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**FUNDAMENTALS OF NUCLEAR
MATERIALS PHYSICAL PROTECTION,
CONTROL AND ACCOUNTABILITY**

Edited by E.F. Kryuchkov

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Accounting, control and physical protection of nuclear material:
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This textbook makes a systematic presentation of essential information on nuclear material accounting, control and physical protection (NM AC&PP). Its first part deals with the objectives of and conditions for NM AC&PP development in the context of non-proliferation of nuclear weapons and contains an overview of the relevant legal framework and key regulatory documents. In its second part, the book describes the basic features of today’s NM accounting and control (NM A&C) systems and their components. Considerable attention is given to issues associated with computerization of A&C operations. The third part is devoted to physical protection of nuclear materials and facilities.

The book is intended for students reading Safety and Non-Proliferation of Nuclear Materials (as part of Nuclear Physics and Technology) and specializing for their master’s degree in Physical Protection, Accounting and Control of Nuclear Materials (as part of Engineering Physics). It may be useful for senior students and postgraduates in their studies of nuclear material accounting and control systems.

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FOREWORD

This book provides systematic explanation of the principles of Accounting, Control and Physical Protection of Nuclear Materials (NM AC&PP) and may serve as a teaching aid and a methodological guide to support instruction in discipline 140309 “Security and Non-Proliferation of Nuclear Materials”. The book consists of three parts. Part 1 deals with the objectives and conditions of developing NM AC&PP systems in the context of non-proliferation. Analysis of the main processes, of nuclear material forms and flows in a nuclear fuel cycle, is basic to studying the possible methods and procedures of NM AC&PP. Part 1 will also give an overview of the associated legal framework and key regulatory documents. It addresses the international safeguards and their interfaces with national non-proliferation programs. Basic knowledge is provided concerning the program for developing the national non-proliferation safeguards system in Russia and its foundation, to wit – accounting, control and physical protection of nuclear materials. Special consideration is given to the approach of safeguards categorization and to the concept of NM protection in depth. The objectives and forms of integrated accounting, control and physical protection are discussed.

Part 2 of this teaching aid deals with the principles designed into modern systems of NP accounting and control (A&CS). It addresses two levels of this system: federal and operational. This book highlights the notions basic to the modern material balance measurement system and identifies the A&CS components at the facility level. The statistical nature of nuclear material data is demonstrated. As the discussion proceeds, the key terms are introduced, defined and explained using examples for illustration, and the A&CS components are described. Considerable attention is given to the issues related to automation of accounting and control operations.

Part 3 gives a brief account of physical protection as applied to nuclear materials and installations.

This teaching aid will be helpful not only to those who are studying the subjects of security and non-proliferation of nuclear materials, but also to all higher school students receiving instruction in disciplines related to nuclear engineering, as well as to all those who seek basic knowledge of safe management of nuclear materials.

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Part I

NUCLEAR NON-PROLIFERATION. NUCLEAR MATERIAL ACCOUNTING, CONTROL AND PHYSICAL PROTECTION (NM AC&PP) SYSTEMS, THEIR PURPOSES AND CONDITIONS FOR DEVELOPMENT

CHAPTER 1

THE PROBLEM OF NON-PROLIFERATION

1.1. Non-proliferation concept. International non-proliferation regime

The idea of safe nuclear material management underlies all nuclear energy uses, including nuclear power. This idea is basic to international agreements and national laws, such as the Law on the Use of Atomic Energy adopted in our country in 1995. In the eyes of the general public, nuclear materials are safe if they are used under control and exclusively for peaceful purposes.

It is essential to have the term ‘nuclear materials’ clearly defined for subsequent applications. To this end, we shall rely on the terminology found in the nuclear energy law, where three main types of materials are identified:

- nuclear material (NM), which contains fissionable material or is capable of breeding it (e.g., uranium-238);
- radioactive material (RM), which emits ionizing radiation (excepting NM);
- radioactive waste (RW), i.e. NM + RM, which is not intended for subsequent use (e.g., material resulting from reprocessing of irradiated fuel).

It is the first type of materials that is of interest for the purpose of this book. Russia has a clear-cut list of nuclear materials, which will be addressed at length in chapters to follow.

There is a certain contradiction associated with nuclear materials: on the one hand, nuclear power is gaining ground worldwide and, on the other hand, spread of nuclear materials has to be kept under control considering the potential hazard of their use for production of nuclear weapons (NW). This contradictory feature of NM lies at the root of the so-called non-proliferation problem [1–3]. The threat of NW proliferation is countered by international and national safeguards and export control systems.

The USA and the USSR were the first countries to develop their nuclear potential first for military purposes and then for energy generation. The ranks of the nuclear-weapons states have been expanding since the early 1960s. In 1960, France carried out its first test, followed by China in 1964. Some industrial countries made progress with development of nuclear technologies to an extent where they could produce nuclear weapons. Construction of nuclear power facilities was in full swing.

Spread of nuclear technologies in the 1950s–1960s grew to cause concern of the international community about possible global sprawl of nuclear weapons. Many countries were ready to give up production of their own nuclear weapons, provided that other states – their neighbors first of all – would undertake similar commitments. Under these circumstances, Ireland put forward a Draft UN Resolution on non-proliferation of nuclear weapons. In 1961, the General Assembly of the UNO unanimously adopted the proposed resolution, urging all countries to stand up against proliferation of nuclear weapons in the world. The appearance of this resolution showed that the international community was aware of the need for a global agreement on non-proliferation of nuclear weapons. However, 9 years passed before the resolution was legally acted upon in the form of the Non-Proliferation Treaty (1970).

In the 1960s, the global community took a number of steps towards curbing the spread of nuclear weapons and strengthening the control over the use of nuclear materials. The year 1963 saw conclusion of the agreement on banning nuclear tests on the ground and in the atmosphere. This instrument crowned the struggle against arms race by proving its worth as an efficient tool of halting NW spread to non-nuclear-weapons states.

The nuclear threat that loomed over the world during the Caribbean Crisis (Cuban Missile Crisis) prompted states of the Central and South America to set up a nuclear-weapons-free zone. The Treaty for the Prohibition of Nuclear Weapons in Latin America and the Caribbean (Tlatelolco Treaty signed in 1967) bans not only purchase and development of nuclear weapons in this region but also NW disposition there by foreign countries.

