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Research

An Introduction to Nuclear Non-Proliferation and Safeguards

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SKI perspective

Background and aim

The purpose of this project was to compile a course material that covers how the nuclear safeguards system has emerged and how it works today. The produced compendium is directed to both university students and people concerned by safeguards from the industry.

Results

The compendium at hand will be used both within an outside Sweden as course material. It is partly a result from the work done by TKM (Training and knowledge management), which is a working group within Esarda (European Safeguards Research and Development Association) that on a yearly basis educates students from all over Europe. The intention is that the material shall be used in conjunction with courses in former Soviet states as well as in other international associations. In Sweden, the compendium is used in courses given at Uppsala University. This material is made available at SKI:s webpage (http://www.ski.se) in both an English and a Swedish version (SKI report nr:2007:45).

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Contents

Abbreviations

AC	Atomic Commission
AE	AB Atomenergi
AK	Atomkommittéen
BTC	Basic Technical Characteristics
CDT	Combined Development Trust
C/S	Containment and Surveillance
CTBT	Convention on the Physical Protection of Nuclear Material
CVD	Cherenkov Viewing Device
DA	Destructive Assay
DFA	Delegationen för atomenergifrågor
DI	Design Information
DIV	Design Information Verification
ENSRA	European Nuclear Security Regulators Association
FA	Facility Attachment
FOA	Försvarets forskningsanstalt
FOI	Totalförsvarets forskningsinstitut
IADA	International Atomic Development Authority
IAEA	International Atomic Energy Agency
IPPAS	International Physical Protection Advisory Service
INSSP	Integrated Nuclear Security Support Plans
KTH	Kungliga Tekniska Högskolan
IR	Initial Report
ISP	Inspektionen för strategiska produkter
MBA	Materialbalansområde
MTCR	Missile Technology Control Regime
MUF	Material Unaccounted For
NDA	Non-Destructive Assay
NF	Nationernas förbund
NPT	Non-proliferation Treaty of Nuclear Weapons
NSG	NuclearvSuppliers´Group
PIV	Physical Inventory Verification
PSP	Particular Safeguard Provision
RFK	Reaktorförläggningskommittéen
SA	Subsidiary Arrangement
SIR	Safeguards Implementation Report
SKI	Swedish Nuclear Power Inspectorate
SPI	Swedish Inspectorate of Strategic Products
SQ	Significant Quality
VOA	Voluntary Offer Agreement
ZC	Zanger Committee

Part 1 What is nuclear non-proliferation?

Thomas Jonter

Chapter I.1

Introduction

The purpose of nuclear non-proliferation is to prevent the spread of nuclear weapons. Ever since 1945, when the first atomic bombs were dropped over Japan, states, regional organizations, and international organizations have sought, by various means, to limit the possibilities of nations to develop nuclear capacity. These efforts have resulted in the setting up of an international system of cooperation between countries; treaties and conventions have been signed and ratified, and global and regional organizations and national authorities have been established with the aim of stopping the illegal flow of nuclear materials and components. The system is far from perfect, and it isn't one that all the states of the world adhere to. In 1945, there was one nuclear power in the world – the United States. Today, at least nine states have nuclear weapons capacity – the United States, Russia, Great Britain, France, China, India, Pakistan, Israel, and North Korea. Is it possible, in these circumstances, to speak of a successful campaign against nuclear proliferation? That depends, both on the definition of "successful" and on what are considered attainable objectives. An optimistic person would surely say that it could have been a lot worse. Considering that a large number of states were contemplating acquiring nuclear weapons in the 1950s and 1960s, the current number of nuclear weapons states could have been somewhere between 30 and 40 unless the work against nuclear proliferation had been successful. The optimist might add that there hasn't been a nuclear war since August 1945, and perhaps also point out that states such as South Africa, Ukraine, and Kazakhstan have voluntarily relinquished their nuclear arsenals. The system of international treaties and organizations that has been in operation has functioned well, despite certain deficiencies and shortcomings, in the optimistic view.

A pessimistic person would probably argue, for example, that the efforts at non-proliferation have failed to prevent another eight nations, in addition to the United States, from acquiring nuclear weapons. And they have hardly succeeded in making the world a safer place; if anything the opposite is true. More nations have tried and are trying to develop weapons of mass destruction, such as Iran. And in 2006, North Korea conducted its first nuclear weapons test. It is probably only a matter of time before nuclear weapons are used in a conflict, the pessimist would probably claim. We must not forget that two nuclear bombs were dropped over Japan in August, 1945. To this, the pessimist would surely add the threat from terrorist groups, which, according to some experts, have tried to acquire nuclear weapons. We also must not forget that the world has come close to nuclear war on at least a couple of occasions. The Cuban Missile Crisis in 1962 is a case in point.

No, it is not possible to speak of a perfect and fully completed system. The non-proliferation work constitutes a constantly developing process. New conflicts and threat pictures give rise to new needs for measures to be taken, but they may at the same time represent new possibilities for developing and strengthening common international security. For example, when the Soviet Union disintegrated, a number of problems arose in the nuclear domain. Nuclear materials, equipment, and components, including even nuclear weapons systems, went missing as surveillance and control ceased to function. In parallel with this chaos, the door was opened for many newly formed states to join international organizations and receive foreign aid from developed countries for the purpose of creating modern and efficient nuclear infrastructures. Russia began to work together with the United States, the European Union, and other states and organizations to solve the enormous problems that arose in connection with the collapse of the Soviet Union. The end of the Cold War has, indeed, brought about new threats and problems, but at the same time this very fact has led to an increased awareness that we must cooperate globally in order to prevent the spread of nuclear weapons.

The primary aim of the first part of this paper is to describe the historical development of this global non-proliferation system and its central tasks. A second purpose is to discuss the advantages and disadvantages of its current design in order to answer the following question: Can we today say that we have a functioning global non-proliferation system? Does it require further strengthening, and, if so, how can this be achieved?

1.1 What is a nuclear weapon?

Regardless of whether we choose to look at the national and global efforts at nuclear non-proliferation from an optimistic or a pessimistic perspective, we must first acquaint ourselves with this global system such as it is today. After that, we can discuss its possible deficiencies and shortcomings. And a first question that arises is this: What exactly is it that we want to prevent from spreading and that we therefore need to control and supervise? In order to answer that question in more detail we must first grasp, in general terms, what is needed for developing nuclear weapons. At a general level, the following components are necessary:

(1) A motive. There must be a reason for a state to acquire nuclear weapons. This may involve a changed threat picture (real or imagined), or a state's desire to achieve great power status in order to secure influence and power in the international arena (some security policy experts have asserted that this was one of the primary reasons why France decided to become a nuclear power).

(2) Scientific, technological, and organizational expertise. Adequate knowledge of nuclear physics and nuclear chemistry alone does not suffice. Other fields such as classical mechanics and thermodynamic and kinetic theory, as well as knowledge of the metallic properties of uranium and plutonium, must also be included in the scientific expertise. Moreover, this scientific expertise needs to be converted into technical applications in the form of construction of necessary facilities such as reactors and reprocessing and enrichment facilities, and a technical infrastructure must be built that makes this possible. And in order to coordinate all these scientific and technical resources within the framework of an efficient program, far-reaching organizational capabilities are required.

(3) Financial resources. It does not necessarily cost a large amount of money to gather enough weapons-grade fissile material to put together a less sophisticated bomb, if one can find a willing seller (this is the type of simpler bombs that certain experts claim that terrorists may be able to produce), but in order to develop a nuclear weapons program, substantial economic resources are required. A program requires reactors and a staff of skilled scientists, technicians, and professionals who will perform advanced installation and construction work. Also necessary is a large quantity of specially designed steel and concrete materials.

Furthermore, a nuclear arsenal requires maintenance, with parts having to be exchanged and repaired. All of this requires substantial financial resources.

(4) Weapons-grade fissile material. A nuclear weapon can be based on either the principle of fission or the principle of fusion. In a fission bomb, an explosive chain reaction is started in the nuclear device before the actual weapon is blown apart to release more energy. The explosive effect is dependent on the amount of fissile material, the number of atomic nuclei that are split and the number of fissions that can be produced before the weapon itself is blown to bits. There are two main types of fission bomb. The two different variants are based on different technical and scientific principles. The first fission bomb variant is called the "gun barrel" type, where two subcritical masses of highly enriched uranium (U-235) are brought together at high speed in order to set off a chain reaction. One of the critical masses is pushed, by means of an explosion, through a barrel to reach the other mass. This method is fairly simple, but at the same time the initial explosion tends to obstruct the process of fission that the fissile material is meant to go through. As a consequence, the explosive effect tends to be reduced and the weapon itself tends to become less effective since it is difficult to make use of the full potential of the fissile material.

Figure 1: "Gun barrel"-typ (kanonrör) av kärnvapen

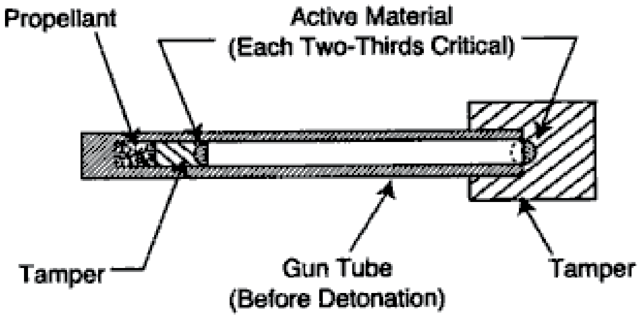

Figure 2-VII. Gun Assembly Principle

The other type of fission device is based on the technically more advanced principle of implosion. In an implosion bomb, a subcritical spherical mass of fissile material (either U-235 or plutonium) is compressed until it reaches a critical stage and a chain reaction sets in. The fissile material is surrounded by a reflector of neutrons, usually beryllium, and a heavy-metal tamper made out of either U-238 or Wolfram. Encircling this device is a hollow sphere where a conventional explosion can be detonated in order to bring about a uniform, symmetrical implosion, which will then press the tamper in against the fissile material and set off a chain reaction. In this type of bomb, in contrast to the gun barrel type, the effect of the conventional explosion leads to numerous repetitions of the fissile reaction, thus making possible the full use of the fissile material. Put differently, this means that the explosive effect is bigger and more predictable in comparison with the simpler gun barrel bomb. If U-235 is chosen as fissile material, the uranium must undergo an enrichment process consisting of several steps. If, on the other hand, one chooses to produce a plutonium device, the uranium needs to be reprocessed in order to separate the plutonium. These processes are both costly and technically complicated (on the characteristics of uranium and plutonium, see below).

Figure 2

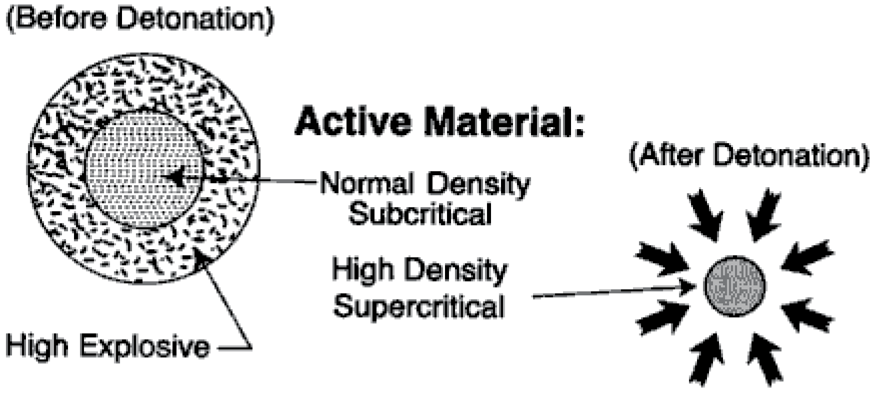

Figure 2-VIII. Implosion Assembly Principle

In a fusion bomb, or a thermonuclear device as it is also called, two isotopes such as tritium or deuterium are brought together (fused). This process must, however, be initiated by another strong energy force, usually a fission device which sets off the fusion reaction. These two steps can be made more powerful through the use of a shell consisting of U-238, which encircles the two explosive devices. The isotopic composition of U-238 makes it impossible to use for the purpose of setting off an explosive chain reaction. On the other hand, U-238 can be manipulated to produce a series of nuclear fissions if it is exposed to a constant external bombardment of neutrons that have been released through separate processes of fission or fusion. Theoretically, an endless series of consecutive steps of fission and fusion can ensue, and this weapon has a considerably stronger explosive effect than the pure fission bomb. On the other hand, it requires more technical and scientific precision to produce.

The more technically advanced thermonuclear bomb, on the other hand, which is based on the principle of fusion, must be loaded with tritium or deuterium. In addition, a certain amount of either U-235 or plutonium must be included in the fusion device to serve as a trigger (for definitions of fission and fusion, see below).

(5) Other necessary equipment. Even if points one through four are realized, this does not imply that nuclear capability has been achieved. It is also necessary to have the capacity to efficiently launch or deliver the nuclear weapons. A weapons-carrier system needs to be developed. This might involve construction of fighter planes or bombers, or the manufacture of submarines that serve as weapons carriers. Surface-to-air missiles can also be used, but whatever system is chosen, it will constitute a technically advanced project. Although fighter planes, for example, can be purchased from another state, they must be partially reconstructed in order to fit the developed nuclear weapons type.[1]

(6) The ability to conduct nuclear tests. The developed nuclear weapon must be tested in order to determine if it functions adequately or if modifications are required. Significant technical and scientific resources are necessary for conducting high-quality tests.

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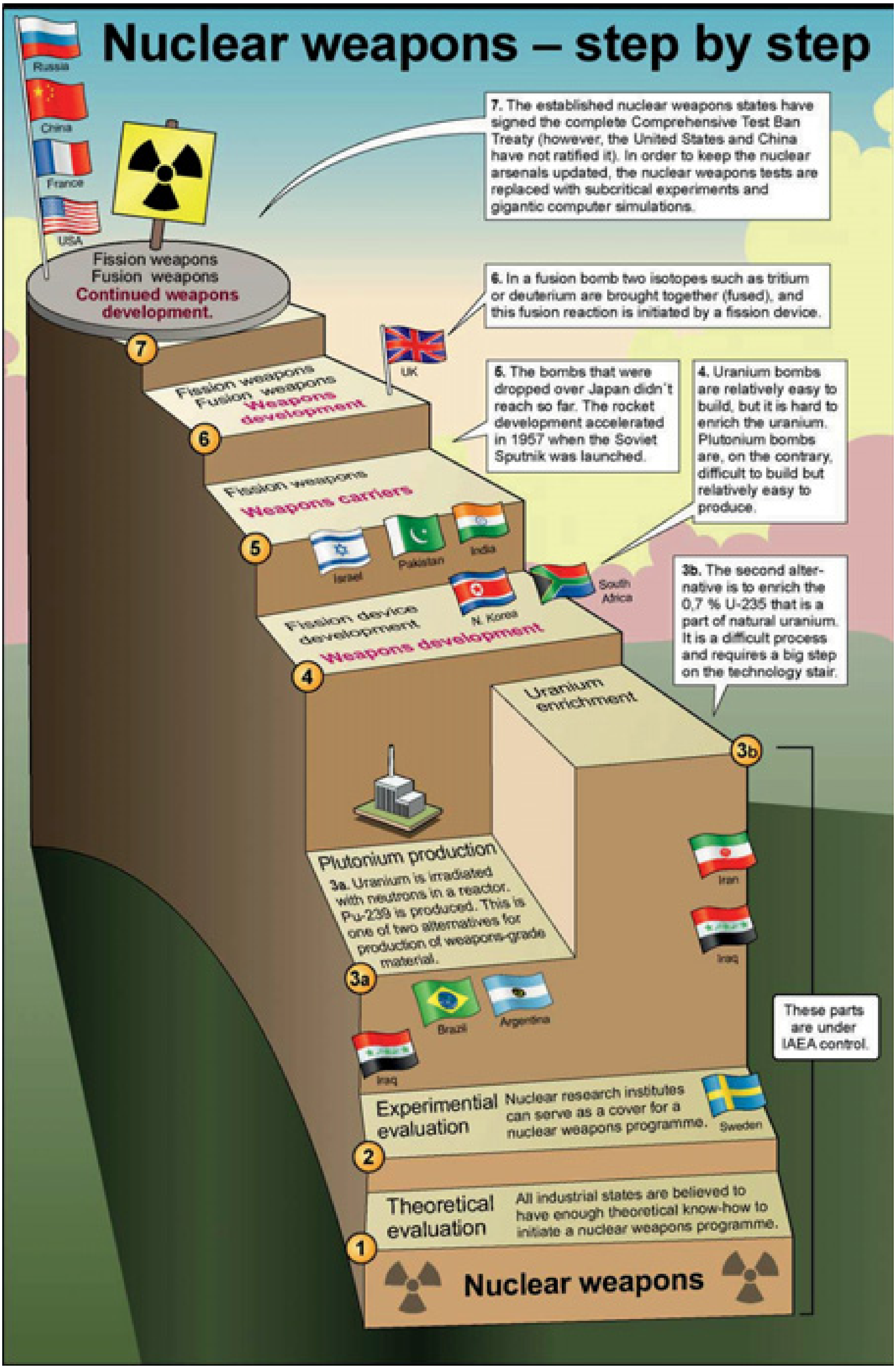
[1] To be sure, terrorist groups that have acquired a sufficient amount of weapons-grade fissile material to produce a simple device may be expected to use unsophisticated types of weapons-carriers

Nuclear weapons – step by step



7. The established nuclear weapons states have signed the complete Comprehensive Test Ban Treaty (however, the United States and China have not ratified it). In order to keep the nuclear arsenals updated, the nuclear weapons tests are replaced with subcritical experiments and gigantic computer simulations.

6. In a fusion bomb two isotopes such as tritium or deuterium are brought together (fused), and this fusion reaction is initiated by a fission device.

5. The bombs that were dropped over Japan didn't reach so far. The rocket development accelerated in 1957 when the Soviet Sputnik was launched.

4. Uranium bombs are relatively easy to build, but it is hard to enrich the uranium. Plutonium bombs are, on the contrary, difficult to build but relatively easy to produce.

3b. The second alternative is to enrich the 0,7 % U-235 that is a part of natural uranium. It is a difficult process and requires a big step on the technology stair.

3a. Uranium is irradiated with neutrons in a reactor. Pu-239 is produced. This is one of two alternatives for production of weapons-grade material.

Nuclear research institutes can serve as a cover for a nuclear weapons programme.

All industrial states are believed to have enough theoretical know-how to initiate a nuclear weapons programme.

These parts are under IAEA control.

The figure above lists the main technical steps in the production of fissile nuclear weapons. As shown in the figure there are two alternative routes leading up to a first device. Either one produces a uranium bomb (U-235, which is produced through an enrichment process), or a plutonium device (a production process which involves reprocessing of the uranium). Regardless of whether one chooses U-235 or plutonium as fissile material, the production steps in weapons production are identical with those in peaceful nuclear energy production up to the point where fissile material is produced. The subsequent step is a process in which the nuclear material acquires weapons-grade quality. The systems that most states in the world maintain for producing nuclear power can in principle be used for producing weapons-grade nuclear material if certain technical adjustments are made, such as separating the uranium and exchanging the fuel in the reactors more frequently. In light of this, it is important obviously to maintain surveillance and control of all nuclear energy facilities (reactors, storage facilities, laboratories, etc.) that deal in some way with nuclear materials that can be used, either in their existing condition or subsequent to certain modification processes, for nuclear weapons production.

As is evident from the list of the six main aspects of nuclear production cited above, an effective security system in the nuclear non-proliferation domain must consist of several parts. The most important components that must be prevented from spreading are the fissile materials or nuclear materials that may be used for nuclear weapons production. What does this imply and what measures have been taken in order to prevent proliferation at the global, regional and national levels? Are the nuclear materials thorium, U-235 and plutonium the only materials that are to be kept under surveillance and controlled in accordance with international regulations?

As the above exposition makes clear, there are several materials and components that need to be controlled and supervised. An effective non-proliferation system should also include control over equipment and other components that may form part of a nuclear capacity. But matters are not that simple. The reasons for this are manifold and some of them are discussed in chapter 2, which deals with the historical development of the nuclear materials control system. To produce effective and binding treaties that most of the world's states will accept and abide by is a difficult undertaking, given that states often have divergent political and economic interests. What is perceived by one state as a step forward in the global work of non-proliferation can be felt by another country to constitute a national threat. In the last resort, the success of international cooperation depends on how effectively the world's states are able to cooperate with each other. And this, in turn, depends on the degree of trust between nations and the extent to which treaties on non-proliferation are observed. Today we can speak of a fairly comprehensive global system of nuclear non-proliferation that intervenes in several areas; it is not only nuclear materials that may be used for nuclear weapons production that are subject to controls, but also a series of other products and components which are regulated by different international and regional organizations. As already stated, it is not a question of a system that is perfect for all time. It is a system that is constantly changing, and this is because the world is constantly changing. During the Cold War the world was controlled by the two superpowers, the United States and the Soviet Union. It was a bipolar and rather predictable world, and the two powers facing each other in the global arena were fairly equal in terms of weapons technology; they dominated the world, controlled the flow of nuclear technology and thus kept other potential "challengers" at bay. The United States and the Soviet Union sought allies among the states of the world and formed two blocs that were dependent on one or the other superpower in the Cold War game. Today we live in a multipolar world, which, for this reason, is also less predictable. Global cooperation can therefore be said to be even more important today. The disappearance of the Cold War blocs has led to new kinds of threats: terrorism and an increase in within-state conflicts in connection with the dissolution of the Soviet Union and the communist systems of Eastern Europe. Many experts have also maintained that the risks of nuclear proliferation have increased since the downfall of the Soviet Union. It has been claimed that the general state of insecurity and the absence of a stable security policy order may induce certain states to try to acquire nuclear weapons of mass destruction. After the terrorist attacks in the United States on September 11, 2001, there has also been an increased fear that terrorists might be able to get hold of some form of weapon of mass destruction, including nuclear devices.

Chapter I.2 The Development of a Global Nuclear Materials Control System

2.1 Historical 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.[2]

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.[3] 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

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[2] Richard Rhodes, The Making of the Atomic Bomb. Touchstone Books, New York 1986, p. 30.

[3] Ibid., p. 42.

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.[4] 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 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.[5]

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, a chemist of Swedish ancestry, 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.

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[4] David Fischer, History of the International Atomic Energy Agency: The First Forty Years. IAEA, Vienna 1997, p. 15. et passim.

[5] Rhodes, p. 303–314.

2.2 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 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.[6]

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

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[6] 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.

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.[7]

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.[8] The year after that, the Russian researchers got started with a laboratory-scale nuclear weapons project.[9] 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 September 1944, and the Russians also lacked other important ingredients such as graphite and heavy water.[10]

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." Sweden thus ended up in ninth place and appeared to be an interesting potential producer. Concerning the Swedish case, the report stated: "Very low grade ore. No reported production but potential possibilities considered fairly good."

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

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[7] 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.

[8] 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.

[9] Skogmar 1997, p. 17.

[10] 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.

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.

In the spring of 1945, the British conducted an investigation which changed their appraisal of the importance of the Swedish uranium reserves. From now on, these were considered to be among the three or four most important in the world (despite the fact that they were low grade), and the only truly major ones in the Western world. All other known uranium assets, plus the uranium already produced, was under the control the United States and Great Britain. This efficient uranium cooperation thus resulted in the United States and Great Britain controlling more than 97 percent of the world's uranium production.[11] The Soviet Union was presumed to have only small quantities at its disposal.[12] 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.[13]

2.3 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.[14] These numbers indicate the explosive force of the world's first nuclear device.[15] 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.[16] 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."[17]

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[11] Holloway, p. 174.

[12] Skogmar 1997, p. 28 et passim.

[13] 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.

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

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

[16] Rhodes, p. 740 et passim.

[17] 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.[18]

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

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[18] Fischer, ibid.

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.[19]

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 become the world's second nuclear power.[20] 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:

- 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.
- To prevent the proliferation of nuclear weapons.
- To control the sale of nuclear materials and other equipment that might be used for nuclear weapons production.
- 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.[21]

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.[22] To summarize, we can say that during the period until 1953, US legislation prohibited export of

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[19] Ibid., p. 19 et passim.

[20] Ibid., p. 21.

[21] Gunnar Skogmar, Atompolitik: sambandet mellan militärt och civilt utnyttjande av atomenergin i amerikansk utrikespolitik 1945–73. Lund 1979.

[22] Skogmar 1997, p. 91 et passim.

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.[23]

2.4 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 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.[24] 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.[25]

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

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[23] Skogmar 1979, p. 30 et passim.

[24] Fischer, p. 22 et passim.

[25] Skogmar 1979, p. 74 et passim.

concerning participation in the IAEA organization[26], 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.[27]

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 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).[28]

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.[29]

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[26] Fischer, p. 30 et passim.

[27] Skogmar 1979, p. 79.

[28] Ibid., p. 35 et passim.

[29] Ibid., p. 36.

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.[30] 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 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. During the period 2004-2007, Sweden sat on the board of the IAEA. Sweden will next take a seat on the board of the IAEA in the fall of 2011.[31]

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.

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[30] Ibid., p. 37.

[31] Ibid., p. 39 et passim.

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:

- 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);
- To demand that operating records be kept (Article XII.A.3);
- To demand and obtain reports (Article XII.A.3);
- To approve the methods for reprocessing used fuel;
- To dispatch inspectors to facilities with which the IAEA has safeguards agreements. The inspectors should in principle have access at any time to locations, data, and personnel connected with nuclear posts that are placed under safeguard.[32]

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.[33]

After protracted negotiations, the Twelve Nation Group succeeded in producing a treaty text. But it wasn't until the 1970s, after the signing of the Non-proliferation Treaty, that the IAEA took over responsibility for safeguards on a wide front. One of the reasons why the IAEA did not take over responsibility for nuclear material control was that none of the proposed basic ideas about using the organization either as a common pool or control station for fissile material was ever realized. Another reason was that the Soviet Union and certain Third World countries, led by India, were against the idea of assigning this comprehensive responsibility to the IAEA.[34] 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

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[32] Ibid., p. 43.

[33] Ibid.

[34] Ibid., p. 82.

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.[35]

2.5 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.[36] 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:

- To prevent the dissemination of nuclear weapons
- To promote nuclear disarmament
- To promote the peaceful use of nuclear energy

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[35] Fischer, p. 29.

[36] Ibid., p. 94 et passim.

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.[37] 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.

2.6 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.[38]

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

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[37] George Bunn, “The Nuclear Non-proliferation Treaty: History and Current Problems.” Arms Control Today. December 2003.

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

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.[39]

2.7 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.[40] 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

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[39] Fischer, p. 106 et passim.

[40] Theodore Hirsch, "The IAEA Additional Protocol. What It Is and Why It Matters." The Nonproliferation Review. Fall–Winter 2004.

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").

Chapter I.3 Non-proliferation Regimes

Aside from the IAEA there are other organizations engaged in nuclear non-proliferation. Each of these organizations specializes in certain aspects of the non-proliferation work. Broadly speaking there are five different areas in nuclear non-proliferation work: nuclear materials control, export control, physical protection, transport security, and the increasingly important work of preventing the illegal handling of radioactive material, so-called illicit trafficking. These five areas consist of a number of different cooperative arrangements in the form of treaties, international conventions, regulations, security norms, inspection routines, well-tried scientific methods, surveillance systems, etc., the common purpose of which is to prevent the spread of nuclear materials and equipment that may be used for nuclear weapons production. This type of international collaboration constitutes a special form of cooperation, which goes under the designation of "international regimes." An international regime comes into being when a number of states with convergent interests establish a joint control regime in a specific domain, with the purpose of achieving common objectives. The members of the regime share the same values and they seek to have these values serve as guiding stars for the control system. In this paper, the emphasis is on nuclear material control (safeguards), since it is of signal importance for the whole field of nuclear non-proliferation, but the other areas will also be dealt with, albeit in more general terms. However, before the five areas of non-proliferation work are presented and discussed, we must deepen our knowledge of how international cooperation can be justified and how international regimes function in theory. All states do not agree on what should be done when various types of control systems are set up, nor do they concur on the objectives to be aimed at when states join together in different forms of international cooperation.

3.1 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 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*. [41] 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 dominant position) in the international system. [42] Evidently, not all states can achieve a position of hegemony. The competition among states in the

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[41] 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.

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

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. [43] 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*.

Schools of liberal thought believe, in contrast to realists, that cooperation can pay off. The first variant of this school of thougth, *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

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[43] 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.

regard as the liberal internationalists' naïve faith in a natural order and the power of reason to bring about peace and security 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. [44] 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

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

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.

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.[45]

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."[46]

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[45] David Held, Democracy and the Global Order. From the Modern State to Cosmopolitan Governance. Stanford University Press. Stanford, California 1995.

[46] 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.

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."[47]

This definition has also been criticized for being too wide and vague [48], 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 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.[49]

In current research, one can distinguish three explanations, all with some validitity, for why states establish and maintain international regimes.[50]

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

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[47] Krassner 1983.

[48] Levy et al., "The Study of International Regimes," p. 270, European Journal of International Relations, 1995.

[49] 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.

[50] 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.

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.[51]

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.[52]

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.[53]

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. [54] 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

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[51] 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.

[52] Ahlström, pp. 87–88.

[53] Ahlström, p. 87.

[54] 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.

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.[55]

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, 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, as already pointed out in chapter 1, 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.

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

3.2 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.

3.3 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.

Chapter I.4 Export Control Regimes

The two most important export control regimes in the nuclear domain are the Zangger Committee (ZC) and the Nuclear Suppliers Group (NSG). Both organizations were established for the purpose of preventing the illicit traffic of nuclear materials and technology, while also facilitating the peaceful use of nuclear energy. In both cases it is a question of political cooperation and not a legal undertaking, which means that no internationally binding sanctions can be implemented. As part of the political commitment, however, the participating states have promised to adjust their respective national legislation so that it will comply with the objectives and purposes of the export regime.[56]

The ZC was set up in 1971, during a meeting in Vienna at which representatives from 15 states hade gathered to work out effective interpretations of the definitional problems involved in article III:2 of the NPT treaty. The problem was that article III:2 was aimed at preventing the military use of nuclear materials and equipment while simultaneously allowing commercial trade in the same products for civil use. The group worked together during the period 1971-74 under the leadership of Swiss professor Claude Zangger, and the meetings resulted in the formulation of two so-called Memoranda of Understanding which were directed towards solving this problem.

Memorandum A, which deals with the export of "source or special fissionable material," solves the problem in three ways. Firstly, the participant states have decided to employ the definition of fissionable material contained in the statutes of the IAEA, viz. statute 20, whenever article III:2 of the NPT is invoked. [57] Secondly, they have agreed that the IAEA safeguards agreements (albeit not in so-called full-scope versions) be applied to nuclear materials that are being exported or to the facility where the nuclear technical equipment is to be used. This rule applies to exports to states that have not signed the NPT treaty. Thirdly, the recipient party must apply the same conditions (contained in the safeguards agreement) in the event of re-export of the received nuclear material or equipment to a third party which is also not a member of the ZC. [58]

Memorandum B consists of a list defining the exact materials and equipment ("single-use" products) which require ("trigger") safeguards according to article III:2. This list is also called the "trigger list." The list is updated continuously according to need and is made public in the IAEA Information Series as INFCIRC/209/Rev.2. The demand for IAEA safeguards applies, in principle, to the facilities where the nuclear materials and equipment are located. Other nuclear facilities in the non-member state are not subject to controls.

The Zangger Committee guidelines clearly constituted a step forward towards a more comprehensive non-proliferation system. But despite this success, a number of states emphasized the many shortcomings of the system. For this reason, another organization, based on stricter requirements, was formed in London in 1975, called the Nuclear Suppliers Group (NSG, a.k.a. the London Group). The NSG is not formally affiliated with the NPT, and this fact has also made it possible for it to strengthen its demands.

The immediate cause for the creation of the NSG was related to India's conducting its first nuclear weapons test in 1974, which clearly demonstrated that the system which had been in effect up to then did not fully work. India had managed to acquire technical equipment,

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[56] Lars Hildingsson, "Exportkontroll inget modernt påfund", Nucleus 2002:1

[57] "plutonium-239, uranium-233, uranium enriched in the isotopes 235 or 233; any material containing one or more of the foregoing; and such other fissionable material as the Board of Governors shall from time to time determine; but the term `special fissionable material´ does not include source material." The term source material has been defined as "uranium containing the mixture of isotopes occurring in nature; uranium depleted in the isotope 235; thorium; any of the foregoing in the form of metal, alloy, chemical compound, or concentrate; any other material containing one or more of the foregoing in such concentration as the Board of Governors shall from time to time determine; and such other material as the Board of Governors shall from time to time determine", Ahlström 1999, p. 320, footnote 55.

