliability of the data collection system can be ensured by a range of measures including one or more of the following: Uninterruptable power supply, sufficient local storage to store the data from the different sensors over a longer period of time, redundancy of the system's vital components, auto-monitoring of different state-of-health parameters, transmission of state-of-health alarms. Networked data collection systems must offer a sufficient level of security against unauthorised access.

Network interfacing equipment is used to interface the data collection system to a public communication network, with the aim to transmit the collected data and, if agreed, to give the IAEA remote access to the system. The following aspects are important: Confidentiality of the transmitted data; prevention of unauthorised access to the safeguards system and safeguards data; IAEA's secure remote access to the data collection system.

Due to the concept of loss-free data acquisition and storage in sensor head/data generator modules, other components such as data buses, communication links, microcomputers, and data collection system are not security relevant and, therefore, may be COTS products. Failures and mains power outages do not result in a loss of data. As only authenticated data are processed in these components, tampering is not possible undetected. The components can be serviced, repaired and replaced by commercial contractors. This will further reduce the IAEA's interference with plant operation.

([9]) Original equipment manufacturer.
([10]) Charge-coupled device.

Prior to authorising equipment for routine inspection use the IAEA requires the systems to successfully pass different evaluations:

- Qualification testing including radiation testing ([11]);
- Third Party vulnerability analysis of the hardware and firmware as regards safety and security including data authentication and encryption methods ([12]);
- acceptance testing including usability review;and
- field testing.

Unattended and remote monitoring techniques for safeguards should have the following features:

- Data authentication at the sensor level
- front end data reduction including data compression and data correlation
- sufficient data storage capacity at the sensor level
- data encryption
- remote data transmission out offacilities to IAEA headquarters
- compatibility between devices ofdifferent origins
- integrated data review
- option for plant operator's performance ofsafeguards activities.

A widely accepted compliance with these features may help to reduce procurement costs and training effort for inspectors and technicians, solve data security issues, and match development efforts spent under different member states programmes in support of the IAEA.

When handling and operating unattended integrated remote monitoring and measurement systems the IAEA should:

- Perform strong configuration controls for data security,
- perform system access controls,
- use approved encryption algorithms,
- apply standardised vulnerability assessments,
- apply vulnerability assessment to entire system,not just to the security algorithm,
- use certified copies ofcommercial-off-the-shelf software,
- provide implementation guidelines for TCP/IP connectivity ofEthernet standard, and
- apply appropriate procedures for key management related to authentication and encryption.

([11]) The IAEA applies the IAEA/Euratom "Common Qualification Test Criteria for New Safeguards Equipment", Version 2.0, January 2002. For environmental testing the IAEA co-operates with the Joint Research Centre at Ispra under the Euratom Support Programme to the IAEA. For radiation testing the IAEA co-operates with the Atominstitut in Vienna. The procedure for irradiation testing is currently being revised under the German Programme in Support of the IAEA.

([12]) The DCM 14 digital camera module was evaluated by an Australian Expert Team in the frame of a joint Australian-German Support Programmes task.

## 6.2 Technical Approaches

Three examples are given for existing or upcoming digital systems complying with the requirements of unattended operation, remote data transmission, and system integration. The given examples cover the major monitoring principles, i.e., image surveillance, radiation monitoring, and electronic sealing. The equipment is designed for integration into systems with new functionality, including the correlation of image data with radiation data and electronic sealing. For example, an image or sequence of images will only be registered, if a certain radiation level or radiation characteristics is present, or if an electronic seal is attached to or detached from a spent fuel cask.

**Optical Surveillance System**

Optical surveillance systems are designed to run in unattended mode. Their advantage is that they do not interfere with plant operations when registering safeguards relevant image information on operator's activities. The safeguards inspector matches this information with the operator's declarations, without the need for his physical presence. The IAEA uses optical surveillance in the following safeguards applications, worldwide:

- Single-camera surveillance at locations that are easily accessible for inspectors,
- single-camera surveillance at locations that are difficult to access including underwater applications,
- multi-camera surveillance for all location types,and
- hort-term and portable surveillance.

The IAEA's current systems are based on the DCM 14 digital camera module and the associated family of single- and multi-camera surveillance systems which were developed between 1993 and 2001 and authorised for inspection use between 1999 and 2002. The IAEA generally requires an equipment lifecycle of up to 10 years. In 2008, the design and most of the technology will be between 10 and 15 years old. Assuming a minimum period of 4-5 years to be necessary to design, develop, evaluate, test, and approve (for inspection use) custom-designed safeguards equipment, the IAEA, adhering to the concept of a digital camera module as the core component, has recently initiated the development of a "next generation surveillance system". This will be addressed in a separate section.

The DCM 14 (see Figure 1) provides the following functions and capabilities: Image acquisition, analogue-to-digital conversion, data compression, data authentication, data encryption, internal and external triggering, maintenance capabilities, power management, battery backup, and local data storage on PC-card. The module including camera can operate on battery power for 10 days at a 10-minutes picture taking interval (or 1 day at a 1-minute interval). In addition to various single-camera configurations there is also the DCM 14-based Digital Multi-camera Optical Surveillance (DMOS) System.

The collected data can be reviewed locally at nuclear facilities and/or at IAEA field offices and headquarters. Furthermore, the system is designed for remote data transmission out of facilities with the transmitted data remotely to be reviewed when received at IAEA field offices and headquarters.

The DMOS system permits the connection of up to 32 cameras. Each camera and DCM 14 is mounted in a tamper indicating enclosure (TIE), i.e., the sealable blue IAEA standard camera housing. The control and recording unit is installed in a 19-inch cabinet. The camera units are connected via RS-485 cables to a custom-designed interface providing the camera data via RS-232 cable to the computer.

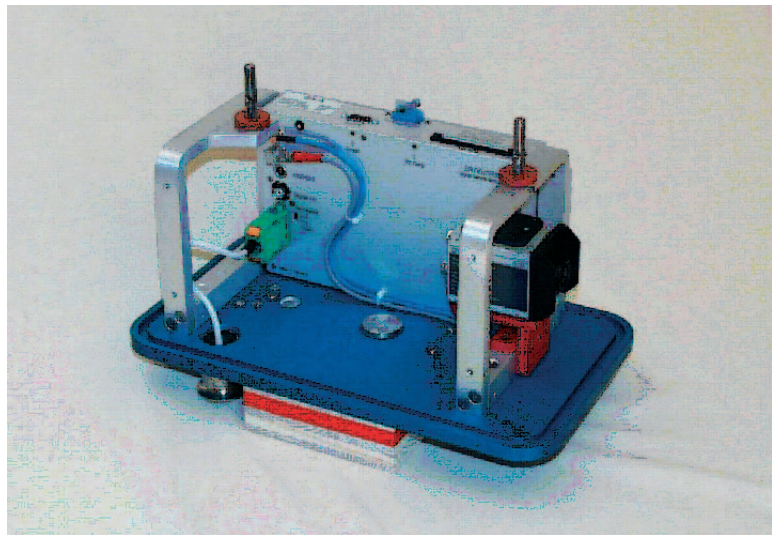

*Figure 1:* Base plate of IAEA camera housing with DCM 14 module and CCD camera (courtesy: Dr. Neumann Consultants)

The DMOS system uses compact low power CCD cameras (OEM products) with auto iris lenses. For facilities with 50 Hz and 60 Hz mains power supply two video standards, CCIR and EIA, are available. The following COTS-components were initially implemented: (1) hardware: industrial PC with TFT ([13]) display and membrane keyboard, SCSI ([14]) array, and digital linear tape drive; (2) operating system: Windows NT 4.0 Server. The DMOS system allows remote image transmission with the option of delayed image retrieval ([15]). Status data are associated with each image file, such as the status of the housing switch of the camera and the temperature in the camera housing. These data should be retrievable at any time without delay, as they can help to monitor and enhance the performance of the unattended system by triggering servicing.

Field experience has resulted in new design requirements (see below) and the requirement of mitigating the general hardware and software (operating systems) obsolescence problem. To facilitate a future replacement programme, the IAEA wants the next generation digital camera module to be compatible with the existing DCM 14-based surveillance technology.

**Unattended Radiation Monitoring**

Unattended radiation monitoring systems developed for the IAEA have so far not been standardised. The objective of the digital unattended multi-channel analyser (DIUM) project is to use as many standardised components as possible. These components are the system enclosure rack with an uninterruptible power supply, external cabling to radiation detectors, and eventually detector assemblies and enclosures.

The DIUM (see Figure 2) will use high frequency sampling and patented digital signal processing. Furthermore, it will be designed for unattended operation in nuclear facilities with the data collected to be retrieved and reviewed locally, in IAEA field offices and/or at IAEA headquarters, or with the data transmitted remotely and reviewed when received there.

([13]) Thin Film Transistor.
([14]) Small Computer System Interface.
([15]) Delayed data retrieval means that each data file is released only after a preset time interval.


*Figure 2:* Digital Unattended Multi-channel Analyser prototype
(courtesy: ICx Radiation GmbH)

The functionality of the DIUM will be comparable with the DCM 14 camera module: local data storage, uninterruptable power supply, data compression, time stamping, authentication, encryption, remote data transmission, trigger capabilities. The data storage capacity will cover 5 days, if mains power or the data collection computer will not be available. In addition, it will provide high voltage to the detector and power to the preamplifier.

The DIUM will be capable of operating with different types of detector heads, e.g., sodium iodide, germanium, and cadmium-zinc-telluride, and it will be designed for installation and integration with other data acquisition modules, such as the DCM 14 digital image surveillance technology, and other digital signal sources. To capture fast processes, e.g., in bulk handling facilities and storage facilities, the measurement time may be short. Therefore, the DIUM will have a high data acquisition rate.

Although universal multi-channel analysers are being widely used in attended and unattended modes, there is no product commercially available, which would perform this task satisfactorily. While capturing fast processes in real time, the instrument is very much comparable to a surveillance camera system taking a picture every second. The difference to optical systems lies in the character of the data. The DIUM is storing radiation spectra and counting rates rather than pictures. In contrast to a digital camera unit, the radiation sensor may be separated from its data acquisition module.

Measurement times are in the range of 100ms to a few minutes. The measurements are similar to those performed in radioactive decay studies after neutron activation with the unattended data acquisition constantly going on and, thus, producing an enormous amount of data. The DIUM system is able to handle very high input counting rates from the radiation detector. This feature will minimise the effect of being overloaded and thereby blinded for important data. A high throughput is desirable, in order to minimise the statistical error for the data analysis.

It is very important to have no dead time periods between two consecutively measured spectra. A continuous stream of spectra with no missing code is stored on a flash memory disk.

The DIUM has an extra large memory to store many short time spectra on the board level. A safeguards-specific feature is embedded authentication and encryption of spectrum data. Together with an accurate time stamping, the authentication record added to each individual spectrum ensures that the data are not tampered with. In addition to the spectrometric input for detectors, trigger inputs and outputs are required for synchronisation purposes and electronic seals. Among the various radiation detectors that may be connected, there are also plastic scintillators and GM-tubes for gamma counting.

The main task of an unattended multi-channel analyser is to acquire repeatedly spectra from the same location, i.e., to detect changes in the radiation field. The interesting information is the difference between consecutive measurements rather than the analysis of a single measurement itself. If not explicitly stopped, the unattended multi-channel analyser will continue to collect spectra and deliver them to a remote computer. Loss-free data acquisition is ensured by storing all data locally in the data module on a removable storage medium. When the local data storage device is full, the oldest data are overwritten. This procedure works rather like a ring buffer, until the storage medium is removed for evaluation and replaced in the data acquisition module.

Local data storage capacity has been designed for up to five days operation until a potential problem may be fixed. When taking a spectrum every second, nearly 500,000 spectra must be stored without loss. Even with the ever-growing capacities of memory cards data compression is mandatory.

Together with the spectrum data a state-of-health record is stored. It contains information like ambient temperatures, detector high voltage and bias current, and preamplifier power. Tampering with the detector and detector failures will cause a change in one or more of such parameters.

The temperature is recorded as one parameter of physical stress. Another stress factor in nuclear facilities is often an elevated level of neutron radiation. Ongoing electronic circuit miniaturisation causes an increased sensitivity to neutrons inducing malfunctions and system crashes. The problem is moderated by using selected memory chips which are not prone to such neutron-induced effects. A software technique using checksums and error correction with watchdog functions ensures safe operation in the standard instrument cabinet.

For reasons of data integrity and authenticity an authentication method similar to the one implemented in the DCM 14 camera module will be used to authenticate individual spectra. The DIUM signal sampling, while taking a spectrum, also acquires true statistical noise in the form of random zeroes and ones as a natural base for all encryption algorithms and hash function. When using the natural noise generator for the encryption all publicly known attacks to falsify the authentication are doomed to fail. The authentication method will be subject to a Third Party Vulnerability Assessment. For remote data retrieval also encryption will be required and approved by the state.

**Electronic Sealing System**

The IAEA 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. While the concept has proven highly successful, the seal technology is not state of the art. The IAEA defined the following requirements for a future electronic safeguards seal:

- High detection probability ofbypassing or short-circuiting of the sealing function;
- tamper-indicating housing which, however, can be opened non-destructively for maintenance, upgrade and/or repair;
- up to 3 years operation on battery, while battery replacement information should be highly reliable;

- high-capacity event-log with support for back-end authentication verification;
- secure communication protocol based on a standardised cryptosystem and state-of-the-art cryptography;
- support for network applications, i.e., network of seals as well as seals in a network of different device types including computers, digital cameras, radiation monitors;
- radiation tolerance through software means such as strict watchdog regime and majority vote variables.

A new seal is the electronic optical sealing system EOSS (see Figure 3) which started to be implemented for inspection use in 2006. The sealing function is realised by using a fibre-optic cable (FOC). The sealing security is based on the fact that fibre-optic cables are generally more difficult to tap or bypass and to repair than electrical wires.


*Figure 3:* Electronic Optical Sealing System prototype
(courtesy: Dr. Neumann Consultants)

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. If 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 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 more than 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.

In the future, it will be desirable to have available an appropriate generic review capability for integrated safeguards systems. Development efforts are going on at LANL and, in connection with the next generation surveillance system, at Canberra Albuquerque, Inc.

# 7. Currently Used Containment and Surveillance Techniques /10/

Containment and surveillance techniques are extensively used by the IAEA, because they are flexible and cost effective. The two main C/S categories are optical surveillance and sealing systems.

Optical surveillance is most effective in storage areas, such as spent fuel storage ponds, with relatively few plant operator's activities that could be interpreted as the removal 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 may be set at a periodic frequency (to be significantly shorter than the fastest possible removal time) or the motion (i.e. scene change) may trigger the recording. Optical surveillance is intrinsically an unattended operation that may be enhanced by the remote transmission of image data or system operation data (i.e. the operational status of the surveillance system).

Seals are typically applied to individual items containing nuclear material. A seal can help to indicate that material was neither introduced into or removed from a container. At the same time, sealing provides a unique identity for the sealed container. Unattended IAEA monitoring equipment is also sealed. Most IAEA seals are applied for extended periods of time, typically several months to years. Seals may be single use seals that have to be replaced when the sealed item has to be opened. Other types of seals are verifiable in situ, i.e. they can be checked for integrity and identity in the field without removal. If the seals are verifiable in situ, then the verification activity must be efficient (to limit

radiation exposure to the inspector) and extremely reliable. The in situ verification activity must consist of checking the item containment, the seal integrity, and the method of the seal's attachment to the item.

Containment is a very complex issue which still lacks sufficient attention. While some solutions are available, it has only been a few years ago that containment verification began to be addressed more in depth.