The problem of nuclear weapons proliferation was first identified at the UNO level by Ireland in 1958. In the mid-1960s, the United States and the Soviet Union started active discussions on issues associated with the prospective non-proliferation agreement which could become a framework for an international regime. In the long run, those negotiations resulted in conclusion of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which became effective in 1970. The Treaty shifted the postulates of the free nuclear trade epoch towards specific and firm commitments in regard to NM uses.

The main achievement of the NPT lies in the fact that the overwhelming majority of countries officially relinquished development and purchase of nuclear weapons. The only states that refrained from

joining the treaty were India, Pakistan, Israel, and Cuba. That is why the NPT, as a universal agreement, serves as a legal framework for implementation of international non-proliferation safeguards. The Treaty became an instrument whereby non-proliferation rules and standards found their way into international as well as national activities.

Starting with its effective date (March 1970), the NPT has been playing a key role in curbing the spread of nuclear weapons. It is the main international instrument that is making the international non-proliferation regime increasingly weighty and far-reaching. Its main provisions will be briefly addressed below.

The first two articles of the Treaty are of key importance, defining the main obligations of nuclear-weapons and non-nuclear-weapons states. It is stipulated there that nuclear states shall not sell nuclear weapons and nuclear explosive devices and shall execute control over them, while non-nuclear states shall not purchase or produce them.

In their negotiations, the signatories to the NPT were guided by the principle that adherence to the Treaty on the territories of non-nuclear states shall be monitored. This stipulation is addressed in Article III.1 of the NPT. The most important provision of this article is that the international safeguards shall apply to all nuclear materials handled in all peaceful nuclear activities of a country within its territory, under its jurisdiction or under its control, whichever is applicable.

In its second part, Article III of the NPT calls upon non-nuclear countries to accept the international safeguards for imported nuclear materials and components, whereby the IAEA safeguards can be extended. In fact, Article III.2 provides an international legal framework for the whole system of control over nuclear export.

Article IV deals with peaceful uses of nuclear energy. The developing knowledge of nuclear energy can serve both peaceful and military purposes. Therefore, the parties to the Treaty undertake to ensure that peaceful nuclear energy uses meet the relevant non-proliferation requirements (of Articles I and II).

Article V is related to peaceful nuclear explosions. It was included in the Treaty on the initiative of Mexico. Essentially, this article says that nuclear states may provide services to non-nuclear states in conducting peaceful nuclear explosions (PNE) under international supervision. Nevertheless, none of the non-nuclear states has so far made an official request for PNE services. This may be largely explained by the fact that

such explosions pose a certain risk to the environment while not being particularly needed.

Delegations of Egypt and Mexico proposed adding to the Treaty a special article on nuclear disarmament. But the question of how clear and firm were the obligations undertaken by nuclear states in accordance with Article VI, is still a point of sharp disagreement and debate. Many non-nuclear countries believe that the Treaty provisions concerning negotiations for effective measures to stop the nuclear arms race have not been met in a satisfactory way.

Article VII deals with nuclear-weapons-free zones (NWFZ). It acknowledges the right of states to set up regional NWFZs. In such a zone, it is forbidden not only to produce, purchase or receive nuclear weapons by non-nuclear parties, but also to store NW owned by nuclear states.

In 1995, a conference was held to discuss NPT prolongation, as the term of the Treaty was expiring. The main result of the conference work was its legally binding resolution on indefinite extension of the NPT. On the other hand, the conference participants voiced their concern about some outstanding problems, with the Treaty universality issues being among them.

It is common knowledge that the non-proliferation regime relies on a number of international arrangements and organizations involving both nuclear and non-nuclear states. This regime is embodied in interrelated international agreements, with the central place among them belonging to the NPT. Other relevant instruments include:

- safeguards agreements; IAEA Statute; conventions under the aegis of the Agency, etc.;
- national legislation regulating nuclear activities in the member-countries;
- relevant Russian–American agreements in the field of nuclear arms reduction;
- agreements on establishment of nuclear-weapons-free zones: Tlatelolco, Rarotonga, Pelindaba and Bangkok treaties.

A whole number of international organizations are essential to the non-proliferation regime. So, an important role belongs to the International Atomic Energy Agency. Using a special system of measures – referred to as the IAEA Safeguards – the Agency monitors the situation trying to prevent NM diversion for purposes other than peaceful uses.

A sizeable contribution to solution of the proliferation problem is made by international export control (EC) regimes. The key instruments of export

control are restrictions on transfer of materials, equipment and technologies included in special check lists. Every country participating in the regime of export control is:

- to create a national legal framework consistent with the agreements concluded;
- to adhere to the EC principles in pursuing its national policy;
- to participate in forums of the member–countries.

In the nuclear sphere, there are two main regimes for controlling export of materials, equipment and technologies – one implemented by the Zangger Committee and the other, by the Nuclear Suppliers’ Group (NSG). On the whole, however, the international system for control over export of mass destruction weapons includes the Missile Technology Control Regime (MTCR), the Australian Group (for chemical and biological products and technologies), and the Wassenaar agreements (for conventional arms, dual-purpose products and technologies).

1.2. Some current problems of non-proliferation

Concern over possible non-peaceful uses of nuclear materials has long been expressed by the world public opinion. Unfortunately, the weapons proliferation problem defies complete and final solution. Some of its ramifications are presented in Fig. 1.1. As the international non-proliferation regime took shape, part of these issues was settled in an acceptable way, while others still need adequate joint actions before they may be resolved. We shall dwell on some of them:

1. Extremely slow reduction of available nuclear arms is a serious problem for the non-proliferation regime. Non-nuclear-weapons countries tend to regard this fact as reluctance of nuclear states to take real, significant steps in this direction. Besides, the problem is complicated by the fact that nuclear arms reduction is an expensive process. Whatever the explanation, unceasing criticism has been directed against nuclear states, voiced during discussions of the Treaty results, for their being too slow in fulfilling their commitments on nuclear arms reduction.