[58] Ahlström 1999, p. 338.

facilities and expertise in spite of the fact that only “peaceful” use of nuclear technology would be permitted according to the NPT, the safeguards agreement, and the Zanger Committee. The US and the UK took the initiative in attempting to establish a stricter form of export control in order to strengthen the non-proliferation regime. A meeting was held in London in 1975, and the year after that a treaty was worked out, the Nuclear Suppliers Agreement. This treaty represented an extension of the “trigger” list drawn up by the ZC. In 1977, the confidential document “Guidelines for Nuclear Transfers” was produced, for the purpose of serving as a framework of rules for participant states. The following year, these guidelines were made public and handed over to the IAEA, which soon thereafter published “Guidelines for Nuclear Transfer” (GNL) as INFCIRC/254. Two other documents were subjoined as appendices to the GNL, “Clarifications of items on the Trigger List” and “Criteria of levels of physical protection.” The NSG represented a distinct tightening up of the requirements as compared to the guidelines that had been worked out by the ZC. In contrast to the ZC, the NSG “trigger list” applies to all non-nuclear weapons states (not only those that are members of the NPT). The NSG list comprises the following materials and equipment:

- Nuclear materials;
- nuclear reactors and nuclear-reactor equipment;
- non-nuclear materials for reactors;
- facilities and equipment for reprocessing and enrichment procedures, conversion to nuclear materials and fuel production, and heavy-water production
- technology related to the items listed above.[59]

In case of export of nuclear materials and nuclear equipment, the following requirements apply:

- the delivered nuclear materials and nuclear facilities should enjoy satisfactory physical protection in the recipient country;
- the recipient state must have signed a full-scope safeguards agreement with the IAEA;
- the recipient party must guarantee that the material will be used for peaceful purposes;
- re-export can only take place if the above-mentioned conditions have been met.

After the Persian Gulf War of 1991, it surfaced that Iraq was running a secret nuclear-weapons program, and for this reason the NSG expanded its mandate to encompass more products which may be used in nuclear activities but which also have other, non-nuclear areas of use (so-called “dual-use” products, NSG Part 2).[60]

The conditions for membership of the NSG were as follows:

- The state in question has the capacity to deliver the products mentioned in GNL Part 1 and Part 2;
- the state must subscribe to the GNL and act in accordance with these;
- a national, legally based export control system must be in force;
- the state must be a signatory to the NPT or a similar non-proliferation treaty.[61]

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[59] Ahlström 1998, p. 348 et passim.

[60] Lars Hildingsson, ”Exportkontroll inget nytt påfund”, Nucleus 2002:1.

[61] INFCIRC/539.

Now that the additional protocol to the NPT has begun to be ratified, the IAEA will acquire information concerning nuclear technical exports. The purpose of this information gathering is to make possible the tracing of equipment and products all the way to the end user. According to the additional protocol, member states are obliged to declare exports of nuclear equipment every three months to the IAEA, whose inspectors will also be entitled to control imported products. The IAEA uses the information to plan its inspections activities and as a basis for its evaluation of the member states.

Of the two export control regimes, the NSG has the largest number of member states (all countries that are members of the ZC are also members of the NSG). The NSG also has more products on its control lists and stricter requirements for exports. For this reason, the NSG has become the leading and most proactive regime for nuclear export control, despite the fact that it does not have formal ties to the NPT treaty. How export controls may come to function in practice will be discussed in chapter 9, where the Swedish nuclear non-proliferation system is presented.

In addition to the NSG and the ZC, there are two other important export regimes connected with the work of nuclear non-proliferation.

The Missile Technology Control Regime (MTCR) is aimed at reducing the risk of proliferation of weapons of mass destruction by means of controlling the trade in weapons-carrier systems (other than aircraft) which may be used for this purpose. The member states have adjusted their national legislation to make it accord with the intentions of the MTCR, and there are checklists for what can and what cannot be re-exported. Today the regime has 32 member states.

The Wassenaar Arrangement on Export Controls for Conventional Arms and Dual Goods and Technologies (formerly called Cocom). The regime has four main objectives: 1) To promote transparency and greater accountability in regard to trade in dual-use equipment and technology; 2) to make use of nationally based legislation to create a system of rules designed to prevent the development and expansion of military capacity in contravention of the objectives of the regime; 3) to complement and strengthen other control regimes in the nuclear non-proliferation and weapons-carrier system domains; 4) to bring about increased cooperation in order to prevent the acquisition of weapons and critical dual-use equipment which may be used against a member state in a region characterized by a gathering security threat. At present, this regime counts 33 states as members.

In 2004, the UN Security Council adopted a resolution (UNSC 1540) aimed at preventing the spread of weapons of mass destruction and weapons carriers. This also includes their transfer to nongovernmental actors (terrorists). Among the measures decided upon was to have all UN member states institute efficient national export control.

Chapter I.5 Physical protection, transport security and illicit trafficking

By physical protection is meant various measures aimed at preventing theft, sabotage and burglaries directed against facilities that use or store nuclear materials and technical equipment. This issue has always been regarded as too complex to be dealt with and regulated by means of one specific and detailed global control regime. Given that different states have varying nuclear infrastructures, based on dissimilar domestic traditions and divergent threat pictures, the general opinion has been that each state individually must assume responsibility for matters of physical protection. It has been considered much too difficult to attempt to design and ratify a uniform, exhaustive, and globally comprehensive rule system. The question of whether it wouldn't be preferable to create a more uniform and specific international regulation has, however, been discussed at great length by experts over the years. The IAEA has also drawn up general guidelines that member states are advised to follow in order to achieve a recommended security standard for physical protection. The first guidelines were published in 1972, and since then they have been revised a number of times. These guidelines, "Recommendations for the Physical Protection of Nuclear Material and Nuclear Facilities," [62] cover the physical protection of nuclear materials during use, storage and transportation, both nationally and internationally. They have been very influential and of great assistance to states in their development of national regulation systems. [63]

A major step was taken in 1980 when the IAEA passed a convention dealing with the management and regulation of transports of nuclear materials between states. In 1987, the Convention on the Physical Protection of Nuclear Material acquired legal force, signifying that the states that have signed the convention have committed themselves to conform to the obligations contained in the articles of the convention. However, it was still felt that the individual states should be responsible for the nationally based physical protection and, as Article III makes clear, for taking effective measures aimed at protecting the nuclear materials in accordance with national legislation and the IAEA convention. The convention is a legally binding agreement but its application, as already mentioned, concerns transports between different states by land, sea, and air. Today 121 states have joined the convention. These states have promised not to export or import nuclear materials from another state that has not signed this convention, or that is unable to guarantee that it can conform to the conditions specified in "Annex 1." The same conditions apply as well to transit traffic of nuclear materials through the territory of signatory states, across international sea territory, and between states that have not signed this convention or are otherwise unable to assure that the stipulated demands of the convention can be met (Article 5:1-7). Annex 1 describes the different levels of physical protection that are required during international transports. On a general level, it can be said that the level of protection depends on the type of nuclear material transported (weapons-grade nuclear material requires the highest level of potection), and on the quantity. Three categories have been decided upon, with category 1 signifying that the highest level of protection is required: protected storage with physical barriers, including electronic surveillance and constant supervision by guards who are in close contact with an

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[62] INFCIRC/225/Rev. 4/Corr.

[63] Mohammed Elbaradei, Physical Protection of Nuclear Materials,

http://www.iaea.org/Publications/Magazines/Bullentin/Bull394/elbaradei.html adequately dimensioned response force. The measures taken must be of a nature that they will guarantee that burglaries and attacks against storage facilities, or removal of nuclear materials, will be discovered and prevented (Annex 1, see appendix).

An immediate consequence of the collapse of Soviet communism was that the new states formed on former Soviet territory lacked both the know-how and the financial resources to construct new structures of security and protection. Several incidents involving the illicit trafficking of nuclear materials and nuclear technology were reported, and as a result the IAEA, the European Union, the United States, and a number of other states took various measures to assist the newly formed states in creating more efficient nuclear infrastructures. As part of this work, the IAEA has designed a series of programs and control systems aimed at helping member states strengthen their systems for nuclear material control and physical protection. In this regard, the most important instrument or, as IAEA General Secretary Mohammed Elbaradei describes it, "the first line of defense in the protection of nuclear materials," is the State System for Accountancy and Control (SSAC). By way of this system, states are able to acquire exact information about the existence and quantity of any nuclear material, and this is of great help in the work to uncover illegal activities. In connection with this system, the IAEA has designed and coordinated programs and plans for technical support with a view to improving the SSAC and the physical protection. One program, the Integrated Nuclear Security Support Plans (INSSP), is particularly important as an instrument for strengthening nuclear security in the member states. Within the framework of the International Physical Protection Advisory Service (IPPAS), the IAEA, at the request of a member state, puts together a group of international experts who will evaluate and suggest ways of improving the physical protection in the country.

Although the convention has been viewed as a great success, many experts argue that the regime needs to be expanded. In recent years, a work of modification has also been carried out. On July 8, 2005, a diplomatic conference agreed on an expanded convention on physical protection of nuclear materials. This includes, in addition to international transports, national handling, storage and transportation of nuclear materials, and protection of nuclear technical facilities. However, it will take many years before it has been ratified by enough states for it to come into force. International recommendations for the physical protection of nuclear materials and nuclear facilities have also been worked out under the auspices of the IAEA – "Physical protection of nuclear facilities." Although these recommendations are not legally binding, the states that have been involved in the process of developing and revising them have taken a moral position and they are therefore expected to abide by them.[64]

Chapter I.6 Nuclear material control – safeguards in practice

By nuclear material control is meant that nuclear materials (uranium, plutonium and thorium or some other material that may be used for production of nuclear energy) that are kept and/or used must be subject to a legally accepted and well-functioning system for verification of

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[64] INFCIRC/225/Rev. 4/Corr.

correctness and completeness. Nuclear material control means that nuclear materials, especially U-235, plutonium and thorium, will not be used for producing nuclear weapons.

The view of how nuclear materials should be dealt with legally and physically/practically has of course varied from state to state depending on their different traditions and experiences. In the early days of nuclear energy, countries rarely had elaborate and well-functioning legislation or systems of regulations with regard to nuclear materials. Awareness of the risks and dangers involved in the development of nuclear energy led to a tightening up of legislation and regulations. International cooperation resulted in the conclusion of bilateral agreements and the signing and implementation of international conventions and treaties. Although the creation of the NPT constituted a major step forward in the establishment of internationally acceptable standards of surveillance and control, there are still differences between countries' systems of nuclear material control. The five nuclear-weapons states, for example, which took part in the formation of the NPT in 1968, do not have the same safeguards agreements with the IAEA as the non-nuclear member states. In 2005, the IAEA had safeguards agreements with more than 156 states, which means that the IAEA conducts inspections in these countries. 65 The Additional Protocol, which entails expanded obligations to account for nuclear activities and increased inspection rights for the IAEA, has been ratified by 118 states. 66 Altogether, the IAEA conducts inspections at 930 facilities around the world. 67 Moreover, the IAEA's agreements are formulated at a rather general level, so that there is a certain scope for national solutions. The IAEA has however produced general instructions for how a national control system should be designed (Guidelines for States' Systems of Accountancy and Control of Nuclear Material). If we consider the management of nuclear materials based on what these agreements mean, implicitly and explicitly, by surveillance and control, we can list four main principles that must characterize an efficient system.

- Duty to uphold a comprehensive and consistent account of nuclear material holdings (Duty of characterization). This means that the holder of the nuclear material must be able to provide an exact account of the materials dealt with, clearly describe changes in the holdings that have occurred over time, and account for in- and outgoing traffic within the country and outside (including givers and recipients);
- Duty to prevent unauthorized persons from gaining access to nuclear materials (Duty of restraint). The holder must be able to set up a system for physical protection, security regulations, and design of installations which is aimed at eliminating unauthorized access. Inaccessibility and impenetrability are two important concepts in this regard (see under physical protection).
- Duty to guarantee reliability (Duty of assurance), which means that the holder must be able to maintain a security system characterized by minimization of the risk level and aimed at eliminating the risks altogether. The system used should be distinguished by public accountability and transparency. The transparency of the system signifies, in this context, that it can live up to two important principles – that it should be possible to verify the materials dealt with, and that this should be done in a confidence-building spirit, meaning that the system should be able to produce confidence.

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65 www.iaea.org/OurWork/SV/Safeguards/es2005.html

66 www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html

67 www.iaea.org/Publications/Reports/Anrep2205/table_a21.pdf

- Duty to observe commitments that have been made (Duty of compliance). This principle implies that one is obliged to follow the laws, regulations, and international treaties and conventions that have been signed or that are otherwise valid. The classic formulation of Roman law, "Pacta sunt servanda" (pacts must be respected), is the guiding principle with regard to this aspect of the management of nuclear materials.[68]

6.1 The IAEA safeguards system

A state that has signed and ratified the NPT treaty and that also possesses nuclear materials and other nuclear-related equipment is also obliged to enter into a safeguards agreement with the IAEA. The safeguards agreement gives the IAEA the right to verify that states' possessions of nuclear materials is consistent with their declared quantities. Further, all states that have signed and ratified safeguards agreements have committed themselves not to transfer nuclear materials and nuclear equipment to states that do not have binding control agreements with the IAEA. [69] For example, Sweden is a member of the IAEA and has signed and ratified both the NPT treaty and a safeguards agreement. This means that Sweden has vowed not to produce nuclear weapons, and to support efforts to prevent other countries from producing them. The IAEA carries out inspections in order to verify that the agreement is respected. The Swedish governmental body The Swedish Nuclear Power Inspectorate (SKI) is the national organization responsible for overseeing the implementation of the treaties. The work of SKI is governed by Swedish legislation and rule systems that have been worked out according to the demands made by the IAEA and to national needs and requirements.

The different agreements regulating safeguards cover the states that have ratified the NPT and other equivalent treaties with the IAEA. Each separate agreement, so called INFCIRC, requires that the concerned state accept the IAEA's safeguards demands regarding all the fissile material (pursuant to the IAEA's list of materials that are subject to surveillance and control) inside the country or that the state has access to outside the country's borders. This means that the state in question creates and maintains a safeguards system that conforms to the four principles described above. There are, however, several kinds of safeguards agreements depending on the nuclear energy profile of the state in question and the historical and geographical circumstances that affected the formulation of the different treaties on nuclear non-proliferation.

The Comprehensive Safeguards Agreement (INFCIRC/153) regulates the non-nuclear countries which, in keeping with the NPT, have declared that they possess nuclear materials according to the definitions and regulations of the IAEA, and which therefore should be subject to surveillance and control. States that have other, equivalent types of bilateral and multilateral arrangements regarding nuclear non-proliferation with the IAEA are covered by other safeguards agreements. This applies to the following treaties: (a) the Treaty for the Prohibition of Nuclear Weapons in Latin America and the Caribbean (Tlatelolco Treaty); (b) the South Pacific Nuclear Free Zone Treaty (Rarotonga Treaty); (c) the Argentine-Brazilian

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[68] These four points have been taken from a talk given by professor William Walker, University of S:t Andrews, which he gave at the 27th Annual Meeting. Symposium on Safeguards and Nuclear Material Management, organized by the European Safeguards Research and Development Association, May 10-12 2005.

[69] INFCIRC/153, www.iaea.org

Declaration on Common Nuclear Policy; (d) the Treaty on the Southeast Asia Nuclear Weapon Free Zone (Bangkok Treaty); and (e) the African Nuclear Weapon Free Zone Treaty (Prelindaba Treaty).

Some states have non-existent or insignificant nuclear material holdings and very little nuclear technical activities. These states have often concluded a “Small Quantities Protocol” (SQP), which means that the various detailed regulations covered by Part II of the Comprehensive Safeguards Agreement are suspended. The IAEA is in the process of changing this by having the concerned states voluntarily sign a Comprehensive Safeguards Agreement (INFCIRC/153). Other states apply a nuclear material control that is not “comprehensive” but more focused on controlling specific materials and equipment, since they do not have large-scale nuclear technical activities (INFCIRC/66/Rev.2). This might involve heavy water, zirconium, or different pumps that are used in one way or another in various facilities or stored in the country.

The five nuclear powers, the United States, Russia (the Soviet Union), France, China, and Great Britain, which have also signed the NPT, are not covered by safeguards, however, since they possess nuclear weapons. But since this exception has been considered unjust, these states have agreed to conclude a so-called Voluntary Offer Agreement (VOA), which means that civilian facilities dealing with nuclear materials in these countries are also covered by nuclear material control.

It is important to emphasize that the treaties and steering documents regulating the international commitments are formulated at a rather general level, and that the individual member states have a large responsibility for designing nationally functioning nuclear material control systems. Choices regarding legislative content and the forming of regulatory bodies, as well as the design of the control system at large, reflect different national traditions and perspectives. Of course, this development work is done in cooperation with the IAEA, and certain minimum levels of surveillance and control must be maintained. The system has also been criticized for not providing adequate protection.

And the truth is that until the 1990s, the IAEA had a rather limited mandate for exercising control within the framework of the existing NPT. The reason was that it was only the nuclear materials and facilities that the states had declared possession of that could be subject to inspection. If a state was carrying out secret nuclear weapons production outside the areas that were subject to inspection (i.e., declared), the IAEA had difficulty discovering this.

When Iraq, which had signed the NPT treaty and was party to a safeguards agreement, managed to deceive the IAEA, it became clear that the control system did not fully work. In February 1992 the work began of improving the safeguards system. This events led to the formation of a work group within the IAEA responsible for developing a more efficient system. In May 1997, the IAEA Board approved the protocol INFCIRC/540, which represents and addition to INFCIRC/153. In 1998, all EU member states signed the additional protocol, and today 114 states have ratified it. The protocol represents a model for expanded safeguards responsibilities for states that have ratified it. According to the additional protocol, the whole nuclear fuel cycle from mine to terminal storage must be accounted for.

Every individual state that has signed a safeguards agreement with the IAEA must put together a so-called Initial Report (IR) in which the state concerned accounts for the nuclear materials it possesses. If the agreement in question is a Comprehensive Safeguards Agreement, the declaration should include, in addition to an account of nuclear materials, information about the design of nuclear facilities, a so-called Design Information (DI, as regulated in INFCIRC/193). The DI presents blueprints and data concerning operating conditions and performance. With this information, the IAEA attempts to delineate and analyze different possible ways of diverting nuclear materials in order to devise an adequate inspection plan for the facility. The owner of the facility is obliged to notify the IAEA of plans for constructing new facilities and of decisions concerning technical modifications (as specified in the demands made by the IAEA in the Facility Attachment, FA). How the actual verification is carried out will depend on the conditions obtaining at the facility in question. The IAEA verifies this DI on an annual basis in order to monitor possible changes that may be significant for the development of the safeguards system. This control activity is called Design Information Verification (DIV).

The methods that will then be used in the verification work in the concerned state constitute a system of safeguards with the following ingredients:

- Receipt of reports on holdings of nuclear materials and changes in these
- Verifications of material flow.
- Regular material balance accounts.
- Independent verification of all nuclear materials in those facilities which, according to the declarations made by the state in question, use nuclear materials that are subject to IAEA controls (this is called Physical Inventory Verification.
- Use of surveillance equipment (containment and surveillance, C/S).

Every state that has ratified the safeguards agreement must have an organization (a governmental authority or supranational body such as Euratom) which acts as a counterpart to the IAEA. Every year the IAEA conducts an evaluation, a so-called Safeguards Implementation Report (SIR), summarizing whether facilities in the member state have fulfilled the objectives. The main purpose is of course to verify whether the declarations the state has made concerning its nuclear materials are correct, or whether illegal diversion of the nuclear material has occurred.

In 2005, the IAEA inspected 930 facilities around the world. It takes 250 IAEA inspectors a total of 21,000 workdays to investigate hundreds of tons of fissile material.

The efficiency of nuclear material controls depends primarily on three interdependent factors:

- The IAEA's aggregate knowledge of the nuclear activities taking place at various locations;
- The IAEA's physical access to relevant sites and facilities where nuclear activities take place;
- The willingness of the international community to intervene, through the United Nations Security Council, against states that do not conform to the agreed-upon conditions regarding nuclear material control.

6.2 Nuclear material control inspections step by step

An inspection process begins when the IAEA sends an advance notification to the authority responsible for national control and surveillance in the state in question. This notification shall include information about the scope of the planned inspection and about the inspectors taking part in it. The responsible national authority verifies that the inspectors the IAEA is planning to send out are certified, and, if such is the case, notifies the concerned facilities that an inspection will take place.

How the actual verification is carried out depends on the conditions prevailing at the facility in question. A Facility Attachment drawn up by the IAEA lists these conditions. The verifications that are carried out must meet the IAEA Safeguards Criteria. After the inspection is completed, an account of the findings is written, a so-called statement that will be delivered to the governmental authority within a certain period of time. The responsible governmental authority or organization, in its turn, checks the inspection results against its own records of its holdings of nuclear materials.[70]

Definitions and criteria71

The IAEA has formulated different goals for the different types of safeguards agreement. For the states that have signed the Comprehensive Safeguards Agreement, the technical objective is to be able to discover if a state is illegally diverting nuclear materials from its civil fuel cycle before it can construct a completed nuclear weapon or other explosive devices (timely detection). At the same time, the purpose of the agreement is to deter such diversions and prevent them from occurring in the first place, since the system is based on early detection of illegal activities. These objectives also include detection of undeclared production or separation of "direct-use," weapons-grade nuclear materials at reactors, enrichment and reprocessing facilities, and facilities which contain so-called hot cells. The IAEA has estimated the time required for producing a nuclear weapon assuming that the necessary nuclear infrastructure already exists (procedures for converting and handling nuclear materials are tested and ready), and based on different assumptions regarding the state of the nuclear material. The inspection and control system has been designed with these calculations in mind.

Type of nuclear material	**Time interval**
Non-irradiated "direct-use" material, e.g., non-irradiated MOX, reprocessed plutonium, uranium enriched to 20 percent or more	one month
Irradiated "direct-use" material, e.g., irradiated fuel	three months
"Indirect use" material, e.g., uranium enriched to less than 20 percent (fresh fuel)	one year

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70 Ibid.

71 Parts of this section are based on a talk given by SKI inspector Lars Hildingsson.

The term “direct-use” implies that the nuclear material can be used for nuclear-weapons production without further enrichment or reprocessing. As can be seen in the table, the holdings of non-irradiated, “direct-use” nuclear materials must be inspected once a month. The reason for this is that, with this type of nuclear material, a state that wishes to do so can develop a nuclear weapon relatively quickly. For nuclear material of the irradiated, “direct-use” type, the IAEA has adopted an inspection interval of three months. When it comes to so-called “indirect use” material, this has to go through either further enrichment or irradiation in a reactor, followed by subsequent reprocessing, for it to be usable in a nuclear device. These are technically complicated and time-consuming processes, and the IAEA has therefore adopted an inspection interval of one year.

Apart from the time aspect, the IAEA uses different measures for the quantities of nuclear material required to produce a nuclear device – Significant Quality (SQ). Material loss during the process has been taken into account in the calculations.

Category of material	**SQ**	**Commentary**
“Direct-use” Pu	8 kg	Total amount of the material
U-2333	8 kg	Total amount of the isotope
U(U235=obs!20%)	25 kg	U-235
“Indirect use” U (U-235=20%)	75 kg	U-235
Thorium	20 metric tons	Total amount of the material

The IAEA’s objective is to be able to detect whether nuclear materials equivalent to one SQ or more have been diverted during a material balance period, and if there has been any non-declared production or separation of “direct-use” nuclear material. The SQ may therefore be used as a detection target, and this puts strict demands on the accuracy of verification and testing procedures. The work of verifying the facilities that are subject to inspection is based on a system where the probability of detection can be measured and divided into different levels:

- High probability of detection 90 %
- Medium probability of detection 50 %
- Low probability of detection 20 %

If diversion of nuclear material has occurred, the material is termed defect. And the different degrees of defect have been divided into three categories:

- Gross defect – all nuclear materials are missing
- Partial defect – up to 50 percent of nuclear materials are missing
- Bias defect – only small amounts are missing (not further specified)

6.3 Safeguards Objectives

The IAEA’s safeguards objectives concern both verifications at individual facilities and verification activities pertaining to the whole country. As concerns individual facilities, there are two main inspection objectives:

Quantitative objective: to be able to discover if one SQ or more has been diverted during a material balance period (the period of time between two balance-sheets), and to verify that no non-declared production or separation of "direct-use" material has occurred.

Qualitative objective: to regularly ascertain that no diversion of nuclear materials has occurred within the calendar year.

In order to achieve full attainment of the qualitative objective during a material balance period, the following is required:

- A verification of the physical inventory (PIV) must have been conducted. Further, inspectors must have investigated whether the material is irradiated or not.
- All inventory changes must have been verified.
- There must be verification that no non-declared production of "direct-use" nuclear materials has been carried out.
- There must be verification that declarations of nuclear material holdings are consistent with the stated changes. If there are deviations from the declared quantities (Material Unaccounted For, MUF), reasonable explanations for these discrepancies must be provided.

In order to achieve the objective of timeliness, the following is required:

- Inspectors must be able to verify whether a minimum of one SQ has been diverted within the estimated time period required for building a nuclear weapon (timeliness goal).
- Possible deviations must be explained satisfactorily.
- The time period between two consecutive PIVs must not exceed 14 months.

If all of these goals are not reached, one speaks of Partial Attainment or Non-Attainment in terms of quantity or time requirements.

When it comes to the evaluation of the country as a whole, as required under the Comprehensive Safeguards Agreement, the goal is the following:

- To verify that all facilities that are subject to safeguards have in effect been inspected.
- That the country has reached the goal of "Full Attainment" regarding a minimum of 70 percent of its nuclear material holdings.
- To verify that the accounts of nuclear material holdings are truly consistent with the stated changes.
- To verify that nuclear material that is verified at one facility has not been borrowed from another facility. This is to be verified through simultaneous inspections at two or more facilities that use similar materials.

6.4 How the IAEA verifies that the goals have been attained

The IAEA has worked out a number of criteria for every type of facility in order to be able to verify that the objectives of nuclear material control have been achieved. These criteria specify the range, normal frequency, and scope of the verification activities, and can thus be said to represent measurable objectives for the inspectors. The criteria are based on the analyses of diversion scenarios and statistical models conducted for each facility. The document describing the different criteria, IAEA Safeguards Criteria, lists a number of facilities which are to be controlled based on different criteria. Among these facilities are:

- Heavy water reactors
- Light water reactors
- Research reactors
- Fuel reactors
- Storage facilities
- Small facilities

Each chapter in this work document consists of a detailed exposition of all the activities that must be carried out if the level of attainment of the different objectives is to be measured in an efficient way. It falls outside the scope of this report to summarize this whole document and describe each individual criterion. After all, this report is meant to serve as a mere first introduction to the issues of nuclear non-proliferation and nuclear material control. In the following, only the main points are discussed.

Accountancy checking. The accounts of the facility in question are analyzed, and must be consistent with other source documents concerning nuclear material holdings. If the facility is located in an EU member state, such as Sweden, these accounts should also be consistent with those of the Euratom. Comparisons are also made between the accountancy and the reports that have been submitted.

Physical Inventory Verification (PIV). Different types of verification are conducted within the framework of a PIV. Of course, the activities vary from one facility to the next depending on the equipment that is used and available.

Verifications of shippings.
Non-declared production of “direct-use” material. In the case of power reactors, inspectors verify that there are no irradiation positions in the reactor core.

Material balance. For bulk material (UF-6 powder, etc.), the Material Unaccounted For (MUF) is evaluated:

MUF = PB + X – Y – PE
PB = Physical inventory at the start of the period
X = Shipped material
Y = Received material
PE = Physical inventory at the end of the period

Interim inspections. If the timeliness criteria are to be fulfilled, inspections must be carried out with a certain frequency depending on the quality of the material (see the table of time intervals above).

Verification of Design Information (DIV). If the DI has been changed in any way, this needs to be verified. At least once a year, a re-examination is carried out regardless of whether any change has occurred.

6.5 The Additional Protocol and its consequences

As described in chapter 2, the discovery of a secret nuclear-weapons program in Iraq in 1991-92 led to the development of a model for strengthening the NPT treaty. The Additional Protocol, which was adopted in 1998, gives the IAEA expanded powers to carry out inspections (complementary access), and entails a stronger obligation on the part of states to provide the organization with information about ongoing and planned nuclear activities. Under the Additional Protocol, the whole nuclear fuel cycle from mining to final storage must be accounted for. Through this additional information, the IAEA is now better prepared to analyze and evaluate the purposes of the various nuclear technology programs of states.[72]

Article I states that the purpose of the Additional Protocol is to strengthen the present safeguards system without undermining it: "the provision of the Safeguards Agreement shall apply to this Protocol. In the case of conflict between the provisions of the Safeguards Agreement and those of this Protocol, the provisions of the Protocol shall apply." Article II lists the different nuclear activities that are not covered by the Safeguards Agreement (SA), but which must be accounted for according to the Additional Protocol. States that have ratified the Additional Protocol have 180 days to hand over accounts of these activities and other information related to them.

The right of IAEA inspectors to complementary access is principally regulated in Articles IV-VI. These articles regulate the IAEA's rights and the obligations of states. For example, the IAEA has a right to demand access to all premises and facilities in a country where the Additional Protocol has the status of law, and the state in question is generally given 24 hours in which to accommodate the IAEA. There is one exception to the rule, however: if an inspector requires access to a premise in connection with an inspection in an area containing buildings covered by Article 5a of the Additional Protocol, the state has only two hours at its disposal. In certain special cases, it may have less than two hours.

Article VII concerns the right of states to limit the IAEA's "complementary access" to a certain building if this is deemed to entail negative consequences such as the leaking of sensitive information or the jeopardizing of security aspects. This should not, however, prevent the IAEA from implementing necessary measures to verify that no non-declared nuclear activity is taking place. Article IX centers on the right of the IAEA to conduct various tests and samplings in the area under scrutiny, a so-called "wide area environmental sampling" (WAES), to ascertain that no irregularities are taking place.

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[72] Theodore Hirsch,"The IAEA Additional Protocol. What it Is and Why It Matters". The Nonproliferation Review/Fall–Winter 2004.

In summary, the state in question is obliged to provide the IAEA with the following:

- Information about ongoing and planned (within a ten-year time frame) research and development related to the state's fuel cycle: reactor development, enrichment/reprocessing of nuclear materials, production of fissile material, etc.
- Information concerning operations that is of relevance to the control of nuclear materials at facilities and in areas adjacent to these facilities where nuclear materials are routinely used.
- Relevant information regarding control of nuclear materials that are included in the IAEA's list.
- General information that specifies the premises, facilities and other buildings contained in each area involved in the fuel cycle, including a map of the locale in question. This also includes buildings adjacent to facilities covered by IAEA safeguards (Article 2a).
- Detailed information about equipment and materials that form part of the fuel cycle.
- Information concerning quantities, field of application, and location of nuclear materials exempted from the Safeguards Agreement.
- Information about export and import of specific equipment and materials.

The coming into force of the Additional Protocol entails that the IAEA can act more effectively during inspections. In principle, the inspectors have a right to demand access to all information that is deemed necessary to throw light on inconsistent or insufficient accounts. They may even conduct inspections in the private homes of employees at the facilities under scrutiny, if this is deemed necessary.

Chapter I.7 Concluding remarks: Is it possible to speak of a comprehensive and effective nuclear non-proliferation system?

On the whole, then, how well does this nuclear non-proliferation system work? Answering this question is no easy task. The system is complex and may seem difficult to grasp, since the different states' involvement in the system differs depending on historical, geographic, and political realities. For example, not all the states of the world participate in the exact same organizations. There are a number of national and regional systems that are adapted to specific conditions, and which therefore require a special design in order to function in practice. But if we limit ourselves to briefly evaluating the four aspects of non-proliferation work, we should be able to draw some general conclusions.

The nuclear material control system has been improved and strengthened since the Additional Protocol came into force. Some experts have claimed that if the Additional Protocol had existed and been practically functional during the 1980s, IAEA inspectors would have discovered Iraq's preparations for acquiring nuclear weapons early on. One can also draw a parallel to the IAEA's verification work in Iran in recent years, where inspectors have reported that the state of Iran has not conformed to the NPT treaty and the ratified Safeguards Agreement. As things stand, Iran has not however ratified the Additional Protocol, which the country signed in 2003. But the developmental work that has gone into the preparations for producing a more trenchant and effective nuclear material control, with the lessons from Iraq in mind, has in itself created a more forceful and encompassing system. And if the Additional Protocol comes into force in Iran, it will be utterly difficult to deceive the inspectors. In summary, the Additional Protocol represents a major step forward. At the same time, it bears pointing out that North Korea carried out nuclear weapons tests in 2006, and that a large number of experts maintain that Iran is attempting to acquire nuclear weapons of mass destruction. How is it then possible to speak of a major step forward? Firstly, North Korea is no longer a member of the NPT treaty. If indeed North Korea actually intends to acquire nuclear weapons (assuming that it does not already have this capacity), there is not much the IAEA can do. The issue has ceased to be a matter of control and surveillance, and has now become a security policy issue. Consequently, the actors that are in a position to do something to change North Korea's current stance, either by political or military means, are the United Nations, the international community, and the great powers. Needless to say, the present situation would also be liable to change if North Korea were to modify its policy. Secondly, in the case of Iran, the conclusion must be that the IAEA actually did discover, in time, that all was not right with the Iranian nuclear energy program. The IAEA has issued reports of breaches of agreements and provision of incorrect information on the part of the Iranian government. In this regard one can thus say, without exaggeration, that the control and surveillance system really has worked.