## *7.1 Surveillance*

Surveillance includes both human and instrument observation. As it is prohibitively expensive to arrange for permanent inspector presence, the IAEA has 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 to support and complement nuclear material accountancy and to provide continuity of knowledge about nuclear materials and other items of safeguards significance between on-site inspection visits.

Effective surveillance is achieved when a camera's field of view covers the entire area of safeguards interest to capture the movement of safeguarded items. Additionally, the picture taking interval is set to record at least two images, should the item be moved, so that its direction of movement can be determined. The image recording frequency may be set at a fixed time interval, which is significantly shorter that the fastest removal time, or may be triggered by scene change detection or other external triggers, such as radiation monitoring or electronic sealing.

Optical surveillance is intrinsically an unattended technique that can be used to record images only, or it may be integrated with other unattended monitoring equipment to provide nuclear measurement, containment history and other data. The IAEA's surveillance systems can also automatically transfer data to IAEA Headquarters or to an IAEA regional office.

Surveillance equipment is designed for the following basic applications:

(a) Single camera systems for easy to access locations,

(b) Single camera system for difficult to access locations,

(c) Multi-camera systems for larger and more complex facilities,

(d) Short term surveillance system for activities that include open core monitoring,

(e) Surveillance systems for remote monitoring,

(f) Underwater closed circuit TV system for attended applications in fuel storage ponds.

IAEA surveillance equipment has evolved from film cameras, through systems based on videotape technology, to today's digital image surveillance (DIS) systems. The evolution of IAEA 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 is inherently more reliable than previous film and videotape technologies. Other benefits include enhanced digital data evaluation, assisted review capabilities, improved authentication and encryption and its facilitation of remote monitoring.

In 1995, the IAEA 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 the essential user requirements

for the IAEA 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 safeguards surveillance system, including:

(1) Digitization of a standard video camera image;

(2) Image and data authentication, ensuring genuineness;

(3) Image and data encryption, ensuring confidentiality;

(4) Image compression to reduce image and data storage requirements;

(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);

(7) Power management to ensure maximum possible operation should the local facility's power fail;

(8) Secure remote surveillance when connected to a communications server.

Safeguards surveillance systems are relatively unique in that the equipment must operate unattended for extended periods in harsh conditions and with a high degree of security 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, meeting the full range of safeguards applications, often in difficult environments. Table II demonstrates the transition from systems implemented in the fourth decade of IAEA safeguards to the DCM 14 based systems implemented in the fifth decade.


*Figure 4:* DCM 14 with video CCD camera (CCD: Charge Coupled Device) (courtesy: IAEA, Vienna)

*Table II:* Replacement and Consolidation Plan for Surveillance Systems

| Application | Film, videotape and early digital systems phased out between 1995 and 2002 | Current Digital Image Surveillance and other systems |
|---|---|---|
| Installed Single-Camera Systems *– for easy to access locations* | Compact Surveillance and Monitoring System COSMOS | ALIS<br>All in one surveillance, mains operated |
| | Photo Surveillance Unit (Twin Minolta System) | ALIP<br>All in one surveillance portable, battery operated |
| Installed Single-Camera Systems *– for difficult to access locations* | Gemini Digital Video System GDTV | DSOS<br>Digital single-camera optical surveillance |
| | Modular Integrated Video System MIVS | |
| Installed Multi-Camera Systems | Multiplex TV Surveillance System | SDIS<br>Server digital image surveillance<br>Up to 6 cameras |
| | Multi-Camera Optical Surveillance System MOSS | DMOS<br>Digital Multi- Camera Optical Surveillance<br>Between 6 and 16 cameras |
| | Upgraded Euratom Multi-Camera Optical Surveillance System EMOSS | FAST<br>FAST company surveillance system<br>*Developed by Euratom for joint inspection use* |
| | DigiQuad Multiplex Video System | |
| Short Term Surveillance System | Short Term TV System | ALIP |
| Surveillance for Remote Monitoring | | SDIS |
| | | DMOS |
| Underwater TV Systems *– for attended applications* | UWTV<br>Underwater TV | UWTV<br>Underwater TV |
| | UWVD<br>Underwater Viewing Device | UWVD<br>Underwater Viewing Device |
| Surveillance Review *– hardware and software* | General Advanced Review Station GARS Version 6.3 | General Advanced Review Station GARS Version 6.4 |
| | MIVS Advanced Review Station MARS | |
| | Multi-system Optical Review Station MORE | |

Surveillance continues to play an important rôle in safeguards. There has been a steady increase in the number of camera units deployed in safeguarded facilities.

In 2003, the IAEA maintained about 800 cameras connected to 400 surveillance systems in 170 safeguarded sites worldwide. Until about 2005, old and new systems continued to coexist. Table III provides an overview of the IAEA's main systems after 2005.

Equipment has also been developed to provide an increasingly sophisticated review capability for surveillance. Following the same technology trends, review stations have evolved from film review tables, through videotape systems (some with advanced features such as scene change detection) to the IAEA's most recent GARS review software that can be run on a personal computer equipped with the appropriate digital media peripherals. Further details of the IAEA's most widely used digital surveillance systems follow.

*Table III:* Optical Surveillance Systems

| Code | Equipment name | Description and applications |
|---|---|---|
| *Videotape: single camera surveillance systems* | | |
| SIDS | Sample Identification System | Facility specific surveillance system integrated with a high-level neutron coincidence counter and triggered by neutrons above a pre-set threshold, allowing MOX sample identification in a fuel fabrication facility. |
| UWTV | Underwater TV | Commercial underwater closed circuit TV system (CCTV) for inspector attended fuel identity verification in storage ponds. |
| *Digital: single camera surveillance systems* | | |
| ALIP | All In One Surveillance Portable | Battery powered, single camera for easy to access locations or for portable surveillance applications. |
| ALIS | All In One Surveillance | Mains powered, single camera for installation in easy to access locations. |
| DSOS | Digital Single-Camera Optical Surveillance | Single camera for installation in difficult to access locations. |
| *Videotape: Multi-camera surveillance systems* | | |
| FTPV | Fuel Transfer Video | Facility specific CCTV system used at fuel transfer ponds. |
| MOSS | Multi-Camera Optical Surveillance System | Videotape based, multiple camera surveillance system for up to 16 cameras.<br>Phasing out. |
| VSPC | Video system | Facility specific CCTV system for up to 4 cameras on a split display screen. |
| *Digital: Multi-camera surveillance systems* | | |
| DMOS | Digital Multi-Camera Optical Surveillance | Multiple camera surveillance system for up to 16 cameras with remote monitoring capability. |
| SDIS | Server Digital Image Surveillance | Multiple camera surveillance system for up to 6 cameras with remote monitoring capability. |
| *Surveillance review systems* | | |
| GARS | General Advanced Review Station Software | For the review of ALIS,ALIP, DMOS, DSOS, GDTV, SDIS surveillance. |
| MORE | Multi-system Optical Review Station | For COSMOS, MIVS, MXTV, MOSS, DigiQuad. Phasing out. |

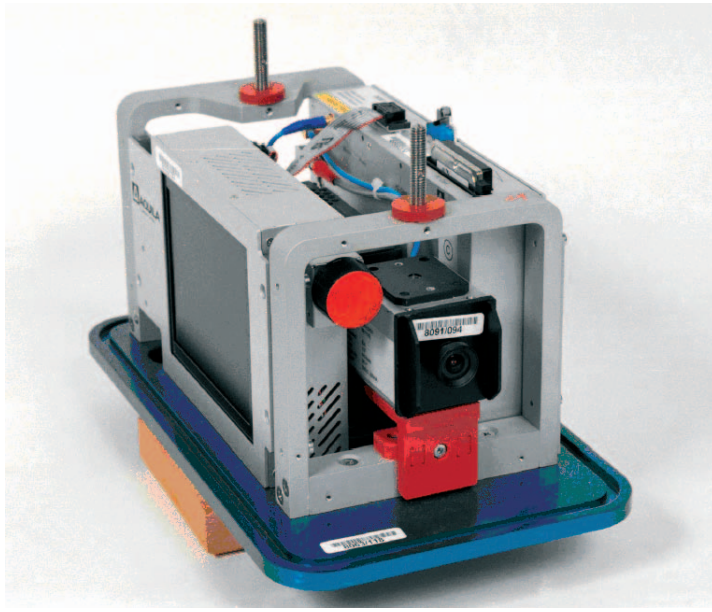

*Figure 5:* ALIS: All In One Surveillance Unit
(courtesy: IAEA, Vienna)


*Figure 6:* DSOS: Digital Single Camera Optical Surveillance System
(courtesy: IAEA, Vienna)

**Installed single camera for easy to access locations**

**ALIS.** The All In One Surveillance Unit (Figure 5) is a mains operated, fully self-contained digital surveillance system based on the DCM 14 digital camera module. 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. Images and associated log files are stored on PCMCIA flashcards. With a 660 MByte flashcard installed, ALIS can record between 40,000 and 50,000 images, depending on the compression used.

**Installed single camera for difficult to access locations**

**DSOS.** The Digital Single Camera Optical Surveillance System (Figure 6) 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.

**Installed multi-camera**

**SDIS.** The Server based Digital Surveillance System (Figure 7) was initially developed for remote monitoring applications. 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 sorts and classifies image and other data and can securely transfer images and data to IAEA offices. 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. Figure 8 shows the internal parts of SDIS. Two modes of operation are available:

(1) Unattended: The data are stored on a removable Jaz-type disk and are physically carried to the GARS equipped review station.

(2) Remote monitoring: The data are transferred to an IAEA office by telephone line (PSTN), ISDN, ADSL, frame relay or satellite link and subsequently reviewed on a GARS equipped review station.

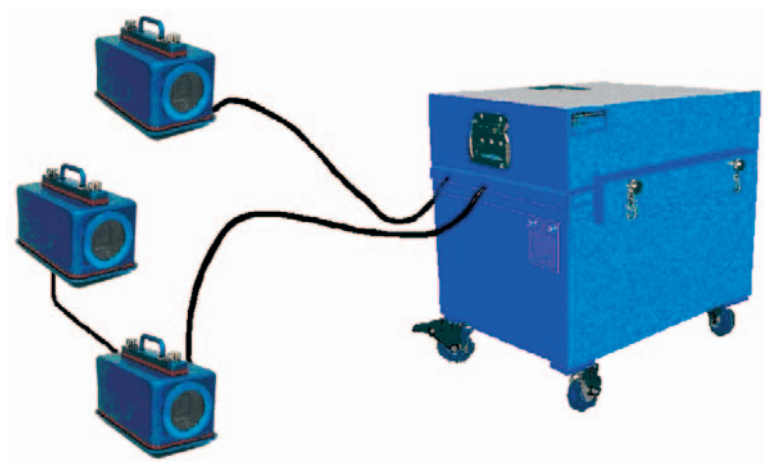

*Figure 7:* SDIS: Server based Digital Surveillance System
(courtesy: IAEA, Vienna)

*Figure 8:* SDIS server ('blue box' – lid open) (courtesy: IAEA, Vienna)

**DMOS.** The Digital Multi-Camera Optical Surveillance (Figure 9) 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 large RAID array prior to final storage on a removable digital linear tape (DLT).

*Figure 9:* DMOS: Digital Multi-Camera Optical Surveillance (courtesy: IAEA, Vienna)

**:Short term surveillance**

**ALIP.** The All In One Surveillance Portable unit (Figure 10) is a battery operated, fully self-contained digital surveillance system based on the DCM 14 digital camera module. It consists of a camera, a video terminal, the DCM 14 digital camera module, a mains operated power supply and a set of batteries, 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. Images and associated log files are stored on PC cards. With a 660 MByte flashcard installed, ALIP can record between 40,000 and 50,000 images, depending on the compression used.

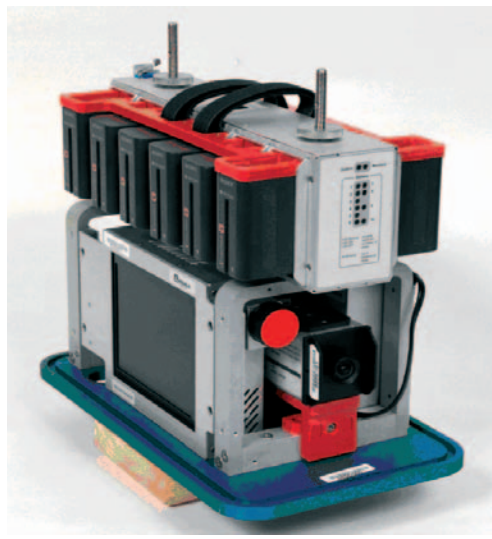

*Figure 10:* ALIP: All In One Surveillance Portable Battery Unit (courtesy: IAEA, Vienna)

**Underwater TV for attended applications**

The portable UWTV system (Figure 11) is mainly used for verifying bundles in spent fuel ponds of CANDU type reactors. It can also be used for all other kinds of underwater inspections. A complete system consists of a radiation hardened camera, a camera control unit (CCU) and various accessories such as a motorized 90 degree rotating head and a light system. Light accessories are available for long and short distance verification activities. For bundle identity verifications, the camera must be capable of reading small letters under limited light conditions and withstand a very high level of radiation, still remaining watertight down to a depth of 15 metres in water. The CCU has a built-in monochrome monitor for on-site review. The video can also be recorded on an external videocassette recorder.

*Figure 11:* UWTV system (courtesy: IAEA, Vienna)

**Surveillance review software**

**MORE.** The Multi-System Optical Review Station (Figure 12) was designed to assist inspector review of COSMOS, MIVS, MXTV and MOSS videotapes. Each MORE system comprises an IBM compatible computer running MORE software (with a built-in DAT drive to archive digitized images), a display unit for the computer, a monochrome video monitor with automatic CCIR/EIA-170 video standard detection, three videotape recorders to replay surveillance tapes and a printer for reports. To utilize the scene change detection option it is first necessary to create set-up files. Regions of interest are defined within the recorded image captured by the camera in the field. Regions of interest are defined in the field of view as areas of safeguards significance (e.g. possible paths for the removal of safeguarded material).

*Figure 12:* MORE: Multi-System Optical Review Station
(courtesy: IAEA, Vienna)

**GARS.** The General Advanced Review Station software (Figure 13) was developed to run on a personal computer with the appropriate media drives to review the recorded images from ALIP, ALIS, DSOS, DMOS, GDTV 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.

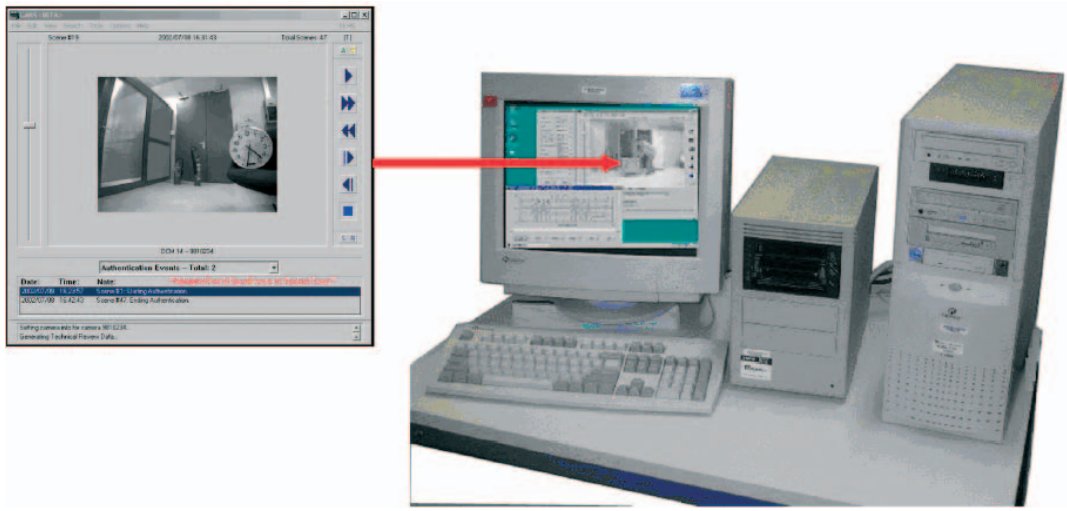

*Figure 13:* GARS software (courtesy: IAEA, Vienna)

**Miscellaneous surveillance systems and options**

In addition to the systems described above, other surveillance systems and equipment to enhance the capabilities of existing surveillance equipment are to be mentioned. Table IV summarizes those systems.