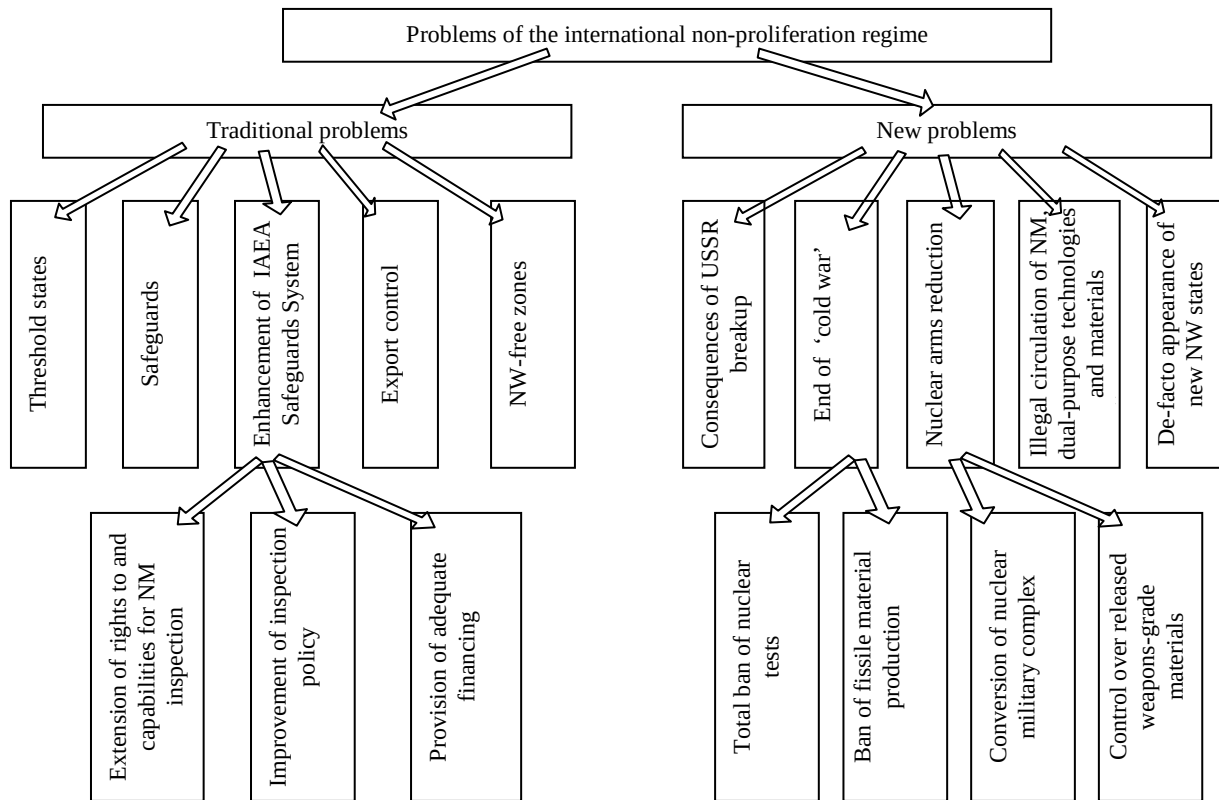


Fig. 1.1. Some problems of the international non-proliferation regime

2. There are many countries today that have not joined the ranks of nuclear-weapons states. No wonder it is often hard to arrive at generally accepted decisions on further steps towards non-proliferation. To be more specific, a number of countries have their military nuclear programs but are not parties to the non-proliferation regime. Some of them, such as Israel, India and Pakistan, already have nuclear weapons in their possession, but refrain from their active deployment. Other states are, in a sense, 'standing at the threshold', as they initiated nuclear weapons programs in one way or another, but for some reason have stopped short at their production. Such states are Libya, Iran, North Korea, Brazil, and Argentina. Among the 'threshold' states, a special place belongs to the South African Republic, which built its own store of nuclear weapons but later – in 1990 – destroyed it. In most cases, an urge to possess nuclear weapons is caused by regional political problems between states and by the temptation of gaining a dominating role in the region.

It should not be forgotten that some countries (Japan, Germany, Sweden, Australia, etc.) are fully equipped economically and technically to produce nuclear weapons but are willingly committed to keep their non-nuclear status.

3. Breakup of the USSR in 1991 made an enormous impact on the global non-proliferation regime. The Soviet Union had always paid serious attention to safe use of nuclear materials, with the system of appropriate measures fairly well provided. But the methods used to this end were those of a totalitarian state, which was the owner of nuclear materials; and inside the state, such materials had practically no commercial value. The state set up a regime of secrecy and discipline, with all instructions strictly followed and failure to do so seriously punished.

The situation changed drastically after the USSR collapsed and reforms were launched in the country.

Firstly, the Soviet nuclear economy ceased to be an integral entity. The smoothly running system of interfacing and cooperation between Minsredmash (the predecessor of Minatom) enterprises was largely destroyed.

Secondly, the commercial value of nuclear materials became obvious.

Thirdly, the national borders became more easily penetrable, providing greater possibilities for smuggling or uncontrolled import/export of nuclear materials. This gave rise to the problem of illicit NM circulation, casing the need for tighter control over export of nuclear materials and dual-purpose products, as well as improved customs procedures.

Finally, the very approach to NM security was lop-sided. Nuclear centers were protected mostly against external intrusion. Today, nuclear materials need protection from both outsiders and insiders.

All the above circumstances called for serious revision of the attitude towards NM management, ie. towards its accounting, control and physical protection. This book will deal primarily with various aspects of these three components in management of nuclear material.

Distribution of the nuclear industry potential in the USSR

In 1991, the collapse of the Soviet Union resulted in breakup of its formerly huge nuclear economy (Table 1.1).

Table 1.1

Nuclear industry potential at the time of the USSR collapse

	Russia	Ukraine	Belarus	Kazakhstan	Central Asia	Trans-Caucasian republics	Baltic republics
Nuclear weapons	+	+	+	+	–	–	–
Ship-borne nuclear power systems	100 %	–	–	–	–	–	–
Nuclear power units (GW)	28 (20.2)	14 (12.9)	–	1 (0.3)	–	2 (0.8)	2 (3.0)
Research reactors	25	2	1	2	1	1	1
Uranium mining and primary processing	40%	20%	–	10%	30%	–	–
UO ₂ production				>80%			
Uranium enrichment	100 %						
Irradiated fuel reprocessing	100 %						

The Soviet Union had signed the Non-Proliferation Treaty. When it ceased to exist, Ukraine, Belarus and Kazakhstan were left with nuclear weapons in their possession. The question was whether this amounted to appearance of new nuclear-weapons states.