In regard to the efforts to improve the physical protection, major successes have been registered in recent years. The large-scale infrastructure investments aimed at creating security and control systems in the former Soviet Union must on the whole be considered a successful undertaking, although certain substantial problems remain to be solved. Many observers feared that large numbers of Russian scientists and nuclear materials would disappear to so-called rogue states or terrorist organizations, but 10-15 years later we can conclude that this did not come to pass. A new and more efficient nuclear infrastructure – comprising modern legislation, independent oversight authorities, and modern security systems satisfying international standards – is taking shape in the Baltic countries, Russia, and the Ukraine. To be sure, there are still significant problems in terms of nuclear power facilities and storage facilities that do not maintain a high enough security level, particularly in the Central Asian states. But if one examines the statistical data on known incidents of illegal trafficking of nuclear materials, one must nevertheless exclaim: It could have been a lot worse.

The Convention on the Physical Protection of Nuclear Material, which came into force in 1987, must also be considered a success. The states that have signed the Convention have committed themselves to abiding by its obligations. To be sure, individual states are still the ones responsible for the design and surveillance of the physical protection. It would be desirable if the efforts made to extend the global responsibility to also include nuclear power facilities and national storage and transportation of nuclear materials were to meet with success. At the same time, it should be said that it is in the nature of things that each individual nation has a stake in protecting its nuclear material and equipment.

How, then, should the efficiency of the existing export control regimes be judged? Given the number of known cases of deviation from the intentions of the regimes, one can wonder whether they are really all that effective in preventing the proliferation of nuclear weapons. Export control regimes such as the ZC and NSG are founded on a political cooperation in which the member states promise to abide by the principles sustaining the cooperation, but there are no legal means by which sanctions may be used against states that violate any of these principles. For example, Russia's export of nuclear related equipment to India must be considered a clear breach of NSG principles. Nor has cooperation within the field of nuclear export control succeeded in preventing China from exporting a nuclear reactor (Chasnupp-1) to Pakistan, despite the fact that Pakistan has not signed the NPT treaty. China was a member of the ZC at the time, but not of the NSG, and this meant that China was not required to demand that all nuclear reactors in the recipient country be subject to IAEA safeguards controls (which it would have had it been a member of the NSG).[73]

A country that violates the principles of a regime becomes the target of harsh international criticism. However, great powers seem to be able to afford this without the consequences being punishing. In contrast, a country the size of Sweden would hardly get away with it the way China did. At the same time, it is important to underscore that a growing number of states are joining the export regimes; today China, for example, is also a member of the NSG. Although important steps forward have been taken in terms of stopping up many of the holes that existed when the NPT treaty was the only regulatory framework in place, the overall conclusion must be that the export control regimes, as presently designed, remain the weakest link in the overall system of nuclear non-proliferation.

Chapter I.8 Sweden's nuclear history

8.1 Sweden and the Heavy Water policy, 1945-70

Swedish research in nuclear energy started early. In 1945, the Swedish government appointed the so-called Atomkommittén (Atomic Committee, AC), which was assigned the task of studying and producing reports about the possible uses of nuclear energy in Sweden. Nuclear energy and nuclear weapons represented a new and partly unfamiliar world. The government basically wanted information and knowledge about how nuclear energy research might develop in the years to come. It was primarily the civil use of nuclear energy that attracted the prime minister, Tage Erlander, and other prominent political figures in Sweden. Sweden had just lived through several years of military preparedness and energy rationing during World War II. Oil deliveries had been sharply curtailed, with various reports indicating, moreover, that the world's oil supplies would probably come to an end within a couple of decades. Against this backdrop, many within the political elite regarded nuclear power as the dominant source energy of the future. Just as oil had earlier replaced coal, decision-makers now dreamed of letting nuclear power take over from insecure oil. Further down the line was the vision of a Sweden that would be self-reliant in terms of energy production. The overall picture also includes technological and scientific developments in Sweden. Sweden had made great advances in nuclear physics. In his memoirs, Erlander relates how he talked to the Danish Nobel laureate Niels Bohr, and especially to his old friend Torsten Gustavsson, a physics professor, about the possibility of using this new technology. Some of these conversations also concerned the possibilities of building Swedish nuclear weapons. Erlander

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[73] Lars Hildingsson, "Exportkontroll inget modernt påfund", Nucleus 2002:1.

writes that, for several years in the late 1940s and early 1950s, he was positive towards the idea of constructing Swedish nuclear weapons. [74] Those among the Swedish political elite who advocated nuclear weapons production maintained that a Swedish nuclear weapon would serve to guarantee a strong Swedish defense. The Swedish policy of non-alignment required, so the nuclear-weapons advocates argued, a forceful military power that could convince both of the superpower blocs that Sweden actually had the capacity to uphold its policy of neutrality in case of war. It was against this background that the Supreme Commander of the Swedish Armed Forces assigned the Swedish Defense Research Agency (FOI) the task of conducting research on the possible uses of nuclear weapons as early as September 1945.

In 1947, the government-owned company, AB Atomenergi (AE), was formed as a sort of joint venture between the state, the academic world of research, and private industry. The AE was primarily to concern itself with research and development in the field of peaceful nuclear energy. The FOI would, for natural reasons, be responsible for research on the military uses of nuclear energy.

Moreover, Sweden possessed rich uranium deposits that could be used for domestic production of nuclear energy. The country's leading physicists and chemists became associated with the AE and FOI. Contacts were made with the Royal Institute of Technology in Stockholm and with Chalmers Technical Institute in Gothenburg with the aim of stimulating and developing research in the nuclear-energy field.

For the reasons mentioned above, Swedish decision-makers opted for a reactor type using heavy water as moderator and natural uranium as fuel. As a byproduct from the uranium production one could also, through the application of technical know-how, manufacture weapons-grade plutonium. The Swedish nuclear energy program was set up so as to contain both a civil and (if the Swedish government and parliament were to make such a decision in the future) a military side. [75] The preconditions for a successful nuclear energy program in Sweden were deemed to be very good.

In 1946, the FOI was commissioned by the AC to explore the prerequisites for production of Swedish uranium, as well as separation of isotopes and plutonium production. Importing uranium was considered difficult given the strict US export control of nuclear materials and equipment. It was primarily the skiffer and kolm in the Swedish provinces of Närke, Västergötland, and Östergötland that were deemed to be of interest for the possible production of uranium in Sweden. As early as 1948, a method for extracting uranium from kolm was developed, and in 1950 the board of the AE decided that a uranium extraction facility would be built in Kvarntorp, Närke, with an annual production capacity of five tons. The facility was completed in 1953.

Up until 1956, the prerequisites for a Swedish atomic energy program were analyzed by a number of government agencies. The Atomic Energy Committee produced reports and private industry conducted negotiations with the government and the research community about the design of such a project. Meanwhile, an increasing volume of research grants had been made available by the government, and in 1956, finally, parliament made the decision to launch the project. The project came to be called "The Swedish Line," and it constitutes, alongside the

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[74] Tage Erlander, 1955-1960, p. 75 et passim. Stockholm 1976.

[75] Larsson, Karl-Erik, "Kärnkraftens historia i Sverige". Kosmos 1987, p. 127 et passim.

JA-37 Viggen and JAS 39 Gripen fighter aircraft projects, one of the largest industrial efforts ever carried out in Sweden.[76] This large-scale effort continued until 1970, when parliament cancelled the project.

8.2 Sweden's first reactor – R 1

In 1954, Sweden's first reactor was completed, the so-called R 1, situated at the Royal Institute of Technology in Stockholm. However, the reactor was not loaded with Swedish uranium, since no large-scale production of uranium had been started. Instead, the AE borrowed three tons of uranium from the French Commissariat à l'Énergie Atomique (CEA). It was decided that the reactor would be moderated with heavy water (five tons were imported from Norway), even though graphite was a possible alternative. Given that Sweden had not yet started its own uranium production, it was natural to choose this technology since it required lesser amounts of uranium.[77]

The AE research director, Sigvard Eklund (who was later to become the second Secretary General of the IAEA) assumed responsibility for the reactor project. Eklund made use of his extensive international network of contacts, particularly in France, during the planning and construction of R 1. The US facility CP 3 in Chicago served as a model for the first Swedish reactor. The reactor was built in a rock shelter, and in due course came to be driven with the effect of 1 MW.[78]

R 1 was, to a large extent, a training object, by means of which research and knowledge within the field of nuclear energy could be carried forward. For example, researchers at the reactor were engaged in studying the behavior of different materials during neutron radiation, and in measuring neutron cross-sections for uranium. Such information was of great value to both the AE and the FOI in their work of calculating the different sequences of chain reactions.[79] In 1953, another reactor-like facility was constructed in the same rock shelter as R 1, the ZEBRA (Zero Eenergy Bare Reactor Assembly). This facility was used for studying uranium rod configurations in reactor cores, something that was of particular significance for the design of the heavy-water reactor system.[80]

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[76] Stefan Lindström has analyzed the prelude to the "Swedish Policy" up until 1956, when the project was launched.

[77] Ibid. p. 131. In a talk titled "Swedish Uranium History," Erik Svenke has discussed methods of extraction and the Swedish policy in the uranium field, Technical Museum October 14, 2000. See also Strandell, Erik, Uran ur skiffer: Ranstadsverket: 40 års utveckling av processer för utvinning av uran ur mellansvenska alun skiffrar, parts 1 and 2, 1998.

[78] Interview with Bengt Pershagen conducted on November 16, 2001. On the background of R 1, see Eklund, Sigvard, "Den första svenska atomreaktorn", Kosmos 1954, vol. 32.

[79] Fjaestad, Maja, Sveriges första reaktor. Från teknisk prototyp till vetenskapligt instrument. SKI Report 01:1, p. 37 et passim.

[80] Brynielsson 1989, p. 202.

8.3 The construction of R 2 and the nuclear energy cooperation with the US

For Sweden's part, the "Atoms for Peace" program dictated the choice of next reactor, R 2. This reactor, which was put into operation in 1960 in Studsvik outside of Nyköping, was based on light-water technology and came to be used exclusively for research purposes. This alternative had not been possible before, since Sweden did not have access to enriched uranium. But after the Geneva conference in 1955 it became possible to buy both enriched uranium and complete reactors from the United States at favorable prices.

On January 18, 1956, the United States and Sweden signed a comprehensive cooperation agreement. Through this treaty, Sweden could obtain certain amounts of enriched uranium and heavy water, to be used for research purposes. There was an obvious condition built into these cooperation agreements: the recipient country pledged not to use the acquired nuclear materials for nuclear weapons production. [81]

R 2 was a bigger and, in terms of its power, stronger reactor than R 1, with a thermic power of 50 MW. The reactor came to be used primarily for material testing for future reactor development. For example, studies were made about the optimal design of nuclear fuel rods that were to be used in future nuclear power facilities. [82]

8.4 The Ågesta Reactor

The nuclear energy program of 1956 planned for the construction of 5 to 6 nuclear power plants by 1965. Even before the program was made public, one of these plants had started to obtain a concrete design – the R 3 at Ågesta, south of Stockholm. The reactor facility was designed for the combined production of heating and electricity. The AE and the Stockholm Electricity Board signed an agreement specifying that Ågesta would be used for the delivery of heating to the Stockholm suburb of Farsta. The facility was based on heavy-water technology and used natural uranium in the form of oxide as fuel.[83]

Ågesta was finally put into operation on July 17, 1963. The reactor was a prototype facility with a power of 65 MW, of which 55 MW were used for district heating of Farsta and 10 MW for electricity production. In 1965, the operation was taken over by Vattenfall. The primary reason why the facility was shut down in 1974 was that it was considered uneconomical. [84] The new security requirements that were instituted at this time also contributed to the decision

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[81] On the US-Swedish nuclear energy cooperation, see Jonter, Thomas, Sverige, USA och kärnenergin. Framväxten av en svensk kärnämneskontroll 1945-1995. SKI Report 99:21.

[82] Interview with Bengt Pershagen and Carl Gustaf Österlundh, October 5, 2001. On the development of the R 2, see Larsson 1987, p. 138.

[83] "Svensk atomenergipolitik", p. 29 et passim.

[84] Brynielsson, p. 211. See also "The Ågesta Nuclear Power Station. A Staff Report by AB Atomenergi". Edited by B McHugh. Stockholm 1964.

to close the facility. [85] Ågesta never did become a major power supplier. This partial failure notwithstanding, the white book Svensk atomenergipolitik (Swedish atomic energy policy) considers that the main objective was achieved: to acquire the necessary experience in industrial reactor production, reactor operation, and fuel production for the continued development of nuclear energy in Sweden. [86]

8.5 Marviken

The next planned reactor, on the other hand, the so-called R 4, was built but was never put into operation. R 4 was built at Marviken outside of Norrköping, and was meant to be Sweden's second power reactor. The project turned into a complicated affair which, after a number of revisions, was shelved in 1970. [87] Why, then, was this heavy-water reactor never put into operation? There were a number of reasons. Firstly, light-water technology became commercially successful in the period when the R 4 facility was being constructed. Light-water technology could be presented as a financially more advantageous and operationally more secure alternative. Secondly, the price of enriched uranium from the United States was lowered even further, which translated into reduced operational costs for light-water facilities. [88] Thirdly, the security aspect in itself was an important reason why the project was abandoned. It was primarily the overheating technology that was deemed to cause the biggest security problems. It was feared that the overheating might result in the collapse of the fuel elements. [89]

The government-owned AB Atomenergi closed shop in 1968, but its construction and nuclear fuel activities were taken over by ASEA, whereby a new company owned jointly by the government and private industry was formed, namely, ASEA-ATOM. The AE continued as a kind of research institute. From now on, the private power industry and light-water technology took over. But this did not imply that all the investments made in heavy-water technology were wasted money. On the contrary, much of the knowledge, technology and personnel resources that had developed over the years could now be channeled into the light-water technology that was taking over completely. Or, to use Karl-Erik Larsson's formulation: "Light-water technology was off to a flying start." [90]

According to the 1956 bilateral cooperation treaty with the United States and its additional paragraphs, the Swedish government agreed to allow US representatives from the AEC to conduct inspections at nuclear energy facilities in Sweden. The purpose was to verify that Sweden abided by the agreement, which said that nuclear materials and equipment bought from the United States could only be used for peaceful purposes. The United States

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85 Personal communication from Nils Göran Sjöstrand to Thomas Jonter, June 15, 2001. Sjöstrand was a member of the Reactor Committee at the time, and remembers the discussions concerning the closure of Ågesta. The new security demands would, according to Sjöstrand, have necessitated modifications that were prohibitively expensive.

86 Svensk atomenergipolitik, p. 29 et passim.

87 Brynielson, p. 222 et passim

88 This was a primary consideration when the project was shelved, according to Bo Aler (interview, January 18, 2002).

89 Interview with Erik Haeffner, September 29, 2001.

90 Larsson 1987, p. 151.

government thereby had the right to inspect the construction of each reactor before it was put into operation. This applied also to other facilities that used uranium and heavy water of US origin. The US inspectors had a right to study various operational data for the facilities and to get access to accounts of holdings of nuclear raw materials.

It was primarily articles VI and VII in the cooperation treaty between the United States and Sweden that regulated the inspections procedures. The issue of how the inspections were to be dealt with in practice was not decided once and for all. A practical arrangement can be said to have developed after 1956, which included the US security regulations as set out in the Atomic Energy Act of 1946 and its additions, and the Swedish legislation and security routines.

The first US inspection did not take place until 1960, at the AE's reactor in Studsvik, the so-called R 2. [91] It was not until R 2 was put into operation in 1959 that there was any reason for inspectors from the AEC to visit Sweden. But the visit in 1960 had been prepared through discussions about conditions and delivery of information material concerning the design of the safeguards system, such as the brochure "Material Accountability." [92] The supervisory authority in Sweden at this time was, in the last resort, the Delegation for Atomic Energy Issues (DFA). But it was the so-called Reactor Placement Committee (RFK), which had been formed at the same time as the DFA and placed under its authority, which handled the practical security aspects. The RFK gave directives to the AE regarding security management and what routines to apply with regard to the accounting and storage of nuclear materials. [93]

During the first inspection in May 1960, routines for the continued management of security controls in accordance with the bilateral agreement were discussed. The AEC and the AE agreed to develop an accounting system for material holdings through which the AEC would receive such accounts by the quarter. The accounting system would be concerned with the uranium that Sweden had obtained from the United States, where the uranium was being stored, how it was being transported during the quarter, and how it was being used.

An accounting system was worked out which satisfied the requirements of the AEC. [94] This meant that the AE was not obliged to account for quantities that fell below the limits specified by the IAEA. Quantities of nuclear materials that merely exceeded these limits by a very small amount did not have to be accounted for more than once a year. The AE committed itself to sending transcripts and documentation of materials delivered to other facilities and institutions (later on also to third countries). Moreover, these reports were to specify where in a facility the materials were placed. [95]

The US inspections in Sweden took place once or twice a year. In the first years, inspections were limited to a conversation with the AE about the information contained in the quarterly reports, and also, during visits at Studsvik, control of the R 2 reactor's fuel elements in the

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[91] May 24–25, 1960, John V. Vinciguerra, AEC to Christer von Essen, AE. "Uranredovisning AEC t o m 1962", Central Archive in Studsvik AB(CA).

[92] "PM. ang. sammanträde i Atomic Energy Commission den 10 februari 1959", written by Stig Ramel, Ministry for Foreign Affairs; From C C Vogel, AEC to Nils Montan, April 13, 1959, Ministry for Foreign Affairs. "Uranredovisning AEC t o m 1962", CA.

[93] On the safeguards system that was in place in the period 1956–1972, see Declaration of June 27, 1957 (No. 460).

[94] From Orneman to Blomberg, October 18, 1961, SR2. "Uranredovisning AEC t o m 1962",CA.

[95] "Anteckningar från sammanträde med kontrollanter från AEC", Silfverstolpe May 17, 1961, CA.

uranium bank, basins, or transport bottle. Furthermore, the AEC kept itself informed about the various experiments that were being conducted or planned in Sweden. From 1964 on, the inspections also included physical inventory of holdings of plutonium and Pu-Be neutron sources. For this reason, inspectors also visited FOI facilities at Ursvik in 1964-66. The inspections also covered other institutions and storage facilities that were not located in Studsvik, such as the Isotope Technical Laboratory at the Royal Institute of Technology and repositories in the form of rock shelters that the AE utilized in Vällingby north of Stockholm. [96] From 1968 on, inspections also covered ASEA-ATOM's facilities in Västerås, since this newly formed company was making use of nuclear materials of US origin. [97]

When Sweden signed the NPT treaty on August 19, 1968, and later ratified it on January 9, 1970, the terms of cooperation with the United States changed. By signing the NPT treaty, the Swedish government had agreed to place itself under the control of the IAEA. This meant that the US inspections could now be discontinued. However, it was to take until January of 1975 before the IAEA safeguards system was fully accepted by the Swedish government. The United States wanted Sweden to join the regulatory framework of the IAEA as quickly as possible. The Swedish government preferred, however, to wait and see how the negotiations between the other so-called threshold states [98] and the IAEA would turn out.

For this reason, an interim agreement was signed in March 1972 between Sweden, the United States, and the IAEA, which meant that the IAEA, for practical purposes, took over the earlier US safeguards control. When Sweden finally accepted the IAEA security system in its entirety, the Swedish government claimed that the delay had been due to the protracted negotiations between the IAEA and Euratom. The Swedish government maintained that the reason was that it did not want a safeguards system that differed too much from what the EEC countries (the then European Union states) might agree on. [99]

In order to manage the adjustment, the supervisory and security systems in Sweden had to be modified. This resulted in the issuing of new regulations for the DFA in 1971. According to the new regulations, the DFA would assume responsibility for the control of nuclear fuel and, in particular, fissile material, in accordance with Sweden's international commitments. On July 1, 1974, new directions were issued again, and the authority was renamed the Swedish Nuclear Power Inspectorate. The regulatory body was assigned wider responsibilities and the staff was greatly expanded.

8.6 Light water reactors take over

The first light-water rector in Sweden, Oskarshamn 1, was put into operation in 1972. It had been commissioned in 1966 by the Oskarshamn Power Group ltd. In the years 1968-71, eight reactors were commissioned by different companies. Three of these are so-called pressurized

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[96] "Beträffande inspektion och kontroll av anrikat uran och plutonium", April 27, 1965, "Uranredovisning kontroll", CA. With the help of former researcher Anders Fröman at the Swedish Defense Research Agency (FOI), I was able to find the inspections carried out by FOI.

[97] From Orneman to Hagsgård, September 24, 1968, "Safeguardredovisning till AEC", CA.

[98] States that have the technical ability to produce nuclear weapons and are suspected of having made preparations for such production are commonly called threshold states.

[99] Van Dassen, Lars, Sweden and the making of Nuclear Non-proliferation: From Indecision to Assertiveness. SKI Report 98:16.

water reactors, and they were placed at Ringhals. During the 1970s and 1980s, a total of twelve reactors were built for electricity production; of these, ten are operated commercially today. They are all light-water reactors using enriched uranium as fuel.

Sweden today has 12 reactors for electricity production; of these, ten are operated commercially. They are all light-water reactors using enriched uranium as fuel.

Barsebäck nuclear power plant
Barsebäck 1 (boiling water reactor, 630 MWe, started 1975, shut down 1999)
Barsebäck 2 (boiling water reactor, 630 MWe, started 1977, shut down 2005)

Ringhals nuclear power plant
Ringhals 1 (boiling water reactor, 860 MWe, started 1976)
Ringhals 2 (pressurized water reactor, 870 MWe, started 1975)
Ringhals 3 (pressurized water reactor, 920 MWe, started 1981)
Ringhals 4 (pressurized water reactor, 910 MWe, started 1983)

Oskarshamn nuclear power plant
Oskarshamn 1 (boiling water reactor, 500 MWe, started 1972)
Oskarshamn 2 (boiling water reactor, 630 MWe, started 1975)
Oskarshamn 3 (boiling water reactor, 1200 MWe, started 1985)

Forsmark nuclear power plant
Forsmark 1 (boiling water reactor, 1018 MWe, started 1980)
Forsmark 2 (boiling water reactor, 960 MWe, started 1981)
Forsmark 3 (boiling water reactor, 1230 MWe, started 1985) [100]

In 1980, Sweden held a referendum on nuclear power in which a majority of the population voted for a nuclear phase-out, which was to be completed by 2010. In 1984, Sweden adopted a new law, the so-called law of conditions, which states that the owners of the reactors will be responsible for the terminal storage of spent nuclear fuel and nuclear waste.

Chapter I.9 The Swedish Nuclear Material Control[101]

The Swedish nuclear non-proliferation work is regulated by national legislation, international treaties and agreements, and the EU constituent treaties and ordinances. The national regulatory framework consists primarily of the Act on Nuclear Activities (1984:3), which regulates nuclear technical activities. The law’s third paragraph states that nuclear technical activity is to be conducted in a way that satisfies security requirements and that is in line with the international non-proliferation obligations that Sweden has promised to uphold.

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[100] www.wikipedia.org

[101] To a large extent, this chapter is based on interviews with inspectors at SKI: Lars Hildingsson, Mats Larsson, Göran Dahlin, Kåre Axell, Stig Isaksson and Martina Dufva.

International obligations refer, in this instance, primarily to the Euratom treaty, the NPT treaty and its ancillary safeguards agreement, the CTBT, the Convention on the Physical Protection of Nuclear Material, the export control regimes of the NSG, the Zangger Committee, and the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies.

Of these treaties and conventions, the NPT and the safeguards agreement have had the largest impact on the development of the Swedish nuclear material control. Together with the other EU states, Sweden signed the Additional Protocol of the NPT in 1998. The Additional Protocol took effect on April 30, 2004, when all EU states and the European Commission ratified it. In Sweden, this undertaking necessitated a number of legislative amendments, which were completed by the year 2000. [102]

The Swedish Nuclear Power Inspectorate (SKI) has overall responsibility for oversight and control in Sweden. This assignment also includes, according to paragraph 2 of the Nuclear Technology Law, making sure that Sweden abides by its international commitments in the nuclear non-proliferation area. To be able to act effectively, SKI cooperates with other government authorities that have some knowledge of or that are otherwise charged with preventing the spread of nuclear materials or nuclear technology equipment: the Swedish Defense Research Agency (FOI), the Swedish Inspectorate of Strategic Products (SPI), the Swedish Security Service (SÄPO), the Swedish Customs Service, and the Swedish Radiation Protection Authority (SSI).

In addition to the EU Treaty, Sweden is also, as a member of the European Union, obliged to follow Euratom’s ordinance on nuclear material control. When Euratom was formed in 1957, the idea was that this organization would serve as an oversight authority for the whole EEC (later to become the EC and EU). For instance, there are today no national oversight authorities in Germany and Italy. Sweden, however, determined to keep its national oversight authority as it joined the European Union in 1995. The Swedes maintained that a nationally organized oversight system would provide more effective control and a higher degree of transparency, while also functioning better as a conduit for information to the media and the public. Furthermore, Sweden would also retain other parts of the nuclear infrastructure as national organizations: export control, reactor security, physical protection, transportation, etc. Against this background, it would be reasonable to also assign the practical handling of nuclear material control issues to a national authority in Sweden. Euratom was initially skeptical of Sweden’s decision to maintain its national organizations, but this has later turned out to be to the benefit of both the IAEA and Euratom. For example, the ratification of the Additional Protocol went very smoothly partly for this reason. Thanks to the work done by SKI, Sweden was able to quickly meet the Additional Protocol’s requirements for an account of technical data, ongoing research, and future plans in the nuclear field. Sweden’s neighbors Finland and the Baltic countries also decided (partly on the recommendation of SKI) to maintain their national authorities upon entering the European Union.

What does this special arrangement entail in practice for SKI and Sweden? It is important to know that the European Commission is the legally mandated counterpart to the IAEA as regards traditional nuclear material control (the Safeguards Agreement). Consequently, the

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[102] Mats Larsson, ”SKIQ –Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll – Fysiskt skydd och Transportsäkerhet”, February 21, 2006. Unpublished manuscript.

various reports and accounts from the Swedish facilities are sent to Euratom which in its turn transfers them to the IAEA. SKI receives a copy of this correspondence. The Commission's responsibilities vis-à-vis the IAEA are regulated by the Safeguards Agreement INFCIRC/193, which is a trilateral treaty between the IAEA, the Commission, and the EU's non-nuclear weapons states. But when it comes to Sweden's obligations under the Additional Protocol, SKI assumes the main responsibility for these. The Additional Protocol has been subsumed under the Safeguards Agreement.

All companies and organizations that own or in some other way have access to or deal with the nuclear materials uranium, thorium, and plutonium are to be subject to nuclear material control. All changes should be reported to SKI, including certain technical information. [103] SKI maintains a national nuclear material database in which every gram of nuclear material is accounted for. Excerpts from the database are used in connection with every inspection in which SKI is involved. The Swedish facilities' accounting for nuclear materials is regulated by Commission Regulation 302/2005 (Euratom).

9.1 Inspection and surveillance

The Commission and the IAEA have different specific objectives and demands with regard to nuclear material control, and this has practical consequences for the way inspections are carried out. Each facility that is to be covered by surveillance and control submits to the Commission a technical description called Basic Technical Characteristics (BTC). On the basis of this BTC, a control plan, the Particular Safeguard Provision (PSP), is drawn up by the Commission. SKI and the facility in question get to comment on the contents before the plan is confirmed.

The IAEA's control and surveillance is mainly regulated by two documents which describe this activity in detail: the Subsidiary Arrangement (SA), which is designed for each state, and the Facility Attachment (FA), which applies to each specific facility. The methods employed for verification and evaluation follow the IAEA's Safeguards Criteria.

In due course, valid SAs and FAs are negotiated between the Commission, the IAEA, and the concerned state, but this has not yet happened for Swedish facilities. It is important to emphasize in this regard also that the Commission is the legally mandated formal counterpart to the IAEA. The control procedures spelled out in the SA and FA are not used by Euratom inspectors when they inspect facilities in Sweden. At these inspections, only the PSP is used as a nuclear material control plan.

SKI inspectors conduct at least one inspection per year at all major facilities in Sweden. These facilities comprise ten nuclear power plants, the fuel factory in Västerås, facilities and one reactor at Studsvik, and the former uranium factory at Ranstad where nuclear materials are stored. Each year, lesser quantities of nuclear materials are also inspected at 30 universities, colleges, and hospitals. But these inspections are carried out only at randomly selected sites.

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[103] Some exceptions are granted. For example, there is no accountancy and control of ore whose uranium content is below 200 ppm, Mats Larsson, "SKIQ –Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll – Fysiskt skydd och Transportsäkerhet", February 21, 2006. Unpublished manuscript.

The European Commission conducts some four inspections annually at every major facility (at the eleven nuclear power plants, Studsvik, the fuel factory in Västerås).

The IAEA also conducts about four inspections per year and facility. In recent years, however, the frequency of inspections has increased as a consequence of the Additional Protocol's coming into force, and this means that some new routines need to be worked out.

9.2 How is the safeguards work regulated and administered in Sweden?

The way inspections are organized depends on whether it is a question of a so-called activity-centered oversight or an international commitment. The routines of the latter are thoroughly spelled out in the regulatory frameworks of the IAEA and the EU. In addition to the running inspections, which are carried out at different intervals according to the strategic value of the nuclear material [104], so-called physical inventories (PIVs) are to be conducted. A PIV consists in the verification of all nuclear materials within a Material Balance Area (MBA) once a year. The MBA is defined in the IAEA's FAs and the Commission's PCPs, which are specific for each nuclear facility (for example, a reactor with its adherent basins and points of entry can constitute an MBA). SKI participates during PIVs at the nuclear facilities. On the other hand, SKI is not present at every international routine inspection carried out by the IAEA or the Commission. The decision on whether to participate or not is made on a case-by-case basis, even though Swedish participation may facilitate the inspection work at the various facilities. Now that the Additional Protocol has come into force, SKI will be standing by to participate in these international routine inspections on short notice, since the new conditions give the IAEA the right to demand complementary access to all premises within the area of the facility within two hours.

With respect to the Commission's inspections, SKI participates as an observer. This does not imply that SKI is always a passive participant; the Swedish inspectors may offer advice and provide assistance during the controls, based on their experience and knowledge of the facilities. Such a request for help and assistance must, however, come from the Commission.

9.3 What happens during an inspection?

1. A so-called notification is received from the IAEA or the Commission at least one week before the inspection is to take place, wherein it is explained what the inspection is meant to comprise and who is to carry it out.
2. SKI verifies that the inspectors are approved by Sweden (that they are, so to speak, "licensed" to conduct inspections in Sweden), and sends a message to the facility that is to be inspected.

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[104] Estimated time required for converting the nuclear material to nuclear devices.

3. The inspectors must have entry permits in order to be able to conduct the inspections, and to receive these they are required to have taken a basic security course (no more than three years previously) and to be in possession of a valid doctor's certificate.
4. A prefatory meeting is held between the inspectors from SKI, Euratom and the IAEA, and those responsible at the facility in question. At this meeting, the order of priority for the different inspection features is decided upon. The optimal method of control may vary, namely, from one inspection to the next, and from one facility to another.
5. The inspection. It bears underlining that the inspection procedure will look different depending on whether it is an activity-centered oversight (SKIQ 12) or an inspection corresponding to international requirements (see below).
6. SKI writes an inspection report, which is then sent to the concerned facilities.
7. The IAEA sends a "Statement" to the Commission which, after appending its own opinion to it, forwards it to SKI, which will then learn whether the IAEA has any complaints. If the IAEA has criticisms concerning aspects of the activity that have not been satisfactorily explained, these will be expressed in the IAEA's annual report. Unless the discrepancies that have been established are corrected, the IAEA may hand the matter over to the UN General Assembly, which in its turn can let the Security Council decide whether or not sanctions should be instituted.

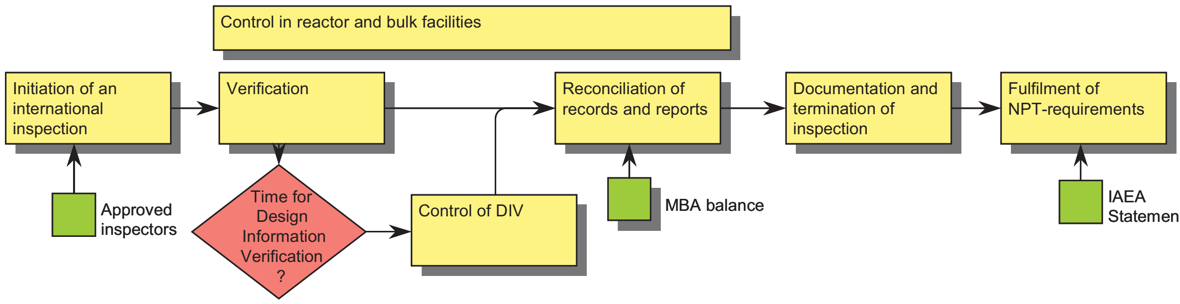

Figure Nuclear Material Control Inspection[105]

9.4 International inspections at Swedish nuclear power plants

Routine inspections. These inspections are based on the Euratom treaty and the Safeguards Agreement between the EU, the IAEA and Sweden, and take place every three months. An inspection of this kind includes the control of surveillance equipment (during which simpler matters are taken care of such as the switching of memory cards in the surveillance system), a review of the accounts, and the counting of fuel in the basins and storage facilities.

Inspections at a so-called Bulk Handling Facility – a facility with many accounted for items, where materials in loose form are handled (powder, pellets, fluids). These inspections are carried out for example at the fuel factory in Västerås, where the accountancy is reviewed and a few items may be verified. They are conducted by the IAEA, the Commission and SKI.

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[105] The figure is from Mats Larsson's unpublished manuscript, "SKIQ -Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll - Fysiskt skydd och Transportsäkerhet", February 21, 2006.