*Table IV:* Optical Surveillance Systems

| Code | Equipment name | Description and applications |
|---|---|---|
| FAST | FAST company surveillance system | Multiple camera digital surveillance system, developed by Euratom for joint use applications. Under evaluation in 2003. |
| LRFO | Laser Range Finder Option | Option for the attachment of DCM 14 based cameras to counter in-front-of-lens tampering. Under development. |
| VMOS | VACOSS-S/MOSS System | Option that allows the integration of the MOSS multi-camera surveillance system with a remotely verifiable VACOSS seal. Phasing out with MOSS. |
| WCSS | Wall Containment Sensor System | Wall penetration detection for triggering surveillance images. Under evaluation in 2003. |

## 7.2 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 the 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.

In 2006, the Agency was using eight types of safeguards authorized sealing devices with a number of other systems under development and not yet authorized for use. We have organized the sealing systems discussion by the categories of passive, active, and special applications. This is not a priority ranking, but it is an ordinal one. That is, the Agency currently fields some 30,000 passive seals a year, the order of 2,000 active seals, and the order of 300 – 500 special application seals.

**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 Agency Headquarters for examination. Passive sealing systems represent by far the most common form of Agency seal.

Metal Seal

The Metal Seal is extensively used for sealing material containers, material cabinets and IAEA safeguards equipment. It is the Agency's most popular single-use passive seal with some 18,000 used annually. The seal has 2 metallic parts which, when engaged, cannot be separated without leaving evidence due to damage. A metal wire 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 main advantages of the seal are its simplicity, physical robustness, and its small size and weight. Attachment and detachment efficiency is important to limit the radiation exposure of the inspector. The main disadvantage is that verification must be performed at the IAEA's headquarters. To this end, the seal is detached in the field by cutting its wire and brought to IAEA Headquarters for identification. Unique identification of each seal is obtained by imaging random scratches on the inside surface of the metal cap and by comparing the images before installation and after removal (Figure 14).

*Figure 14:* Comparison of metal cap seal images for seal validation (courtesy: IAEA, Vienna)

Adhesive Seal

The Improved Adhesive Seal is made of special material which cannot be removed without leaving evidence of seal damage. 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 ease of use, low unit price, and low operations, maintenance, and logistics (OM&L) train. The seal is intended for use in a wire wrap application and on different surfaces (metal, plastic) and is available in two sizes. The Agency uses about 12,000 of these seals per year.

COBRA Seal

The COBRA seal consists of a plastic body and a fibre-optic loop. 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. 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 seal verifier stores digital images and is able to compare the patterns. This procedure enables the inspector to automatically verify the seal identity and integrity in situ and to conveniently store the pattern in a computer. The main advantages of the seal are that it is small, light and inexpensive. This is an in-situ verifiable passive seal (other than the ARC seal, a special applications seal) where multiple verifications on site are possible, a wide temperature range is acceptable, and no electrical power is required. It can stay attached for long periods of time, in some cases, years. The Agency is using about 1,200 such seals per year.

Sample Vial Secure Container

The Sample Vial Secure Container (SVSC) is a small plastic container used to seal liquid samples of nuclear materials. It consists of a small cylindrical body and a cover. A small metal plate with an engraved serial number is inserted inside the cover and the cylinder's bottom. The SVSC is uniquely identified by a pattern (swirls) injected into the mould during fabrication. The main advantages of the SVSC are its small size, ease of use, ability to contain highly radioactive materials (for a limited period of time) and low price. The Agency is currently using about 1,500 SVSCs per year.

**Active Sealing Systems**

Active Sealing Systems require power for the seal to operate. This is usually supplied by a long life on-board battery. In every case, active sealing systems, either fielded or under development, are either fibre optic or electromagnetic loop monitoring devices.

VACOSS 5.0 Electronic Seal

Electronic seals are being used with increasing frequency in IAEA applications as remote monitoring becomes more universally applied. The first IAEA electronic seal, originally conceived in the 1970s, was the Variable Coding Seal System (VACOSS-S), shown in Figure 15. This seal uses electronic encoding methods in conjunction with a fibre optic loop. The VACOSS-S Electronic Seal is intended for high reliability, long duration surveillance in applications that require periodic access. The time, date and duration of openings and closings of the loop are recorded internally for later retrieval. The fibre optic loop is monitored with a light pulse every 250 ms for continuity of the light path. The internal batteries have an operational lifetime of 18 months. For installations with multiple seals in proximity, the seals may be connected in series. All seals connected in this fashion can be read in sequence without changing the connection. The seal electronics are potted, in order to prevent intentional manipulations. A tamper switch detects any opening of the seal housing. The seal housing is opened only to replace the internal batteries and openings are recorded as tamper events. An interface box enables communication between the seal and the reader. The seal is reusable and in situ verifiable. It is mainly used for applications where multiple openings and closings are expected or when the seal is combined with a remote monitoring system. The Agency currently uses about 1,500 such seals in attended and remote monitoring applications. The VACOSS system is being replaced by the EOSS system beginning in 2006/2007. However, VACOSS systems will continue to be used until the full inventory of EOSS systems has been established. This will take several years to accomplish.


*Figure 15:* VACOSS 5.0 Electronic Seal with fibre optic loop, interface box and palmtop computer (courtesy: IAEA, Vienna)

**Special Application Seals**

Special Application Seals may be passive or active, but are typically designed for special applications, perhaps in just a few facilities. They are usually approved for safeguards use in these limited applications only.

Atomic Energy of Canada Ltd. (AECL) Random Coil (ARC) Seal

The ARC seal was developed for underwater applications such as for sealing stacks of spent fuel bundles stored in bays of CANDU reactors. The seal body is mounted on a stud used to fix the fuel in the bay. A reading device is used to obtain the seal's signature, store it and provide verification results. The ARC seal is a single use seal. Multiple in-situ verifications are possible. About 200 such seals are in use, but the seal is rapidly approaching the end of its useful life and a replacement is under development. The seal is constructed to contain a randomly oriented coil of wire. Verification is accomplished by transmitting ultrasonic pulses through the seal with a suitable transducer and observing the unique pattern of reflections. Verification consists of comparing the pattern obtained when installed with that obtained during subsequent in situ checks.

Ultrasonic Sealing Bolt (USSB)

The sealing bolt has been designed for closing and securing shipment and storage containers of LWR spent fuel assemblies in underwater applications. Verification is accomplished by transmitting ultrasonic pulses through the bolt with a suitable transducer and observing the unique pattern of reflections. Verification consists of comparing the pattern obtained when installed with that obtained during subsequent in situ checks.

T-1 Radio Frequency Seal (TRFS)

The first-generation TRFS seal technology is in use at the Savannah River K-Area Material Storage Facility. It is a battery-powered, in-situ verifiable, electronic seal that communicates through an RF link to an interrogator/transceiver. Multiple seal units can communicate with a single interrogator/transceiver up to 250 feet away. The RF transmission is authenticated but not encrypted.

## 7.3 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 closes it. The severity of the 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, continuity of knowledge 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 detector, computer network, data storage and video surveillance equipment. The 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. Presently, there is only one approved design for instrument cabinets.

Nuclear Material Storage Containers

Containers are generally specified by the user facilities, not the IAEA. 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 the many different types of containers with minimum impact on the inspection process and minimum intrusion to the operator. Periodically, the Agency 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, 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.

# 8. Research and Development Projects /11/

## 8.1 Optical Surveillance

The Next Generation Surveillance System (NGSS) is an important IAEA development project in cooperation with the German and United States 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) comprising design of candidate hardware architectures, selection and irradiation testing of crucial components, prototype design, and performance evaluation. 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. Furthermore, review application prototyping and designing of review database and data consolidator were performed.

For the new technology the following features are deemed crucial:

- Cameraunit: Mid- and high-level radiation tolerance, colour imagery, enhanced tamper indication, picture taking at higher frequencies over extended intervals, Ethernet connection with TCP/IP ([16]) protocol, and hardware mostly based on Field Programmable Gate Arrays (FPGA).
- Storagemedia of the digital camera module: It is anticipated that due to obsolescence of the PC-cards the transition to another commercial-off-the-shelf technology will be necessary. At a certain development stage the most appropriate solution has to be found.
- Batterybackup: While for the DCM 14 a Li-Ion battery proved to be the best choice, during the development of the next generation digital camera module this has to be re-evaluated.
- Colour display for portable single-channel system:ruggedness.
- Operating system for multi-channel system:not necessarily mainstream OS such as Microsoft.

## 8.2 Seals

Metal Seal

New developments aim at in-situ verification. Since 2004, work is underway to augment or replace the internal optical signature ("scratch 'n solder" pattern) with an intrinsic surface signature. The laser surface authentication (LSA) method uses a captured laser speckle pattern to create a unique and highly counterfeit resistant physical signature of the top and bottom halves of the metal seal. The top signature can be read in-situ as many times as desired. The bottom signature can be verified upon removal of the seal. In either case, a verification result is available in the field as opposed to a forensic examination at Agency headquarters. A second significant effort is the development of an eddy current wire integrity instrument to detect cut and splice attempts on standard Agency wire. This instrument, if successfully deployed, is the first Agency instrument available to quantitatively check for cut and splice attempts on simple wire.


*Figure 16:* Metal Cap Seal (courtesy: IAEA, Vienna)

([16]) Transmission Control Protocol/Internet Protocol.

Adhesive Seal

Since 2004, the Agency has embarked on the design of a new adhesive seal, using an iterative process between a seals design contractor and a vulnerability assessment team. This approach is maximizing the robustness of the product prior to fielding the next Agency adhesive seal, hopefully in the mid 2007 time period.

Several variants are being considered for special use applications of the adhesive seal:

- Use of one-way chromatic (colour changing) inks or other materials to identify tamper attempts using temperature extremes or solvents.
- Use of optically stimulated luminescent (OSL) materials to produce a dosimetric adhesive seal with a dynamic range of 1 μSv (.1 mR) to 10 kSv (1 MR), compared to current commercial label products with detection sensitivities limited to a minimum threshold of about 50 mSv (5 R).

COBRA Seal

A project to enhance the COBRA seal has been authorized by the Agency and is in Phase III of four phases of development. These enhancements are so extensive that the IAEA considers this project as a new development rather than an evolutionary change to the existing Cobra seal. The following design changes will decrease vulnerability while reducing inspector workload.

- Design changes to the seal and seal verifier to ensure that light is transmitted bi-directionally through the fibre-optic loop during verification.
- Development of a new seal verifier that automatically compares reference and verification data providing a metric that quantifies this comparison.
- Development of a system that allows transmission of encrypted and authenticated seal data to Headquarters electronically.
- Design changes to the seal and seal verifier to automatically identify the seal using a 2-dimensional bar code.

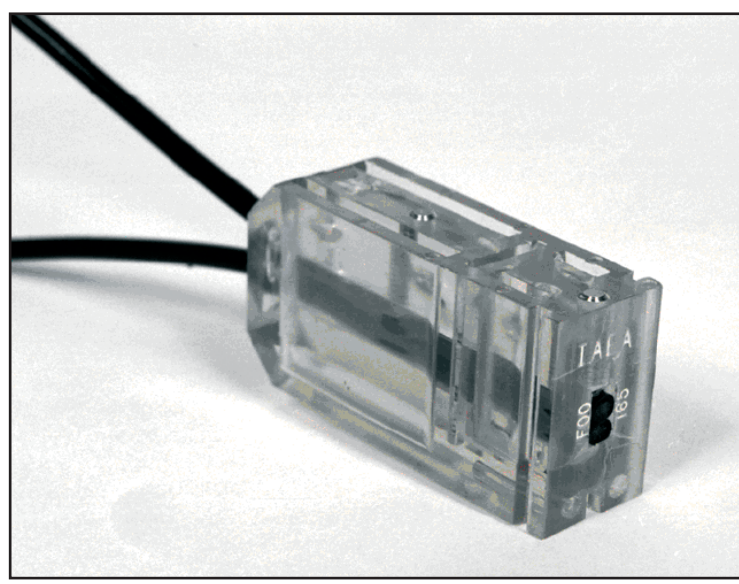


*Figure 17:* COBRA Seal (courtesy: IAEA, Vienna)

Sample Vial Secure Container (SVSC)

Although there is currently a large stock of SVSCs, the manufacturing tools to produce the SVSC have been "mothballed" and it is unknown whether this capability can be restarted. If not, a replacement for the SVSC will have to be developed.

EOSS Electronic Seal

The Electronic Optical Sealing System (EOSS) is the newest active seal system to become a Category A device, being approved for use in 2005. In time, it will replace the current inventory of VACOSS seals, although a phase-in period will certainly be required. Like the VACOSS, it is an active fibre optic loop system, but with enhanced operability in radiation environments and improved tamper resistance characteristics. Also, the EOSS is fully capable of supporting remote monitoring (RM) applications.


*Figure 18:* EOSS Seal (courtesy: IAEA, Vienna)

Hi-G-Tek DataSeal

The Agency is currently testing a new inexpensive commercially available RF seal. This new seal was designed for use in the transportation industry by the Hi-G-Tek company. This seal is a battery-powered, in-situ verifiable, electronic seal that communicates through an RF link to an interrogator/transceiver. An internal battery, providing a 5-year expected life, powers the seal. However, the battery cannot be replaced. The seal must be discarded at the end of its battery life. The IAEA has obtained preliminary test results, including an early vulnerability assessment, which are very promising. In addition to the great interest that safeguards inspectors have indicated in such a seal, it is operationally attractive from an operations, maintenance, and logistics standpoint.

JRC CANDU Seal (JCS)

The European Commission Joint Research Centre CANDU Seal (JCS) is currently under development as a replacement for the ARC seal. The JCS is a derivative of the Ultrasonic Sealing Bolt (USSB). The USSB and JCS are products of the Joint Research Centre, Ispra. Both versions require an ultrasonic reading device, which interrogates both the identity and integrity of the sealing bolts used to contain spent fuel. The seal is also much cheaper than the ARC seal with the reader using Windows as opposed to DOS based software.

T-1 Radio Frequency Seal (TRFS)

Since 2004, the T-1 seal became the first seal capable of remote monitoring from the Headquarters in Vienna and data is monitored routinely.

## 8.3 Containment Systems

Instrument Cabinets

Since 2004, the Agency is pursuing the potential use of x-ray fluorescence (XRF) authentication methods. The system provides an authentication technique for surface areas through the application of elemental XRF compounds, and subsequent reading of those XRF signatures. A feasibility study is envisaged to determine if the method can be used to examine removal and replacement of cabinet panels.

Nuclear Material Storage Containers

The Agency has engaged the Joint Research Centre, Ispra, to determine the feasibility of containment verification with laser surface mapping techniques. In this approach, an entire surface area of a container is scanned with a laser and a reflected amplitude image obtained. Subsequent images generate a matching signature whereas surface penetrations or the wrong container altogether generate a non-matching signature.