In this situation, the whole world community and, first of all, Russia made enormous efforts to prevent nuclear weapons from sprawling into several countries and jeopardizing the regime of non-proliferation.

Russia removed all nuclear weapons from the territories of Belarus, Kazakhstan and Ukraine. Today, all nuclear arms of the former USSR are kept within Russian borders.

As a result, Ukraine, Belarus, Kazakhstan and all other ex-Soviet republics joined the NPT. The situation was rectified, and Russia succeeded to the Soviet Union as a party to the Non-Proliferation Treaty.

Ship-borne nuclear power systems – carried first of all by submarines as well as by other vessels with nuclear reactors – are all found in Russia (the latter, e.g., belonging to the Murmansk Shipping Company).

As regards nuclear power plants, in 1991, Russia was left with 29 power units whose total capacity was 21.2 GW(e). Ukraine had 14 power units totaling 12.9 GW, while Kazakhstan owned one nuclear power plant with a 350 MW(e) fast neutron reactor BN-350. Part of the energy generated by the BN was used for desalination of seawater. BN-350 was shut down and is awaiting dismantling.

In Transcaucasia, only Armenia has a nuclear power plant consisting of two VVER-440 reactors. In 1989, the plant was closed down in reaction to popular anti-nuclear sentiments as well as for reasons of safety, considering that the plant was sited in a region of high seismic activity. Later, however, after the alarming energy crisis of 1992–1995, it was decided to restart the reactors. The government of Armenia appealed to Russian Minatom for restoration of the NPP, as some of its equipment had gone into a bad state of repair over the time of its disuse. One power unit was successfully restarted and by 1999, the NPP was supplying 36 % of all electricity generated in this country.

In Lithuania, Minatom built the Ignalina NPP with its two RBMK-1500 power units. Both units are shut down today.

Uranium mining may be pointed out among the Nuclear Fuel Cycle (NFC) stages listed in Table 1.1. It is only 40 % of all uranium mines that are found in Russia, Ukraine accounting for 20 %, Kazakhstan for 10 %, and Tajikistan, Kirghizia and Uzbekistan for 30 %.

It is an important fact that the most hazardous – from the viewpoint of proliferation resistance – NFC capabilities are all sited in Russia. These are uranium enrichment, reprocessing and plutonium separation facilities.

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CHAPTER 2

MAIN TECHNOLOGIES OF THE PRESENT-DAY NUCLEAR FUEL CYCLE AND THEIR SIGNIFICANCE FOR THE NON-PROLIFERATION REGIME*

Nuclear material (NM) is essential for two self-sustaining nuclear reactions which are accompanied by liberation of large energy amounts, namely:

- **chain fission reaction involving heavy nuclei.** The nuclear material in this reaction includes natural isotopes of uranium and thorium, man-made transuranic isotopes – mainly those of plutonium, as well as of neptunium, americium, curium, berkelium, and californium, and the man-made ^{233}U , which can be produced by exposure of thorium to neutron radiation;
- **thermonuclear fusion reaction involving nuclei of light isotopes.** The nuclear material here includes hydrogen isotopes (deuterium and tritium). Natural hydrogen comprises 0.015 % of deuterium and none of tritium. Other nuclear materials are heavy water (D_2O) and lithium whose isotope ^6Li is capable of vigorously producing tritium in the reaction $^6\text{Li}(n,\alpha)\text{T}$.

Thus, nuclear materials are:

- feed materials – uranium and thorium ores, natural uranium and thorium, depleted uranium (with low content of ^{235}U);
- special materials – enriched uranium (with high content of ^{235}U), plutonium, and ^{233}U ;
- transuranic elements – Np, Am, Cm, Bk, Cf;
- heavy water, deuterium, tritium, lithium.

Nuclear technologies include:

- NM production;
- NM storage, transportation and use;
- NM reprocessing and recycling;
- radioactive waste treatment and disposal.

Nuclear technologies and safe NM management are interrelated. The term “safety” – taken broadly – implies radiation safety, nuclear safety, etc. In terms of non-proliferation, it means security from NM theft or diversion for production of nuclear explosives or other illicit uses.

* This chapter was prepared with the help of V.A. Apse and A.N. Shmelyov, based on the book by V.A. Apse and A.N. Shmelyov “Nuclear Technologies”. M.: MIFI, 2001.

This section will be focused on description of nuclear technologies and on their analysis from the viewpoint of proliferation resistance. Non-proliferation of nuclear materials may be ensured if they are handled under conditions where their theft or diversion for illegal purposes are so difficult and dangerous and the risk of detection so high that potential transgressors are bound to be discouraged.

Nuclear technologies should be provided with such a system of physical protection, accounting and control that:

- a) it would be practically impossible to gain unauthorized access to nuclear materials;
- b) theft of small NM quantities by personnel would be quickly discovered, and any further attempts of using this route barred;
- c) diversion of NM kept under international safeguards would be easily detected by international inspections.

This chapter will deal mainly with nuclear technologies viewed in the context of non-proliferation.

Nuclear fuel concept

Nuclear fuel is a material containing nuclides which undergo fission when exposed to neutrons. Fissionable nuclides are represented by:

- natural uranium and thorium isotopes;
- man-made plutonium isotopes;
- isotopes of transuranic elements (Np, Am, Cm, Bk, Cf);
- man-made isotope ^{233}U (resulting from capture of neutrons by ^{232}Th).

Normally, isotopes of uranium, plutonium and thorium with an even mass number (even-numbered isotopes) will undergo fission only under action of fast neutrons (fission reaction threshold approximating 1.5 MeV). On the other hand, uranium and plutonium isotopes with an odd atomic mass number (odd-numbered isotopes) can be split by neutrons of any energy, including thermal neutrons. The fission neutron spectrum is a spectrum of fast neutrons (with the average energy of ~ 2.1 MeV), which are quickly moderated to an energy level below the fission threshold for even-numbered isotopes. It is impossible to have a chain fission reaction on even-numbered isotopes due to a small portion of neutrons with energy above the fission threshold. Neutron moderation is good for sustaining a chain fission reaction on odd-numbered isotopes, considering that fission cross-sections of these isotopes grow as neutron energy decreases.