At both these types of facilities seals are checked. IAEA and EU have different criteria for fuel factories; EU inspects every 6 weeks whereas IAEA inspects every 3 months. At the fuel factory the inspectors from the EU-commission also come 5-6 times every year to put seals on the transport contailners to be sent out of the European union.

Annual inventory. All nuclear materials at the facility must be inventoried at least every fourteen months. The result of the inventory is verified by SKI, the IAEA, and Euratom, a so-called PIV. The inventory coincides with the annual fuel change at nuclear reactors. At this time, all fresh fuel is verified through number identification and random NDA measurements. The irradiated fuel is verified with the aid of a CVD (Cherenkov Viewing Device). Further, it is verified that all the fuel is to be found at the declared sites.

At “bulc-handling” facilities the PIV is conducted during a longer maintenance stop. It is then a matter of removing all materials from the machines and equipment in order to render possible measurements. Verifying all materials is an arduous and complicated process, and therefore a statistical regulatory framework has been developed. The inspection begins with the drawing up of a measurement plan, in which the facility is divided into different zones depending on the different materials that are to be found there. Next, various verification methods are used for different parts of the stock: Non-Destructive Assay (NDA), Destructive Assay (DA), weighing, and verification of scales and labels. When these segments have been completed and all items in the inventory have been ticked off, a statistical calculation is made that also takes into account the accuracy of measurements and the material flow. This calculation produces the so-called Material Un-Accounted For (MUF), and, more importantly, an uncertainty in the calculated MUF called sigma (MUF). The MUF and sigma (MUF) may not exceed a specific amount decided upon by the IAEA or the Commission in relation to the total amount used during a year or since the previous inspection at the facility. The process takes some five days to complete, and engages more than ten persons.

Sometime during the year, the so-called “Design Information” is verified (DIV), the “Design Information” is a declaration concerning the technical construction and performance of a facility that is submitted to the IAEA (and EU) as soon as a facility starts to use nuclear materials. The IAEA uses the DIV to design a nuclear material control that is as efficient as possible. During the annual review process, these declared technical data are tested directly on-site to measure the quantities that may actually be produced. If, for instance, it were to emerge that facilities in a particular country have a much bigger production capacity than declared, this might raise suspicions. Of course, there might be satisfactory explanations for this, but if such is not the case the most common result is a stricter and modified inspection strategy on the part of the IAEA. If this does not suffice, sanctions may be instituted.

In principle, SKI does not conduct any measurements on its own to verify the nuclear material content; instead, the organization relies on the IAEA’s results, which are included in its so-called Statement. But if the need should arise for SKI to carry out its own measurements, it has its own CVD-detector which can be used for controlling irradiated material. If need be, external expertise can also be recruited (Department of Radiation Science, Uppsala University and the Swedish Defense Research Agency).

Chapter I.10 Export Control in Sweden

Nuclear exports from Sweden are regulated through supranational, international and national ordinances, agreements and laws. Sweden's membership of the European Union implies that the country is obliged to follow Council Directive no 1334/2000, which was drawn up to deal with the control of dual-use products and technology. In Article 2 of the directive, dual use is defined as: "products including software and technology that may be used for both military and civil purposes, and all articles that may be used for non-explosive purposes and that may contribute in some way to the production of nuclear weapons or other nuclear devices."

Export is defined as the transfer of products, which are listed in an appendix to the directive, outside of the EU. This export requires a license. A license is also required for the transfer within the EU of particularly sensitive products, including nuclear technical products and particularly sensitive nuclear materials (Article 21 and Appendix IV of the directive). The license should be issued by the national authority in the country where the exporter is active. There are different types of license. They may be individual (a one-time export license), global (time-limited and applicable only to the countries and products listed in the license), or general.

SKI is the authority responsible for license issuing as concerns appendix 1 and the products falling under category O. [106] This Category 0 list is identical with the NSG Trigger List. Within the European Union depleted, natural and low-enriched uranium may be transferred freely between member states without permission. With regard to dual-use products, categories 1-9, the Swedish Inspectorate of Strategic Products is the responsible authority. The ISP is a governmental body charged with controlling the export of munitions and other strategic products that are grouped into three spheres of activity:

- War equipment. In this sphere of activity, the SPI deals with exports of weapons, ammunition, surveillance and measuring equipment or other products developed for military use.
- Dual-use products. This sphere of activity comprises materials, products, and technology that have been developed for civil use but that may at the same time be exploited for the development of weapons of mass destruction or other military equipment.
- The Chemical Weapons Convention. In this area, the SPI regulates the export of various materials and types of equipment that may somehow, according to this convention, be used to produce chemical weapons. [107]

Sweden is also a member of two export control regimes in the nuclear field: the Zangger Committee (ZC) and the Nuclear Suppliers Group (NSG). As described more fully in chapter 4, the ZC has produced a so-called trigger list (publicly available as IAEA document INFCIRC/209) to be able to act more effectively to uphold observance of Article III of the NPT treaty. In summary, membership of the ZC entails a requirement that nuclear materials that in some way come into contact with the products on the list must be subject to IAEA safeguards. Member states have also agreed to exchange information on issued export licenses

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[106] http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=SV&numdoc=32000R1334&model=guicheti

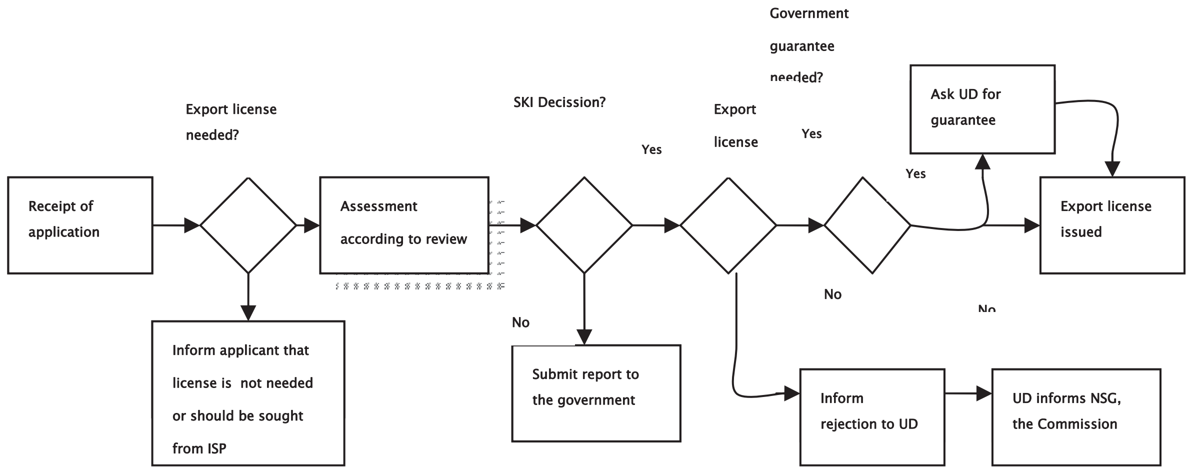
[107] On the other activities of the SPI, see www.spi.se.

for products covered by the list. For Sweden's part, this means that SKI puts together an annual report that is forwarded to the Unit for Strategic Export Control of the Ministry for Foreign Affairs, which in its turn reviews the report and, if necessary, takes appropriate measures. Thereafter, the report is sent to the ZC.

Unlike the ZC, the NSG has no juridical connection to the NPT treaty. The purpose behind the creation of the NSG was to strengthen the then export control system, which was deemed insufficient in many ways. New guidelines were developed, resulting in the drawing up of two export control lists: one Trigger List for Single-Use (published as INFCIRC/254/Part 1) and one for Dual-Use (published as INFCIRC/254/Part 2). Products on the first list also form the basis for the reporting done by Sweden to the IAEA in accordance with the Additional Protocol concerning exports of nuclear technical equipment. [108] The list in the Additional Protocol has not, however, been included in the latest updates of the NSG's first list.

The Swedish export control is regulated by the Law (2000: 1064) on control of dual-use products, and by various ordinances. The law and the ordinances that have been issued in connection with it may be said to complement the Council's ordinance, and they are aimed at regulating the handling of license issuing. [109]

Handling of export application



1. An application is submitted to SKI. There are ready-made forms to be used for this purpose.
2. SKI examines whether the application form is filled out correctly and if the product in question requires an export license.
3. An evaluation is made of the product's possible areas of usage and potential end users, according to a standard review plan. Expert advice may be sought from outside the SKI organization if necessary, for example from the Ministry for Foreign Affairs (UD) or the Inspectorate of Strategic Products (ISP). A key question in the evaluation is whether the recipient state is a signatory to the NPT treaty and a member of the ZC or

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[108] Larsson, "SKIQ -Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll - Fysiskt skydd och Transportsäkerhet".

[109] Directive (2000: 1217) on control of dual-use products and technical assistance; Swedish Inspectorate of Strategic Products regulations (TFS 2000:24) on export licenses; Swedish Inspectorate of Strategic Products regulations (TFS 2005:25) on requests for export licenses.

the NSG. The IAEA's safeguards reporting is also taken into consideration, as is the issue of whether the country is subject to any kind of trade sanctions on the part of the EU or the UN. Part of the evaluation consists in investigating what kind of guarantee is required of the recipient party. If the recipient state is a member of the NSG, SKI is authorized to make a decision on its own in accordance with paragraph 8 of Ordinance 2000:1217; the same rule applies to lesser amounts of nuclear materials, according to the same paragraph. To aid it in this task, SKI uses two databases: the NSG database NISS, which contains information about demands for "complementary information" and rejections with regard to dual-use, and SKI's own database KUT, which is used in connection with the handling of matters of export of nuclear technical products.

4. SKI assesses whether a license decision needs to be made or not.
5. SKI submits its statement to the government (unless the matter concerns exports to NSG members).
6. A decision is made by the government (or by SKI, if the matter concerns exports to NSG members).
7. Through the Ministry for Foreign Affairs, the government communicates its decision to the NSG, the Commission, and the other EU states. This happens if the application is rejected also. The idea is that if a country has decided against exporting nuclear materials to a particular recipient country, other states involved in the control regime cooperation should not give permission to such exports either.

After it was revealed that Iraq was running a secret nuclear weapons program in the early 1990s, the IAEA made an inquiry among its members as to whether they might be willing to file reports on a voluntary basis concerning issued export licenses for the purpose of strengthening the nuclear material control. Sweden responded positively to this request and, since 1993, the Swedish government has submitted quarterly reports to the IAEA. Subsequent to Sweden's becoming a member of the European Union in 1995, this reporting activity has concerned exports to countries outside the EU. After the Additional Protocol was signed in 1998 and ratified in 2004, Sweden is also obliged to report exports (including transfers within the EU) of technical equipment. According to the Additional Protocol, the IAEA is also authorized to demand confirmation of receipt from the recipient state, even if the recipient country is a European Union state. As regards data about Swedish exports, these are collected from the database KUT. [110]

Chapter I.11 Physical protection and transport security in Sweden

11.1 Physical protection

Physical protection in Sweden has two main tasks: (1) to prevent unauthorized entry and sabotage at nuclear facilities, which might result in radiological damage; (2) to prevent

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[110] Larsson, "SKIQ –Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll – Fysiskt skydd och Transportsäkerhet".

unauthorized dealings with nuclear materials which may result in the proliferation of nuclear weapons. [111] Sweden has signed and ratified the Convention on Physical Protection of Nuclear Materials, which entails that specific security and protection requirements must be met in connection with the transportation of nuclear materials. [112] SKI and Sweden have also engaged themselves in the effort to develop revised IAEA global guidelines for physical protection, "The Physical Protection of Nuclear Material and Nuclear Facilities" (INFCIRC/225/rev.4.). These guidelines are meant to serve as internationally recognized recommendations.

Physical protection in Sweden is regulated by the Act on Nuclear Activities and the regulations of SKI. Swedish legislation stipulates that the physical protection at a facility must be documented in a plan approved by the responsible authority, i.e., SKI. This plan is to be followed by anyone who is responsible for running a facility. All changes must be reported to SKI (SKIFS 2004:1, chapter 2, paragraph 11). Inspections are conducted at regular intervals at the different facilities to investigate whether SKI regulations are being observed. These inspections follow a specifically designed plan.

A continuous follow-up analysis of the threat picture against Swedish nuclear facilities is carried out jointly by SKI, the National Police, and the Swedish Security Service. For practical purposes, this means that the Security Service produces an annual written report in which the current threat picture is analyzed. In addition, the threat picture is reviewed and followed up at least once a year. SKI informs licensees of the current threat picture. [113]

In August 2005, SKI's board decided on the adoption of a new directive on physical protection in Sweden (SKIFS 2005:1). These new rules have taken five years to develop and are based on a partly new and modified analysis of the threat picture against Swedish nuclear energy facilities. There are three main reasons why a new regulatory framework has been developed: (1) A different threat picture, with a stronger emphasis on protecting nuclear materials against sabotage and proliferation at the hands of terrorists; (2) the need to gather all rules within the framework of one directive in order to facilitate the work of evaluating the physical protection and its general application at the facilities; (3) the international recommendations, put together by the IAEA primarily, have changed, and this necessitates accommodations on Sweden's part. [114] The tragic terrorist attacks in the United States on September 11, 2001 resulted in the shelving of the draft version of the new directive which had been worked out by then. In the light of September 11, the Swedish regulatory work had to start again and take into consideration a changed threat picture.

The new directive, which took force on January 1, 2007, contains measures that can be summarized in eight points:

- Physical barriers, including different types of fences and solid structures, should be put up to prevent illegal encroachments.

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[111] Stig Isaksson, "New Swedish Rules for Physical Protection", *Nucleus* 2005:3

[112] *Sveriges överenskommelse* 1985:24.

[113] Larsson, "SKIQ –Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll – Fysiskt skydd och Transportsäkerhet".

[114] Stig Isaksson, "New Swedish Rules for Physical Protection", *Nucleus* 2005:3.

- Security guards should be on hand who can control access of persons and vehicles to the facility, and inspect materials and equipment being brought in and out of the facility, and also provide overall control of the facility.
- Technical surveillance systems should be installed with the capacity to discover and verify any unauthorized access to the different parts of a facility at an early stage.
- Routines should be developed to make sure that the technical surveillance systems and equipment function satisfactorily.
- Routines should be developed and functioning technical equipment put in place for verifying that no illicit objects are brought into the facility (security control).
- Routines should be developed and functioning technical equipment put in place for controlling access to certain parts of the facility, which should only be open to specific persons.
- Routines should be developed for verifying that only persons with authorization are given access to the facility (security clearance).
- Routines should be developed for denying unauthorized persons access to information concerning the facility's security system.

The Swedish police are invested with the legal authority to defend, including through the use of violence, nuclear facilities in case of an attack or sabotage action. There is in place a long-standing cooperation between individual nuclear facilities, the local police, and the national antiterrorist unit. [115] Shortly after the September 11 attacks, SKI participated in an international meeting in Bonn with seven European states. The meeting signaled the start of an established international cooperation between Belgium, Finland, France, Spain, the United Kingdom, Sweden, and Germany, aimed at strengthening the physical protection. This cooperation led to the formation, in 2004, of a formal organization, the European Nuclear Security Regulators Association (ENSRA), whose task it is to further the exchange of information and experiences among the participant states.

11.2 Transport Security

Swedish transport security regarding radioactive material is primarily regulated by four laws.

- The nuclear technology law. This law defines what is to be categorized as nuclear material and nuclear waste and further it states that you need a permit to transport nuclear materials.
- The radiation protection law. This law deals with activities concerning radiation, for example transports of radioactive materials. A transport can occasionally contain materials that are neither nuclear materials nor nuclear waste, but that are nonetheless radiant. In these cases, the radiation protection law applies.
- The law on transportation of hazardous materials. Hazardous materials are divided into different categories, of which class 7 is radioactive material. A subcategory is fissile material that has specific security regulations. All transport of radioactive material has to be conducted in accordance with the regulations on transporting hazardous material, aside from the nuclear technology law and the radiation protection law.

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[115] Ibid.

- The atomic responsibility law regulates insurance issues pertaining to transports of radioactive materials. [116]

Domestic transports are normally carried out by truck, while international transports to Sweden are done by boat to a Swedish port, and from there by truck. A significant proportion of these transports are voluminous and sometimes heavy. For example, a Swedish boiling water reactor has between 450 and 700 fuel elements depending on its effect. Each fuel assembly contains circa 200 kilograms of uranium oxide. The fuel assemblies of pressurized water reactors weigh some 450 kilograms. During the revision shutdown, which occurs in principle once every year, about one fifth of the fuel elements in the core are exchanged. Spent fuel is usually transported with the ship Sigyn to the interim storage facility, CLAB, outside of Oskarshamn. Ships that are used for transportation of nuclear materials must be certified according to the requirements stipulated in the internationally agreed-upon INF Code (Irradiated Nuclear Fuel Code). [117] To prevent theft and sabotage during transportation, certain physical protection conditions must be met, concordant with the levels of physical protection discussed in chapter 5.

Inspections may be carried out by SKI to verify whether the licensee meets SKI's requirements as regards the decisions made in accordance with the provisions of the nuclear technology law. [118] License-issuing authorities for transports of class 7 hazardous material (radioactive material) are: the Swedish Rescue Services Agency, the Swedish Rail Traffic Authority, the Swedish National Police, the Swedish Maritime Administration, the Swedish Civil Aviation Authority, SKI and SSI.

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[116] Eric Häggblom, ”Lagar och myndigheter vakar över frakterna”, *Nucleus* 2002:1.

[117] Ibid.

[118] Larsson, ”SKIQ –Ledningssystem för SKI:s verksamhet. Icke-spridningskontroll – Fysiskt skydd och Transportsäkerhet”.

Annex I

Levels of physical protection for nuclear material during storage incidental to international nuclear transport include:

For Category III materials, storage within an area to which access is controlled;

For Category II materials, storage within an area under constant surveillance by guards or electronic devices, surrounded by a physical barrier with a limited number of points of entry under appropriate control or any area with an equivalent level of physical protection;

For Category I material, storage within a protected area as defined for Category II above, to which, in addition, access is restricted to persons whose trustworthiness has been determined, and which is under surveillance by guards who are in close communication with appropriate response forces. Specific measures taken in this context should have as their object the detection and prevention of any assault, unauthorized access or unauthorized removal of material.

Levels of physical protection for nuclear material during international transport include:

For Category II and III materials, transportation shall take place under special precautions including prior arrangements among sender, receiver, and carrier, and prior agreement between natural or legal persons subject to the jurisdiction and regulation of exporting and importing States, specifying time, place and procedures for transferring transport responsibility;

For Category I materials, transportation shall take place under special precautions identified above for transportation of Category II and III materials, and in addition, under constant surveillance by escorts and under conditions which assure close communication with appropriate response forces;

For natural uranium other than in the form of ore or ore-residue; transportation protection for quantities exceeding 500 kilograms uranium shall include advance notification of shipment specifying mode of transport, expected time of arrival and confirmation of receipt of shipment.

Table: Categorization of Nuclear Material

Material	Form	Category		
		I	II	IIIc/
1. Plutoniuma/	Unirradiatedb/	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
2. Uranium-235	Unirradiatedb/ uranium enriched to 20% 235U or more uranium enriched to 10% 235U but less than 20% uranium enriched above natural, but less than 10% 235U	5 kg or more	Less than 5 kg but more than 1 kg 10 kg or more	1 kg or less but more than 15 g Less than 10 kg but more than 1 kg 10 kg or more
3. Uranium-233	Unirradiatedb/	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
4. Irradiated fuel			Depleted or natural uranium, thorium or low-enriched fuel (less than 10% fossile content)d/e/	

a/ All plutonium except that with isotopic concentration exceeding 80% in plutonium-238.

b/ Material not irradiated in a reactor or material irradiated in a reactor but with a radiation level equal to or less than 100 rads/hour at one metre unshielded.

c/ Quantities not falling in Category III and natural uranium should be protected in accordance with prudent management practice.

d/ Although this level of protection is recommended, it would be open to States, upon evaluation of the specific circumstances, to assign a different category of physical protection.

e/Other fuel which by virtue of its original fissile material content is classified as Category I and II before irradiation may be reduced one category level while the radiation level from the fuel exceeds 100 rads/hour at one metre unshielded.

Part II The verifying regime of nuclear safeguards

Ane Håkansson

Chapter II.1

Introduction

In previous chapters we have discussed the formal structure of nuclear safeguards, where various international treaties play a prominent role. In the following we will take a look at the verification regime within nuclear safeguards, i. e. describe the methods and techniques that are available to reassure the world community that concluded treaties are adhered to.

No agreements, how conclusive they might be, can be formulated completely "waterproof". There are always opportunities for a party in the agreement to circumvent the entire agreement or part of it. The construction of the agreement can, however, be designed in such a way that violation of the agreement is easily detected by seeing to it that the agreement includes elements that can be verified in principle as well as in practice by objective methods. To illustrate, "political" agreement formulations like e. g. "I undertake at any moment to show the openness that international coexistence requires" should be avoided. A formulation to be preferred is e. g. "I undertake at any moment to give such information that it can be clarified that no more than 8 kg of plutonium is missing in my inventory of nuclear material".

Within international safeguards it is for political reasons, however, inevitable, that elements not being unequivocal are included in the agreements. This implies that the controllable elements must be given considerable weight in the agreements. On the other hand it can be observed that nuclear safeguards are well suited for agreements where controllable quantities are involved. Often the agreements include more or less radioactive material, which can be detected fairly easily. Furthermore, such material must be stored in a satisfactory way and containers and buildings for this purpose can be monitored e. g. by TV surveillance. Before construction of buildings of nuclear-technology relevance, drawings and other design material could (and should) be documented and checked, so-called design integrity verification (DIV). The area around a nuclear-technology facility can also be the subject of satellite surveillance with the purpose of detecting improper movements. A technology increasing in importance is environmental surveillance or "environmental sampling", implying that stationary or mobile measuring stations detect the various fission products being produced, and to a certain extent being released to the environment, in all nuclear-technology activities. As an example the global networks of detectors for airborne activity can be mentioned, by means of which it is intended to detect nuclear weapons tests [1].

As has been mentioned in previous chapters the verifications being stipulated in the agreements are performed during inspections. Such inspections can be performed by inspectors representing national as well as international authorities. The inspectors have access to different types of technical equipment like handheld instruments or instruments that are easily transportable and can be mounted at the facilities to be inspected. Certain permanently installed instruments are also used and the use of these is expected to increase in the future. The measuring methods are supplemented by logging routines, where all nuclear material entering a national system must be balanced by all corresponding material exiting from or being stored in the system. This balance sheet is also checked regularly during the inspections. It is easy to realize that the nuclear safeguards can be designed as extensive as desired and the challenge of the regulatory authorities is to use methods that at least are compatible with

- high capability to detect irregularities
- low cost
- minimum intrusion in the regular activities
- suited for in-field service

The last item is important in cases where the inspection is performed with instruments accompanying the inspectors. In this context ´suited for in-field service´ means that the instruments must be robust and moreover have properties making them easily transportable. Often this implies a certain waiving of performance. For permanently installed equipment other criteria are applied as a rule. In such a context properties like precision, long-term stability and reliability play a more prominent role than e. g. size.

A central concept within nuclear safeguards is verification. In spite of its formal importance the concept has no unequivocal definition [2]. In nuclear safeguards verification could mean the process bringing about a certainty that a state adheres to or does not adhere to an agreement. Verification could also mean that a certainty has been achieved. This conceptual ambiguity may not seem too dramatic, but it has far-reaching negative consequences partly for the method development and partly for the formulation of what measurable quantities that are relevant for nuclear safeguards and with what precision these must be determined for "certainty" to be achieved. Thereby we also touch upon *determination*, which is semantically connected with the concept of verification.

To illustrate the difference between these concepts and also the problems nuclear safeguards face if the concept definitions lack in unambiguousness, we chose as our example a spent nuclear fuel assembly being stored at CLAB and to be verified by an inspector from IAEA.

All fuel assemblies to be stored at CLAB are accompanied by a declaration containing a large number of parameters (see Appendix 1). By a suitable measuring method we can check that the fuel parameters A, B, C, … are in agreement with the declared values. It should be noted that to make the comparison between the measured and declared values, A, B, C, … must *be determined.* If the inspector finds that the actual properties of the fuel are in agreement with the declared ones, what has he accomplished? Has he performed a verification or has his insight that the fuel is in agreement with the declared values allowed him to verify the fuel? Another question: The measured values of A, B, C, … have a certain precision, how good a precision is required to state that the properties of the fuel are in agreement with the declared ones?

In another case (unlikely, but still something that nuclear safeguards must be prepared for) the documentation of declared fuel parameters is missing. The inspector measures these parameters. What has he accomplished? Verification? He has evidently *determined* the fuel parameters, but without connection to declared values the concept of verification lacks meaning. The concept of verification is thus in its nature relative, while determination rather is an absolute concept, because the measured values do not depend on additional information. The *relevance* in the concept of determination has, however, in this context only meaning in relation to additional information.

In the latter scenario we are forced to realize that nuclear safeguards can only conclude that the properties of the fuel assembly *seem* to correspond to the expected ones and articulate criticism and possibly approve of the fact that the fuel declaration is missing. Methods under development [2] have, however, the potential of giving inspectors the tools required to express their opinion on whether the fuel has been used in the reactor in a way compatible with non-military activities.

In contexts where surveillance takes place, problems like those mentioned above are exposed to even more stringent tests. How is, for example, the relevance of the information in a photograph or a video sequence quantified? This is an area getting successively more interest in parallel with the development above all in information technology. Today neither costs nor work efforts are discouraging when equipping facilities requiring protection with surveillance cameras and other sensors. These sensors can be connected to each other and to other larger networks, even to internet. With this development several questions become urgent, and above all two of these stand out as particularly important:

- How can the large amount of information, which can be extracted from a system, be analyzed to reveal irregular patterns?
- The efficiency of a system is dependent on how well the system itself is constructed but also on how well the various parts (the sensors) work separately and together in the system. Today powerful evaluation methods, making the quantification of the total detection efficiency of a given system possible, are, however, missing.

In this context two concepts are in focus; *performance* and *assurance*. With performance is meant that the function of a sensor (e. g., camera) in all aspects meets the specified requirements. An informal division can be made between the physical and functional requirements that must be met. The physical requirements include, for example, that the sensor must cope with specified environmental parameters like radiation level, temperature, etc. The physical requirements can in addition be that the noise level of the output signal is less than or equal to the specified requirements. The functional demands on the other hand mean that the specified requirement should take into account the environment the sensor is planned for. From the specification of the functional requirements it should be possible to draw conclusions as to what types of sensors that are suitable in a given application. To supervise a door, for example, it might be better to mount contacts indicating whether the door is open or closed than to use a video camera. The latter might be hidden or is not suitable for other reasons. If a camera is to be preferred, the functional requirements must give advice on spectral region, properties of the lens, etc. The functional requirements include also the properties a sensor must have to work in the anticipated way in a system, e. g. regarding communication between different parts of the system. A possible trivial consequence of this discussion is, that it is seldom a good idea to choose, e. g. for cost reasons, an apparatus having been designed for a completely different purpose than the anticipated one, even if the apparatus meets the physical requirements and even if it intuitively seems to meet the functional requirements. How the functional requirements should be formulated and how the quality of the information from a sensor or a surveillance system should be quantified is currently almost an open question. Something about this issue will be discussed in Sect. 1.2.

How sure can you be that the construction work, the fabrication and the test procedure of a sensor meets the requirements being brought forward to ensure that the sensor has good performance? The answer to this question involves the concept assurance. At present especially various administrative routines are used to guarantee that all work to be done to produce a

sensor or an instrument has actually been performed and with sufficiently high quality. This procedure, however, gives only qualitative answers, and therefore research projects have been initiated to study, if it is possible to find methods for quantitative evaluations of the performance of a sensor and what assurance that can be assigned to this [3].
In the extension of this discussion one easily ends up in problems regarding applicability. To illustrate: An electric switch can, e. g., be specified to stand 10^6 switchings. Can such a switch be used in a system where the time span before exchange of components includes 10^5 switchings?

To give some insight into what parts of the problem complex, that need to be considered in a project aiming at designing methods for quantification of performance and assurance, a description based on principle will be given below, that can also serve as a background to the following chapters dealing with various sensors and instruments being at the disposal of nuclear safeguards.

1.1 Outline for achieving performance and assurance

It might be feasible to breakdown the subject of this section into the following items in order to clarify some of the issues governing the performance of a device and how its operation can be assured.

Technical items:
Design integrity, e.g. guidelines for part usage and test, software quality assurance and design reviews.
Engineering functions including reliability, quality assurance and system safety.
Product assurance consisting of elements needed to establish confidence that the pro-duct is being designed and manufactured as intended to meet the reliability goal.

Non-technical item:

- Usage, e.g. cost, set-up, maintenance and interpretation of data.

1.1.1 Technical items

Design integrity
To be able to ensure that a device fulfils all demands put forward, one has to consider design integrity. Primarily a matter for contractors of technical devices, some words on this matter could be feasible here. One definition of design integrity is the process to ensure that all design documents are accurate and reflect the most up-to-date version of the design. Even rather trivial constructions often demand hundreds, maybe thousands of documents describing all facets of the construction.

To exemplify one can think of two typical cases when design integrity is not considered in the construction process of a device

- Design features that originally were added to the construction in order to comply with the requirements are removed or changed without notice.

- New design features were added that contradicts other features. In both cases, there is a high probability that the device will not work as stated by the requirements.

The following items can be settled regarding design integrity:

- It is an important issue that the documents are consistent within themselves as well as between them.
- Any changes in one document should be propagated through all documentation and through the project as a whole.
- Every change should be logged and readily accessible through a report system.
- To the definition should be added security against the possibility that design criteria are exceeded.
- All aspects of the design process should be synchronized in order to get full control over quality and cost.

Engineering functions

In the document, MIL-STD-810F issued by the US Department of Defense (DOD), various test strategies and recommendations are described at length. In addition, as an example on how a project may be set up in order to achieve the given quality and assurance criteria, the report "Performance Assurance Implementation Plan for the ICS Project" (1996) issued by Hughes Information Technology Systems is presented in EOSDIS Core System Project (501 – CD-001-004).

In a compendium like this, it would become too lengthy to detail the content of these documents. However, some general remarks can be made. In different ways, both publications stress the significance of a strict project organization in order to prevent technical and operational problems and for controlling the evolutionary development of a project. That conclusion holds for developing new safeguards devices as well. Especially it should be noted that an overall strategy should be adopted, i.e. if a system of devices is revised, then any new devices added to this system should, according to a number of criteria, fit both conceptually and technically into the system.

To achieve performance assurance, a basic consideration is to correlate the requirements to a specific application of a device. One cannot expect a device, designed for one application, to function according to the requirements in another application. Even small differences between the applications may become fatal. On the other hand, it is probably cost effective and otherwise feasible to use generic aspects of a device. For example, a gate switch intended for use in a non-radiation environment should nevertheless comply with the same requirements that are put on switches used in areas with high-level radiation. Besides the redundancy aspect, it is possible to reduce the number of different items that must be available. Although these "heavy duty" switches are inherently more expensive compared to simpler constructions, the larger number of one type makes it possible to get a lower price a piece.

Product assurance

Apart from the demand that a device or a part of a device should fulfill certain requirements, the contractor or supplier should be urged to present a strategy for design integrity. If not, it becomes impossible to know whether the device will operate as reliable as quoted in the specifications. Some agreement should also be settled in order to allow full insight into the manufacturing process. In many cases the latter is not possible due to restrictions a producer may have implemented and it becomes necessary to rely on a well-renowned manufacturer with documented ability to manufacturing high-quality products.

1.1.2 Non-technical item

Usage, cost issues
As mentioned above it may be a good idea to reduce the number of different types of devices, a conclusion that holds for the parts lists of the devices as well. Another aspect in this context is the performance/price ratio of a device rather than absolute costs. This ratio is depending on functionality and therefore on demands issued by the authorities. To be able to find a maximum value of this ratio it is vital that the authorities scrutinize their needs in the first instance. In a second step contractors and others could tailor the devices accordingly.

Usage, set-up and maintenance
Set-up recommendations and maintenance of a device should be governed by rigorous procedures that in every aspect should be tested prior to issuing the device. Areas to put attention to are:

- Mounting of devices. A surveillance camera, for example, has certain properties such as angle of view. Here it is important that the whole view is undisturbed. Otherwise one may consider additional cameras to cover the whole field of view. It should be possible to define a “figure of merit” that aids the mounting of devices in order to maximize the coverage.
- Mounting of transmission lines should be subject to specified constraints in order to avoid mechanical and other damages to the lines.
- Mounting of switches should be made in such a way that the actual status of the switch corresponds directly to the physical status of e.g. a gate. Here one may specify a range of opening angles where the device should output a signal.

Interpretation of data
Interpretation of data is of main concern. To structure the discussion let us first consider quality assessment of data and then interpretation of results. Assessment of data here means the consideration of the quality aspect of the data produced by a device. Three items have been identified: 1. Lack of data. 2. Bad data. 3. Data of undetermined quality.