Conduits

Since 2004, a bench scale prototype for a conduit monitoring technique has been developed at Oak Ridge National Laboratory in the United States. The technique is able to detect malicious penetrations to the conduit, and distinguish those penetrations from common events such as vibrations and inadvertent cable movements using a proprietary electronic signal analysis method.

ACKNOWLEDGEMENT

Gotthard Stein's invaluable advice during compilation of this article is greatly acknowledged.

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# Nuclear Forensic Methods in Safeguards

K. Mayer ([1]), M. Wallenius

## 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 ten years significant developments in the mentioned area which safeguards can now 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

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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 suffers 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 information measurements and the respective data interpretation provide are expected to prove (or disprove) 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 though 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. 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.

| Isotope | Isotopic Composition [Mass%] | | |
|---|---|---|---|
| | Q1.1 | Q1.2 | Q1.3 |
| $^{234}U$ | 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) | 28.235 (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) |

*Table 1:* Isotopic composition of uranium and plutonium in a seized sample containing radioactive liquor. Measurement uncertainty $U_C$ (k=1) is given in brackets and refers to the last two digits of the isotope abundance.

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 vary 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 (Fig.1).

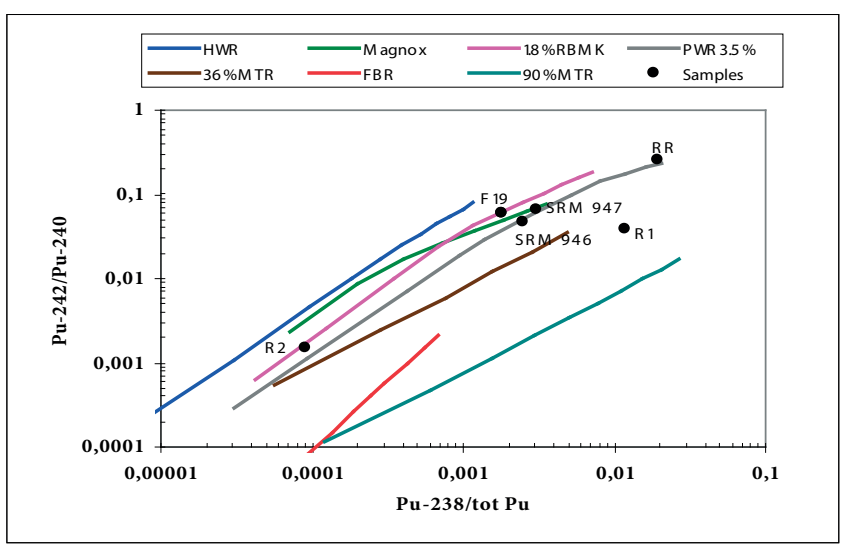


*Figure 1:* Pu isotope correlation for different types of reactors [2]. SRM 946 and SRM 947 (both are NBS certified Pu reference materials) originate apparently from pressurized water reactors, as well as sample RR used in a round robin exercise. F19 and R2 denote seized materials, which can be attributed 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 [3], 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 Pu) as well as on the parent/daughter relation. Fig. 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 (Fig. 2b). The data in the model calculations were obtained by combining burn-up calculations, decay calculations and isotope mixture calculations.

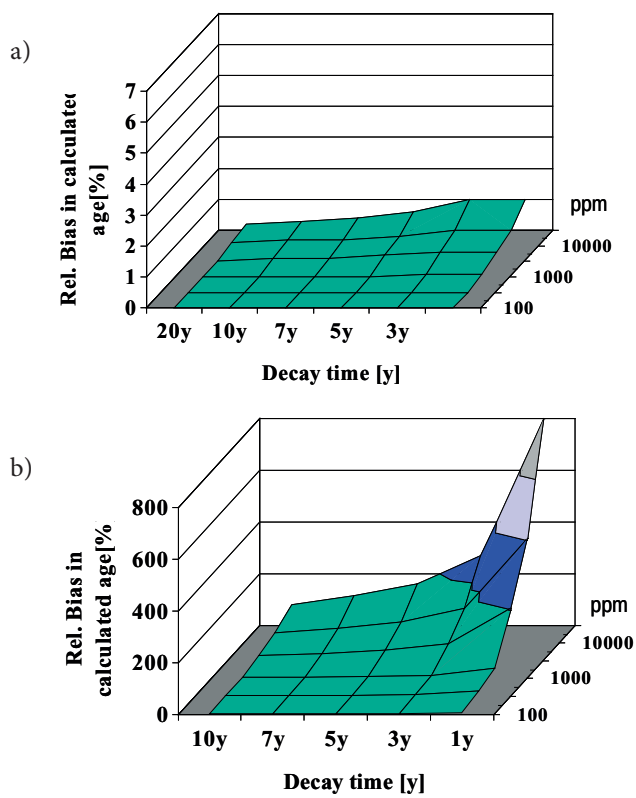


*Figure 2:* Relative bias in the age of reactor grade Pu (a) and weapons grade Pu (b) using the $^{238}Pu/^{234}U$ parent daughter ratio as a function of the age and of the amount of residual uranium [4].

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 [5]. 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 micrometer 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 Fig. 3 that age determination can only be successfully performed for particles of highly enriched uranium.

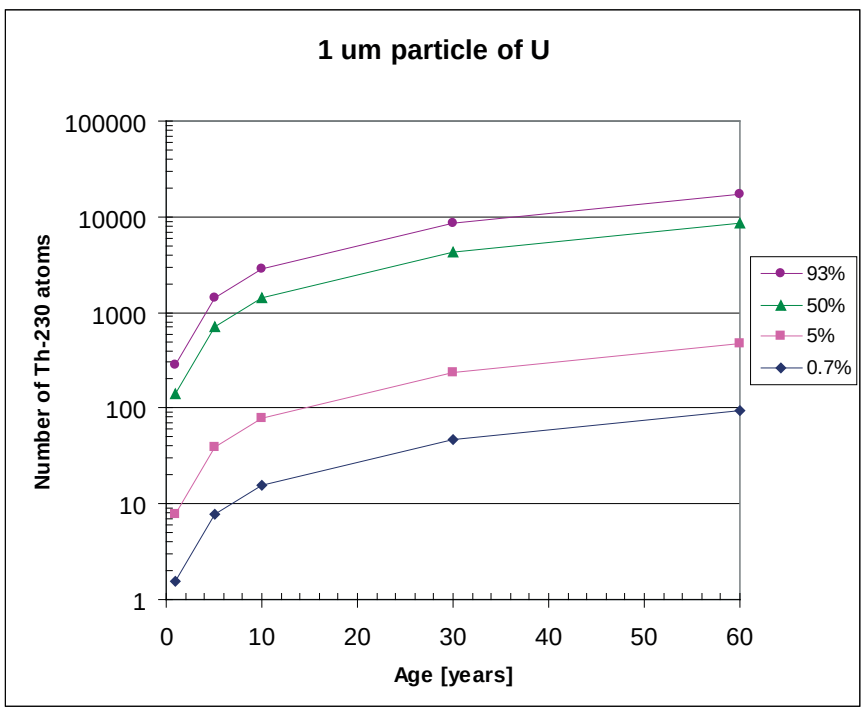


*Figure 3:* The decay of $^{234}$U produces $^{230}$Th. The number of $^{230}$Th atoms contained in a uranium oxide particle (with an assumed number of $10^{10}$ atoms of uranium) depends on the age of the particle and the initial enrichment.

## 3.3 Metallic impurities

Metallic impurities are present in nuclear material samples at varying concentration levels. In starting materials (e.g. ore concentrate) the impurities may have the character of accompanying elements and are present in relatively high concentrations. In intermediate products (e.g. yellow cake) 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.

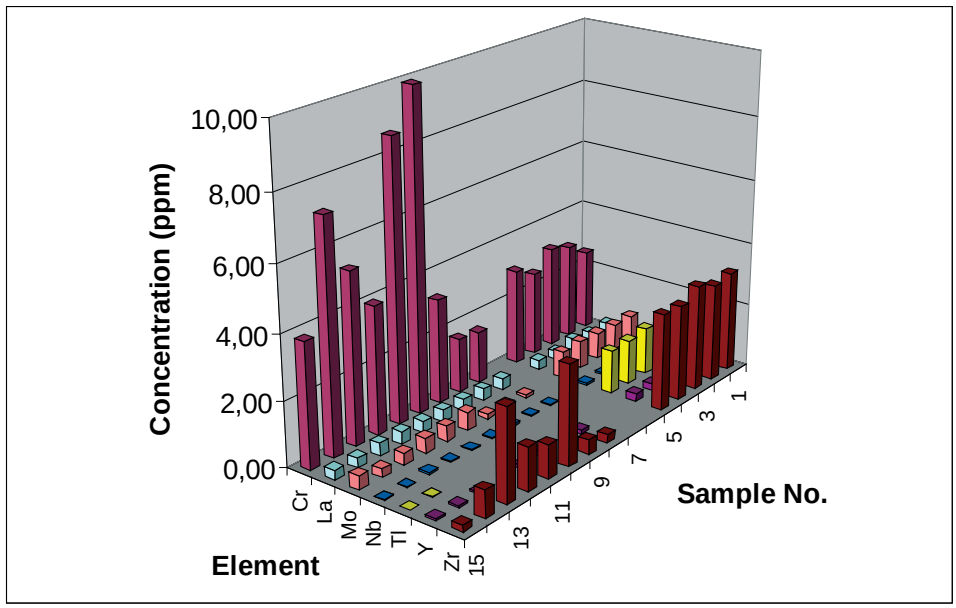


*Figure 4:* Selected metallic impurities in intermediate natural uranium products. Samples 1 to 5 are apparently of the same origin.

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. 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 [6].

## 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 [7]. 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. 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) [8]. 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 [9]. It could be shown that the lead isotopic composition of yellow cake provides useful information to distinguish between natural uranium materials of different origins. 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.

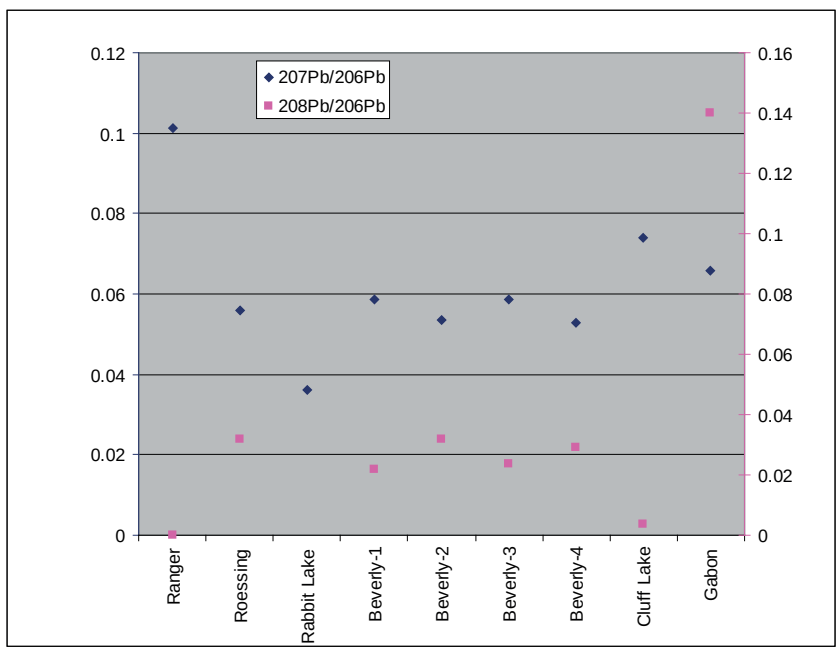


*Figure 5:* Lead isotope ratios observed in yellow cake samples from different mines [9]. Combined uncertainties, $U_c$ (with k=2) on the ratios $n(^{207}Pb)/n(^{206}Pb)$ and $n(^{208}Pb)/n(^{206}Pb)$ are between 0.000 2 and 0.000 08, thus too small to be visualized on the above graph.

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).

| 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* |

*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.

## 3.2 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 6 shows examples of chromatograms obtained from yellow cake samples from Germany and Gabon [10].

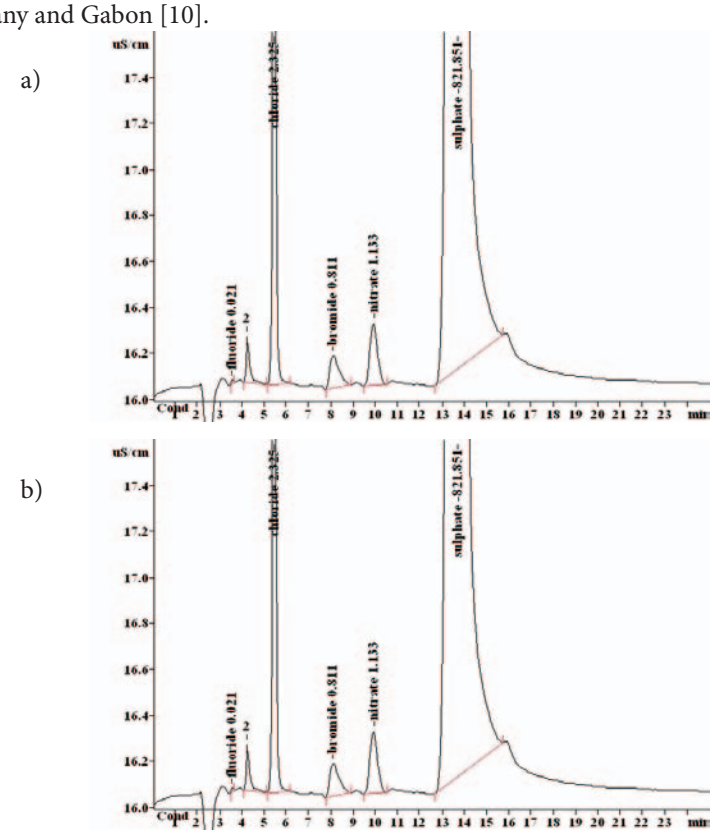


*Figure 6:* Anionic impurities in yellow cake samples from a German mine (a) and from a Gabonese mine (b) by ion chromatography.

## 3.5 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. Fig. 7 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.