It is only natural fissionable isotopes (^{235}U , ^{238}U , ^{232}Th) that are found in primary nuclear fuel, while secondary nuclear fuel contains man-made fissile nuclides (^{233}U , ^{239}Pu , ^{241}Pu).

The ^{238}U and ^{232}Th isotopes are natural nuclear materials that are of little use as nuclear fuel, since they are only split by fast neutrons. But they can successfully serve for producing fissile nuclides (^{233}U , ^{239}Pu), i.e. for breeding secondary nuclear fuel. These nuclides are often referred to as fertile isotopes.

The present-day nuclear power industry runs on natural uranium, which consists of three isotopes:

- ^{238}U with the content of 99.2831 % and half-life $T_{1/2} = 4.5 \cdot 10^9$ years;
- ^{235}U with the content of 0.7115 % and half-life $T_{1/2} = 7.1 \cdot 10^8$ years;
- ^{234}U with the content of 0.0054 % and half-life $T_{1/2} = 2.5 \cdot 10^5$ years.

The uranium isotope ^{235}U is the only natural nuclear material which is fissionable by neutrons of any energy and gives rise to an excess of fast neutrons. It is owing to these neutrons that a chain fission reaction becomes possible. Most power reactors run on uranium enriched in ^{235}U by 2–5 %. Fast reactors use uranium enriched to 15–25 %. Research reactors operate on uranium of medium or high enrichment (20–90 %).

Enriched uranium contains ^{235}U in amounts exceeding its concentration in natural uranium (0.71 %). It is generally agreed that:

- low enrichment is $X_5 < 5$ %;
- medium enrichment is X_5 between 5 and 20 %;
- high enrichment is X_5 between 20 and 90 %;
- superhigh enrichment (for weapons-grade U) is $X_5 > 90$ %.

Production of enriched uranium results in depleted uranium, with ^{235}U content below the natural level (normally 0.2–0.3 %).

The following types of nuclear fuel are in use:

- metals, metal alloys, intermetallic compounds;
- ceramics (oxides, carbides, nitrides);
- cermet (with metal fuel particles dispersed in a ceramic matrix);
- dispersion fuel (coated fuel particles dispersed in an inert, e.g., graphite, matrix).

A fuel element is a basic structural form of nuclear fuel in a reactor, which consists of an active part (fuel core containing fissile and fertile NM) and a cladding. Fuel claddings are usually made of metal, such as stainless steel and zirconium alloys. In the case of spherical elements, fuel particles are coated with layers of silicon carbide and pyrolytic carbon.

In terms of geometry, fuel elements appear as rods, ring-shaped elements, plates, and spheres. Reactor fuel inventory is distributed among a large number of fuel elements; so a VVER–1000 reactor will have 48 000 fuel rods.

Fuel elements are combined into fuel assemblies (FA), with their number varying from several pieces to several hundreds of fuel elements in one FA.

Fuel assemblies are installed to form the reactor core, which is the site of a controlled chain reaction of nuclei fission by neutrons, with nuclear energy converted into heat. This heat is carried off by coolant to be converted into electricity. The reactor core plays the same role as does an ordinary boiler, in which fossil fuel is burned. This analogy allows using customary terminology, such as “nuclear fuel”, “fuel burning”, “fuel burnup”, though nuclear fuel does not “burn” in the usual sense of the word.

Nuclear fuel cycle concept

The processes of fuel fabrication, use and reprocessing may be all covered by the notion of nuclear fuel cycle (NFC).

Main stages of the NFC

1. Uranium ore mining and extraction of uranium compounds.
2. Nuclear fuel fabrication.
3. Nuclear fuel use in reactors.
4. Temporary on-site storage of irradiated fuel assemblies (IFA).

Next stages depend on the choice between two options – open NFC or closed NFC.

- 5a. Burial of irradiated fuel in geological repositories – in an open NFC.
- 5b. Chemical reprocessing of irradiated fuel – in a closed NFC.
6. Separation of radioactive waste (RW), its treatment and disposal.
7. Recycling of uranium and plutonium, their refabrication into nuclear fuel and subsequent reuse in nuclear reactors.

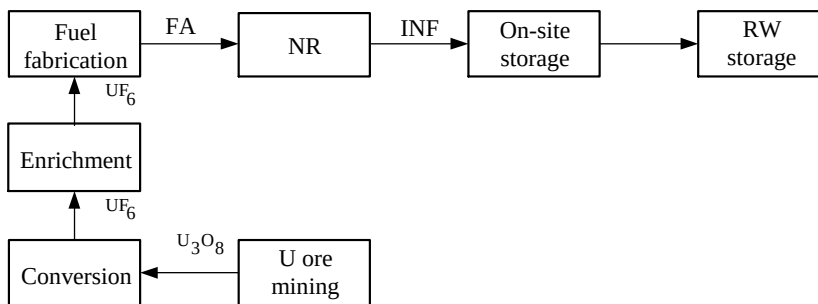
As regards the expediency of closing the fuel cycle, there two points of view:

1. It is not expedient to close the NFC. Chemical reprocessing of irradiated fuel is associated with technological and political problems, such as:

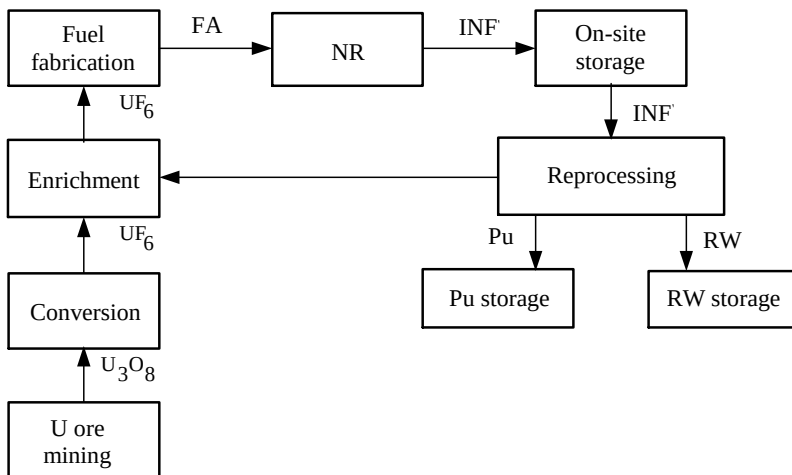
- a) NM can be stolen for production of nuclear weapons;
- b) Fuel reprocessing is complicated and hazardous;
- c) RW treatment and disposal are complicated and hazardous.