Lack of data.
It can be imagined that in many cases, lack of data actually contains information. For example, a gate switch may assume the two values “1” or “0” where the “0”, i.e. no signal, means for example that the gate is closed. The output can, however, also imply a malfunctioning device. Seemingly trivial, this example forms the basis for a recommendation that *no device should be designed to output a null signal*. Only then the definition of “lack of data” becomes meaningful. In the example one would design a switch that outputs coded signals e.g. a digital signal consisting of a switch ID, status of the switch and various transmission information. A brief scan of the market shows a whole range of circuitries that could be feasible in such an application and that are readily available at a reasonable price. Even better is to replace the switches with tachometers or similar devices in order to achieve a one-to-one correspondence between the output and the actual opening angle of a gate.

The above discussion necessitates the implementation of some network design governed by a central read-out unit checking switches and other devices on a regular basis.

Bad data and data of undetermined quality

These items are somewhat interconnected since a criterion, that implies that the data are of undetermined quality, immediately puts a limit on the definition of bad data. In this context it should be noted that bad data could be obtained even if no technical problems are present. For example, a surveillance camera could be mounted in such a way that it does not cover relevant areas or items. Such a case must, however, be avoided through adequate set-up recommendations.

A reasonable starting point for the discussion is that a quality assessment of data includes none or little human involvement. Therefore a careful design, incorporating both hardware and software criteria, is crucial in order to read out the status of various devices. In the switch example above, if the central unit reads the status of the switch successfully, it can be concluded that both the switch and the transmission line work as intended. If it is not possible to read out the switch according to the criteria (for example due to a malfunctioning device or transmission line), one would define the outcome as bad data or data of undetermined quality.

A similar approach could be used to assess the data from a digital surveillance camera. Using a read out system, that logs the transmission of all pixels, would aid to determine whether the whole information has reached the system or not. A similar approach could be used for various types of radiation detectors included in spectroscopic systems as well.

In conclusion, instead of using the concept of good data, bad data and data of undetermined quality, it may be feasible to introduce *usable* and *non-usable* data granted that *a proper design of devices and read-out systems is assumed.* The definition of these quantities is then clear from above by stating that *usable data comprise data that can be read out to their full extent from a device, otherwise they are regarded as non-usable data.* In the latter case the system should bookmark and possibly report such events.

Interpretation of results

The data from various devices make up the result and will eventually be subject to human scrutiny. Here one would anticipate a higher degree of confidence if a system were designed in such a way that it presents only a few, easy recognizable parameters and that the information in all intermediate stages is processed by the system in accordance with well-defined criteria. Such parameters to present could be:

- Information of malfunctioning devices and transmission lines.
- Information of tampering of devices.
- Presentation by a system for pattern recognition analysis.

The first two items may be trivial and could easily be achieved by using a logging function of a central read-out unit provided that the devices are equipped with a tampering indicating system. The third item represents a somewhat new approach in the application of safeguards. This concept will not be discussed at length in this compendium. However, some principal remarks will be made here.

Consider a large system consisting of various devices such as digital cameras, switches, radiation detectors, etc. Here it would be feasible to connect the devices in a network that is governed by a central read-out unit. During normal circumstances the output of these devices represents a large amount of combinations that create certain patterns. The idea is that activities not approved by the authorities could generate patterns in this large amount of information that differ from normality, and by using adequate software it may be possible to detect such events.

Pattern recognition is in some sense still regarded as a novel technique but has proven its potential in many areas including military applications and medicine, see e.g. [4].

Chapter II.2 Nuclear energy production

Burning fossil or bio fuels implies that chemical energy is utilized, i. e., rearrangement of the atomic electrons is the origin of the energy production. A reasonable description of such processes could be that "atomic power" is produced.

When using uranium in a nuclear reactor, the force binding the constituents in the nucleus together is used. This "nuclear force" is between 10^6 and 10^7 times stronger than the atomic force. These circumstances consequently give rise to a high energy density in the fuel, which is attractive to utilize for energy production primarily for three reasons:

- to produce a given amount of energy a relatively small amount of fuel is required when compared with chemical production methods
- a given amount of produced energy gives rise to a relatively small amount of waste when compared with chemical production methods
- in all processes (uranium mining, enrichment, etc.) leading to the final reactor fuel, chemical energy is used. When using the fuel a very large energy multiplying effect is thus obtained, which is advantageous from economic and environmental points of view.

One further comment could be added in this context; the waste being produced is well localized, i. e., spreading of the waste in the surrounding environment can with adequate techniques in principle be completely eliminated. Against these advantages comes the drawback that nuclear power production requires complicated technical and administrative systems and that the consequences of a nuclear power accident might be severe if all security systems fail simultaneously.

Uranium is abundant in the earth crust and is roughly as common as tin. In nature uranium appears in the form of three isotopes with the following abundances, ^{238}U (99.3%), ^{235}U (0.7%) and a very small abundance of ^{234}U. Uranium is a toxic heavy metal and can give rise to chemical poisoning if entering the human body. On the other hand the radioactivity in natural uranium is low and it is not dangerous even to touch it.

The Swedish nuclear power program implies that today nuclear power plants account for about half the national production of electricity. See Table 2.1. The Swedish nuclear power plants being in operation today (2006) are: Forsmark (3 units), Oskarshamn (3 units) and Ringhals (4 units). The nuclear power plant at Barsebäck with its 2 reactors has been closed down due to political decisions. At present (2007) power enhancements are planned for the Swedish reactors together roughly corresponding to one of the Barsebäck reactors.

Table 2.1. Electric-power production in Sweden during 2004 and 2005 (Data from Svensk Energi). The abundant water resources in 2005 implied a significant increase in the hydroelectric-power share. In spite of the termination of the operation of the second reactor at Barsebäck in 2005, nuclear-power production shows only a small decrease.

Electric power production	**2005 [TWh]**	**2004 [TWh]**	**Change [%]**
Hydroelectric	72.1	60.1	20
Wind	0.93	0.85	9
Nuclear	69.5	75	-7
Other heat generated	12.2	12.9	-5
Total electric power production	**154.7**	**148.8**	**4**

2.1 The fission process

2.1.1 Binding energy

The process behind nuclear power is fission (nuclear splitting). Fission means that an atomic nucleus is split into two fragments (fission products) when a sufficient amount of energy is supplied to the nucleus, induced fission. In certain heavy nuclei fission can take place spontaneously. The energy released in a fission process corresponds to the difference in total binding energy before and after the fission occurred, see below. The nucleus of a chemical element consists of protons and neutrons, so-called nucleons. The number of protons defines the element. Hydrogen has one proton while uranium has 92. The repulsive electric force between the positively charged protons is counterbalanced by the strong (nuclear) force. This force acts between the nucleons in the nucleus and holds it together. Each nucleon is bound by the strong force to the nucleus with a certain amount of energy, the binding energy. The proton/neutron binding energy thus represents the amount of energy required to remove one proton/neutron from the nucleus.

In Fig. 2.1 it is shown how the binding energy per nucleon varies with the mass number of the nucleus (the sum of the proton and neutron numbers). The energy unit electron volt is defined as the kinetic energy acquired by an electron accelerated over an electric potential difference of 1 volt. 1 eV is thus equal to 1.6×10^{-19} Joule (J).

As can be seen in the figure, the binding energy per nucleon increases up to the mass number 56 and than deceases with increasing mass number. The practical implication of this observation is that if two light nuclei merge together, energy will be released. This process is called fusion and is the mechanism behind energy production in stars. It is energetically allowed up to mass number 56. For heavier nuclei energy can be released, if they undergo fission.

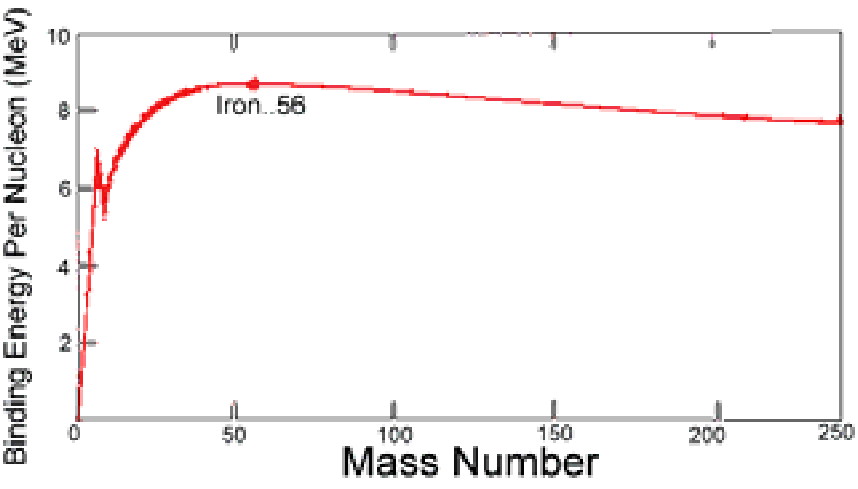


Fig. 2.1. Binding energy per nucleon as a function of mass number. Up to mass number 56, energy can be released through fusion. At higher mass numbers only fission can provide energy. From Beiser, Arthur, Concepts of Modern Physics 4th ed. McGraw-Hill, Inc.: New York.

2.1.2 Energy production in the fission process

From quantum mechanical considerations it can be anticipated that the neutron energy required to induce a fission reaction is lower for nuclei with odd mass number. To generate fission in ^{238}U, for example, a neutron with a kinetic energy of 1.5 MeV is needed, whereas a few tens of meV is sufficient for ^{235}U. A ^{238}U nucleus can also capture a neutron to form ^{239}U, which decays via β emission to ^{239}Pu. The latter isotope shows a fission behavior similar to ^{235}U. For this reason ^{238}U is named a fertile nucleus as opposed to, for example, ^{235}U and ^{239}Pu being fissile nuclei.

The uranium isotope ^{235}U consists except for the 92 protons also of 143 neutrons. When a slow or thermal neutron hits a ^{235}U nucleus, it can cause fission of the nucleus. In the process two fission products are formed with mass numbers on average distributed as illustrated in Fig. 2.2. In addition 2 – 4 neutrons are released in the fission process.

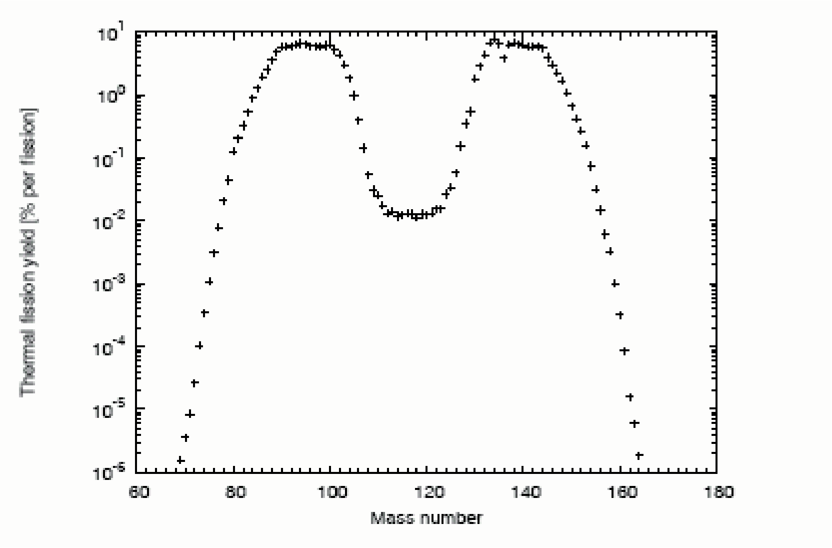


Fig. 2.2. Mass distribution of fragments produced in fission of ^{235}U *induced by thermal neutrons. Note the asymmetric distribution, where the most probable fragment masses are 96 and 140. From England and Rider, LA-UR-94-3106, Los Alamos National Laboratory, October 1994.*

The probability that a nucleus undergoes fission when it absorbs a neutron, is given by the so called cross section, see fig 2.3. The cross section is a complicated function of the actual nuclear structure in the target nucleus and of the neutron energy. From Fig. 2.3 it is evident that in general the cross section decreases when the neutron energy increases (note the logarithmic cross-section and energy scales). It is actually advantageous to use slow neutrons to induce fission reactions in ^{235}U.

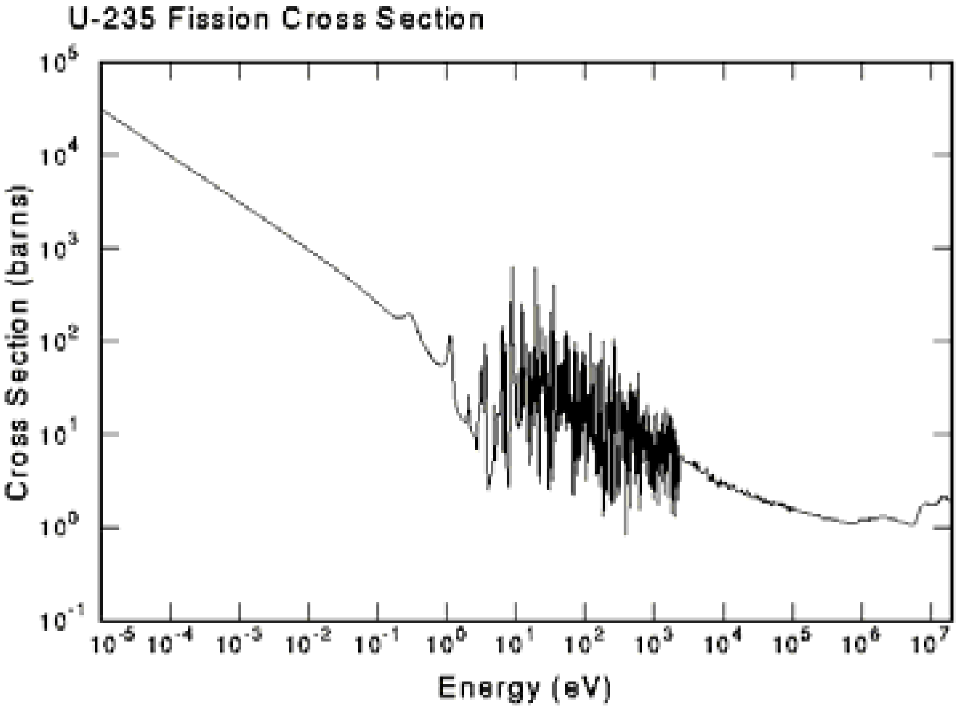


Fig. 2.3. Fission cross section for ^{235}U *as a function of neutron energy. The resonance region between 1 eV and 1000 eV is clearly visible in the figure.*

When a 235U nucleus undergoes fission, on average 2.42 neutrons are released with a summed energy of 5 MeV. The total released energy of about 195 MeV is distributed accordingly

- Kinetic energy of the fission fragments: 168 MeV
- Kinetic energy of the fission neutrons: 5 MeV
- Prompt gamma radiation: 7 MeV
- Gamma radiation from decaying fission fragments: 7 MeV
- Beta radiation from decaying fission fragments: 8 MeV

The total released energy in a single fission reaction is in microscopic terms very small and corresponds roughly the energy required to lift a grain of sand a distance of 1 m. Seen from a macroscopic perspective the picture is completely different: the energy produced via fission of 1 kg of uranium corresponds to that generated by 90 tons of coal.

2.2 Reactor physics – a brief summary

2.2.1 Chain reaction

A method to create slow neutrons to be used to induce fission processes in ^{235}U is thermalization (moderation). This means that fast neutrons are forced to lose energy via repeated collisions with light nuclei like, e. g., hydrogen in water. After a number of collisions the neutron energy has been reduced to a level corresponding to the thermal energy in the surrounding material. They are then called thermal neutrons with typical energies of 0.025 eV. In most commercial reactors of today light water is used as the moderator, which in addition serves as the cooling medium to extract the produced heat.

The fission neutrons released in a fission reaction can after moderation be used to induce fission in other fissile nuclei resulting in new neutrons. This process is sometimes called a chain reaction and the number of neutrons and therefore the number of fission reactions increases exponentially with time, a prerequisite for the devastating explosive force of nuclear weapons. If the exponential growth of the number of fission neutrons is limited, it is possible to obtain the controlled energy production signifying a nuclear power reactor. A condition to create and sustain a controlled chain reaction is therefore that a “balanced” number of fission neutrons is available.

How large is a “balanced” number? The multiplication factor k_∞ describes the number of neutrons being produced per unit time for each neutron being absorbed in an indefinitely large and homogeneous mixture of fuel and moderator. The time derivative of the number of neutrons can mathematically be written

$$\frac{dn}{dt} = n\frac{k_\infty - 1}{\tau} \tag{2.1}$$

or

$$n(t) = n(0)e^{t\frac{k_\infty - 1}{\tau}} \tag{2.2}$$

where   is the *period*, i. e., the time elapsed between the production and absorption of the neutron. Obviously the neutrons have different histories and the period should be considered as a typical mean value. From eqs. (2.1) and (2.2) it can be concluded that $k_\infty = 1$ means that the number of neutrons is constant and the reactor is “critical”. If $k_\infty > 1$ or < 1 the reactor is “supercritical” or “subcritical”, respectively. To generate a sustainable chain reaction it is required that $k_\infty = 1$. In an actual reactor neutrons are lost not only by absorption but also by “leakage” from the reactor core. Therefore the k_∞ value of an actual reactor must be considerably larger than unity, and k_{eff} is defined via the relation

$$k_{eff} = \frac{n_{produced}}{n_{absorbed} + n_{leakage}} \tag{2.3}$$

k_∞ is thus a function of the properties of the fuel-moderator mixture only, whereas k_{eff} is a function of k_∞ and the geometrical configuration of the reactor. To maintain the power of a reactor at a given level it is thus required that $k_{eff} = 1$ and accordingly that $k_\infty > 1$.

The period is typically 10^{-5} s in a thermal reactor, which according to Eq. (2.2) means that if k_{eff} is slightly larger than 1, e. g. 1.001, the value of n/n(0) in one second would become $2.7 \text{x} 10^{43}$, i.e., the reactor would run out of control and most of the fuel be consumed in a very short time, even if it were possible to maintain the reaction. Nature, however, supplies a phenomenon extending the period and allowing a reactor to be controlled in a safe way. About 0.65% (β) of the 2.42 neutrons on average released in a fission reaction are delayed because they originate from neutron-rich fission products decaying with an average half life of 8.8 s, giving an average life time of $\tau = 8.8/\ln 2$ s = 12.7 s. The average delay is thus $\beta\tau =$ 0.083 s to be compared with 10^{-5} s discussed above. With the same value of $k_{eff} = 1.001$, *n/n(0)* becomes = 1.01, which is a small increase easy to control.

For a light-water reactor of the type installed in Sweden its negative temperature coefficient is a typical design feature. This means that the reactivity defined as $\rho = (k_{eff} - 1)/\ k_{eff}$ decreases with increasing temperature. In the operation of a reactor this means that an increase in the reactivity increases the temperature, which in turn tends to reduce the reactivity. The fact that this negative feedback control is inherent in the reactor concept is an important safety aspect in the operation of the reactor.

2.2.2 Reactor types

The most common reactor types in the world today are light-water reactors. These can be subdivided into boiling-water reactors (BWR) and pressurized-water reactors (PWR). In the former Eastern block countries in particular pressurized-water reactors (VVER) and light-water cooled, graphite-moderated reactors (LGR) are used. The latter type of reactors has a design with an inherently positive temperature coefficient, which in principle increases the risk for severe accidents. The graphite-moderated core implies additional risk in case of fire. A well-known example of this reactor type was unit 4 at Tjernobyl, which experienced a total breakdown in 1986.

Most of the reactors in Sweden are of the BWR type (Forsmark, units I – III; Oskarshamn, units I – III; Barsebäck, units I – II and Ringhals, unit I). Fig. 2.4 illustrates schematically how a BWR is constructed.

In the reactor core the heat causes the water to boil under a pressure of about 70 bar. The result of the boiling is that the amount of *void*, i. e. the fraction of steam compared to water increases towards the top of the core. After having passed by the steam dryers in the upper part of the reactor tank, the produced steam is fed directly to the turbines, which in turn propel the electric generators. In the condenser, in Swedish reactors cooled with seawater, the remaining steam condenses back to water and is fed back to the core.

The power control in a BWR is accomplished partly by control rods and partly by the amount of water being pumped into the core. At incidents requiring a fast stop the steering rods are pushed up into the core between the fuel elements. The control rods contain boron, which has a large capture cross section for neutrons, and the number of fission reactions in the core is reduced at a fast rate. When starting a BWR the control rods are slowly retracted from the core and the reactor starts producing power. When about 70% of full power has been reached, more water (moderator) is pumped into the core using the feed water pumps and more power is generated. Under normal circumstances the fine tuning of the reactor power is performed by means of the power to the feed water pumps.

One drawback of the BWR system is that the produced steam contains radioactive substances contaminating the turbines. Furthermore, the simulation of the void is a complication factor. The advantages are the simple and fast control (tuning) of the reactor power, and the relatively simple and therefore comparatively cost-effective design.

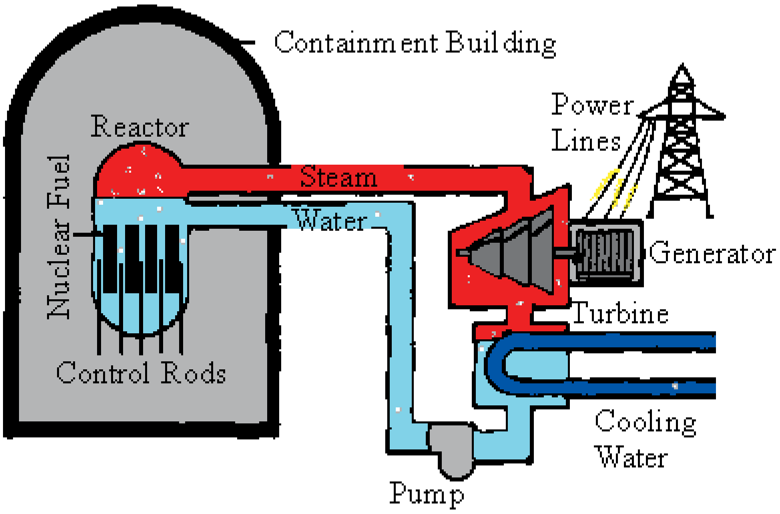


Fig. 2.4. Principle layout of a boiling water reactor (from College of Engineering University of Wisconsin – Madison).

The only Swedish reactors of the PWR type are located at Ringhals (units II, III and IV). The principle design of these reactors is illustrated in Fig. 2.5.

In this reactor type the water is heated to typically 320 oC under a pressure of about 155 bar, and is fed to the steam generators, where heat exchange to a secondary coolant circuit takes place. In the secondary coolant circuit the transferred heat causes boiling of the water at a lower pressure and steam is generated. This steam drives the turbines. Similarly to the BWR system control rods are used for coarse control of the reactor power. The control rods are pushed into the core from above and are integrated parts of the fuel elements. For fine tuning of the reactor power neutron-absorbing boron is added to the moderator water. The drawbacks of the PWR system are the relatively slow power control and the complicated and accordingly expensive system for steam generation. On the other hand the turbine steam is free of radioactivity, facilitating service and overhaul of the turbines. Furthermore the neutron transport in the core is relatively simple to simulate due to the absence of void.

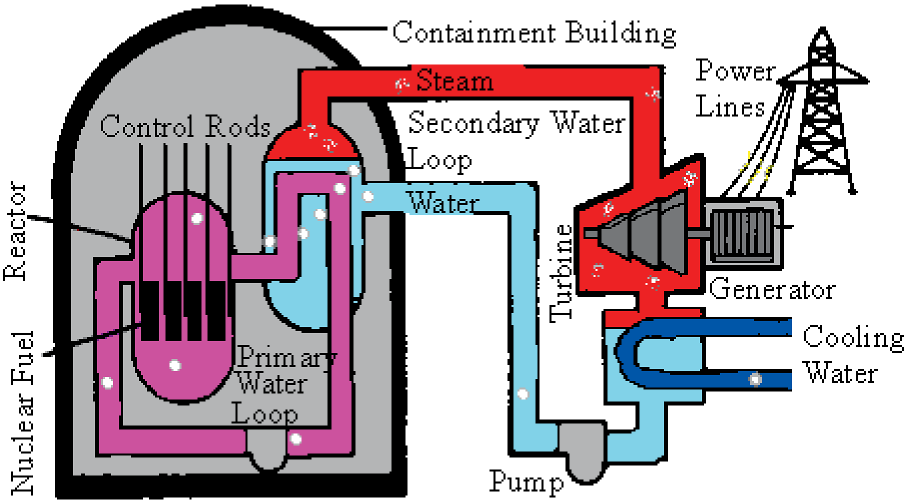


Fig. 2.5. Principle layout of a pressurized-water reactor (from College of Engineering University of Wisconsin – Madison).

For both of the reactor types installed in Sweden the fuel is run in cycles of a length of about 11 months. During the revisions being performed in the summer season, when the consumption of electricity is the lowest, about 25% of the core is exchanged with new fuel. Thus the fuel is typically used during 4 to 5 cycles before it is considered spent.

2.3 Nuclear fuel

The low-enriched fuel (low-enriched uranium, LEU) being used in non-military nuclear power reactors can at most contain 5% by weight (w/o) ^{235}U. A typical enrichment today is between 3 and 4 per cent. Most of the fuel is thus ^{238}U and this is of importance for the geometrical configuration of the fuel briefly being described below.

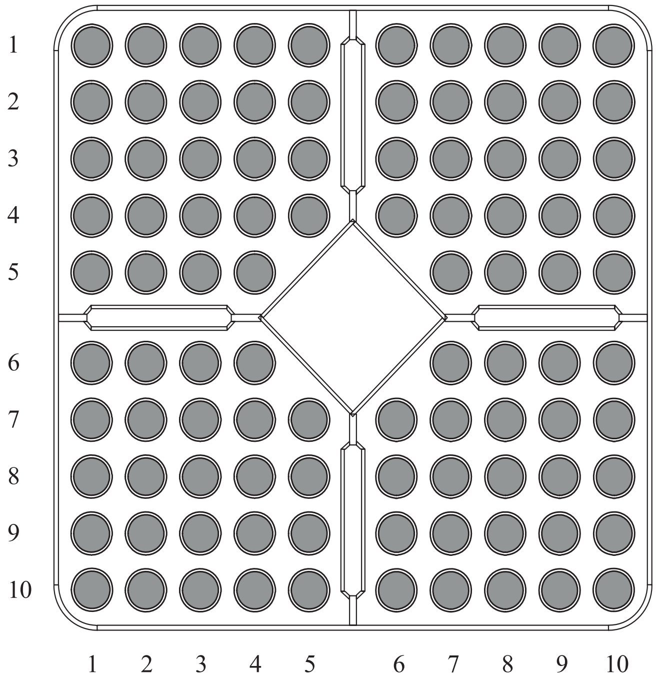
Also ^{238}U contributes to the energy production via so-called fast fission, i. e. by the fact that neutrons not yet thermalized have a certain probability of inducing fission in ^{238}U. Also in these fission reactions neutrons are emitted and these contribute typically between 2 and 4% of the total reactor power.

From Fig. 2.3 it is obvious, that there is a neutron energy region where the fission cross section has strong oscillations called resonances. The absorption cross section in ^{238}U has similar resonances at higher neutron energies, and to avoid that neutrons with these energies disappear via absorption in ^{238}U before being thermalized and capable of causing new fission processes, it is important to accomplish that the thermalization takes place before the neutrons reach the fuel. The probability that a neutron escapes this so-called resonance capture is denoted *p*. With the purpose of increasing *p*, so-called "heterogeneous geometry" is utilized [8], i. e., the fuel is distributed in a particular geometrical configuration instead of being homogeneously mixed with the moderator. Another reason to use a heterogeneous geometry is that the fast fission factor *ε* increases. This parameter is defined as

$$\varepsilon = \frac{n_{fast} + n_{thermal}}{n_{thermal}} \tag{2.4}$$

i. e. the ratio between the sum of the number of neutrons produced by fast fission in ^{238}U and by thermal fission in ^{235}U and the number of neutrons produced by thermal fission only. For more efficient use of the fuel it is desirable to have the fast fission factor as large as possible. In a typical reactor fission with fast neutrons in ^{238}U contributes a few percent to the totally generated power.

Resonance absorption in ^{238}U takes place preferentially in the surface region of the fuel. This means that the fuel volume inside the surface (the bulk) does not contribute to the absorption of not fully thermalized neutrons. A boundary condition for an effective use of the neutron flux by means of a heterogeneous geometry is therefore that the distribution of the fuel in the moderator is designed with relatively large pieces of fuel making the volume-to-surface ratio large.



Fuel rods, inner diameter = 8.36 mm
Fuel rods, outer diameter = 9.62mm
Distance rod to rod = 12.70 mm
Distance rod to corner rod = 12.55 mm

Fig 2.6. Cross section of a SVEA 96 S fuel assembly from Westinghouse Atom. Note the wall surrounding the fuel assembly and the tube structure in the middle and between rod lines 5 and 6. The motivation for these structures is discussed in the text.

Many criteria have to be taken into account when designing LWR fuel. Concentrating on the nuclear aspect one important issue is the usage of materials that exhibit a small absorption of thermal neutrons. Often alloys with zirconium as a main constituent are used. Another important issue is to obtain the proper volume ratio between fuel and moderator through the heterogeneous geometry discussed above. A typical nuclear fuel is therefore made of cylindrical, sintered uraniumdioxide pellets, about 1 cm long and 1 cm in diameter. The pellets are stacked into about 4 m long zircaloy tubes that are filled with argon and sealed. The tubes or fuel rods are mounted together in an array that forms the fuel assembly.

The principal design of a modern nuclear fuel assembly is illustrated in Fig. 2.6. The cross section of a SVEA 96 S fuel assembly from Westinghouse Atom is shown schematically in the figure.

The fuel assembly in Fig. 2.6 is designed for BWR reactors, which can be judged from the channels leading the wet steam axially through the fuel assembly. Also the zircaloy box surrounding the fuel assembly has the task of leading the water and steam so as to give the best thermal contact between the fuel and the moderator/cooling medium.

The construction of nuclear fuel assemblies is under continuous development and new designs appear regularly on the market. Above all this concerns BWR fuel, where an important area of development is the accomplishment of a predictable behavior of the steam generation and its convection. This has led to the development of fuel assemblies with partly shorter fuel rods, i. e., where a fraction of the fuel rods have a length between 1/3 and 2/3 of the full-length rods. Other regions of development are so-called burnable absorbers used to soften the radial burn-up profile of the fuel rods during the first year in the reactor core.

Chapter II.3 Non-destructive assay in nuclear safeguards

In chapters 3 to 6 we will discuss a few techniques used in non-destructive assay (NDA) to achieve some of the goals set for nuclear safeguards. Presently there are not a vast amount of approved techniques available but the research on and developments of adequate techniques are rather extensive. In this chapter we will present a few existing techniques but also, to some extent, research efforts being pursued in the field.

Most work in the area is concentrated on how to utilize basic principles including both physical and applied mathematical methods. Because of this we will focus the discussion here on these basic principles and their potential use rather than describing the, in many cases preliminary, equipment developed.

In this context, NDA may be defined as the experimental procedure of gaining knowledge on the safeguards relevant properties of an object by using various physical measuring techniques while keeping the integrity of the object intact.

Many objects encountered in nuclear technology, such as nuclear fuel assemblies, comprise a high degree of technical complexity and thus high economical values. One obvious reason why NDA is the preferred basis for instrumentation and methodology intended for in-field inspections is therefore that it offers the possibility to give information without destroying the object of interest and also that it gives minimal interference with regular activities at a facility. The latter aspect is important since the acceptance to new safeguards measures among operators in many cases depends on that smooth, efficient and cost-effective inspections can take place. Another aspect of NDA is that the methods, in general, does not require specially equipped laboratories as are often the case for destructive assay (DA). It should be emphasised, however, that NDA cannot replace DA in the general case but serves as a complement.

Fuel parameters of safeguards significance

- Burnup: The amount of energy extracted from a fuel assembly. A commonly used unit is GWd/tU (Gigawattdays per tonne uranium). Typical discharge burnup today is 45 GWd/tU for BWR fuel and 55GWd/tU for PWR-fuel.
- Cooling time: The period of time elapsed between the last outtake and the measuring date.
- Initial enrichment: The percentage by weight of ^{235}U to total uranium content. Maximum allowed enrichment for civil reactors is 5%. Nuclear-propelled naval ships may use enrichments up to 95%.
- Integrity: Describes to what extent a fuel assembly is intact and that no unnoticed attempts to dismount the assembly have been made.
- Irradiation history: Describes the number of power cycles, the power outtake and the length of each power cycle and maintenance period.

The developments made in NDA reflect, and in many ways are governed by, achievements made in various fields of technology. Especially the development of small yet powerful computers has been imperative in order to construct fast and accurate data acquisition systems for radiation detectors, while keeping the total cost on an acceptable level.

In this section the discussion will be restricted to NDA used in safeguarding spent nuclear fuel assemblies from light-water reactors. This approach is motivated by the fact that spent nuclear fuel, in principle, may be used for illegal production of nuclear devices through its content of 239Pu. At this stage one should point out, however, that nuclear fuel operated in civilian reactors, in practice does not offer an immense source of 239Pu. In fact, about 50% of the Pu produced in a civil reactor is burned *in situ*, contributing to about 30% of the total power of the reactor. Only a fraction of the produced plutonium in a BWR-fuel assembly is therefore left in the spent fuel which is not easily retrievable due to the mixture of highly radioactive, even-numbered plutonium isotopes that emit alpha particles and produce thermal power. About 1 percent of the burnt out fuel consists of plutonium.