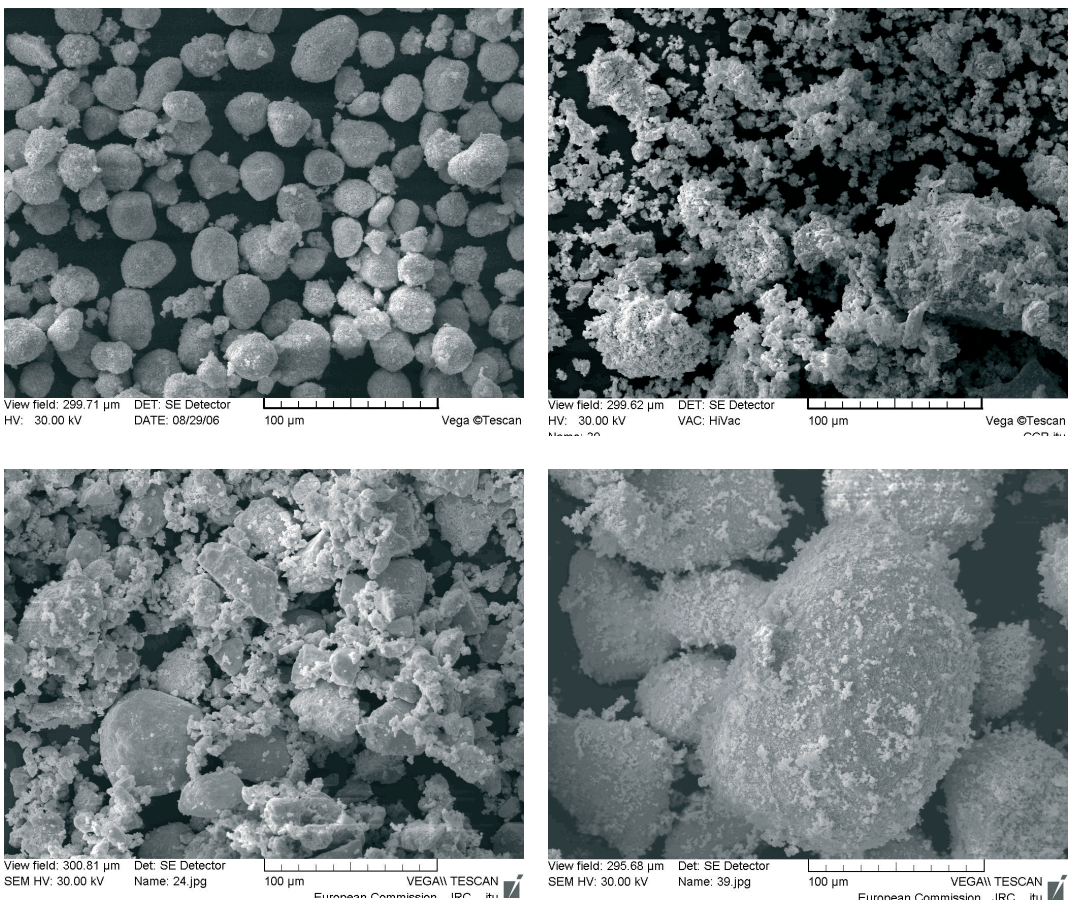


*Figure 7*: Comparison of microstructure in four UF4 samples.

# 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.

## Acknowledgement

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[9] J. Svedkauskaite-LeGore, K. Mayer, S. Millet, A. Nicholl, G. Rasmussen, D. Baltrunas, Radiochim. Acta 95 (2007) 601-605

[10] V. Badaut, M. Wallenius, K. Mayer, Addressing Verification Challenges – International Safeguards Symposium, 16-20 October 2006, Vienna, Austria

# Remote environmental sampling for the detection of clandestine nuclear weapons production and testing

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The verification of arms control treaties is essential for their success. Most critical are situations in which states are not fully cooperative with the inspecting party and in particular, if the inspectors have no access to – or not even knowledge of – the site of activities banned under a treaty. In these cases, the inspectors rely on remote sensing technologies. For the Comprehensive Nuclear-Test-Ban Treaty (CTBT) it was possible to design a verification system that relies on a global remote monitoring system to provide the first evidence of a clandestine nuclear test. On-site inspections would follow as a second step.

In this paper, the emerging capabilities of analysing air samples are described with their benefit for remote verification of nuclear arms control treaties ([1]). These are eminent in two applications. Firstly, krypton-85 and other radioactive isotopes could be used to verify the Nonproliferation Treaty (NPT) because they can indicate unreported production of plutonium. This is not yet put into practise. In part 1 of this paper, the technical capabilities are discussed. Secondly, radioactive debris from nuclear explosions will be used to verify the CTBT. This is covered in part 2 of this paper.

## Part 1: Detection of clandestine nuclear weapons production by atmospheric krypton-85

The methodologies and procedures for detecting non-reported nuclear activities relevant to the NPT have made significant progress since the Additional Protocol was negotiated. During the intrusive inspections in Iraq, new methods have been applied. The International Atomic Energy Agency (IAEA) has gained a legal foundation for enhanced inspections by the member states agreeing on the Additional Protocol in 1997. It has opened the doors for the nuclear inspections capabilities to become more effective and powerful. This is of high importance, since the most significant gap and biggest challenge for verification of nuclear non-proliferation is the detection of clandestine weapons-usable materials production.

The urgency in fixing this verification gap became obvious for the first time with the shock caused by revealing the clandestine nuclear weapons program in Iraq in 1990. The next blow was the expellation of the IAEA inspectors by North-Korea leaving the IAEA with no means to verify whether this country is separating plutonium. In 2002 Iran's unreported uranium enrichment facilities have become known and were then put under on-site inspections and while Iran promised not to build again any unreported facility, there are no operational verification means in place to detect remotely any highly enriched uranium (HEU) or plutonium production that an NPT member state might operate somewhere clandestinely.

([1]) Office of Technology Assessment: Environmental Monitoring for Nuclear Safeguards, Congress of the United States, Washington DC, September 1995. Kalinowski, M.B.; Feichter, J.; Nikkinen, M.; Schlosser, C.: Environmental Sample Analysis. In: R. Avenhaus, N. Kyriakopoulos, M. Richard, G. Stein (eds.): Verifying Treaty Compliance. Springer Berlin, Heidelberg 2006, pages 367-387.

This verification gap is causing distrust in the IAEA nuclear safeguards system and probably increases the escalation dynamics related to Iran's nuclear program. Therefore, part 1 of this paper focusses on the question how scientific research could contribute to closing the verification gap. The goal is to provide the IAEA inspectors with tools for remote detection of clandestine nuclear-weapons-materials production.

Ever since Iraq's clandestine nuclear program shocked the non-proliferation community in 1990, the IAEA tried to improve its nuclear safeguards system. First, the major 93+2 program was set up ([2]). It resulted in the 1997 Additional Protocol ([3]). Although it expanded the legal basis for more comprehensive safeguards activities, hardly anything has so far been achieved in providing the IAEA with technical means to detect clandestine activities from a distance.

Environmental sampling is still restricted to the locations that are routinely visited by inspectors anyway. Satellite imagery has been demonstrated as a powerful tool to detect clandestine facilities ([4]). Consequently, the IAEA established an analysis unit for satellite imagery. However, this tool is used mainly for investigation of known facilities, in particular for preparing inspections and for verifying building outlines as compared to those stated in facility declarations. Though uranium enrichment facilities have a few features that can be observed in satellite imagery (size of buildings, heat generation), this technology is not at all capable of providing an indication of clandestine reprocessing for plutonium (or uranium-233) separation. The operation of the plutonium (or uranium-233) production reactor might be detected by satellite image analysis.

| | | **Satellite images** | | **Air samples** | |
|---|---|---|---|---|---|
| | | **Visible light** | **Infrared** | **Stand-off** | **Regional network** |
| Plutonium production | Reactor | Yes | Yes | Yes | Yes |
| | Reprocessing | No | No | Yes | Larger facilities |
| Uranium enrichment | Conversion | No | No | Yes | Larger facilities |
| | Calutron/EMIS | No | Yes | Yes | No |
| | Gas diffusion | Yes | Yes | Possible | No |
| | Centrifuges | No | No | Unlikely | No |

***Table 1:*** *Detectability of various process steps in the production of fissile materials* ([5]).

Environmental sample analysis might add on satellite image analysis and might even close some of their gaps. Table 1 gives an overview on how the capabilities based on air samples and satellite images compare to each other with regard to the relevant steps in production of nuclear weapons-usable materials.

([2]) The 93+2 program owes its name to the fact that it started in 1993 and was planned for a duration of 2 years so that it would produce sufficient results by the time of the NPT Review and Extension Conference in 1995, in order to provide satisfying answers to the critical issue of clandestine activities. The officially stated goal of the 93+2 program was to enhance the efficiency and effectiveness of nuclear safeguards.

([3]) Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards, INFCIRC/540 (corrected), approved by the IAEA Board of Governors on 15 May 1997.

([4]) B. Jasani and G. Stein (eds.) Commercial Satellite Imagery – A Tactic in Nuclear Weapon Deterrence, Springer, 2002.

([5]) This table is modelled after Table 9.1 in: International Panel on Fissile Materials, Global Fissile Material Report 2007, Chapter 9: Detection of clandestine nuclear material production. www.fissilematerials.org

In 1997 and 1998, a technical committee was brought together by the IAEA in order to study the technical possibilities of Wide Area Environmental Sampling (WAES) under the NPT Additional Protocol. The committee confirmed earlier findings that krypton-85 would be the best suited tracer for plutonium production ([6]). This radioactive isotope is a by-product of breeding plutonium as well as uranium-233. It is released into the atmosphere during chemical separation of spent fuel or special breeding targets. Therefore, it is a good indicator for plutonium separation.

However, the IAEA expert committee concluded that WAES was not feasible due to the enormous costs. According to this study, a network of monitoring stations with 25 km grid size, operating continuously, would be needed to cover relevant parts of the globe. Even if regions which lack the required infrastructure for clandestine reprocessing facilities were omitted, the whole system would require hundreds or even thousands of expensive detectors. The report ([7]) of the technical committee was printed by the IAEA but has never been released to the public, although it is often referred to and even quoted in publications by experts who had served as committee members ([8]).

In spite of the lack of transparency, the following became known about the study. The simulation methods applied were outdated and the study was clearly biased against WAES; accordingly, the conclusion was that WAES is infeasible. The requirements on WAES defined by the study were far too demanding. New sensor technologies were not taken into account. In particular the ultra-sensitive trace analysis of krypton-85 allows for a radical cost reduction. The proof of principle for using atmospheric krypton-85 to detect plutonium production at a distance was given by a case study on the German pilot reprocessing plant at Karlsruhe ([9]).

Progress in safeguards methodologies based on environmental sampling is not only urgently needed with regard to the Model Additional Safeguards Protocol related to the NPT. It would at the same time address verification issues for a Fissile Materials Cutoff Treaty (FMCT). For both treaties, further scientific-technical work is required and would support political progress in non-proliferation and disarmament of nuclear weapons. Even without a formal agreement, it would be highly beneficial to develop and demonstrate verification means that could be used as national technical means or by NGOs and independent citizens to detect clandestine nuclear activities, especially those related to fissile material production.

A new opportunity occurred when the IAEA Board of Governors decided in 2004 to call for help in exploring novel technologies and verification approaches to detecting clandestine activities. The IAEA started its Novel Technologies Program ([10]) and collected technical proposals from member states. In April 2005, the IAEA organized a workshop on detection of uranium enrichment. In September 2005, the IAEA hosted a Technical Meeting on Noble Gas sampling and monitoring, and in August 2006 another one on Laser Spectrometry Techniques. The purpose of these meetings was to explore future research and development needs for applying these new methods to nuclear safeguards under the NPT Additional Protocol.

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([6]) Kalinowski, M.B.: Measurements and Modelling of Atmospheric Krypton-85 as Indicator for Plutonium Separation. In: C. Foggi, F. Genoni (eds.), Proc. Workshop on the Status of Measurement Techniques for the Identification of Nuclear Signatures, Geel, Belgium, 25-27 February, 1997, EUR 17312 EN, pages 67 72.

([7]) Use of Wide Area Environmental Sampling in the Detection of Undeclared Nuclear Activities, Member State Support Programs to the IAEA, STR-321, 1999.

([8]) For example P.W. Krey, K.W. Nicholson, Atmospheric sampling and analysis for the detection of nuclear proliferation, Journal of Radioanalytical and Nuclear Chemistry 248, No. 3 (2001), pp. 605-620.

([9]) Kalinowski, M.B.; Sartorius, H.; Uhl, S.; Weiss, W.: Conclusions on Plutonium Separation from Atmospheric Krypton-85 Measured at Various Distances from the Karlsruhe Reprocessing Plant. Journal of Environmental Radioactivity 73/2 (2004), 203-222.

([10]) J. Whichello, D. Parise, and N. Khlebnikov: IAEA Project on Novel Techniques. INESAP Information Bulletin No. 27, pages 27-30. http://www.inesap.org/bulletin27/art07.htm

Visionary thinking combined with cutting edge science and technology is required to identify practical procedures for remote environmental sampling. This can only be achieved by a group that is not bound by diplomatic constraints and short term approaches. To address these needs and to support the IAEA in developing new verification methodologies, the International Network of Engineers and Scientists Against Proliferation (INESAP) facilitated the establishment of an independent Group of Scientific Experts (iGSE) ([11]). This network of specialists is attempting to follow the precedence set by the highly influential work of independent expert groups who supported progress towards a nuclear test ban treaty in the past ([12]).

The goal for the iGSE will be to develop and demonstrate technologies and procedures for remote sensing and other novel methodologies that allow detection of clandestine nuclear-weapons-usable materials production. The expected outcome will be technical progress in related verification methodologies, their demonstration in field exercises, and the public availability of new measurement results as well as of conclusions that can be drawn with respect to production of plutonium and highly enriched uranium (HEU) production. The unique features of this project are the combination of the required expertise; the independence of scientists from governmental, diplomatic and organizational interests; and ensured unrestricted publication of the results.

The technical areas to be considered by the iGSE should focus on the issues with the greatest urgency and the best prospects for significant progress. Therefore, environmental sampling is selected as the first topical focus.

The most promising new sensor technology is a novel ultra-sensitive trace analysis of krypton-85 ([13]). It will allow for radical cost reductions in any concepts of sampling and analysing air for nuclear safeguards. The technology is now being developed at the Carl Friedrich von Weizsäcker Center for Science and Peace Research at the University of Hamburg. It is based on an atom trap and, therefore, called atom trap trace analysis (ATTA). This method is highly selective and sensitive because only krypton-85 atoms are selectively guided by laser beams that are finely tuned to the atomic energy levels into a magneto-optical trap where they rest for up to a second while they are identified by their fluorescence quanta. One by one they are counted. The first such device has been built at the Argonne National Laboratory and went operational in 1999. It is used for ground water and ice core dating studies and had not been previously considered for safeguards applications.

The research project at the University of Hamburg has two goals. The efficiency of counting krypton-85 atoms will be increased and the instrument will be optimized for applications in the field. The main advantage of ATTA in comparison to the traditional beta counting method is the required sample size. In order to achieve the wanted minimum detectable concentration with one-hour beta counting a sample volume of 100 liter air or more has to be taken. This needs to be pre-processed in the field in order to reduce the volume of the shipping container. The pre-processing removes the noble gas fraction from the air by cryo-adsorption. Since this requires liquid nitrogen, a carrier gas and electric power in the field, sample taking is too expensive for large scale routine applications. In contrast, ATTA could be successfully applied to samples of 1 liter. This would be very cost-efficient. If applied as random sampling during routine inspections, the air sampling would cause almost no additional costs.

([11]) iGSE: Detection of Clandestine Production of Nuclear-Weapons-Usable Materials. Project Summary INESAP Information Bulletin No. 27, pages 4-8. http://www.inesap.org/bulletin27/art01.htm

([12]) The Group of Scientific Experts (GSE) was formed in 1976 at the Conference on Disarmament in Geneva. It coordinated and focused the worldwide development of verification technologies and analysis methods for a comprehensive nuclear test ban treaty. Most importantly, it demonstrated them in technical experiments called GSE Technical Tests (GSETT-1 in 1984, GSETT-2 in 1991, and GSETT-3 started in 1995).

([13]) Kalinowski, M.B.; Daerr, H.; Kohler, M.: Measurements of krypton-85 to detect clandestine plutonium production. INESAP Information Bulletin No. 27, pages 9-12. http://www.inesap.org/bulletin27/art02.htm

Regarding Wide Area Environmental Sampling, the future improvements in implementing a sampling scheme based on ATTA could raise the usefulness and quality of krypton-85 sampling in comparison to the monitoring scheme that was previously studied and discarded due to its high costs.

Shorter sampling periods could reduce the detection thresholds by one order of magnitude. Mobile air samplers could be used instead of having stationary monitoring sites. The mobility would allow the inspection agency to undertake surprise measurements on very short notice.