2. It is expedient to close the NFC. Irradiated fuel contains valuable NM suitable for fabrication of nuclear fuel. A closed NFC affords self-sufficiency in meeting national energy demands.

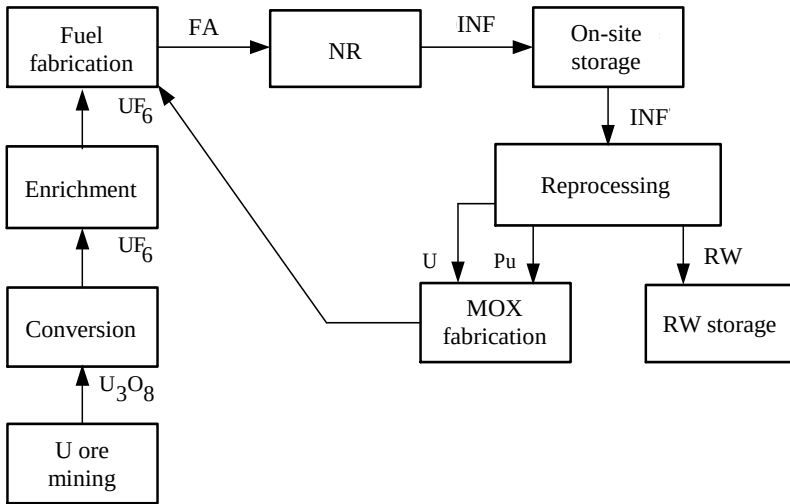
An NFC can appear in one of several forms: there are one open and two closed options. They are schematically shown in Fig. 2.1.



A)



B)



C)

Fig. 2.1. Open NFC (A) and 2 types (B, C) of closed NFC

A. Open (once through) NFC

1. Uranium ore mining.
2. Production of U_3O_8 .
3. Conversion of U_3O_8 to UF_6 .
4. Enrichment of UF_6 .
5. Fuel fabrication (fuel elements and assemblies).
6. Use of nuclear fuel in reactors.
7. On-site storage of INF.
8. Final disposal of INF in geological repositories.

B. Closed NFC with use of regenerated uranium

1. Uranium ore mining.
2. Production of U_3O_8 .
3. Conversion of U_3O_8 to UF_6 .
4. Enrichment of UF_6 .
5. Fabrication of nuclear fuel (fuel elements and assemblies).
6. Use of nuclear fuel in reactors.
7. On-site INF storage.
8. INF reprocessing with separation of uranium, plutonium and RW.
9. Return of regenerated uranium to conversion and enrichment stages.

10. Plutonium disposition in special storage facilities.
11. Final disposal of RW in geological repositories.

C. Closed NFC with use of regenerated uranium and plutonium

1. Uranium ore mining.
2. Production of U_3O_8 .
3. Conversion of U_3O_8 to UF_6 .
4. Enrichment of UF_6 .
5. Fabrication of nuclear fuel (fuel elements and assemblies).
6. Use of nuclear fuel in reactors.
7. On-site INF storage.
8. INF reprocessing with separation of uranium, plutonium and RW.
9. Return of regenerated uranium to conversion and enrichment stages.
10. Fabrication of mixed uranium–plutonium oxide fuel (MOX fuel) based on regenerated uranium and plutonium.
11. Final disposal of RW in geological repositories.

INF reprocessing capabilities are available in seven countries: USA, UK, France, Russia, China (nuclear-weapons states), Japan and India. One of the main objectives pursued in development and use of nuclear technologies is control over NM at all NFC stages to prevent their diversion for military purposes.

There are three possible ways of diverting NM from energy uses to military applications:

1. Forcible theft following an external terrorist attack at a nuclear facility or a vehicle carrying NM.

To prevent such events, physical protection systems are created.

2. Non-forcible, covert theft by site personnel.

To prevent it, NM accounting and control systems are set up.

3. Covert diversion authorized by the national government.

This is prevented by a system of international safeguards and agreements on peaceful use of NM:

- a) Treaty on the Non-Proliferation of Nuclear Weapons (NPT);
- b) regional agreements on non-proliferation of nuclear weapons;
- c) Zangger Committee (Nuclear Suppliers Group) for control over export of nuclear materials, technologies and components.

Periodic inspections of nuclear sites by IAEA experts are the main mechanism of control at the governmental level.

Let us consider the main factors making NM theft attractive at various NFC stages.

1. NM quantity and quality required for producing nuclear explosives:

- critical mass of 100 % ^{235}U – 50 kg;
- critical mass of 100 % ^{239}Pu – 15 kg;
- critical mass of 100 % ^{233}U – 17 kg.

The critical mass values are given for a metal sphere without a reflector (which almost halves the critical mass). The IAEA introduced the unit of Significant Quantity (SQ). Detection of stolen 1 SQ calls for a special investigation and for notification of the UN Security Council. The SQ value is roughly half that of the critical mass (metal sphere minus reflector):

$$1 \text{ SQ } (^{239}\text{Pu}, ^{233}\text{U}) = 8 \text{ kg}; 1 \text{ SQ } (^{235}\text{U}) = 25 \text{ kg}.$$

2. Simplicity of stealing NM, with low probability of detection.
3. Simplicity of turning NM into a nuclear charge.

The attractiveness of NM diversion at various NFC Stages is qualitatively assessed in Fig. 2.2.