On the other hand if a state does not concern itself with energy production, civil reactors could, in principle, be operated in a way that maximises the production of 239Pu. This is achieved by irradiating the fuel at low neutron fluxes during a comparatively short time i.e. producing low-burnup spent fuel. For that reason it is a challenge to develop measuring techniques that reveal such irradiation histories and, indeed, attempts in this direction have been made [2].

The basis for NDA on spent fuel is the radiation field surrounding the fuel. The major contribution to this radiation field consists of gamma radiation from various fission products. A smaller but important contribution consists of neutron radiation from spontaneous fission of certain nuclei and from fission reactions in remaining fissile material, triggered by the "spontaneous neutrons". In addition, electrically charged particles such as alpha and beta particles are emitted, but since their range is short compared to the dimensions of a typical fuel assembly, the direct detection of this radiation is presently not of great interest. However, beta particles can through their interaction with the surrounding matter give rise to Cerenkov radiation, that can be detected as explained below.

Depending on the nature of the radiation emitted from spent nuclear fuel, the discussion will be divided into two parts; methods based on gamma-ray detection and methods based on neutron detection. As will be clear, both techniques are of interest and are in many cases complementary. An account will also be given on a technique based on the Cerenkov radiation.

As the forthcoming two sections will deal with measurements of gamma radiation, it is feasible to discuss to some extent the origin of this radiation and the physical foundation for its detection.

3.1 Production of gamma-emitting fission products

Given a specific type of fuel, the production rate of various fission products is governed by the fission rate which, in turn, depends on the neutron flux and thus on the power outtake of the reactor.

A typical feature of the fission process is that the fission products generally are nuclei far from the β-stability line on the nuclear chart. This means that the fission products are neutron- or proton-rich nuclei that easily decay by emitting beta particles or positrons with a half-life ranging from a few milliseconds to several decades. Among the neutron-rich nuclei, some have mass number 137 and by successive beta decay they eventually end up in the notorious nucleus of ^{137}Cs.

The process that involves a one-step neutron capture leads to fission products that are so-called direct fission products and among these ^{137}Cs is a prominent representative. The amount of direct fission products produced demonstrates, in principle, a linear dependence on burnup. Thus the dependence on initial enrichment is negligibly weak, since varying the enrichment only results in a corresponding variation in burnup for a given neutron flux.

The nucleus ^{137}Cs and its simple dependence on burnup, makes it suitable for NDA of spent nuclear fuel for two reasons:

- The long half-life (30.17 years) makes it possible to perform NDA many decades after discharge of the fuel assemblies. The long half-life also implies that the amount produced is not a strong function of the details of the irradiation history.
- The fact that the amount of ^{137}Cs produced, in practice, depends only on burnup makes it feasible to use as a norm in NDA measurements.

Here it may be of interest to derive a simple expression for the production of 137Cs as a function of irradiation time in the reactor. To do this, we start the analysis with the following differential equation

$$\frac{dN}{dt} = K_1 p - \lambda_1 N \tag{3.1}$$

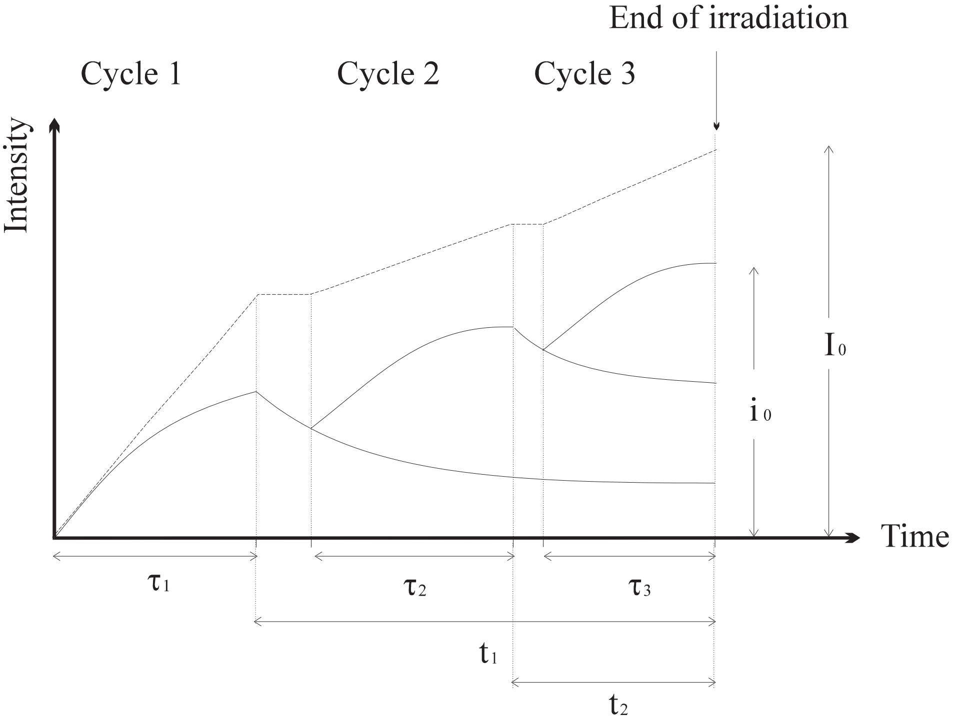


Fig. 3.1. The amount of ^{137}Cs produced in a fuel assembly operated during 3 power cycles with 2 maintenance periods. For comparison, the dotted curve is obtained when no decay is taken into account.

Here N is the amount of ^{137}Cs and p is the power level during one power cycle. In this treatment we assume p to be constant which is a good approximation during normal operation. The parameter λ_1 is the decay constant of ^{137}Cs and K_1 is a constant. The general solution of eq. (3.1) is

$$N(t) = \frac{K_1 p}{\lambda_1}(1 - e^{-\lambda t}) \tag{3.2}$$

During each power cycle n, the fuel is irradiated for a period of time τ_n, producing the amount N_n. The total amount N produced when the fuel has been burned out completely is N_n summed over all power cycles, and is thus described by

$$N = K_1 \sum \frac{\beta_n}{\lambda_1 \tau_n}(1 - e^{-\lambda \tau_n})e^{-\lambda t_n} \tag{3.3}$$

In this expression, the burnup is defined as $\beta_n = p\tau_n$ and t_n represents the period of time from the end of power cycle n to the end of the last power cycle. A case where a fuel assembly has been irradiated for 3 power cycles is illustrated schematically in Fig. 3.1.

For ^{134}Cs, with a half-life of 2.1 years, the relation between concentration and burnup is more complex, see Fig. 3.2. The production of ^{134}Cs is governed by neutron capture in ^{133}Cs, which in turn depends linearly on burnup. Hence, the concentration of ^{134}Cs depends essentially quadratically on burnup.

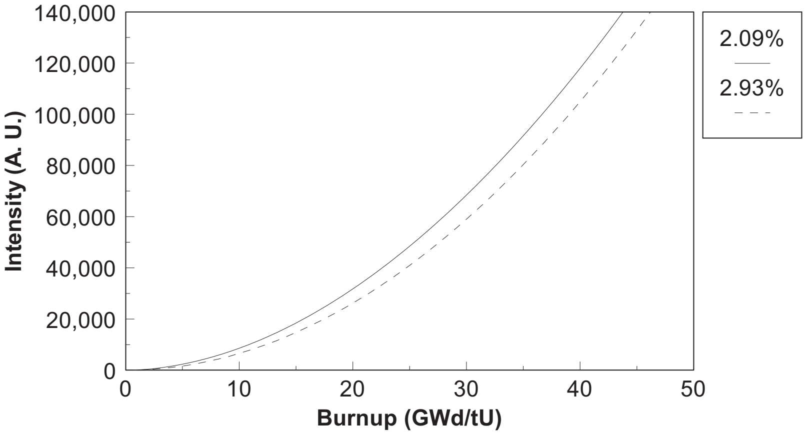


Fig. 3.2. Calculated ^{134}Cs intensity versus burnup for two different initial enrichments.

The dependence on initial enrichment is also displayed in Fig. 3.2. As shown, for a given burnup the amount produced decreases as the initial enrichment increases. This behaviour can be understood by noting that an increase of initial enrichment implies an increased fraction of the neutron flux is used for fission and, consequently, a smaller fraction is available for capture in ^{133}Cs to produce ^{134}Cs.

The concentration of ^{154}Eu depends in an even more complicated way on burnup and is illustrated in Fig. 3.3.

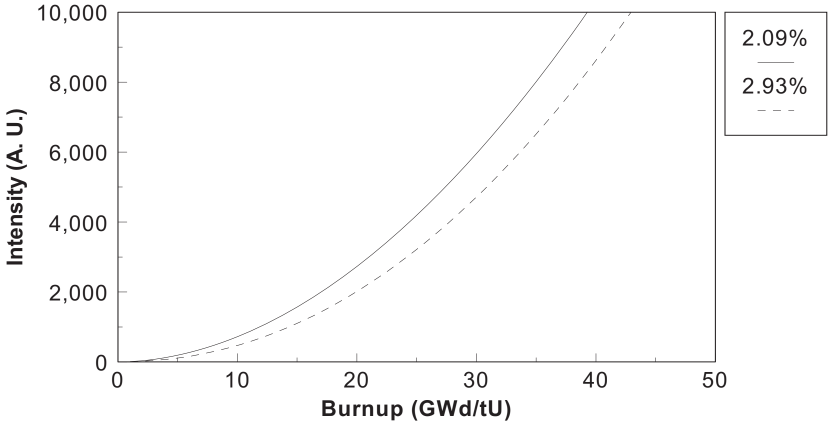


Fig. 3.3. Corresponding result as in Fig. 3.2 but calculated for ^{154}Eu.

The complex dependence of ^{154}Eu is due to the fact that it is produced via many different mass chains, five of which are of major importance, see Fig. 3.4.

A similar dependence on initial enrichment as in the ^{134}Cs case can be noted and, in principle, for the same reason.

For ^{134}Cs and ^{154}Eu, where the intensity does not follow a linear relationship with burnup, the above analysis becomes more complicated in principle. However, by making a simple approximation one obtains expressions that still provide sufficient accuracy. Assume that the intensity N depends on burnup as in eq. (3.4).

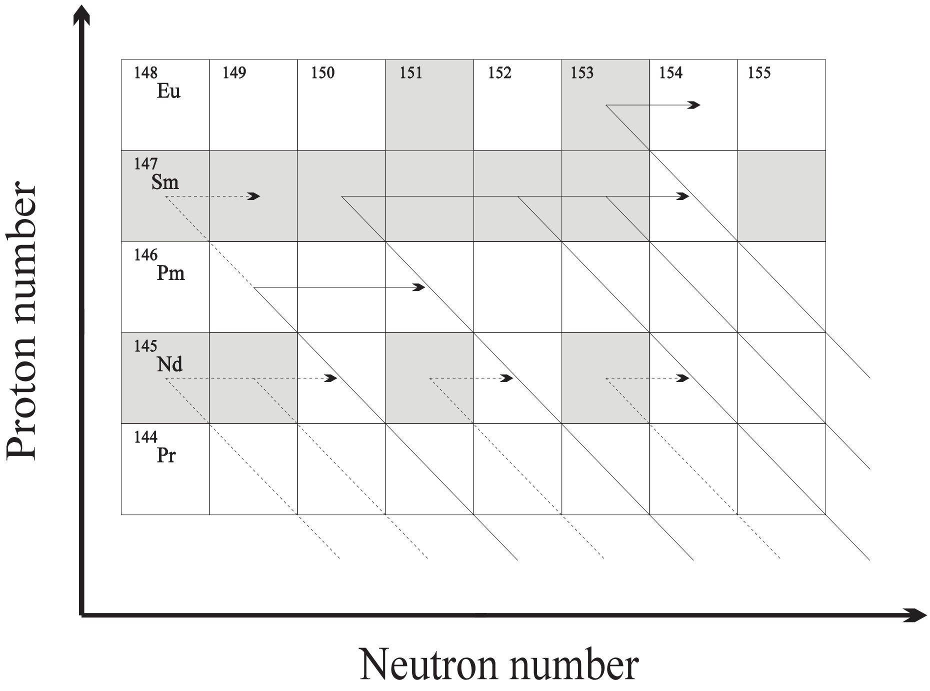


Fig. 3.4. The five mass chains mainly contributing to the production of ^{154}Eu.

$$N = K_2 \beta^{\kappa} \tag{3.4}$$

The intensity contribution N_n for each power cycle n can now be calculated by first generalising eq. (3.1) according to

$$\frac{dN_n}{dt_n} = \kappa K_2 p^{\kappa} t_n^{\kappa-1} - \lambda_2 N_n \tag{3.5}$$

Solving for N_n yields the exact solution of eq. (3.5)

$$N_n(\tau_n) = \kappa K_2 p^{\kappa} e^{-\lambda\tau_n} \int_0^{\tau_n} t_n^{\kappa-1} e^{\lambda_2 t_n} dt_n \tag{3.6}$$

The integral of eq. (3.6) has in general no analytical solution and must therefore be approximated. Substituting t_n with $x_n \cdot \tau_n$ yields

$$N_n(\tau_n) = \kappa K_2 p^{\kappa} \tau_n^{\kappa} e^{-\lambda\tau_n} \int_0^{1} x_n^{\kappa-1} e^{x_n \lambda_2 \tau_n} dx_n \tag{3.7}$$

If $0 < \lambda\tau_n < 1$, the exponential of the integrand in eq. (3.7) can be expanded into

$$\mathrm{e}^{x_n\lambda_2\tau_\mathrm{n}} \approx 1 + \mathrm{x}_n(\mathrm{e}^{\lambda_2\tau_\mathrm{n}} - 1) \tag{3.8}$$

provided that $0 \leq x_n \leq 1$. Using this approximation eq. (3.7) may now be written as

$$N_n(\tau_n) \approx K_2 p^\kappa \tau_n^\kappa \left\{1 - \frac{1}{\kappa+1}\left(1 - e^{-\lambda_2\tau_n}\right)\right\} \tag{3.9}$$

It follows that an approximate expression corresponding to eq. (3.3) in the case of ^{134}Cs and ^{154}Eu becomes

$$N \approx K_2 \sum \beta_n^\kappa \left\{1 - \frac{1}{\kappa+1}\left(1 - e^{-\lambda_2\tau_n}\right)\right\} e^{-\lambda_2 t_n} \tag{3.10}$$

where κ is equal to 2 for ^{134}Cs and in the range of 1.3 - 2 for ^{154}Eu.

Eq. (3.10) is also approximate in the sense that details of the production and depletion are not explicitly taken into account. For 154Eu, the relative importance (which varies with the specific reactor operation) of the various neutron capture reactions (see Fig. 3.4) are all embedded in the parameter κ. However, for many purposes eq. (3.10) provides a simple description that is sufficiently good for analysis of experimental data.

3.2 Detection of gamma radiation

Gamma quanta interact with matter through the electromagnetic force. There are three main processes that provide the basis for detection of gamma radiation: Photoelectric effect, Compton scattering and pair production. The electromagnetic interaction also leads to various secondary phenomena that can be used for detection, e.g. scintillations in many materials and electron-hole production in semi-conductor material. The following discussion is brief and for a thorough treatment the reading of [5,6] is recommended.

3.2.1 Scintillator detectors

The basic feature of scintillation detectors is that light pulses of optical photons are created when the detector material is hit by gamma radiation. Common materials that exhibit the property of luminescence i.e. the property to absorb energy and re-emit it in the form of optical photons are organic crystals such as trans-stilbene ($C_{14}H_{12}$), anthracene ($C_{14}H_{10}$) and naphthalene ($C_{10}H_8$). In addition to organic crystals various organic liquids might be considered. These consist of an organic scintillator in an organic solvent. Among inorganic scintillators NaI, CsI, and bismuth germanate (BGO) are prominent representatives.

Referring to Fig 3.5, the energy levels of an organic scintillator molecule consist of electron singlet states S_x and triplet states T_x and each of them is subdivided into several rotational states S_{xy} and T_{xy}. Typically the energy spacing between the electron levels is a few eV and between the rotational states a few tenths of eV.

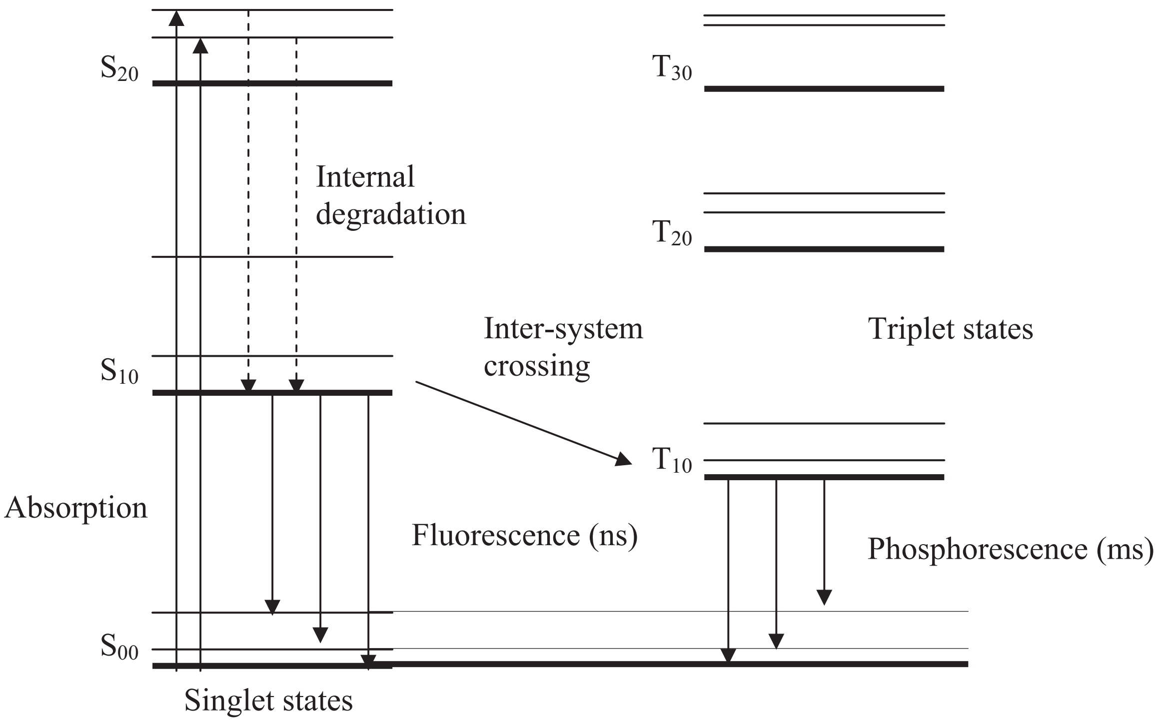


Figure 3.5. Energy levels of an organic scintillator molecule.

Ionisation energy from gamma radiation is absorbed in the material by lifting electrons from the ground state S_{00} to one of the excited levels S_{xy}. These levels generally de-excite within a few picoseconds to the S_{10} state through the process of internal degradation. Eventually the S_{10} state de-excites to a S_{0y} state by emitting a photon. This fluorescence process takes place within the order of ns and gives rise to a fast component of the detector signal. As seen in the left-hand part of Fig. 3.5 the self-absorption within the material is usually very small (the down arrows are shorter than the up arrows).

In a process called inter-system crossing, some singlet states are converted into triplet states. In Fig. 3.5 the T_{10} state having a lifetime of up to several milliseconds is populated. A transition between the T_{10} and S_{0y} states gives rise to phosphorescence with characteristic times in the millisecond range. Alternatively the T_{1y} states may be thermally excited back to the S_{10} state. When this state eventually de-excites, a slow component (delayed fluor-escence) of the detector signal is obtained. A typical light output from an organic scintillator may thus be written $N(t) = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$, which is schematically shown in Fig. 3.6, where A is usually larger than B. The rise time of the pulse has been omitted in Fig. 3.6. Although not clarified, the energy absorption in liquid scintillators seems to take place in the solvent that eventually transfers the energy to the scintillator component where the scintillation process takes place in the manner discussed above.

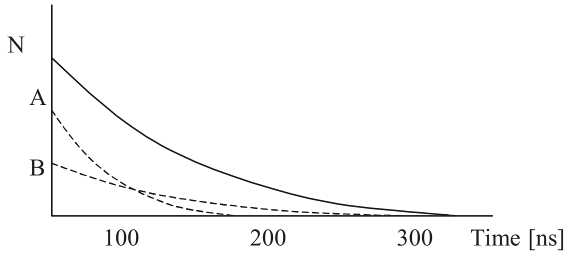


Fig. 3.6. Typical light output from an organic scintillator showing the fast and slow components.

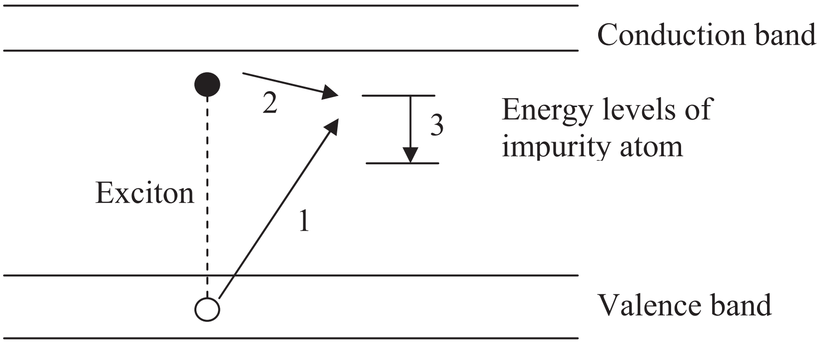


Figure 3.7. Energy levels of an inorganic crystal. The scintillating process starts with a hole that excites an energy level of an impurity (1). An electron de-excites the level (2) by emitting photons (3).

By mixing the scintillator with a solid plastic solvent, a versatile scintillator is produced. A combination often used is polyphenylbenzene with an additive of p-Terphenyl.

A special feature of plastic scintillators is their extremely short decay constant of (2-3) ns, which necessitates taking into account the rise time of the light pulse, i.e., $N(t) = N_0 f(\sigma, t) e^{-\frac{t}{\tau}}$ where $f(\sigma,t)$ is a Gaussian with a standard deviation σ in the range of (0.2 – 0.7) ns.

The organic scintillators are available in a variety of sizes making them very versatile. Especially plastic scintillators can be machined in virtually any shape and size, and sheets of several square meters are not unusual. A main drawback with liquid scintillators is that they are generally poisonous and flammable, and thus should be handled with great care as hazardous material.

Another type of scintillator material comprises the inorganic crystals. The scintillation process for these materials is different in that it is governed by the band structure of a crystal and not by the molecular structure. In Fig. 3.7 the band structure and a typical excitation are shown.

The scintillation process begins with radiation energy being absorbed by the crystal, creating an electron-hole pair, a so-called exciton. This exciton can move rather freely in the crystal and when it encounters an impurity level in the normally "forbidden" energy region the hole component may excite the impurity atom. This atom can be de-excited e. g. by an electron from the exciton and radiation is emitted. Typically this radiation consists of UV-photons and in order to facilitate the detection of it, a small amount of a “wavelength shifter” is added to the crystal transforming the radiation into optical photons.

A very useful property of scintillators is that the intensity of the light produced is proportional to the energy deposited in the detector, i.e., the detector exhibits a certain degree of energy resolution. The energy resolution of a scintillator detector is mainly governed by the number of optical photons produced per energy unit deposited in the detector. Typically between 5000 and 50 000 photons per MeV deposited energy are produced, which can also be expressed such that (200 – 20) eV of deposited energy is required to create one optical photon. This means that scintillators exhibit relatively low energy resolution (10 – 25)% at 1332 keV gamma-ray energy) and therefore are used in applications where a simple and robust technique is of higher importance than good energy resolution.

NaI crystals are brittle and hygroscopic implying that the detector must be encapsulated in such a way that moisture cannot reach the crystal. The energy resolution is among the best for scintillators, around 10% at 1332 keV. CsI, on the other hand, has higher average atomic number than NaI, which increases the absorption cross section of the material, which, in turn, implies higher efficiency for gamma detection. CsI is also hygroscopic and special measures have to be applied. A special feature of CsI is its capability to discriminate between gamma radiation and charged particles. This is an important property being used in basic nuclear physics research, but has not yet found its applications in NDA of spent nuclear fuel.

Even higher detection efficiency is exhibited by the bismuth germanate (BGO) detector. This detector material has an energy resolution in the order of 15% at 1332 keV. A main advantage when using BGO detectors is the fact that they are not hygroscopic.

3.2.2 Photomultiplier tubes

The light pulse of a scintillator is most commonly detected and amplified by a photomultiplier tube (PMT).

The PMT is a device that transforms optical energy into electric energy with a minimum of noise. The main layout of a PMT is schematically shown in Fig. 3.8 and the principle of operation is as follows:

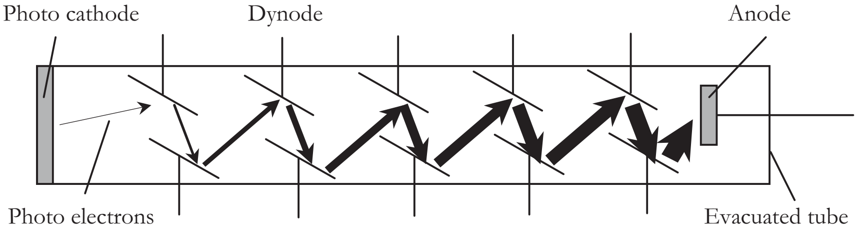


Figure 3.8. Schematic layout of a PMT.

A photon hitting the photo cathode creates n electrons that are accelerated through an electric field towards the first dynode. There, δn new electrons are produced that are accelerated towards the next dynode where $\delta^2 n$ electrons are produced and so on until the electrons reach the anode where a signal is derived.

If the number of dynodes is N, a total amplification factor or gain of $\alpha\delta^N$ is obtained where α is the fraction of all photoelectrons collected by the internal structure of the PMT. For conventional materials $\delta = 5$ and $\alpha = 1$. For a ten-stage PMT the overall gain will thus be about 10^7. Typically (1000-2000) V is applied between the photo cathode and the anode, while the potential difference between adjacent dynodes is typically 200 V.

Characteristics of PMTs are high gain, very low noise level and high availability of a variety of sizes, from a few mm in diameter up to several tens of cm, and various geometries that allow the experimenter to tailor his detection setup. The drawback is the vulnerability inherent in a construction based on evacuated glass tubes. Also, at high-intensity measurements, a high count rate may force too large a current to flow in the tube causing the dynode potentials to drop, which implies the introduction of a non-linear response of the PMT. In some applications where a small depth of the detector is preferable, it might be more feasible to use photodiodes available on the market, even if they exhibit a larger noise level.

3.2.3 Semiconductor detectors

When hit by gamma photons, semiconductor materials, such as germanium or silicon, react by creating electron-hole pairs. During the process, the electron component is elevated from the valence band to the conduction band (see Fig. 3.9) and becomes more or less free, while the hole component rapidly is “filled” by a neighbouring valence electron thus leaving a hole behind it. As this process is repeated the hole moves across the crystal as a positive charge relative to the negatively charged surroundings.

If an electric field is applied across the crystal, the holes tend to move towards the cathode and the electrons, in the conduction band, towards the anode. These movements correspond to a current creating an output signal composed of a slow hole component and a fast electron component as shown schematically in Fig. 3.10.

As shown in fig. 3.9 the band gap energy of a semiconductor is of the order of 1 eV implying that electrons are easily excited into the conduction band by thermal energy. Such excitations thus produce a highly unwanted background noise that can be decreased by cooling the detector.

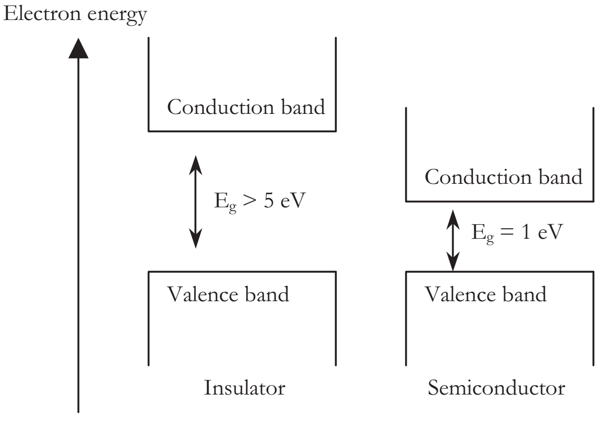


Figure 3.9. The band structure of an insulator material and a semiconductor crystal.

Similar to the case of scintillators, the energy resolution is governed by the number of electron-hole pairs created. For germanium, 2.96 eV is required to create one electron-hole pair or about 340 000 pairs are created per MeV of deposited energy. This number is a factor of 10-100 larger than the corresponding quantity for scintillators. Typical energy resolution of germanium detectors is therefore about 1 keV at 1332 keV gamma-ray energy or 0.07 %, and detectors based on semiconductor technology offer the highest energy resolution available today.

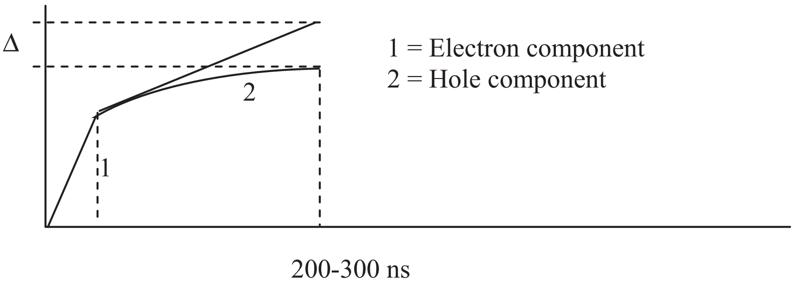


Figure 3.10. Output pulse from a semiconductor detector. The hole component has a tendency to be trapped in impurity levels within the crystal. As a consequence the amplitude of the hole component may decrease as compared to the unaffected case. This effect gives rise to the so-called ballistic deficit Δ.

A major drawback of semiconductor materials is that they need to be cooled. For the germanium (Ge) detector it is convenient to use liquid nitrogen (at a temperature of 77 K) to demonstrate its excellent properties (see Fig. 3.11).

Such a cooling is often achieved by using dewars as illustrated in Fig. 3.12. An increasingly common method for cooling is to use a closed-loop system filled with a suitable gas that is compressed and expanded in a way similar to the principle of ordinary refrigerators.

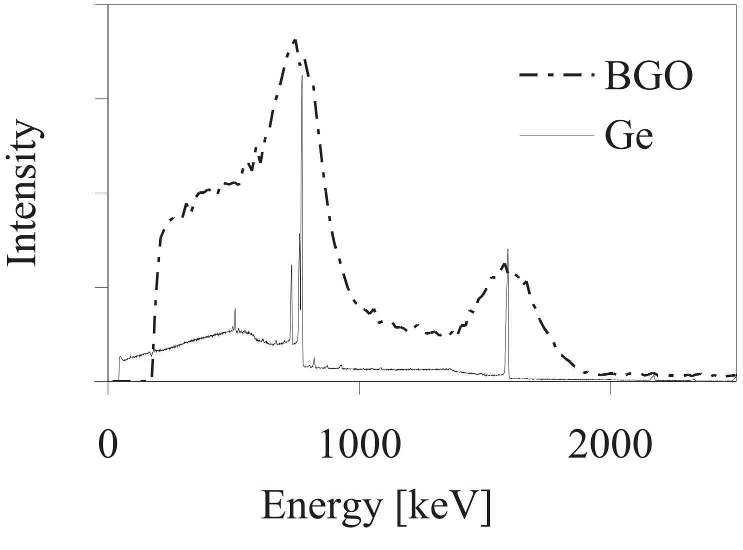


Figure 3.11. Comparison between a spectrum of the 1596 keV radiation from ^{140}Ba, recorded with a BGO detector, and the corresponding spectrum recorded with a Ge detector.

Semiconductor detectors are subtle, fragile instruments. The arrangement for cooling makes the detectors somewhat bulky and their main application is therefore in various stationary applications. However, during the last decades, some systems based on Ge technique have been issued for in-field applications [7].

The size of Ge detectors is limited due to the complex fabrication of the crystals. The largest Ge detectors today have volumes of about 500 cm3. However, in many applications where quantitative analysis is to be carried out, they are, due to their superior energy resolution, the only choice. Fig. 3.11 shows the difference of the energy resolution between a Ge and a BGO detector. The spectra shown in Fig. 3.11 correspond to measurements of a fuel assembly with a cooling time of about 20 days. The superior energy resolution of the Ge detector is obvious.

Figure 3.12. A typical Germanium detector with its dewar vessel.

There are developments to create new semiconductor materials suitable for gamma-ray detection. A main issue here is to get independent of the cooling requirement. Such materials are for example cadmium telluride (CdTe) and mercury iodide (HgI2). Detectors based on these materials can be operated in room temperature but they presently exhibit bad performance since the hole component tends to be severely trapped in impurity energy levels within the crystals, which impairs the spectral quality. Also, such detectors cannot be made in large volumes using the present technology. The upper limit of the volume of a CdTe-detector is typically about 0.05 cm3.

3.2.4 Ion chambers

A third detector type is the ion chamber. These types of detectors find their main application in harsh environments and for monitoring purposes. The principle of operation of ion chambers is well known since a long time and is quite simple (see fig. 3.13).