However, it still remains unclear to what extent and under what conditions remote sampling in combination with transport modelling can detect clandestine plutonium separation of significant quantities with sufficiently high detection and low false alarm probability. In order to evaluate this, simulation studies are under way at the University of Hamburg in cooperation with the Max Planck Institute for Meteorology and the Meteorological Institute of the University Hamburg ([14]). The study is carried out as task under the German Support Program for the IAEA ([15]).

Atmospheric transport simulations will be used to determine optimum procedures for location-specific and wide area environmental air sampling to detect clandestine reprocessing activities. Based on the results on sensitivity and source attribution, the inspection procedures will be optimized in order to achieve maximum detection probability with optimum source location.

The goal is to provide the IAEA with all information and technology required to implement this krypton-85 tracer approach and to close the safeguards gap regarding the detectability of clandestine plutonium production.

For detecting unreported production of highly enriched uranium, the task is even more challenging, because the signatures are weaker. In fact, they appear to be too weak to be even detected with a stand-off system in close vicinity of the release point. In this inspection scenario, the IAEA would apply a mobile system that could sense the off-gases of industrial facilities from outside their fence. Even under the assumption of a source strength that is 100 times larger than commercial uranium centrifuge enrichment plants, the emitted concentration would be too low. For a LIDAR (laser radar) system tuned at the most sensitive excitation energy for the UF6 molecule, the detection limit is three orders of magnitude below the expected concentration right above the stack ([16]).

# Part 2: Detection of clandestine nuclear weapons test by atmospheric radioxenon

The Comprehensive-Test-Ban Treaty (CTBT) has been 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 178 states and ratified by 144 (as of March 2008), 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.

([14]) Kalinowski, M.B.; Feichter, J.; Roß, O.: Atmospheric krypton-85 transport modelling for verification purposes. INESAP Information Bulletin No. 27, pages 17-20. http://www.inesap.org/bulletin27/art04.htm

([15]) Task C.38 Simulation of Atmospheric Noble Gas Concentrations to Assess Sampling Procedures for the Detection of Clandestine Reprocessing

([16]) Bösenberg, J.: Kalinowski, M.B.: Detectability of Atmospheric UF6 and HF as Indicators for Uranium Enrichment with Lidar. INESAP Information Bulletin No. 28. To be published in April 2008.

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 321 stations in order to monitor the whole globe. 250 of these have already been built by March of 2008. It 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 ([17]). More precisely, the radionuclide network consists of three components: 80 particulate stations, 40 noble gas systems ([18]) collocated with particulate stations and 16 radionuclide laboratories ([19]). 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 ([20]).

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.

Atmospheric and underwater tests release a large amount of radioactivity and will easily be detectable. The challenge is to detect traces from underground explosions. Even if they are designed for full containment, there is always a risk that the containment fails and radioactivity is released unintentionally into the atmosphere. 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.21 The isotopes that are most likely released are gaseous non-reactive fission products. Due to their fission yield and half-lifes, there are four CTBT relevant noble gas isotopes, Xe-135, Xe-133m, Xe-133 and Xe-131m ([22]).

([17]) Hoffmann, W., R. Kebeasy and P. Firbas (1999): Introduction to the verification regime of the Comprehensive Nuclear-Test-Ban Treaty. Physics of the Earth and Planetary Interiors, 113, 5-9.

([18]) The number of 40 noble gas systems is a compromise after some delegations were hesitant during the Geneva negotiations to agree to this technique at all. A noble gas test experiment performed at the Institute of Atmospheric Radioactivity in Freiburg, Germany, convinced all interested parties of the advantage to have noble gas systems. It is up to the Conference of States Parties to decide after Entry into Force of the CTBT to increase the numbers of noble gas systems.

([19]) Schulze, J., M. Auer and R. Werzi (2000): Low level radioactivity measurement in support of the CTBTO. Applied Radiation and Isotopes 53, 23-30.

([20]) Kalinowski, M.B.: Comprehensive Nuclear-Test-Ban Treaty CTBT Verification. In: R. Avenhaus, N. Kyriakopoulos, M. Richard, G. Stein (eds.): Verifying Treaty Compliance. Springer Berlin, Heidelberg 2006, pages 135-152.

([21]) C.R. Schoengold, M.E. DeMarre, E.M. Kirkwood. (1996). Radiological effluents released from U.S. continental tests 1961 through 1992. United States Department of Energy – Nevada Operations Office, DOE/NV-317 (Rev.1) UC-702, Las Vegas, August 1996.

([22]) De Geer, L.-E. (2001): Comprehensive Nuclear-Test-Ban Treaty: relevant radionuclides. Kerntechnik 66/3, 113-120.

The challenge of monitoring atmospheric radioxenon concentrations results from the fact that many nuclear facilities release the relevant isotopes as normal operational release ([23]). 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 ([24]). 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 ([25]).

The announced nuclear test undertaken by North Korea on 9 October 2006 was a chance to demonstrate the functionality of the radioxenon monitoring system ([26]).

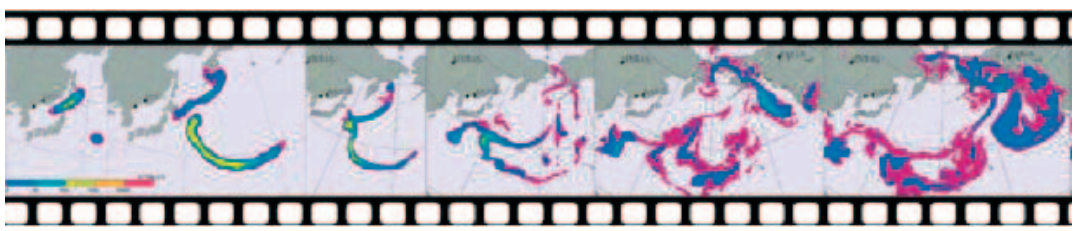

***Figure 1:*** *"The above film strip shows from left to right the movement of the xenon-133 plume interms of calculated ground level concentrations assuming a surface emission of 1015 Becquerel at the time and coordinates of the 9 October event . The scene on the far left illustrates how the plume starts travelling to the east, while the shots on the far rights how the plume arriving at the Yellowknife station (CAX16)."* ([27])

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."* ([28])

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 week, 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.

([23]) Kalinowski, M.B.; Tuma, M.P.: Global radioxenon emission inventory based on nuclear power reactor reports. Submitted to Journal of Environmental Radioactivity in March 2008.

([24]) Kalinowski, M.B.; Pistner, Ch.: Isotopic signature of atmospheric xenon released from light water reactors. Journal of Environmental Radioactivity, Volume 88/ 3 (2006), 215-235. http://dx.doi.org/10.1016/j.jenvrad.2006.02.003

([25]) Gerhard Wotawa, Philippe Denier, Lars-Erik DeGeer, Martin B. Kalinowski, Harri Toivonen, Real D'Amours, Franco Desiato, Jean-Pierre Issartel, Matthias Langer, Petra Seibert, Andreas Frank, Craig Sloan and Hiromi Yamazawa: Atmospheric transport modelling in support of CTBT verification – Overview and basic concepts. Atmospheric Environment 37 (18) 2529-37.

([26]) Kalinowski, M.B.; Ross, O.: Data analysis and interpretation of the North Korean nuclear test explosion of 9 October 2006. INESAP Information Bulletin No. 27, pages 39-43. http://www.inesap.org/bulletin27/art12.htm

([27]) Idid.

([28]) Provisional Technical Secretariat of the CTBTO PrepCom: Press Information PI/2008/05, 26 February 2008. www.ctbto.org

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: ([29])

> *"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 North Korean explosion being of nuclear nature, this is still not a robust proof.

The doubts whether North Korea has in fact tested a nuclear device were addressed by a short statement based on national technical means of the USA. It is quoted in full length here: ([30])

> *"Analysis of air samples collected on October 11, 2006 detected radioactive debris which confirms that North Korea conducted an underground nuclear explosion in the vicinity of P'unggye on October 9, 2006. The explosion yield was less than a kiloton."*

Unfortunately, no details were provided about what exactly the US air plane collected on its flight over the Japanese Sea. The word "confirm" indicates that the findings of the sample analysis might not have been clear enough to legitimate the use of the stronger word "proof".

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 cost close to the Demarcation line between the two Korean states between 11 and 14 October ([31]).

([29]) Paul R.J. Saey, Andreas Becker and Gerhard Wotawa: North Korea: a real test for the CTBT verification system? Part II: noble gas observations. Spectrum Issue 10, August 2007, pages 20-21.

([30]) Office of the Director of National Intelligence, Public Affairs Office: Statement by the Office of the Director of National Intelligence on the North Korea Nuclear Test. ODNI News Release No. 19-06, Washington, 16 October 2006.

([31]) Ringbom, A., Elmgren, K., Lindh, K.: Analysis of radioxenon in ground level air sampled in the Republic of South Korea on October 11 – 14, 2006. Report FOI-R-2273-SE, Stockholm 2007.

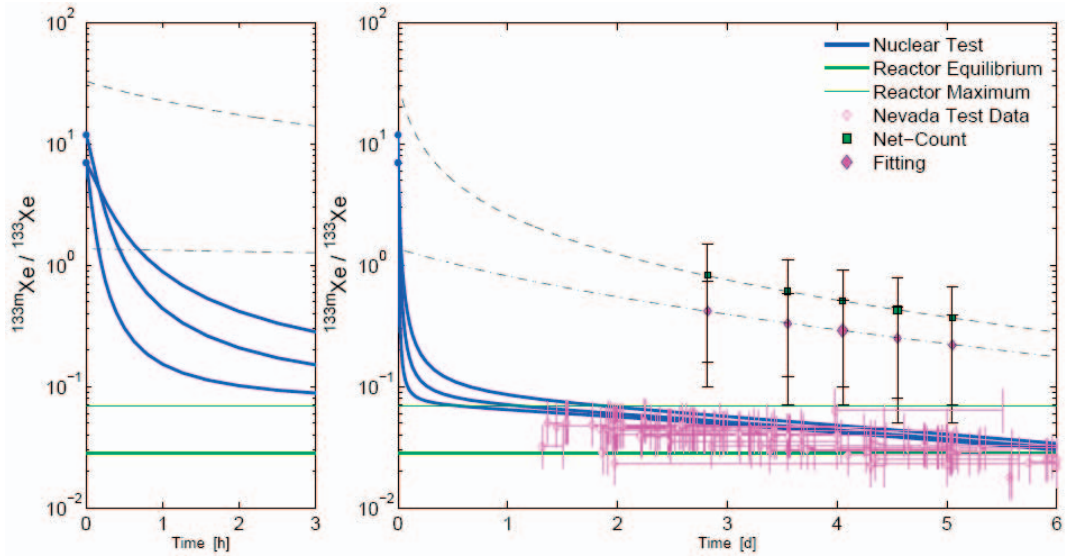


***Figure 2:*** *Isotopic ratio of Xe-133m/Xe-133 as it develops over time after the explosion. The data from samples taken in South Korea in October 2006 are put in perspective with historic data from the Nevada Nuclear Test site and simulated curves that follow the radioactive decay for various scenarios.*

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. 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).

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 ([32]) as well as historic data as reported from the Nevada Test Site ([33]). 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

([32]) M.B. Kalinowski, Ch. Pistner (2006).
([33]) C.R. Schoengold, M.E. DeMarre, E.M. Kirkwood. (1996).

occur in nuclear reactors. The Nevada data lie in the range of the reactor ratios and suggest that no discrimination is possible 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 North Korean 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.

# Conclusions

Improving verification capabilities is an important contribution that scientists can make to help to solve a problem that could otherwise lead to the escalation of a conflict. In particular, closing the verification gap related to clandestine nuclear-weapons-materials production is of high urgency. Together with other new technologies and inspection procedures this will hopefully provide the IAEA with the technical capabilities of the IAEA to detect any possible clandestine activities in countries like Iran. As a result, trust in verification could be gained and further escalation of conflicts about suspect nuclear programs could be prevented and the danger of preemptive measures could be minimized.

CTBT verification would remain inconclusive unless radioactivity is detected. It needs to be taken into consideration that radioactive emissions frequently occur from legitimate sources. The risk of false alarms has to be minimized by smart analysis methods. Their basic principles have been developed and their applicability has been successfully demonstrated for the North Korean nuclear test of October 2006.

These new verification technologies will have to be put in perspective to the long-term goal of a nuclear-weapons free world. Environmental monitoring activities will play an important role in facilitating future treaties like the proposed Nuclear Weapons Convention and gain importance if less nuclear facilities are present.

# Environmental Sample Analysis

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## 1. Introduction

Environmental sample analysis becomes increasingly important for treaty verification. The first applications date back to the beginning of nuclear weapons programs. The first treaty verified with environmental sampling activities as national technical means (NTM) is the Partial Test Ban Treaty (PTBT, 1963). For the Comprehensive Nuclear-Test-Ban Treaty (CTBT, 1996) measurement of atmospheric radioactivity represents one out of four sensor technologies applied for the International Monitoring System (IMS) that is currently being established. After the 1st Gulf war, the monitoring and verification mandate gave IAEA strong tools to apply various nuclear material- and radioactivity measurements in Iraq since 1991. The successful implementation of environmental sampling in Iraq was the baseline for further development. Following the 93+2 development programme for enhancing the effectiveness and efficiency of nuclear safeguards for NPT (Non-Proliferation Treaty, 1968) verification, the IAEA started to apply routinely swipe sampling in nuclear facilities.. Environmental sampling got an enhanced legal basis with the Additional Protocol in 1997 which includes provisions for both location specific and wide-area environmental sampling.

Detection of relevant radioactive indicators in the environment poses a strong opportunity for treaty verification. The full potential of this method develops with the recent advances in powerful methods for determining possible source areas with atmospheric transport simulations. 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. The Provisional Technical Secretariat of the CTBTO Preparatory Commission in cooperation with the World Meteorological Organisation is currently putting this ground-breaking approach for source location in an operational mode.

This paper puts a focus on measuring radioactivity in the atmosphere because this kind of environmental sample analysis has found the broadest range of application for the verification of international agreements. However, there are other opportunities related to environmental sampling of non-radioactive tracers, for example greenhouse gas emissions with relevance to the Kyoto Protocol. It can be expected that the increasing number of applications, the growing experience and the related scientific progress with regard to analysis of air samples for radioactivity will also promote similar applications on non-radioactive tracers for the verification of international agreements.

## 2. Definitions, goals and general procedures

The *environmental sampling* for various treaty verification purposes is rather broad issue. In this chapter it means that a sample is taken from the ambient environment in order to analyze it for traces of chemical compounds, elements or isotopes that can serve as an indicator that is relevant for the verification purpose. This indicator can be identical to or part of the characteristic signature that is created by the activity or facility being investigated. Since this paper deals mainly with applications in the context of nuclear arms control and non-proliferation, the tracers of interest are radioactive isotopes.

Unlike the sampling that occurs inside the inspected and verified processes, environmental analysis needs some kind of carrier that is dispersing the signals and keeps them in a form where they can be collected. Typical *sampling media* are air, water, biota and soil. If environmental samples are taken continuously over extended periods of time without interruption, time series can be analyzed in order to detect anomalies and changes of background tracer levels. This is a special case of environmental sampling called *monitoring*.

Dispersion may occur for basically any release but the distribution of signatures in the environment is especially effective for gases and small particles. Typically the release is travelling in 3-dimensional space and when sampled in sufficient volume it may reveal a signature of interest. Environmental traces are naturally the strongest the closer the sample is taken to the release point. The environmental monitoring can even occur inside the building that is to be verified. On equipment surfaces, the signal can be so strong that simply by cleaning the surface with a cotton swipe is collecting enough material for verification purposes.