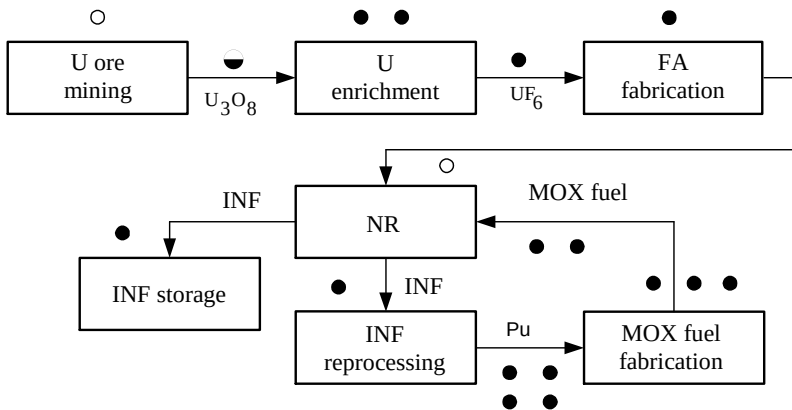


Fig. 2.2. NFC stages in terms of their attractiveness for NM diversion.

The number of dots corresponds to the attractiveness of a stage. The most attractive stages are those of INF reprocessing, plutonium separation, fabrication of mixed uranium-plutonium fuel and its recycling in reactors.

The main NFC stages will be now regarded from the viewpoint of proliferation resistance (Table 2.1).

Table 2.1

Relative hazard of NFC stages

NFC stage	Vulnerability to theft	Vulnerability to diversion	Proliferation risk
Ore mining	Low	High	Low
Conversion to UF ₆	Low	H – L (IAEA)*	Low
Enrichment	High	H – L (IAEA)	High
Fuel fabrication	Low	H – L (IAEA)	H – L (enrichment)
Use at NPPs	Low	H – L (IAEA)	H – L (enrichment)
Storage of IFAs	Low	H – L (IAEA)	H – L (enrichment)
INF reprocessing	High	H – L (IAEA)	High
RW disposal	Low	Low	Low

* H – L (IAEA): High to low, depending on monitoring by the IAEA.

1. Uranium ore mining and primary processing

Vulnerability to theft (VT): low. For 25 kg of weapons-grade plutonium to be produced, it is necessary to have about 5000 kg of natural uranium or 5000 t of uranium ore. It is difficult to steal such a quantity of uranium ore without being noticed.

Vulnerability to diversion by personnel (VDP): high. Uranium mines and primary processing facilities are not covered by the IAEA safeguards.

Proliferation risk (PR): low. Natural uranium is not suitable for making nuclear explosive devices.

2. Conversion to nuclear fuel (unenriched uranium for CANDU reactors) or to uranium hexafluoride for enrichment.

VT: low, as in uranium mining.

VDP: dependent on whether the processes are covered by the IAEA safeguards.

PR: low. Natural uranium is unusable in nuclear explosives.

3. Uranium enrichment in ²³⁵U.

VT: high. A nuclear explosive device would only take 25 kg of weapons-grade uranium. Such a weight can be carried by one person.

VDP: dependent on whether the process is covered by the IAEA safeguards.

PR: high. The Nuclear Suppliers' Group placed an unofficial embargo on export of enrichment technologies.

4. Fabrication of nuclear fuel (fuel elements and assemblies).

VT: low. One FA weighs 300 to 500 kg and would take special transport for conveyance.

VDP: dependent on whether the processes are covered by the IAEA safeguards.

PR: between low and high depending on the fuel enrichment.

5. Use of nuclear fuel in reactors.

VT: low, due to FA weight, radioactivity and location inside the reactor vessel.

VDP: dependent on whether the reactor is covered by the IAEA safeguards.

PR: between low and high depending on fuel enrichment and on availability of reprocessing facilities.

6. INF storage.

VT: low, due to FA weight, radioactivity and residual heat.

VDP: dependent on whether the storage facility is covered by the IAEA safeguards.

PR: between low and high depending on the availability reprocessing facilities.

7. INF reprocessing.

VT: high. INF reprocessing relies on remotely controlled equipment standing between personnel and NM. Though there are areas where Pu-containing materials are accessible for theft.

VDP: dependent on whether the reprocessing facility is covered by the IAEA safeguards.

PR: high. Reprocessing facilities generate plutonium, which can be used in nuclear explosives. The Nuclear Suppliers' Group placed an unofficial embargo on export of reprocessing technologies.

8. Radioactive waste disposal.

VT: low, due to high radioactivity and heat release, with low content of fissile materials.

VDP: low, due to small percentage of fissile materials.

PR: low, due to high radioactivity and heat release, with low content of fissile materials.

Reactors of different types differ in the attractiveness for NM theft. There are two characteristics determining such attractiveness (Table 2.2):

- 1) quantity and quality of nuclear fuel loaded;
- 2) quantity and quality of nuclear fuel produced.

Table 2.2

Reactor fuel loaded and produced

Reactor type	Loaded fuel	Produced fuel, kg/GW·year	Note
IRT	5–10 kg (90 % ^{235}U)	–	Low power
HTGR–770	8.1 t ^{232}Th 0.7 t ^{235}U (93 %)	200	–
VVER–1000	100 t UO_2 (3–5 % ^{235}U)	200	–
RBMK–1000	150–180 t UO_2 (1.8–2 % ^{235}U)	250	Continuous refueling
CANDU–600	100 t UO_2 (0.7 % ^{235}U)	350	Continuous refueling
LMFBR–1000	10–15 t UO_2 (15–25 % ^{235}U)	1500–ONFC 250–CNFC	–

1. Research reactors

Some research reactors still run on highly enriched uranium fuel. But their thermal power being low (several megawatts), the ^{235}U inventory is no greater than 5–10 kg.

Following the IAEA resolution, research reactors are being converted to fuel of medium enrichment, with ^{235}U content making no more than 20 %. The critical mass of such uranium is 830 kg.

Secondary fuel is not produced in research reactors as their fertile material quantities are small and neutron fluxes are low.

2. High-temperature gas-cooled reactors

These reactors use highly enriched dispersion fuel (93 % ^{235}U) and thorium as fertile material. Fuel particles clad in pyrolytic carbon and silicon carbide are dispersed in a graphite matrix to be subsequently fabricated into spherical or rod-type fuel elements.