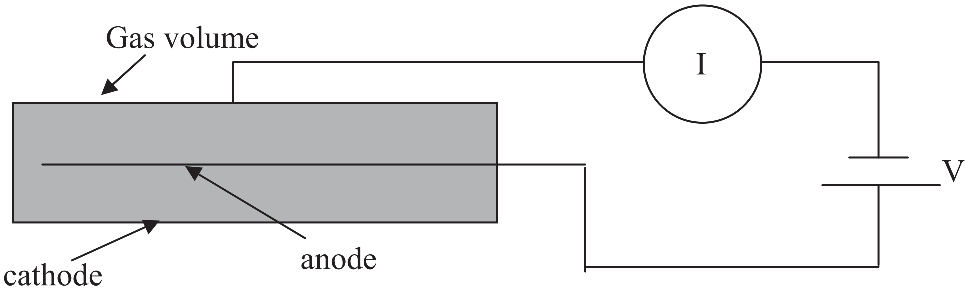


Figure 3.13. Principal layout of an ion chamber.

A gamma quantum that enters the gas volume has a certain probability to interact with the gas molecules. In such a process electrons and positively charge ions are liberated and drift towards the anode (central wire) and cathode (enclosure), respectively. In this process a current is created, the magnitude of which is proportional to the gamma flux. The current is in the order of tens of nA and thus must be measured with specially constructed equipment.

The ion chambers are low-cost, robust and reliable devices but their energy resolution is poor and therefore they are generally not used in applications where spectroscopic information is needed.

3.3 Production of neutron emitting isotopes

In the year 1920, Rutherford proposed the existence of a neutral particle embedded in all nuclei. The particle was purely hypothetical, and Rutherford could not support the idea by experimental evidence. It was not until 1932 when Chadwick, using the experimental results of Bothe and Becker (1930) and I. Curie and F. Joliot (1932), was able to show that neutral particles indeed reside in all nuclei except for hydrogen; the neutron was discovered.

The suspicion that neutrons have about the same mass as protons was clarified by using scattering experiments where neutrons were first produced by exposing e.g. beryllium to alpha particles and then bombarding light elements such as hydrogen, lithium, etc. with the neutrons. By observing the angular and energy distributions of the emitted protons, Chadwick concluded that the mass of the neutron must be “very nearly the same as the mass of the proton” [8]. Today we know that the rest mass of the neutron is 1.0014 times the proton rest mass or $1.67495 \cdot 10^{-27}$ kg, corresponding to a rest energy of 939.573 MeV.

Besides the special feature of slow neutrons to induce fission reactions, various capture reactions take place during irradiation of the fuel in the reactor core. A capture reaction may occur when a neutron of feasible energy hits a nucleus. In such a reaction the mass number of the capturing nucleus is increased by one unit, and often the resulting nucleus is unstable. In fact, the presence of all elements heavier than uranium (trans-uranic elements) is a consequence of such reactions, which is the reason for the extremely small abundance of such elements in nature.

Fig. 3.14 shows an example how a trans-uranic element such as ^{244}Cm is produced as a consequence of a series of neutron capture reactions and beta decays.

The two main neutron sources in spent nuclear fuel are spontaneous and induced fission and especially the two isotopes ^{242}Cm ($t_{1/2}$ = 163 days) and ^{244}Cm ($t_{1/2}$ = 18 years) are of interest in this context. Both isotopes spontaneously fission and thus emit neutrons that can be utilised for NDA on spent nuclear fuel. For cooling times exceeding a few years the contribution from ^{242}Cm is negligible and the main contributor to the neutron flux is ^{244}Cm. If the fuel assembly under study is surrounded by water, these fission neutrons are moderated and fission reactions in the remaining fissile material in the fuel and specifically in ^{239}Pu are likely to occur. Thus the neutron flux from spent fuel depends mainly on the amount of ^{244}Cm but to some extent also on the ^{239}Pu content. This fact may be utilised to determine the burnup (through the ^{244}Cm amount) and potentially offers a method to determine the fissile content of the spent fuel (through the fraction depending on the ^{239}Pu content). In practice it turns out, however, that the latter parameter is exceedingly difficult to determine on spent fuel and this is presently not done on a regular basis.

$$^{239}\mathrm{Pu}(4n,\gamma)^{243}\mathrm{Pu} \xrightarrow[\text{5 hr.}]{\beta} {}^{243}\mathrm{Am}(n,\gamma)^{244}\mathrm{Am} \xrightarrow[\text{26 min.}]{\beta} {}^{244}\mathrm{Cm}$$

Figure 3.14. Production of ^{244}Cm in a reactor. The production route for ^{239}Pu is neutron capture in ^{238}U forming ^{239}U, which beta decays into ^{239}Pu.

3.3.1 Detection of neutrons

The scintillators discussed earlier may be used as neutron detectors as well. Especially lithium iodide (LiI) is often used for detection of low-energy neutrons through the reaction $^{6}\mathrm{Li}(n,\alpha)^{3}\mathrm{H}$. However, in nuclear safeguards this is not a very common technique. Instead the use of fission chambers has found some applications [9].

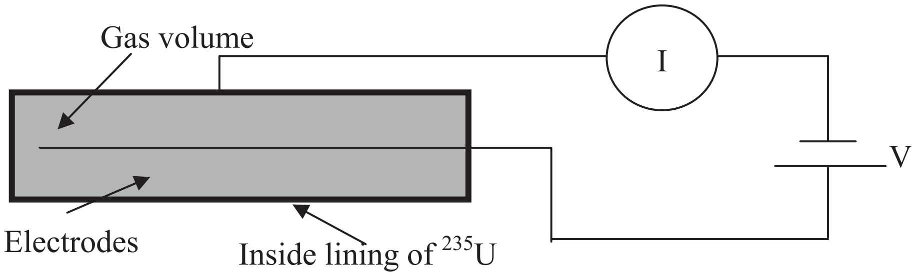


Figure. 3.15. Schematic layout of a fission chamber.

A fission chamber is in principle an ion chamber equipped with a thin ^{235}U lining on the inside of the gas enclosure as shown schematically in fig. 3.15. When a thermal neutron hits the lining, a fission reaction may occur and the positively charged fission fragments are ejected into the gas volume and by collisions with the gas molecules create electrons and ions that eventually are collected, giving a measurable current. The fission chamber is a simple and reliable device but suffers from the fact that the lining gradually “burns out”. This is most evident for in-core neutron detectors where these devices are exposed to neutron fluxes in the order of 10^{13} n/cm^{2} · s. In that particular application special measures are taken in the construction of the fission chambers by adding e.g. ^{238}U to the lining material, which will gradually be converted into the fissile ^{239}Pu. These types of detectors are referred to as regenerative detectors and it has been reported [10] that the sensitivity of such detectors does not vary by more than ±5% for an accumulated neutron exposure (fluence) of 4.8×10^{21} n/cm^{2}.

The fission chamber detectors can be tailored for use in many applications such as in-core diagnostics of reactors. The fill gas is usually argon at a pressure of several atmospheres in order to ensure that the fission fragments are stopped within the detector module. Typically fission chambers operate at a few hundreds volts.

A non-desirable property of fission chambers is the "memory", which is due to a collection of beta emitting fission products within the detector volume. This effect may turn up, when the detector has been exposed to high neutron fluxes during an extended period of time and manifests itself as a "dark current". Often, however, the dark current decreases relatively fast due to the short half-lifes of the fission products and reaches a negligible level within 10 days or so.

Chapter II.4 NDA techniques based on gamma radiation. Quantitative measurements

In this section we will discuss techniques that enable quantitative measurements. Since these techniques are based on measuring the intensity of various gamma-ray energies, equipment offering good energy resolution is needed. As has been discussed earlier there are several detector options to choose among but in order to obtain high-quality data the only feasible choice is the Ge detector. However, as we already have seen, this detector type demands special arrangement for cooling and is thus not very suitable for in-field use. The possibility of high-precision instruments, based on CdTe detectors, is conceivable but this technique is currently under development.

4.1 The gamma burnup verifier (GBUV)

This system [2,11] normally makes use of the facility infrastructure. A typical arrangement is shown schematically in fig. 4.1. The equipment shown is normally used for various diagnostics on fuel assemblies such as investigations for leakages. Such installations are available in all Swedish BWR nuclear power plants (NPP) and also at the interim storage facility CLAB in Oskarshamn.

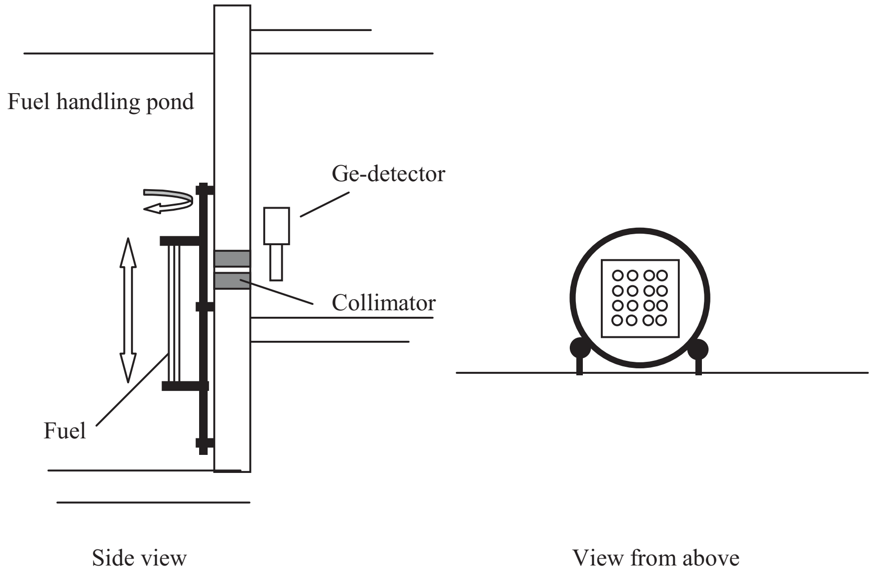


Figure 4.1. Schematic view of a GBUV-installation in a Swedish NPP (side view, left and from above, right). Not drawn to scale.

The fuel assembly is inserted into a fixture, mounted on an elevator on the inside wall of a fuel handling pond. The fuel assembly to be measured can be rotated 360º using a stepping motor device. The elevator system used to move the fuel assembly vertically is connected to an adjustable speed control, which is used to optimise the speed with respect to fuel length, scanning time etc. The fuel assembly is scanned along its length four times, each scan covering one of the four corners of the fuel assembly.

During a scan, gamma radiation from the assembly passes through a horizontal slit of a collimator mounted in the pool wall. This allows the detector at the back-end of the collimator to cover a horizontal slice of the assembly with a height of a few mm.

By using the high-resolution capability of the detector system, the intensity distributions of ^{137}Cs, ^{134}Cs and ^{154}Eu are recorded and from these it is possible to determine the burnup, cooling time, initial enrichment, decay heat and, to a certain extent, the irradiation history of the fuel assembly.

The method makes use of the different dependence on burnup β and cooling time T (through the decay constants λ) of ^{137}Cs, ^{134}Cs and ^{154}Eu. From the discussion in chapter 3, the following expressions for the measured intensities can be formulated:

^{137}Cs :

$$I_1 = K_1 \beta e^{-\lambda_1 T} \tag{4.1}$$

^{134}Cs or ^{154}Eu:

$$I_2 = K_2 \beta^{\kappa} e^{-\lambda_2 T} \tag{4.2}$$

where K_i is a constant. The parameter κ equals 2 for ^{134}Cs and 1.3 - 2 for ^{154}Eu.

Combining eqs. (4.1) and (4.2) yields

$$\beta = \left(\frac{I_2}{K_2} \left(\frac{K_1}{I_1} \right)^{\frac{\lambda_2}{\lambda_1}} \right)^{\left(\kappa - \frac{\lambda_2}{\lambda_1} \right)^{-1}} \tag{4.3}$$

and

$$T = \frac{1}{\lambda_2 - \kappa \lambda_1} \ln \left\{ \left(\frac{I_1}{K_1} \right)^{\kappa} \frac{K_2}{I_2} \right\} \tag{4.4}$$

The accuracy involved in determining burnup and cooling time is typically within ±2 % and ±(60 – 100) days, respectively (see [2]).

As a rather elaborate arrangement is needed to perform NDA using GBUV, one may not expect such equipment to be installed worldwide. Therefore GBUV is not used as a regular part of IAEA’s safeguards. Some recent achievements have nevertheless been reported [12].

4.2 Computerised tomography

The development of small and powerful computers enables the analysis of very large amount of data per time unit. This has enabled the possibility to perform emission tomography, which means the technique to determine the source distribution within an object by mapping the radiation field in a large number of points outside the object, see Fig. 4.2. The purpose of this technique in safeguards is to determine the integrity of spent nuclear fuel assemblies i.e. to conclude that an assembly is complete and that no fuel rods have been removed or replaced without notice.

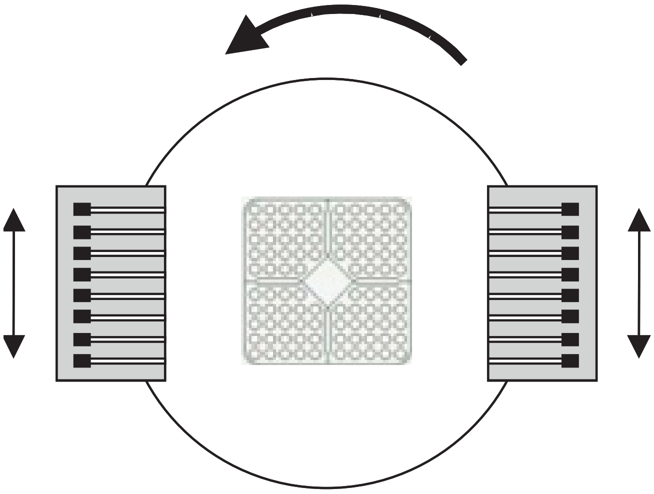


Figure 4.2. Schematic view of a set-up for tomographic measurements of a fuel assembly. The collimator and detector arrangement to the right can be moved across the assembly while the assembly is rotated in order to obtain various projection angles.

The field is quite new and there is no experience of using tomography on a regular basis. However, a few attempts have been made and below follows a very brief account of one of them.

At Uppsala University, a tomo-graphic technique has been developed [13], which is based on an algebraic approach. The basic expression for the algorithm used may be written

$$W(E_\gamma)\underline{A} = \underline{I}(E_\gamma) \qquad (4.5)$$

Here $W(E_\gamma)$ is the absorption matrix, i.e. a matrix describing the attenuation of a gamma ray with energy E_γ along a path from a radiating point within a fuel assembly to the detector. The vector $\underline{A}$ represents the unknown activity distribution and the vector $\underline{I}(E_\gamma)$ represents the measured gamma-ray intensities.

The method developed may be divided into two parts:

- The calculation of the absorption matrix W using operator-declared data of the geometry of the investigated fuel assembly.
- The actual reconstruction using an iterative technique to solve eq. (4.5) for $\underline{A}$.

To be able to calculate W the cross section of a fuel assembly is divided into a number of elements called pixels. In this process the simplification is made that only pixels representing regions of fuel material contribute to the gamma-ray emission, other pixels are pre-set to zero. For a specific set of measuring positions, the relative intensity at the detector from each finite valued pixel is calculated. It is important to note that such calculations are done for each fuel type.

The calculated relative intensities, called the contribution coefficients, are introduced as the M×N elements of the absorption matrix W where M is the number of measurements and N is the number of pixels. For clarity eq. (4.5) may be rewritten as

$$\begin{pmatrix} w_{11} & w_{12} & w_{13} & \cdots & w_{1N} \\ w_{21} & w_{22} & w_{23} & \cdots & w_{2N} \\ w_{31} & w_{32} & w_{33} & \cdots & w_{3N} \\ \cdot & & & & \\ w_{M1} & w_{M2} & w_{M3} & & w_{MN} \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ \cdot \\ A_N \end{pmatrix} = \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ \cdot \\ I_M \end{pmatrix} \qquad (4.6)$$

where w_{mn} = contribution coefficient of measurement m from pixel n. A_n = activity in pixel n. I_m = intensity of measurement m.

A unique solution of eq. (4.6) is only defined if $M \geq N$. Taking into account the statistical uncertainty associated with the vector $\underline{I}$, the number of equations M should be larger than N by a large factor. Typically several thousands of measuring points are necessary to achieve a sufficient amount of data.

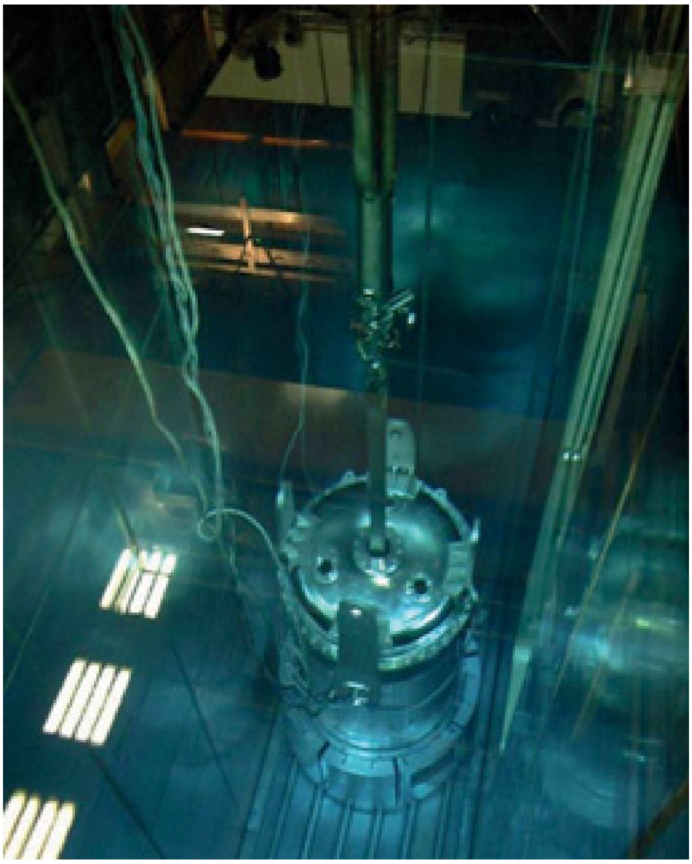


Figure 4.3. PLUTO standing on the pool floor while a fuel assembly is inserted into measuring position.

To test the method, a device called PLUTO was designed and constructed. The device, which can be seen in Fig. 4.3, was approximately 5 m high, 2m in diameter and weighed about 27 tonnes. PLUTO was primarily constructed for high-precision determination of the radial intensity distribution of a fuel assembly for the operator needs. This motivated the heavy and stable layout, which, obviously, makes this device somewhat bulky to transport from site to site.

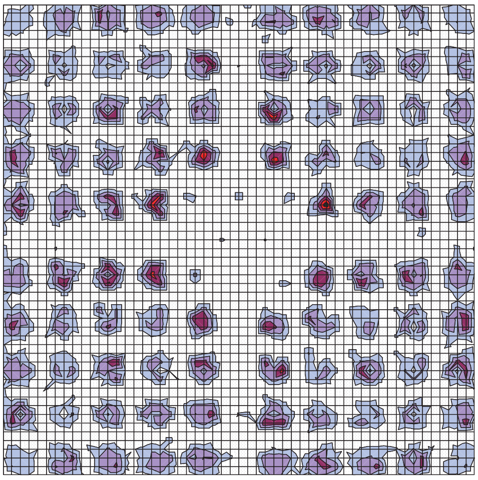


Figure 4.4. A cross sectional view of a SVEA 96 fuel assembly as measured with PLUTO.

However, as a test platform PLUTO served well and the results indicated that a modified technique indeed could be used for safeguards purposes. An example of the results from measurements using PLUTO is shown in Fig. 4.4. In the figure, the individual fuel rods are clearly seen and the quality is such, that a missing or replaced fuel rod could easily be detected.

Although the development of tomographic systems for safeguards purposes is at an early stage, the tests performed well and their results are promising.

4.3 Other instruments

In addition to the GBUV, there is a whole range of instruments that are used for verifying enrichment and plutonium isotopic composition of materials other than spent fuel. Let us briefly describe the Hand-held Assay Probe HM-5 as an example.

The design of the HM-5 includes a NaI detector that may be replaced with a CdZnTe detector in cases where better energy resolution is necessary. At most 50 spectra, each with 1024 channels, can be stored in the non-volatile memory of the HM-5. These spectra may be transferred to a computer for further processing. Fig. 4.5 shows the HM-5 device.

Figure 4.5. The HM 5 device. (Photo: IAEA).

The versatility of the HM-5 is used not only for comprehensive safeguards inspections but also for investigations under the conditions of the Additional Protocol. In fighting illicit trafficking the HM-5 is useful for law enforcement services to detect and identify nuclear and radioactive materials being smuggled across borders.

Chapter II.5 Gamma-ray techniques. Qualitative measurements

Under this heading we find instruments verifying on a level called “gross defect” which basically means that the device should aid to verify whether there is fissile material in a location or not.

5.1 The spent fuel attribute tester (SFAT)

Normal storage of fuel assemblies implies that the assemblies are located in racks standing on the bottom of a fuel storage pool. The distance from the top of the fuel assemblies to the water surface is in the order of 10 m and typically 25 assemblies (in Sweden) are placed in the storage rack. It is of great safeguards interest to verify if each position in the racks is filled or not filled with spent fuel, according to the operator declaration. Therefore the SFAT has been developed.

The SFAT consists of a detector head (see fig. 5.1) based on a NaI or a CdTe detector. A watertight pipe functions as a collimator and is mounted onto the detector head.

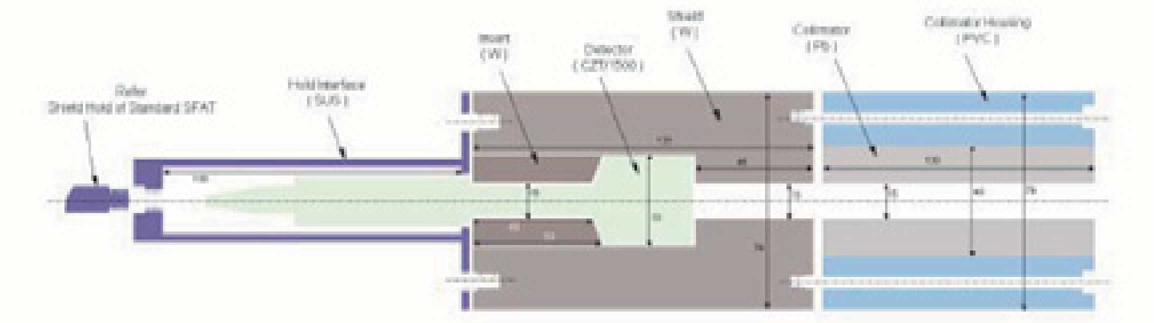


Figure 5.1. The SFAT detector head (from ref. [14]).

The detector and pipe is submerged using a wire together with a fuel handling machine, and positioned slightly over the top of a fuel assembly (see Fig. 5.2). The detector signal is fed into a data acquisition system consisting of a multi channel analyser.

If the read-out system displays a spectrum where a ^{137}Cs signal is present, this indicates a high probability that the position contains spent fuel. In general, a contribution from ^{60}Co emanateing from various activated construction materials such as the top plate of the assembly is also visible (see Fig. 5.3).

The accuracy of the technique would increase drastically by using the CdTe option since the ^{137}Cs peak would be well separated from the large background mainly from ^{60}Co. For a detailed account on the SFAT, we refer to e. g. [14].

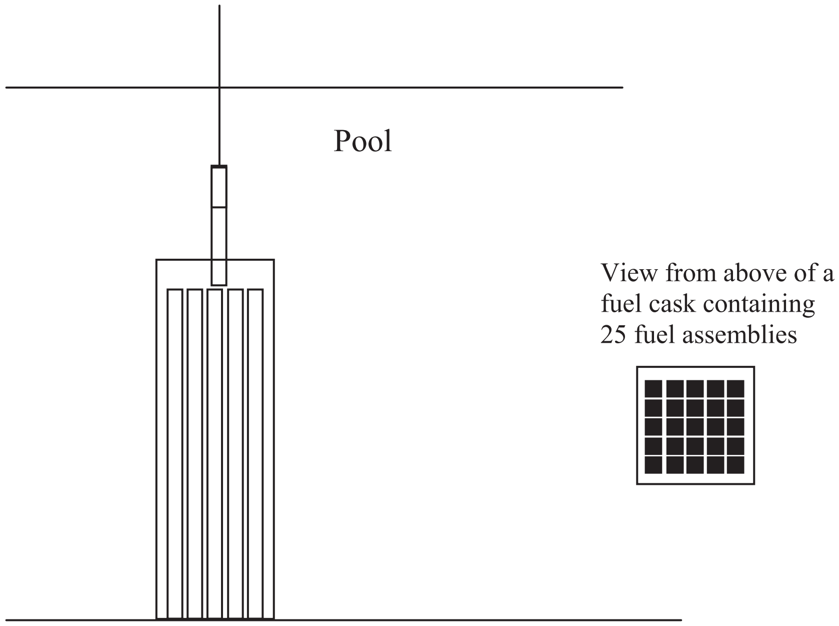


Fig 5.2. A schematic view of a fuel cask containing 25 fuel assemblies standing on the bottom of a fuel handling pool and an SFAT detector hanging just above the fuel.

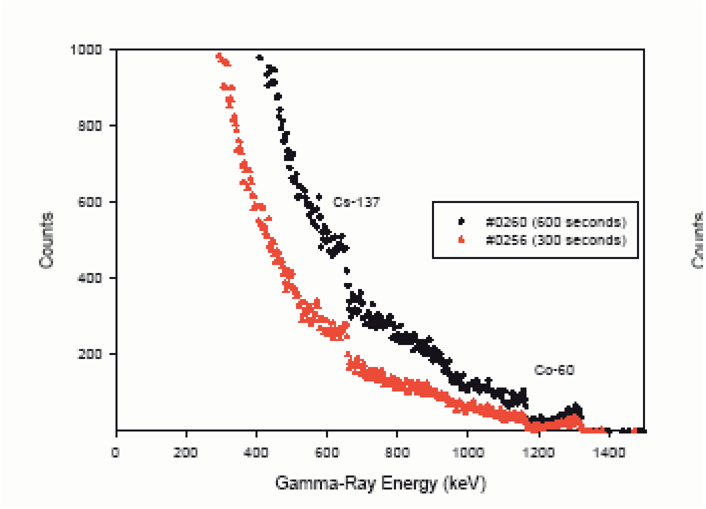


Figure 5.3. Typical spectra from an SFAT detector (from ref. [14]).

5.2 Miscellaneous qualitative techniques

5.2.1 Cherenkov viewing devices

In this group we find two devices that indirectly utilizes nuclear interactions through the secondary phenomenon of Cherenkov light. The basic application is gross defect verification, but recently the ability to, at least to some extent, verify on the level of partial defect, i.e.

verifying that 50 % or more of the fuel rods are missing or replaced in a fuel assembly, has been demonstrated.

ICVD and DCVD

Gamma radiation from spent fuel interacts with the water surrounding a fuel assembly mainly through the photoelectric effect, which means that fast electrons are produced. These electrons may propagate through water with a speed exceeding the speed of light in water, giving rise to the phenomenon of Cherenkov light. Also some beta-emitting isotopes give rise to Cherenkov radiation. The basic principle for Cherenkov emission is illustrated in Fig. 5.4.

The intensity distribution of Cherenkov light has its maximum in the invisible ultraviolet region, but a smaller fraction can be seen as a bluish dim light around fuel assemblies with short cooling times. Also for assemblies with long cooling times a small fraction of the Cherenkov light is still present. However, the intensity is very low and special devices have been developed in order to detect this light [17].

The basic feature of the Cherenkov viewing device (ICVD) is the image intensifier tube together with UV-filter (see Fig. 5.5). In such a way the handheld device may be operated in the ambient light of the facility.

The device is carefully aligned right above a fuel assembly and because the intensity of Cherenkov light is largest near the fuel rods, a cross sectional picture of the assembly can be viewed on the image intensifier screen. The signal is very typical for spent fuel and can therefore be used to verify whether there is a fuel rod or not in a certain position.

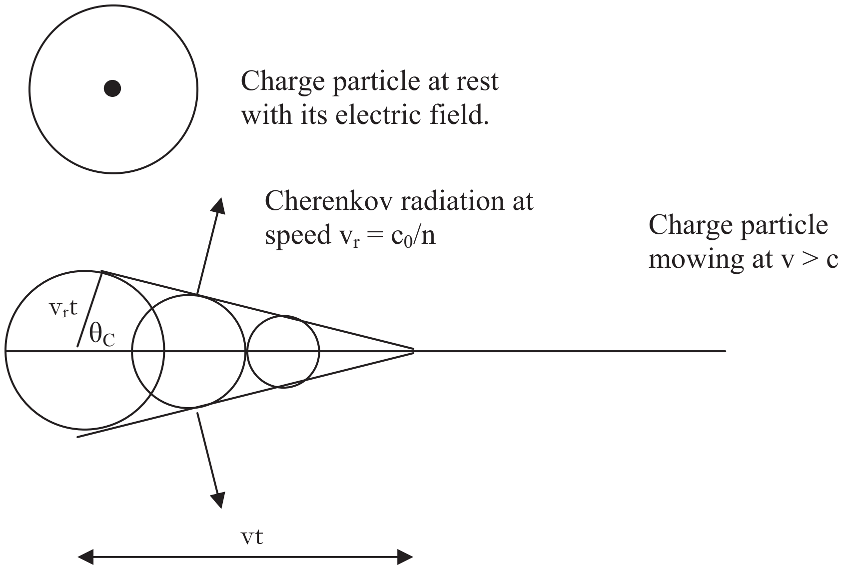


Figure 5.4. The Cherenkov radiation is emitted from the surface of a cone (Mach cone). The emitting angle is given by: $\cos(\theta_C) = v_r/v = c_0/nv$.

The more sophisticated digital Cherenkov viewing device (DCVD) [16] digitises the signal from the image intensifier making it possible to store the picture on a suitable medium. Also, the digitised signal may be analysed with advanced image processing techniques allowing, at least in certain cases, the inspector to decide whether an individual fuel rod is missing or not.

Figure 5.5. The ICVD. The UV-transparent objective is to the right and the eyepiece to the left. The instrument stands on the two handle bars. (Photo: IAEA).

Fig. 5.6 shows a ray-tracing simulation of an image produced by a DCVD. The figure shows an 8x8 BWR fuel from above and the fuel rods are seen against a bright background of Cherenkov light. If a rod is missing, a bright spot would be expected to appear in the corresponding position.

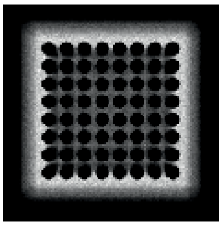


Figure 5.6. A simulation of a picture from a DCVD. The fuel rods in an 8x8 BWR-fuel are clearly seen as dark dots. Image courtesy of SKI and Lens-Tech AB, Sweden [17].

Chapter II.6 Techniques based on neutron measurements

In this section we will present an approved technique for NDA on spent fuel, based on detection of neutrons. The main purpose of this technique is to verify burnup and cooling time. A more detailed description can be found in [9] and [14].

6.1 The fork detector irradiated fuel measuring system (FDET)

In an attempt to offer a fast and reasonably accurate technique for verifying burnup, the fork detector irradiated fuel measuring system (FDET) was developed [9,18]. The technique utilises neutrons from spontaneous decay of primarily 244Cm. The schematic layout of the FDET system is shown in Fig. 6.1. The two prongs are filled with polyethylene and contain four fission chambers and two ion chambers arranged symmetrically. Two of the fission chambers are surrounded by cadmium wrapping in order to filter away the slow or thermal neutrons, whereas the other two are bare and consequently register the epithermal and thermal neutron flux. The main reason for this arrangement is that the epithermal flux is less sensitive to variations in the boron content of the pool water in case of measurements on PWR fuel. The ion chambers detect the flux of gamma radiation integrated over all energies, the so-called *gross gamma* signal. The signals from the detectors are fed to a charge sensitive pre-amplifier and a pulse shaper circuit shielded by a tungsten alloy.

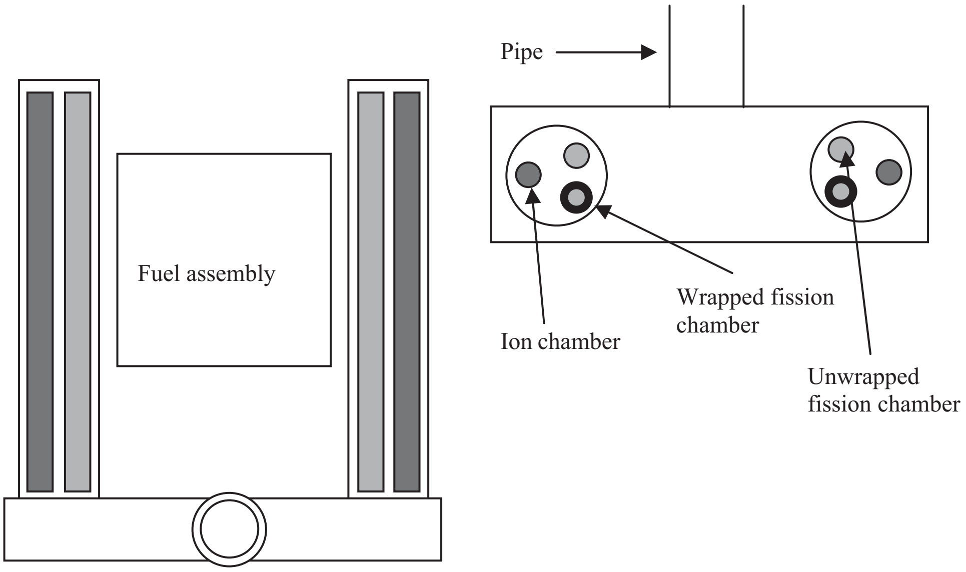


Figure 6.1. The FDET seen from above (left) and from the front (right).