It is also important to notice that environmental sampling is a *dynamic process* with respect to time. The sample taken represents the traces of that particular location in space and moment in time. It may also contain traces of the past either by accumulation over time or due to mixing and re-suspension. This is especially true when collecting samples close to sites where the emissions are frequent. The verified substances may also decay, for example by radioactive decay or by chemical reactions. Decay may occur before or after the sampling and also during the sampling process in case of extended sample periods.

The *detection goal* depends on the treaty obligations to be verified. The major purposes for environmental sample analyses are the following.

- Detect the existence ofa clandestine facility and its location
- Determine the source strength
- Verification ofdeclarations
- Verification ofnon-existence by complementary access

Typically the *verification procedure* based on environmental signals is following this pattern:

- First,the scope of verification defines where to take the samples, the used technique, the amount of samples needed to cover necessary signals (either presence of signals or absence of them).
- Samplesare collected as described in procedural instructions. To ensure the integrity of samples some precautions may be necessary to make sure that the sampling is not mixing signals from other places or that a relevant signal is not missed.
- Theenvironmental sample is measured and the measurement result is analyzed. This can be a challenging scientific problem, if the verification requires that even very small signals close to the detection limit need to be measured.
- Aftercompleting the analysis, the analyst may have quite detailed results at hand. It still needs to be evaluated whether the detected signal is reliable and if the result is in line with declared facts.
- Basedon the overall understanding of uncertainties, detection limits and representativity of the sample, one can draw (or refuse to draw) the final conclusions based on verification criteria.

# 3. Applications

## 3.1 Early applications

Before environmental sampling became a verification procedure for arms control treaties, it has been extensively applied secretly by governmental agencies and laboratories as well as openly by independent scientists. Already in the fall of 1944, the method of xenon-133 detection in atmospheric air samples was used for the search of evidence for reactor operation in Germany. In 1949, the Soviet Union was not able to keep its first nuclear explosion secret, because the analysis of aerosol particles in air filter samples taken by the US Air Force revealed the evidence.

Since 1951, the USA determined the amount of Russian weapons plutonium production from the total atmospheric content of krypton-85 by subtracting the known sources (Operation "Bluenose"). All krypton-85 in the atmosphere was released during the reprocessing of nuclear fuel elements or plutonium breeding targets. Towards the height of the arms race in the Cold War, this method was applied and the results published by independent scientists (Sittkus/Stockburger 1976; von Hippel/Albright/Levi, 1986). Atmospheric nuclear testing released significant amounts of radioactivity into the atmosphere and was distributed within one or two weeks across a whole hemisphere. It rested for months and years in the stratosphere. The fall-out was detected world-wide in all kinds of media. Typically, hot particles were identified in air filters or on vegetation; radioactive noble gases were found in atmospheric air samples; fission and activation products were found in precipitation, sediments, surface waters and agricultural products.

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 kilometers, detected and traced back to the source.

## 3.2 UNSCOM IAEA and UNMOVIC

Before the 1990's, the verification of the NPT made no use of environmental sampling in the sense covered in this paper. The nuclear safeguards were focusing on declared facilities and materials to detect the diversion of nuclear material handling facilities for nuclear weapons purposes. Only non-routine swipe samples were applied under certain circumstances. A significant step forward for environmental monitoring occurred while searching for the weapons-of-mass-destruction programs in Iraq just after the first Gulf war by UNSCOM, IAEA and UNMOVIC (Donohue and Zeisler, 1992). The discovered environmental traces of biological, chemical and nuclear weapon developments were crucial prove for understanding what kind of clandestine programs Iraq was running. During the

inspections the inspectors got access to the facilities where the development was going on, the picture was forming piece by piece and the evidence given by environmental samples was so obvious that it did not leave space for denial of programs (Baute, 2005).

This was an important step also for the nuclear material safeguards. A new method was introduced that could even after a long period of time reveal the use of undeclared materials. When the IAEA started a process to strengthen the safeguards system, environmental sampling played a very important role.

## 3.3 From Program 93+2 to the Additional Protocol to the NPT

One of the main goals of the so-called Program 93+2 to enhance the efficiency and effectiveness of nuclear safeguards was to develop methods for detecting clandestine nuclear activities. This effort led to the negotiation of the Model Additional Protocol (INFCIRC/540, 1997). Since this protocol has began to be implemented (Cooley, 2005), environmental sampling is not only complementing the assurance of presence of declared materials; it is used also to assure the absence of undeclared materials and activities. This approach is currently extensively being used for safeguards by taking cotton swipe samples inside inspected facilities during inspections and during complementary access to locations and sites.

The Additional Protocol has the potential of increasing the importance of environmental sampling even further as more sampling methods may be introduced. It distinguishes two different approaches under the provision of complementary access. The location-specific environmental sampling in Article 6 can already be applied to certain special locations of interest with regard to nuclear materials. Its purpose is to resolve discrepancies in the range of adjacent facilities.

In Article 9, the Additional Protocol foresees so-called wide-area environmental sampling that could be conducted anywhere in a country under inspection. This would in the future enable the collection of nuclear material traces further away from nuclear facilities, tens or even hundreds of kilometres away from a facility handling nuclear materials (Nicholson, 2004). However, according to Article 9, "the Agency shall not seek such access until the use of wide-area environmental sampling and the procedural arrangements therefore have been approved by the Board" of Governors. Further research is under way to provide a scientifically sound basis for an assessment of the effectiveness of this method under certain assumptions regarding procedural arrangements. Especially, the related methods are under field-testing, and the results are promising from the verification point of view.

If the environmental sampling is used for verification purposes, one has to take care of the sample chain of custody, so that in the end the conclusions can be drawn with high assurances that the sample has not been tampered, changed or contaminated. Therefore, the sealing of the samples and proper containment are necessary requirements. The purity of the samples has to be assured. In some cases, the traces used for verification are less than nanograms of material. This is why the laboratories are required to always analyze a set of blank samples to assure the absence of cross contamination of real samples.

## 3.4 CTBT

The Comprehensive-Test-Ban Treaty (CTBT) has been opened for signature in September 1996. Though the CTBT has been signed by 175 states and ratified by 121 (as of May 2005), 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. This will consist of 321 stations using four different sensor technologies to detect seismic, infrasound, hydroacoustic or

radioactivity signals (Kalinowski, 2005). 80 of these stations have radioactivity detectors. Two parallel systems are being installed, one for the measurement of radioactive particles on filter samples, the other for radioactive noble gases.

The most likely future scenario for a clandestine nuclear test is an underground explosion. Radioactive material produced during underground testing could be released into the atmosphere by leaking through geological faults. Since gases have a larger probability of being released in this way than particle-bound radioactivity, noble gas monitoring is very important. Additional advantages of noble gases are that they are chemical inert and that they 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 (T.W. Bowyer et al., 1998).

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 is the fact that these are the released to the atmosphere by nuclear power plants during routine operations. The relative abundance of different radionuclides in the samples can be used to determine whether a nuclear reactor or an explosion produces the material. 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.

The radionuclide stations submit regularly their measurement data to the International Data Centre (IDC) in Vienna. The IDC does the analysis and sends reports to the member states. 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%.

## *3.5 Future opportunities*

Since many years, there is broad consensus that a Fissile Material Cut-off Treaty (FMCT) should be negotiated at the Geneva based Conference on Disarmament (CD). In 1995 the Shannon Mandate was agreed according to which the CD should negotiate a ban on the production of fissile material, "... a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."

Since this would involve former military facilities a conflict of interest arises between the goals of transparency versus military confidentiality. For this reason, non-intrusive ways of monitoring the non-production of plutonium are required. A combination of remote sensing methods like satellite

imagery as well as measurement and modelling of krypton-85 in the atmosphere can serve the purpose to ensure a high confidence in compliance with a cut-off agreement without compromising too greatly perceived national security requirements by releasing sensitive information.

The same applies to possible bilateral or regional agreements for freezing the production of nuclear weapons-usable materials. This has been proposed for South Asia as well as for the Middle East. In the latter case, a broader approach has been taken by proposing a weapons-of-mass-destruction free zone.

## *3.6 Examples for non-radioactive tracers*

The Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction (CWC) entered into force on 29 April 1997. The chemical industry has obligations for declaration and will be subject to verification inspections on a basis of managed access. The CWC has an extensive Verification Annex and the Organisation for the Prohibition of Chemical Weapons (OPCW) is in the process of establishing its work. Remote verification is of minor importance for the CWC. Environmental measurements have some significance in investigating an allegation of the use of chemical weapons in a war.

Another case for environmental sampling is the verification of greenhouse gas emissions that are reported by member states according to the UN Framework Convention on Climate Change and the Kyoto Protocol. This kind of verification is currently limited to national technical means and depends strongly on atmospheric transport modelling to determine regional source strengths based on observations.

There are further UNEP Conventions for which environmental sample analysis might be applied in order to verify compliance:

- Vienna Convention for the Protection ofthe Ozone Layer
- Montreal Protocol on Substances that Deplete the Ozone Layer
- Stockholm Convention on Persistent Organic Pollutants (POPs)
- Basel Convention on Transboundary Movements ofHazardous Wastes

# 4. Indicators and technologies for their measurement

## *4.1 Radioactive particles*

For nuclear material safeguards, the major indicators of use of materials are the actinides and derived fission and activation products. A broad variety of analytical techniques for traces of indicator nuclides has been developed (Foggi and Genoni, 1997; Donohue, 2002; IAEA, 2003). Technologies and methods applied in the context of identifying sources of illicit nuclear material trafficking have been summarised under the new working area of nuclear forensics (Koch, 2003; Mayer, 2005).

Usually, the actinides have reasonably long half-lives making them easy to be detected with various mass spectrometric assays. Verification of uranium is typically based on 235U/238U ratio and ratios of minor isotopes to each other (234/235/236). If the material has been introduced to a reactor, one can detect also various isotopes of plutonium. In addition to the effective ratio of 240Pu to 239Pu, ratios of different plutonium isotopes to 235U are also important attributes of nuclear material. The isotopic ratios can reveal information on how the material has been irradiated, if separation processes are used at the facility and about the time since separation or irradiation occurred.

In the nuclear material analysis the samples can be analyzed using either bulk or particle analysis.

Bulk analysis means that the whole sample or part of it is completely analyzed and the average isotopic abundances of the material are reported. This is useful method if one can assume that the material is more or less homogenised throughout the sample. Usually, the whole sample can be analyzed when using non-destructive methods like High-Resolution Gamma Spectrometry to detect the fission and activation products. When destructive methods are applied, the analyzed part of the sample is lost nearly completely in the analysis process. Therefore, the sample is usually split and part of the sample is archived to make sure that something is still left if further analyses need to be performed later.

There are a number of destructive analysis methods for nuclear material samples:

- ThermalIonisation Mass Spectrometry (TIMS) and Inductively Coupled Plasma Mass Spectrometry (ICPMS) to detect uranium and plutonium isotopes.
- Accelerator Mass Spectrometry (AMS) to detect specially the presence of236U and 129I.
- Alphaspectrometry after radiochemical separation to detect the amount and isotopic composition of uranium and plutonium.

In particle analyses methods, individual particles are analyzed separately. By doing so, more detailed information can be retrieved even if the inspected facility has been performing operations with various kinds of isotopic compositions. The detected particles may tell different kinds of stories about the used materials, the time when the operations are done with these materials, what did happen to the material before it was left over as a separate particle etc.

Typically there are 2 methods that are routinely used to detect and characterize the particles of interest:

- SecondaryIon Mass Spectrometry (SIMS) is a rather automated method that is able to pick the selected particles and perform mass spectrometric analysis with prepared samples.
- hermalIonization Mass Spectrometry with fission track etching (FT-TIMS) is more laborious but also more accurate method to define the true isotopic composition of even the smallest particles. In this method the sampled material is irradiated with a neutron flux and after the etching the fissioned particles are shown visually in the prepared sample surface. Then these particles are picked with micromanipulator and analyzed individually using TIMS.

In order to identify and characterise nuclear explosions, various radio-chemical and nuclear analytical methods have been successfully applied. Early methods focused on total beta counting of rain samples and auto-radiographs of single hot fall-out particles. The most reliable method for timely and continuous monitoring is to collect aerosol particles on air filters. This was done by various laboratories on the ground level as well as on high altitude with the help of air planes and balloons (Miller K.M. and R. J. Larson (2002). For example, the Ba-140 concentrations in the atmosphere that were reported in the literature and that were thought to indicate a nuclear test explosion at large distances range from 30 to $5{\cdot}10^5$ μBq/m$^3$.

For the CTBT, the list of relevant particle-bound fission and activation products is long and includes barium-140, lanthanum-140, zirconium-95, as well as anthropogenic radioisotopes with other legitimate sources like cesium-137, iodine-131 and technetium-99m. The selection of these isotopes as indicators is based on their production rate in an explosion as well as on their half-life.

The sequence of the monitoring activities starts with a 24-hour sampling period. A high volume pump draws at least 500 m$^3$ per hour through a filter. The sample will be allowed to decay for 24 hours in order to reduce the background that is dominated by short-lived natural radionuclides. Measuring the radioactivity with a High-Resolution Gamma Spectrometer typically takes another 24 hours. A very high sensitivity for traces of anthropogenic radioactivity is achieved. For Ba-140 it is below 30 μBq/m$^3$.

4.2. Radioactive noble gases Since the first nuclear weapons were built many 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 world wide 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 today Kr-85 atmospheric background level is approximately 1.5 $Bq/m^3$ and the Xe-133 level is around a few $mBq/m^3$. In the southern hemisphere the mean atmospheric activity concentration of Kr-85 is lower by 0.1 to 0.2 $Bq/m^3$ (Winger et al. 2005) and the atmospheric activity concentration of Xe-133 is well below the detection limit of the existing systems of < 1 $mBq/m^3$ (Stocki et al., 2005) at most locations. The world wide Ar-37 background level is in the order of $mBq/m^3$. Special counting techniques have to be applied to detect these low activities. For the detection of Kr-85 and Xe-133 liquid scintillation counting and proportional counting techniques are used. The measurement of the 2.8 keV decay energy of Ar-37 requires special low-level gas proportional counters.

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) (Auer et al, 2004). 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 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.

# 5. Atmospheric modelling

5.1. Introduction If relevant radionuclides are detected in the atmosphere, this information is of use for verification purposes only if it can be attributed to a certain geographical area as possible source region. Atmospheric modelling is applied for this and other purposes (Kalinowski, 2001).

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 (Feichter et al., 2002). 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.

GEMS (Global and regional Earth-system Monitoring using Satellite and in-situ data), a project recently started and funded by the 6th framework program of the European Commission attempts to develop assimilation capability for greenhouse gases, reactive gases and aerosols from global to regional scales (50km) and covering the troposphere and stratosphere.

## 5.2 Atmospheric transport processes and characteristic time scales

At a given location and time, the atmospheric chemical composition is mostly determined by transport of the substance or its precursor into or out of the area. The atmosphere possesses a large spectrum of motions from planetary waves, synoptic scale disturbances, meso-scale processes to turbulent exchange. The scales of motion that are important for the transport of a specific constituent depend on the atmospheric residence time of the species in question. Generally, the distribution of highly reactive species is dominated by chemical and microscale interactions at surfaces, while that of less faster reacting species is dominated by fast mixing processes, and that of slowly reacting species by large-scale transport. On larger spatial scales the winds transport species with long lifetimes far away from the source region. Pollutants predominantly released in the northern hemisphere continents are moved across entire continents and also contribute by interhemispheric transport to the load of the southern hemisphere. Subgrid-scale processes, such as turbulent exchange and vertical transport in clouds, dilute quite efficiently polluted boundary layer air by mixing with free tropospheric air masses. The degree of vertical mixing controls the dry deposition at the ground, the transit time until a parcel enters a cloud or the rate of photochemical decomposition.

Three main circulation regimes can be distinguished in the troposphere. The Hadley Cell is a meridional circulation that is driven by the heating of air in the equatorial region. Equatorial air moves upward and air from higher latitudes moves laterally toward the equator. These lower branch winds, the trade winds (the most persistent wind system of the atmosphere), move over the sea and carry water vapour towards the equator. The trade winds from both hemispheres converge near the equator (Inter-Tropical Convergence Zone ITCZ) and water vapour condenses within the ITCZ forming large cumulonimbus clouds. This flow is balanced by a return flow at higher altitudes. The Hadley Cell is closed by subsidence at about 30° in both hemispheres (horse latitudes). The Coriolis force, associated with the Earth's rotation, deflects moving air parcels to the right direction of the motion north of the equator and to the left south of the equator. Due to this Coriolis force air parcels in the upper branch of the Hadley Cell are deflected to the east and air in the lower branch to the west. Convection in the ITCZ is very effective in transporting atmospheric constituents into higher altitudes. Convection provides also for downward transport within the "downdrafts" and by slow sinking processes in between clouds.

The differential heating between the equator and the poles creates a pole-to-equator temperature gradient which results in westerly wind flow in the mid-latitudes. These zonal winds (jet streams) become baroclinically unstable and in the free troposphere troughs and ridges of low and high pressures are formed. This cyclogenesis results in poleward moving warm air which is lifted above the cold air that is moving towards the equator. This exchange of mass across the latitudes is far less regularly ordered than the regimes in high and low latitudes.

The polar region is in particular in winter covered by a high pressure system, the Polar High. Within this Polar High, air subsidence occurs and at higher altitudes air moves poleward to take its place. This forms a meridional circulation cell.

Table 1 shows typical transit times between different atmospheric reservoirs and of different transport processes.

| | |
|---|---|
| Vertical transport within convective clouds | 1 hr |
| Mixing between the boundary layer and the free troposphere | 2 – 10 days |
| Large scale vertical mixing in the troposphere | 1 – 4 weeks |
| Mixing within a latitude belt | 2 – 4 weeks |
| Hemispheric mixing | 2 – 6 months |
| Inter-hemispheric exchange | 1 yr |
| Stratospheric-tropospheric exchange | 1 – 3 yrs |
| Transport from the Earth‘s surface up to the mesosphere (~50-100 km) | 5 – 8 yrs |

**Table 1** – Characteristic transport times in the atmosphere

## *5.3 Methods for global atmospheric transport modelling*

GCMs (Global general circulation models) and CTMs (Chemistry Transport Models) calculate the large-scale transport of atmospheric constituents by wind (three-dimensional advection) and sub-grid-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. The numerical method used for the solution of this equation should fulfil a number of constraints:

- Accuracy
- Monotonicity (i.e.not introducing new extremes)
- Positive definiteness (no generation ofnegative values)
- Mass conservation

Furthermore, it should be local, i.e. processes far away from that point should not influence the solutions at a given point, and transportive, i.e. the information should propagate primarily downwind. In light of the computational demands of three-dimensional chemistry transport simulations, the advection scheme must also be computationally efficient. This becomes important when using an approximately equiangular mesh in spherical geometry. In this geometry, the spacing between longitudes becomes increasingly small as one approaches the poles and thus very small time steps are required due to the Courant-Fredrichs-Lewy (CFL) condition, in order to maintain stability (‘pole problem’). One method, which has a much less stringent time stepping restriction, is the ‘semi-Lagrangian’ transport (SLT) technique. However, this method is not mass conserving.

Other methods, based on the flux form of the advection equation, have been developed in recent years. These are inherently mass conserving and allow for an SLT-like time step. However, some of them are not strictly monotonic while others do not provide the required accuracy in certain situa-

tions. Though intuitively, advection appears to be a fairly easy process to model, no optimum method has yet been identified that meets all the requirements mentioned above and that is computational effective.

## 5.4 Methods for atmospheric chemistry modelling

Atmospheric chemical reaction rates are usually dependent on temperature, and in many cases also on pressure. There has been considerable work in laboratories to determine the rate constants for key atmospheric reactions, and the results have been compiled in comprehensive evaluations (JPL, Atkinson). Yet, because of experimental difficulties, several reaction rates remain unknown or very uncertain. Photodissociation reactions are governed by the available UV intensity (the actinic flux), the absorption cross section of the molecule, and the quantum yield determining the efficiency of the dissociation reaction. All of these parameters are wavelength dependent. The absorption cross-section and quantum yield may also depend on temperature and pressure.

In general radioactive nuclides behave chemically like stable isotopes of the same element. Their ionizing effect would impact on the atmospheric chemistry only at very high activity concentrations. The formation of ions by radioactive decay may also impact the nucleation of particles and subsequently impact cloud formation and climate.

In an atmospheric chemistry model, the concentration changes of trace gases are computed at each time step by solving a set of ordinary differential equations describing the production and loss rates of the molecule and the reaction stoichiometry. Due to the different time scales for atmospheric reactions (spanning several orders of magnitude), the system is very stiff, and special solvers had to be developed in order to treat the matrix numerically. Two techniques, which are widely used by global modellers, are the "Quasi-steady State Approximation" and the "Euler Backward Iterative Method".

Atmospheric chemical processes are not limited to the gas phase, but also occur on the surface of solid particles and within liquid particles, such as aerosols and cloud droplets. The important role of these so-called heterogeneous reactions on aerosol surfaces has been shown in studies of the stratospheric ozone hole. Reactions on sea salt may also play an important role in the marine boundary layer. Mineral dust particles react with sulfur and nitrogen particles to form sulfates and nitrates, respectively. Clouds control the formation of aerosols and their removal by scavenging. For example, the oxidation of $SO_2$ to sulfate in cloud droplets is much more efficient than in the gas phase. Generally, reaction pathways and rates differ considerably from those in cloud-free air. Moreover, clouds also affect the photochemistry by enhancing the actinic fluxes above the cloud and by reducing it below the cloud compared to clear-sky conditions. Aqueous-phase reaction rates depend on the gas-phase concentrations, solubility and rate of mass transfer of oxidizing agents. The cloud receives trace gases from its inflow region, its vertical winds redistribute the gases, and the cloud transforms the gases through gas and aqueous-phase chemistry.

For many reactive gases, the primary atmospheric sink is reaction with the OH radical or photolytic dissociation. Removal from the atmosphere takes place through deposition on aerosol and land surfaces, uptake by oceans and lakes, and by uptake in cloud droplets and subsequent precipitation. Radioactive decay is treated as a sink in accordance to the half-life.

## 5.5 Downscaling

Atmospheric general circulation models have a typical resolution of 100 – 300 kilometres. Since GCMs are usually considered to yield unrealistic results on spatial scales smaller than several grid cells, there is in general little confidence in the simulated, regional-scale variability. Downscaling techniques are often used to derive variability from GCM simulations on or below the grid-cell scale. They are based

on the assumption that atmospheric variability on small spatial scales is conditioned, though not determined, by larger scales. In recent years, a number of dynamical and statistical downscaling methods have been developed, which are reviewed in Wilby and Wigley (1997) and Giorgi et al. (2001). Dynamical downscaling is based on the application of a finer resolving global model to simulate short episodes or on the nesting of a finer resolving regional scale model. In both cases models are driven by the meteorology produced by the coarse resolving global model. Statistical downscaling is based on the view that regional meteorology is conditioned by the large-scale state of the atmosphere and by the regional topography.

## 5.6 Use of radionuclides as tracers to test atmospheric transport

Not only are atmospheric models applied to simulate the transport of radionuclides. These tracers are in turn playing an important role in understanding atmospheric processes and validating models (for review see: WMO, 2004)

Comprehensive chemical evaluation of thousands of man-made chemicals is a challenging task, which has to comprise transport in and cycling between the atmosphere, the soil, the vegetation and the ocean. Cosmogenic and terrigenic natural radiotracers and radionuclides from nuclear bomb tests have been widely used to test a large variety of relevant processes (Reiter, 1978).

Species used as test tracers should ideally meet the following conditions. They should be chemically inert, sources and sinks should be well known and sufficient observational data should be available for comparison to model results.

Radon-222 measurements at surface sites, by ships or by aircrafts were applied to test models boundary layer transport and exchange between the boundary layer and the free troposphere. The long-range transport of radon from the African continent to subantarctic islands situated at several thousand kilometres downwind from South Africa (radonic storms) provides a test for the treatment of advection and diffusion in global models (Monfray et al., 1988).

Krypton-85 was used to evaluate the inter- and intra-hemispheric transport times. This long-lived radionuclide (half-life of 10.76 years) is produced in nuclear reactors and released during reprocessing of spent fuel. These sources are mostly located at Northern Hemisphere mid-latitudes. This makes it a good proxy for inter-hemispheric transport of pollutants. The very pronounced latitudinal profiles that have been measured for $^{85}Kr$ permit to evaluate the interhemispheric exchange time of approximately 1.1 years (Weiss W., H. Sartorius, H. Stockburger, 1992).

$^{14}CO$ is a very good tracer of stratosphere-troposphere exchange and can also be used to assess the tropospheric OH abundances. The main source for $^{14}CO$ is generation by cosmic rays and the only sink is by OH oxidation. One challenge that models have to meet is to represent accurately the tropopause height since the vertical resolution decreases with height in models. Higher resolution models (typically 60 vertical layers) will certainly help resolve this issue independently of having the correct cross tropopause exchange.

To address the downward transport from the stratosphere to the troposphere, $^{14}CO$ and $^{14}CO_2$ are well-suited tracers. The upward transport from the troposphere to the stratosphere occurs in great part in the tropical regions where convective systems inject lower tropospheric air into the high troposphere/low stratosphere region. The importance of these events would require having vertical profiles in the altitude range 10-22 km regions. No such profiles have been acquired recently and measurements of one radionuclide $^{222}Rn$ or a suite of them including $^{222}Rn/^{210}Pb$ would greatly enhance the observational basis to understand these phenomena.

Radionuclides that condense on particle surfaces provide tests of aerosol physics, e.g. wet and dry deposition. Radiotracers like $^{210}$Pb, $^{7}$Be, $^{10}$Be and $^{90}$Sr have been used for this purpose.

## 5.7. 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 non-evasive 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.

## 5.8. 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.

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 points 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 3 hours and 1° times 1° 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 (Wotawa et al., 2003). 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 (Seibert, 2001). This could be applied in 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, and based on noble gas sampling Xe-133/Xe-131m, Xe-133m/Xe-133, and Xe-135/Xe-133. 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.

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 is now being put in operation. Under this agreement the WMO Regional Specialised Meteorological Centres will run their models to determine potential source regions for radionuclide events of interest and the IDC will receive meteorological analysis data to drive its atmospheric transport models.

# 6. Conclusions

Environmental sample analysis is not a new verification method. It has been applied ever since the first nuclear weapons were produced and tested and related national technical means played a major role in verifying compliance with the Partial Test Bean Treaty of 1963. However, scientific progresses in measurement technologies and source location methods as well as major verification applications for nuclear arms control (UNSCOM/UNMOVIC/IAEA since 1991 and CTBT since 1996) in recent years have brought significant progress. New opportunities are being explored with regard to wide-area environmental sampling according to the NPT Additional Protocol (model agreement of 1997). Further proposals include the to-be-negotiated Fissile Materials Cut-off Treaty (Shannon Mandate of 1995) as well as bilateral or regional agreements on cooperative environmental monitoring as confidence building measures.

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# List of Abbreviations

| | |
|---|---|
| AP | Additional Protocol |
| AGR | Advanced Gas-cooled Reactor |
| Am | transuranic element americium |
| A&C | Accountancy and Control |
| Bq | SI unit of radioactivity: Becquerel |
| BWR | Boiling Water Reactor |
| BU | Burn-Up (Gigawatt days energy released per tonne nuclear fuel) |
| C | graphite (moderator of a thermal reactor) |
| CANDU | Canadian Deuterium Uranium Reactor |
| Cm | transuranic element curium |
| CoK | Continuity of Knowledge |
| CR | Control Rod (to control operation of nuclear reactor) |
| CSA | Comprehensive Safeguards Agreement |
| Ci | unit of radioactivity: Curie (1Ci=37GigaBq=3.7E10Bq) |
| CTBT | Comprehensive Nuclear Test-Ban Treaty |
| DA | Destructive Analysis |
| D2O | Heavy water (with the hydrogen isotope H-2 instead of H-1) |
| EEC | defined by European Economic Community Treaty of Rome 1957 |
| EC | European Commission |
| EURATOM | European Atomic Energy Community (for EC safeguards regulations) |
| FBR | Fast Breeder Reactor |
| FR | Fast Reactor |
| FA | Fuel Assembly |
| FE | Fuel Element (= Fuel Assembly) |
| FP | Fission Products |
| FFP | Fuel Fabrication Plant |
| GCEP | Gas Centrifuge Enrichment Plant |
| Gy | SI unit of absorbed radiation dose: Gray |
| GWe | Gigawatt (1.E9 Watt) electric power |
| HEU | High Enriched Uranium |
| HLW | High Level Waste |
| HTR | High Temperature Reactor |
| HWR | Heavy Water Reactor |
| IAEA | International Atomic Energy Agency |
| IS | Integrated Safeguards |
| IC | Inventory Change |
| IT | Illicit Trafficking |
| KMP | Key Measurement Point |
| LEU | Low Enriched Uranium |
| LLW | Low-Level Radioactive Waste |
| LWR | Light Water Reactor (PWR or BWR) |
| Magnox | C-moderated gas-cooled thermal reactor |
| MBA | Material Balance Area |
| MWe | Megawatt (1.E6 Watt) electric power |
| MLW | Medium-Level Waste |

| | |
|---|---|
| MOX | Mixed Oxide fuel (a mixture of uranium and plutonium) |
| MC | Monte Carlo statistical method |
| MUF | Material Unaccounted For |
| n | neutron |
| NDA | Non Destructive Assay |
| NED | Nuclear Explosive Device |
| NM | Nuclear Material |
| NMAC | Nuclear Material Accountancy and Control |
| NPP | Nuclear Power Plant |
| NPT | Non-Proliferation Treaty |
| NS | Nuclear Safeguards |
| NWS | Nuclear Weapon State (US, Russia, France, UK, China) |
| NNWS | Non Nuclear Weapon State member of IAEA |
| PI | Physical Inventory |
| PIT | Physical Inventory Taking |
| PIV | Physical Inventory Verification |
| PWR | Pressurised Water Reactor |
| Pu | transuranic element plutonium |
| R | SI unit of exposure to ionising radiation: Röntgen |
| RBMK | C-moderated boiling water reactor |
| rd | unit of absorbed radiation dose: rad (1rad=0.01Gy) |
| rem | unit of dose equivalent |
| SFA | Spent Fuel Assembly |
| SFM | Special fissile materials |
| SNF | Spent Nuclear Fuel |
| S/R D | Shipper/ Receiver difference between quantities of nuclear material |
| SSAC | State System of Accountancy and Control for nuclear material |
| Sv | SI unit of dose equivalent: Sievert (1Sv=100rem) |
| SWU | Separative Work Unit (energy needed for enriching) |
| Th | element thorium |
| T1/2 | half-life of radioactive nuclide |
| U | element uranium |
| UF6 | Uranium hexafluoride gas (above 56°C) |
| U3O8 | yellow cake product of U mining |
| Zr | Zircaloy (metal used for fuel cladding) |

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