In addition to the detector head, the FDET consists of a number of steel pipes, 2.45 m or 1.25 m in length. These sections are mounted together to form a support for the detector head (see fig. 6.2). In such a way the FDET becomes reasonably transportable from site to site.

From the pre-amplifier, cables run through the supporting pipe up to the floor where the main electronics are located. These electronics supply the fission- and ion chambers with bias voltages, display and print the neutron rates and the ion chamber currents. By using a fuel-handling machine the fuel assembly is positioned between the two prongs of the FDET and by elevating the assembly, the whole length of the assembly is scanned. A typical result of such a scan of a BWR-fuel assembly is shown in Fig. 6.3.

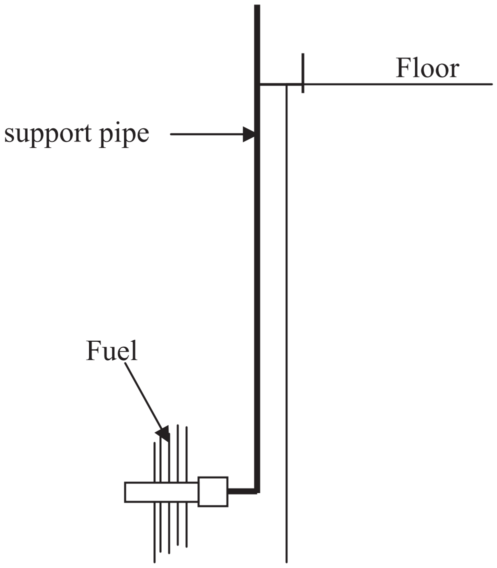


Figure 6.2. The experimental arrangement using a FDET. Not drawn to scale.

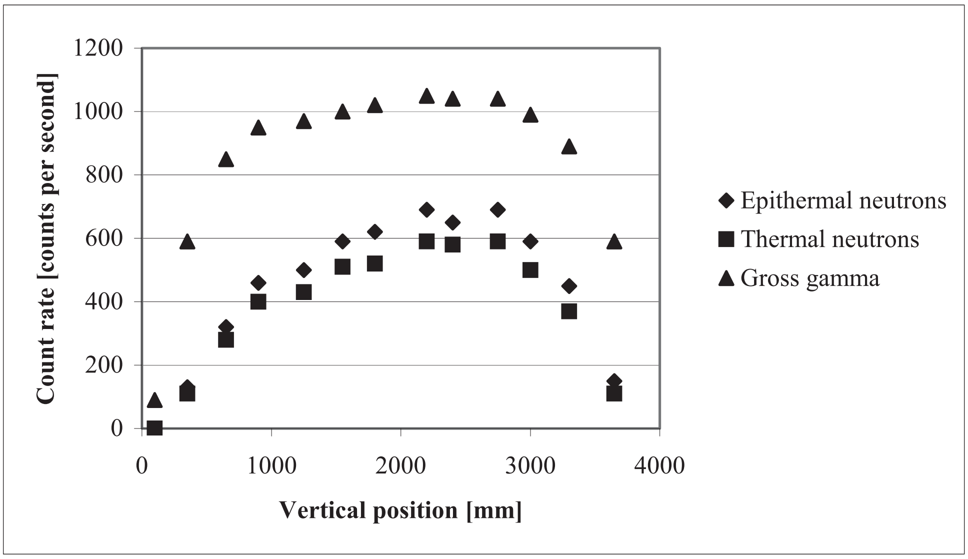


Figure 6.3. Result of a measurement on a BWR-fuel assembly at CLAB. The whole assembly is scanned from bottom (3650 mm) to the top (0 mm). Note the skewed distribution, which is typical for BWR fuels, resulting in higher intensities towards the bottom of the fuel assembly (from ref. [14]).

In a BWR reactor, the upper part of the assemblies is surrounded by moderator water that contains a larger fraction of steam than the bottom part. This means that the moderating ability of the water is lowered and, consequently, the burnup of the fuel is lower in the upper parts. This behaviour is clearly seen in Fig. 6.3 as the upper part of the assembly exhibits lower average intensity of both gamma and neutron radiation. It can be shown that neutron rates depend on burnup as

$$R = a\beta^{b} \qquad (6.1)$$

where *a* and *b* are determined by a fitting procedure. The parameter *b* is about 4.5 and thus governing the strong burnup dependence of the neutron rates. Using eq. (6.1) and various corrections to the measured data it is possible to verify the burnup of a fuel assembly within ±3 %. The cooling time may be estimated by using a combination of the neutron and gamma signals and the accuracy here is typically ±(200-300) days.

Chapter II.7 Surveillance in nuclear safeguards

In nuclear safeguards the notion *containment* alludes to the physical shielding against unauthorized trespassing provided to transport containers, storage pools, certain areas or equipment. One example of containment is the enforced concrete walls surrounding a nuclear power reactor. The means to control the integrity of the physical shielding is *surveillance*, which is the main subject of this chapter, although the generally accepted abbreviation C/S will be used repeatedly.

C/S is an important part of nuclear safeguards, the purpose of which is to be a complement to book-keeping and verifying measurements. An important requirement is that C/S can be conducted at a minimal cost and with minimal interference into the regular activities of a nuclear power unit. An operational requirement is therefore that the surveillance can take place involving a minimum number of personnel or, indeed, unattended. This can either be organized in such a way that the C/S system in real time generates an alarm signal or that the system information is read out and evaluated in connection with inspections.

An important concept within nuclear safeguards is *continuity of knowledge*, meaning that it should be ascertained that no forbidden activity has taken place in between two inspections. C/S is perhaps the most important means to verify that continuity of knowledge is maintained. The common denominator in the various ways that C/S can be conducted to guarantee continuity of knowledge is the search for various types of changes of scenery. If, for example, a normally locked storage container has been broken into, the C/S system must be able to give information on this incident. Another example is if spent fuel has been handled on forbidden transport routes, inside as well as outside relevant plants.

These two examples represent cases where basically two different surveillance strategies must be adopted. For the following discussion the understanding will be facilitated using the distinction between *static* and *dynamical scenarios* introduced in the present textbook.

7.1 Static scenarios

In many of the steps of the fuel cycle, situations appear where nuclear material must be stored separately for a shorter or longer period. Because the material is diverted physically from the handling process, it is important to reassure that the material is stored in such a way that unauthorized access is avoided. In cases where material must be transported or handled in another way, nuclear safeguards should be able to suggest routines for how such handling should be registered and accounted for and to detect afterwards that the handling has taken place.

In the typical case of storage, seals are used to ensure the integrity of a physical shielding, e. g., the casing of a storage container. The purpose of breaking into such a container could be either to introduce material into it or to remove material from it. The seals are therefore also used for identification of the container. In addition to site-specific objects, like e. g. containers and gates, also permanently installed equipment used in nuclear safeguards is sealed, e. g., surveillance cameras. Seals are often used during longer time periods, from months to several years, and are checked in connection with inspections.
The seals can be either of disposable type to be exchanged at every inspection or a so-called *in situ* type. Two commonly used disposable seals are the metallic seal (CAPS) and the improved adhesive seal (VOID).

CAPS is often used to seal containers and permanently installed equipment for nuclear safeguards. These seals are made of metal and designed such that the inspectors can apply them quickly to minimize the exposure to ionizing radiation. The seal consists of a metal wire that is applied to the object being sealed and the wire ends are locked with the knob of the seal. The CAPS seal is used in such a way that before mounting, the microscopic scratches always existing on the metal surface of the seal are photographed. At verification and identification of the CAPS, the seal is removed and sent to the IAEA headquarter in Vienna, where the seal is identified by picture (pattern) recognition.

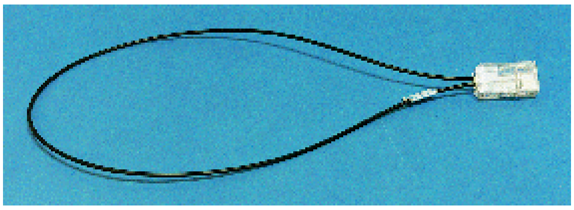


Fig. 7.1. A COBRA seal.

VOID is a type of seal used when sealing for time periods shorter than 24 hours. These seals are made from a material that cannot be demounted without cracking the material along special slits making reuse impossible.

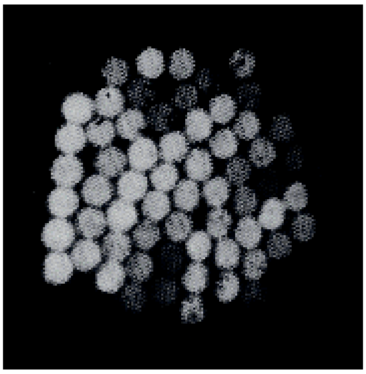


Fig. 7.2 The generated fibre pattern in a COBRA seal.

The fiber optic general purpose seal (FBOS) belongs to the group of *in situ* seals. A typical representative of these seals is the so-called COBRA seal (Fig. 7.1). In this seal the metal wire has been replaced by a bundle of optical fibers. When sealing the ends of the fiber, they will form a unique pattern which can be read out by illuminating one end of the fiber and recording the generated pattern in the other end by a digital camera system, see Fig. 7.2.

In this way a reference picture is obtained, that is used later when verifying on site. Using COBRA III the verification can be performed automatically. Fig. 7.3 shows an Automatic COBRA Image Verifier (ACIV) together with a COBRA seal.

Fig. 7.3. The so-called COBRA III imaging system. The seal is at the bottom of the picture and above that is the read-out equipment. The picture is copied from ref. [21].

In ultrasonic seal (ULCS) and ultrasonic sealing bolt (USSB) particles and wires creating a unique random pattern are introduced in the fabrication process. In the mounting of these seals ultrasonic pulses directed towards the seal are reflected and recorded. These signals give rise to a “reference image” directly corresponding to the seal pattern. In the same way as above the reference image is compared with the picture being recorded in the verification process.

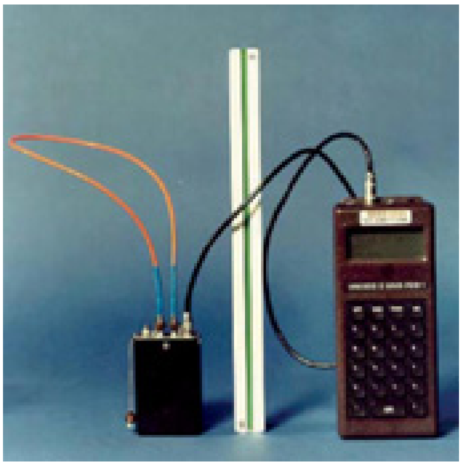


Fig. 7.4. A VACOSS-S seal with read-out unit. The picture is copied from ref. [22].

Electronic seals operate in such a way that a light pulse is emitted into an optical fiber loop with a typical period of 250 ms (applies to the variable coding seal system VACOSS-S), see

Fig. 7.4. If the optical fiber loop is broken, the time and date of the breakage is recorded as well as the time elapsed since the loop was broken. This information is logged into the seal and can be collected for example at inspections. A typical application of the seal is thus, when periodic access to a sealed area is required. The seals can be connected in series in cases where the objects being sealed are located close to each other.

The seals, which are battery powered with a typical operating period of 2 years, consist of electronics cast in epoxy with ceramic particles to render trespassing more difficult. In addition the casing is equipped with contacts recording all attempts to break into the electronics of the seal.

Gate monitors in their simplest form are switches breaking an electric circuit if a gate or a door, closed under normal conditions, is opened. Then an alarm is activated. The gate monitors cannot replace the seals, when for example a container is stored inside the door, because the alarm can be switched off and a door opened for completely legitimate reasons. On the other hand the gateway monitors can protect against non-authorized trespassing.

7.2. Dynamical scenarios

In these scenarios a sequence of events in space and time is searched for. A simple example is the detection of a truck inside a controlled area. By studying the movement pattern conclusions can be drawn whether or not the activities of the truck are legitimate. Another, more complex example is when information from different parts of the society is collected with the purpose of concluding if a state is making preparations for diversion of nuclear material. Such information could be irregular movements in harbours or construction or reinforcement of new or existing infrastructure. Important information could also be if the state is procuring industrial capacity in areas where the state has traditionally not taken a very strong interest.

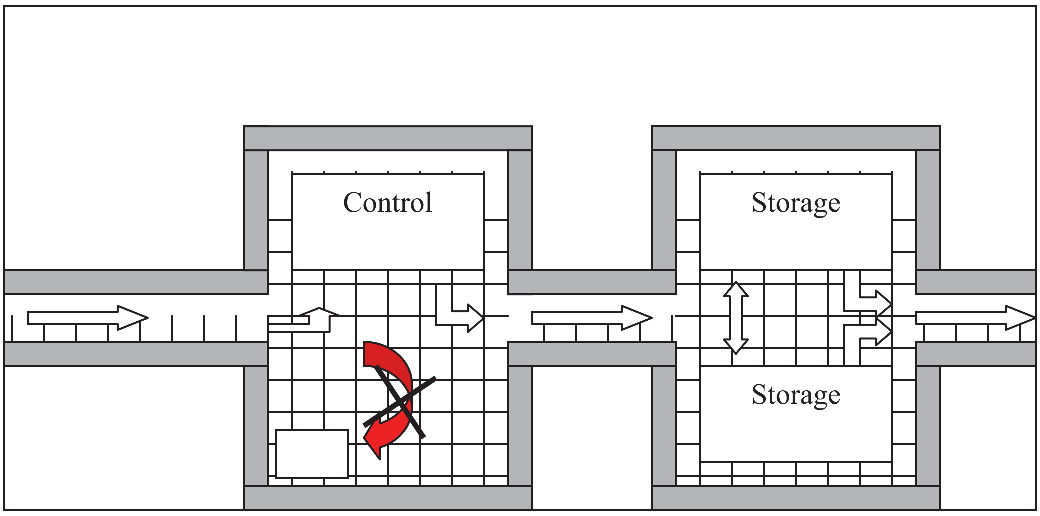


Fig. 7.5. Schematic top view of a facility, where spent nuclear fuel is handled. White arrows indicate routes, along which a fuel-handling machine is allowed to move. These routes are defined by means of a coordinate system indicated in the figure. In the logging of the movements of the fuel-handling machine, a deviating route, e.g., the one indicated by a dark arrow, should be detected, both horizontally and vertically.

The amount of information to be handled in the dynamical scenarios is in general considerably larger than in the static ones. Video cameras, for example, give data in the form of two-dimensional matrices, the elements of which are functions of several parameters. When such "multi-dimensional" information is combined with other information, such as log-book information on how fuel-handling machines have moved (see Fig. 7.5), a situation suddenly appears where the human capacity to compile and interpret the information is insufficient.

Table 7.1. Some surveillance systems with applications. From [17].

Abbreviation	Name	Description and application
SIDS	Sample identification system	Surveillance system integrated with a detector system for simultaneous neutrons. The equipment is site-specific. The system is constructed for identification of Pu in MOX production.
UWTV	Underwater TV	Commercial TV system for underwater use. Used in inspection for verification of ID numbers of fuel assemblies in storage pools.
ALIP	All in one surveillance, portable	Battery-powered camera for easily accessible rooms or for in-field surveillance.
ALIS	All in one surveillance	Camera connected to the main grid for installation in easily accessible rooms.
DSOS	Digital single camera, optical surveillance	Camera for installation in difficult-to-access rooms.
FTPV	Fuel transfer video	TV system to be used at handling pools. The system is site-specific.
VSEU	Video system multiplexer	Camera-based surveillance system developed by Euratom.
VSPC	Video system	TV system for up to 4 cameras with split screen display.
DMOS	Digital multi-camera, optical surveillance	Surveillance system for up to 16 cameras with possibility for remote control.
SDIS	Server, digital image surveillance	Surveillance system for up to 6 cameras with possibility for remote control.
GARS	General advanced review station	For read-out and analysis of data from ALIS, ALIP, DMOS, DSOS, and SDIS.

The development of powerful computers in combination with advanced algorithms has, however, pointed to the possibility to construct extremely competent surveillance systems [19].

Up to now such systems have not had any significant breakthrough, because the technology is relatively new and a thorough examination of the various methods with the purpose of finding out strengths and weaknesses has not yet been undertaken. In the following the discussion will concentrate on the technology and methodology of today, and only a brief discussion of possible future initiatives will be given at the end of the chapter.

Cameras are basic units in usual techniques and Table 7.1 gives an account of various systems and cases where cameras are being used. At present extensive renewal work is under way, in which old analog systems are phased out and replaced by digital systems, so-called digital image surveillance systems (DIS), i. e. the ones being accounted for in Table 7.1.

In Figs. 7.6 – 7.10 some of the systems accounted for in Table 7.1 (the pictures with due permission of the IAEA) are presented.

SDIS is a server-based system first developed as a remote monitoring system. Up to 6 surveillance cameras of the type DCM14 can be connected to the system. The server analyzes and saves pictures and logging data, and this information can either be transmitted directly to the IAEA via telephone lines or satellite link or be stored on a mobile disk for analysis on site. In both cases the final analysis is performed in GARS. SDIS is equipped with reserve power, which can power the system for 48 hours in the event of grid power loss.

Fig. 7.6. The SDIS system with 3 DCM14 cameras connected (left) and the server equipment (right).

UWTV is a portable system primarily produced for under-water inspections in connection with verification of nuclear fuel assemblies. The camera head can be rotated 90° by a motor and is constructed in such a way that information can be read both at small distances, e. g. ID numbers, and at long distances. Connected to the camera is a system of spotlights allowing operation also in poor visibility conditions. The presence of strongly radioactive fuel elements in the immediate neighborhood necessitates the use of radiation-resistant technologies. In addition the system should cope with a water pressure corresponding to a depth of 15 m. The system is equipped with a monochromatic viewing screen and data can be stored on an external video tape.

Fig 7.7. The ALIP system with viewing screen (left) and battery package (on top).

ALIP is a battery-powered system based on a DCM14 camera with an integrated video terminal. In addition to the battery power the system can be operated connected to the main grid. Using battery power surveillance can take place for up to 100 days. The system can typically store 40,000 – 50,000 pictures and logging data on a 600 Mb PCMCIA flash card.

ALIS is a complete camera surveillance system designed for connection to the main grid. Included in the unit there is in addition to the camera unit a user interface with a terminal and display. The system can typically store 40,000 – 50,000 pictures and logging data on a 600 Mb PCMCIA flash card.

Fig. 7.8. The stationary ALIS system.

DSOS is used in applications where high radiation dose levels are involved. The camera, which is based on DCM14, is connected to a read-out unit via a particularly reinforced cable made of composite material. The analysis is made with the same tools as for ALIS.

The software including GARS can handle data from ALIP, ALIS, DSOS, DMOS, and SDIS. The software is PC based and has been designed with the primary goal of being user friendly. The user interface is similar to commercial media players and is used for scanning pictures and other data. Special routines for determination of authenticity and verification of data are implemented for detection of scenario changes as well as for digital image handling.

Fig. 7.9. A DSOS system with the casings of the camera (right) and the read-out unit (left) removed.

Fig. 7.10. The read-out and analysis station GARS.

To the group of dynamical scenarios could be added satellite surveillance, seismic surveillance, and environmental surveillance.

7.2.1 Satellite surveillance

The goal of satellite surveillance is to detect anomalies that can be interpreted as if someone without permission tries to get access to a nuclear facility. Such anomalies could be unexpectedly dense traffic, heavy machinery, new facilities and roads, and large amounts of rocks from excavations. To determine if an unannounced activity has taken place, a so-called "baseline" is required, that the satellite information can be compared to. A baseline is especially compiled information of the region of interest consisting of high-resolution (a few decimeters) satellite pictures, data on buildings and roads, and a digital altitude map. This information is used to construct a three-dimensional model of the region of interest.

Satellite surveillance in the optical wavelength region is not sufficient in this application, because relevant information is lost at night or in cloudy weather. Also infrared surveillance has its limitations in cloudy weather, and therefore synthetic aperture radar (SAR) is used to an increasingly larger extent. The resolution in such pictures is today a few meters (see Fig, 7. 11) and optical surveillance is still necessary as a complement in nice weather.

Figure 7.11. SAR-picture from the Canadian satellite RADARSAT-1. Dark areas are ice and light areas are land. The bright spots within the ring are a group of students from an ice exploration ship (from [20].

7.2.2 Seismic monitoring

The purpose of seismic monitoring is to detect explosions, drilling, or other mechanical machining of the bedrock. Also in this case it is necessary to establish a baseline, before construction work is initiated to take into account traffic, wind blowing towards buildings and other disturbances. The anomalies being looked for are, e. g., fast and unannounced changes in the daily seismic pattern included in the baseline.

7.2.3 Environmental surveillance

Environmental surveillance can partly be used by health-care authorities to supervise the general background radiation level and partly by nuclear safeguards to detect increased radioactivity levels, that could indicate unauthorized activities are being conducted in a facility, Also here it is anticipated that a baseline is available.

Chapter II.8 The future

The overwhelming majority of nuclear power reactors of today and the corresponding support technology belong to what is referred to as “second- and third-generation reactors”. In principle they are the direct successors of the very first reactors, as they use thermal neutrons to maintain the fission process. The decisive differences in comparison with the first-generation reactors are almost completely related to the control and safety systems. The improvements achieved in these systems have made the second- and third-generation reactors (in particular the light water reactors) very safe and efficient facilities. Countries to a large extent employing nuclear power for their energy production have also been able to demonstrate large positive environmental effects. Sweden and France have for example a net inflow of air pollutants due to a. o. fossil energy production outside the borders of the two countries.

The reactor incident at Three Mile Island in the US in 1979, and the accident in Tjernobyl in 1986 have, however, given nuclear power a bad reputation and at present several countries have taken political decisions aiming at long-term phase out of nuclear power. Such decisions can, however, be at variance with ambitions in the global environmental efforts, that is being pointed out more and more often, and attempts to find politically acceptable alternatives to the reactors of today are therefore made. In particular it has been emphasized as an advantage that spent fuel could be used for energy production with the purpose of increasing the capacity factor (burnup fraction). The reactors of today typically use only a few percent of the energy content in the fuel that can possibly be extracted, which in turn implies that the perseverance of the energy production searched for, is limited to of the order of a few hundred years, even if a massive extension of the enrichment capacity is accomplished [21]. Technologies implying a higher degree of fuel utilization and an opportunity to use fertile nuclei like e. g. ^{238}U and thorium is therefore welcome, because these elements are highly abundant in the earth crust. With such technologies the perseverance of the energy production would increase by a factor of a hundred or more. With the aim of increasing the political acceptance, ideas concerning technologies capable of reducing the effective half-life of the nuclear waste have been suggested, which in turn reduces the requirement for storage times from of the order of

100,000 years to a few hundred years. In this context it should be pointed out that the Swedish KBS-3 method for long-term storage of spent nuclear fuel [22] is considered to fully cope with the stated safety requirements.

Today studies are performed aiming at demonstrating the technical feasibility of using other fuels than ^{235}U. These studies can be divided into two trends: accelerator-driven systems (ADS) and fourth generation reactors (GenIV). In this summary there is no space to dive deeper into these technologies and therefore the reader is referred to the accounts given in for example [21] and [23]. On the other hand a very brief summary will be given of possible generic implications on nuclear safeguards that these technologies might have.

One of the basic elements of today's nuclear safeguards is the integrity of the fuel, i. e. a fuel assembly should not without acceptable reasons be subject to demounting or manipulation in any other way. As has been described previously the tomographic techniques aim at supporting the inspection authorities in discovering such manipulations. In ADS and some of the concepts being studied in GenIV it is required that the fissile material is dissolved in a suitable medium, i. e., in short, in cases where the aim is to use the spent fuel for energy production the integrity of the fuel is completely lost. In addition, other processing steps will involve fissile material in liquid form increasing the number of possible diversion scenarios considerably.

A plausible solution to these two problems could be that a small number of facilities around the world are authorized to take care of the processing of spent fuel. In this way the supervision that the operations are conducted in an adequate manner becomes quantitatively manageable. On the other hand a security problem arises when the processed fuel is transported to the production facilities, because this transfer offers diversion opportunities. In addition it is not very likely that states around the world will rely on such a limited production capacity not being under the control of the states themselves. The solution is, however, along the lines discussed by the IAEA Director General in his appearance at Uppsala University on December 13, 2005, that the production capacity of nuclear fuel should be concentrated to a few facilities under international supervision, from which the nuclear power plants all over the world purchase their fuel.

An alternative on the opposite end of the scale is a completely distributed activity, where the capacity to produce new nuclear fuel from spent fuel is localized to the individual countries. A formal advantage is that the spent fuel is processed in the country where it has been produced, which is a principle being advocated by many countries. In this scenario DIV stands out as one of the most important activities concerning nuclear safeguards. Most likely an extended and generally speaking enhanced verification of the design of the facilities will also be required to achieve adequate knowledge that no diversion opportunities exist within the facilities.

From a measurement point of view an extended use of technologies today being used in destructive testing can be anticipated. As the fuel in this sense already is "destroyed", different nuclear chemistry methods can be applied directly on the process material, implying that a good knowledge on the properties of the material can be achieved. Also NDA techniques are of interest, because some GenIV reactors require fuel with some type of structural design and NDA offers the possibility to check the final fuel design. In several of the concepts being studied in connection with GenIV, e. g. the pebblebed reactor, the dimensions of the fuel are so small that different types of methods based on gamma radiation can be used to their full potential. In such cases also alpha spectroscopy might be of interest to study the fuel content of different plutonium isotopes.

In conclusion it can be stated that nuclear safeguards face new challenges concerning future reactor concepts. In particular, three regions can be identified, where special attentiveness is required:

- Formalities: Part of the concepts being used in nuclear safeguards might require redefinition and be given extended meaning, which in turn might imply new types of agreements and new surveillance mechanisms.
- Practicalities: Could and in that case how should fuel production and fuel transports be organized globally?
- Measurement techniques and surveillance: What existing techniques can still be used and what new needs require development work and advancement of new technologies?

Chapter II.9 Concluding remarks

The previous chapters dealt with various techniques for non-destructive assay of spent nuclear fuel assemblies. It should be remarked that there are other objects of interest for verifying measurements as well. Such objects are e.g. fresh fuel assemblies, uranium pellets at assembling facilities and various scraps emanating from fuel production and the production of energy at the NPPs, just to mention a few. For some of these objects NDA may be feasible e.g. measurements in connection to pellet production for verifying the enrichment. In other cases NDA is simply not applicable because of too low gamma-ray energies involved. Therefore NDA is supplemented with various destructive techniques summarized as *destructive assay* or DA. Such techniques generally involve activities where the material to be investigated is dissolved in suitable solutions and eventually is analyzed using various chemical methods. These techniques offer outstanding quality of the obtained information but an obvious drawback with DA is that often highly radioactive material inevitably must be transported to special "hotlabs" for treatment. As DA is not utilized on a routine basis during inspections, it has been regarded as being outside the scope of this compendium. However, for further reading on this subject, ref. [24] is recommended.

In chapter 7 we briefly mentioned other techniques that are used or may be used for verifying activities. Such techniques comprise satellite surveillance and environmental sampling. Although of importance and certainly of increasing importance in the future, these techniques have not been discussed in detail in this text. An account of these techniques can be found in [25].

Although today's verifying measures are adequate for many instances, one can draw the conclusion that more research is needed in order to provide the safeguarding authorities with more efficient methods in order to prepare for a conceivable expansion of nuclear energy worldwide. For the future, two tracks of developments in NDA and C/S should thus be addressed:

- The methodology on how to use various input data such as neutron and gamma-ray intensities has been developed and investigated in detail [2,13,14] and further efforts will probably be directed to the development of new detection technologies. It is antici-pated, for example, that new semiconductor materials will enable high-resolution gamma-ray spectroscopy to be performed at room temperature. Such materials will open up new applications especially regarding smaller, easily transportable, detector system with unprecedented performance. In addition, the concept of coded aperture imaging [26] may turn out to be feasible in order to construct smaller instruments comprising not only energy resolution but also spatial resolution.

- Regarding C/S one can anticipate a development towards a stronger emphasise on various methods of information treatment. The powerful computer technology of today allows for complex algorithms that could be used for pattern recognition. Such algorithms would offer the detection of anomalies in a vast space of information emanating from many different sources. In a first stage this technique could be docked to surveillance systems using existing information sources such as, for example, surveillance cameras, gate monitors, IR-sensors and satellites.

In a text like this it may be feasible to round off with a brief contemplation on the fact that the world, for good and worse, tends to be more and more diverse. This fact tends to increase the risk of actions from non-governmental bodies, such as those with terror on their agenda. This is something we, regrettably, have seen vivid proofs on during the last couples of years.

The problems facing mankind have many facets, for example, one can conclude that an imperative requirement for a peaceful development in the world is the provision of cheap and environmentally sound energy production. In many respects nuclear power fulfils that requirement but the production of nuclear fuel inherently contains stages that can be misused. On the other hand, it is fortunate that the nuclear power technology is sufficiently complicated in order to prohibit non-governmental groups to be in possession of the expensive technology and competence needed to make nuclear weapons. In addition, the various measures of nuclear safeguards have hitherto had a deterrent effect on groups and even States to secretly acquiring nuclear weapons.

Regarding the misuse of certain stages in nuclear power production one should realize that virtually any industrial process can be used in a non-intended way. For example, the medical industry has for sure the capacity and competence to produce large amount of material for use in biological weapons. Also the chemical industry could divert material in its processes that could be used in chemical warfare. For non-governmental groups it is probably more attracttive to infiltrate such production units in order to get into possession of material that could create large-scale damage. In spite of this real threat, it can be noted, that the global medical and chemical industrial complex are not internationally safeguarded today. In the above list of future research activities, one would thus add efforts that aim to expand the non-proliferation regime to include biological and chemical weapons of mass destruction as well.

At the end one has to admit that the ingenuity of man always will offer new challenges to safeguards, let it be nuclear, biological or chemical. Most probably it will not be possible to find the ultimate solution on how to avoid proliferation of weapons of mass destruction in the world. However, taking into account another human property, namely, to never give up, offers us at least the hope for the possibility to find sustainable strategies on how all states in the world could be able to cooperate in order to minimise the risk of proliferation and thus forming a World Community in its true sense.

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Appendix 1

Example of a fuel declaration for a fuel assembly (A05) to be long-term stored at CLAB.

ID nr	**A05**
Fuel type	W15x15
Number of fuel rods	204
Rod pitch (mm)	14.3
Rod diameter (mm)	10.72
Cladding thickness (mm)	0.618
Pellet diameter (mm)	9.29
Cladding material	Zr4
Active length (mm)	3658
Density UO2 (g/cc)	10.41
Density incl. bevellings, pellet cavities, dishing, etc.	10.2465
Number of guide tubes	20
Guide-tube material	Zr4
Outer diameter, guide tube (mm)	13.87
Cladding thickness, guide tube (mm)	0.43
Number of instrument tubes	1
Instrument-tube material	Zr4
Outer diameter, instrument tube (mm)	13.87
Cladding thickness, instrument tube (mm)	0.43
Has the assembly initially included burnable poison rods?	No
Number of spacers	7
Spacer material	Inconel
Weight of one spacer (g)	788

ID nr	**A05**
Initial data	
Initial weight Utot (g)	456610
Initial weight U238 (g)	447505
Initial weight U235 (g)	8908
Initial weight U236 (g)	69
Initial weight U234 (g)	128
Average enrichment % U238	98.006
Average enrichment % U235	1.951
Average enrichment % U236	0.015
Average enrichment % U234	0.028
Density (g/cc)	10.2465
Rod pitch (cm)	1.430
Pellet diameter (cm)	0.929
Rod outer diameter (cm)	1.072
Rod inner diameter (cm)	0.9484
Mounting protocol is attached	
Data after revision 1	
Revision date	
Number of fuel rods	
Number of water rods	
Number of water holes	
Number of homogeneous rods	
Weight Utot after revision (g)	
Weight U235 after revision (g)	
Mounting protocol is attached	
Data after revision 2	
Revision date	
Number of fuel rods	
Number of water rods	
Number of water holes	
Number of homogeneous rods	
Weight Utot after revision (g)	
Weight U235 after revision (g)	
Mounting protocol is attached	

Cycle history EOC MWd/tU BU-increase (MWD/tU)	

1	18507
2	6175
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
ID nr	**A05**
	0.457
	24682
Nodal burnup distribution, final burnup (MWd/kgU)	
1	11.626
2	17.977
3	22.238
4	24.731
5	26.112
6	26.839
7	27.202
8	27.372
9	27.448
10	27.482
11	27.503
12	27.526
13	27.556
14	27.595
15	27.643
16	27.692
17	27.724
18	27.699
19	27.537
20	27.076
21	26.019
22	23.844
23	19.723
24	13.172
	24.889

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