The starting charge of a 770 MWe HTGR contains 8.1 t of ^{232}Th in the form of ThO_2 and 0.7 t of ^{235}U as UC. By the end of in-pile irradiation, the inventory will include: 7.5 t of ^{232}Th , 40 kg of ^{235}U and about 180 kg of ^{233}U , which means that HTGRs generate ~ 200 kg of ^{233}U /GWe·year.

3. Light water reactors

Vessel-type reactors (PWR, BWR, VVER). Such reactors using water as moderator and coolant run on low-enrichment (3–5 % ^{235}U) uranium

oxide fuel. The starting inventory of a 1 GWe reactor is about 100 t of UO_2 . It generates about 200 kg of plutonium per GWe-year.

Channel-type reactors (RBMK). RBMK reactors using graphite moderator and light-water coolant run on uranium oxide fuel of low enrichment (1.8–2 % ^{235}U). The first core of a 1 GWe reactor contains about 150–180 t of UO_2 . It produces approximately 250 kg of plutonium per GWe-year.

The proliferation hazard presented by RBMKs lies in the possibility of channel-by-channel refueling without reactor shutdown.

4. Heavy water CANDU reactors

CANDU reactors are fuelled with natural uranium. The first core of a 1 GWe reactor takes approximately 100 t of UO_2 . Every year, it will generate 350 kg/GWe.

CANDU reactors operate under conditions of continuous refueling carried out without reactor shutdown. This can pose certain difficulties for inspecting the way primary fuel is used and secondary fuel accumulated.

5. Fast breeder reactors

Fast reactors run on uranium oxide fuel of medium enrichment (15–25 % ^{235}U). The inventory of a 1 GWe reactor is 10–15 t, which means that the core contains 2–3 t of ^{235}U . It generates plutonium at a rate of about 1500 kg/(GWe-year) in an open fuel cycle. If the fuel cycle is closed, about 80 % of plutonium will be recycled, and its net output will approach 250 kg/(GWe)-year.

Natural NM mining and primary processing

High chemical activity of uranium and thorium explains why they occur in nature only in chemical compounds. All in all, about 200 uranium and thorium minerals were discovered.

The known rich uranium deposits are relatively scarce. The total uranium reserves in the Earth crust are estimated at 10^{14} t, with another $\sim 4 \cdot 10^9$ t found in the water of seas and oceans (3.3 mg/m³ on the average).

Ore varies in uranium content, appearing as:

- very rich ore: more than 1 % of U;
- rich ore: 0.5–1 % of U;
- medium-grade ore: 0.25–0.5 % of U;
- run-of-mine ore: 0.09–0.25 % of U;
- lean ore: less than 0.09 % of U.

Generally, mined ore contains about 0.1 % of uranium – these are lean and run-of-mine ores.

Uranium reserves are estimated by two cost criteria as:

- cheap uranium, costing under \$ 80 per 1 kg U_3O_8 ; and
- expensive uranium, costing over \$ 80 per 1 kg U_3O_8 .

The threshold value of \$ 80 per 1 kg U_3O_8 was adopted at the time when it marked the border of NPP competitiveness against coal-fired plants.

More than 80 % of proven and probable uranium reserves are found in 8 countries of America (USA, Canada, Brazil), Australia and Africa (SAR, Niger, Angola, Namibia). Two countries, namely, Canada and Australia, produce over 50 % of globally mined uranium. The CIS accounts for about 15 % of the world's resources. The annual uranium output is not large enough to meet the requirements of global nuclear power. The deficit is offset by using reserves, waste processing, and recycling.

There are four methods of uranium production, i.e.:

- underground mining;
- quarrying;
- in-situ leaching;
- recovery from seawater.

The stage of ore mining is followed by its hydrometallurgical processing. Uranium can be extracted owing to high solubility of uranium oxides in acid and alkaline solutions.

Hydrometallurgical processing results in dry concentrate of uranium oxides (mainly, U_3O_8). The concentrate will contain all the uranium found before in the ore, as well as impurities (with 95–96 % accounted for by uranium oxides and 4–5 % by impurities). The impurities, which have to be removed from the concentrate, include powerful neutron absorbers: B, Cd, Hf and rare-earth elements (Eu, Gd, Sm).

The next stage is uranium concentrate purification using a refining process.

The most common method is refining by extraction, with tributylphosphate (TBP) serving as an extracting agent. The TBP density (0.973 g/cm^3) is slightly lower than that of water. To reduce its viscosity, TBP is dissolved in neutral organic compounds. An important property of TBP is its capability of selectively extracting uranium compounds. Uranyl nitrate $\text{UO}_2(\text{NO}_3)_2$ is extracted by this agent from a mixture 10^4 times more efficiently than are impurities.

Isotopic enrichment of uranium

The chief material of nuclear power is enriched uranium, which contains more fissionable ^{235}U than its natural variety does.

Uranium enrichment may be conceptually sketched as follows. The feed material is natural uranium, with its quantity in the formula below represented by F and enrichment in ^{235}U by X_F . As a result, two materials arise: 1) uranium enriched in ^{235}U (product), its quantity denoted by P and enrichment in ^{235}U , by X_P ; and 2) uranium depleted of ^{235}U (waste) found in an amount of W and enriched in ^{235}U as X_W .

Then, the NM balance is described by two equations:

- $F = P + W$ for the uranium mass balance and
- $X_F \cdot F = X_P \cdot P + X_W \cdot W$ for the ^{235}U isotope balance.

These two equations in three unknowns (F, P, W) can be rearranged to have two equations in two unknowns ($F/P, W/P$):

$$\begin{aligned} F/P &= 1 + W/P; \\ X_F \cdot F/P &= X_P + X_W \cdot W/P. \end{aligned}$$

By solving this system, it is possible to find:

a) the rate of natural uranium consumption per unit of product

$$F/P = (X_P - X_W)/(X_F - X_W);$$

b) the rate of waste generation per unit of product

$$W/P = (X_P - X_F)/(X_F - X_W);$$

c) the product-to-feed material ratio θ :

$$\begin{aligned} F &= P + W = \theta \cdot F + (1 - \theta) \cdot F; \\ \theta &= P/F = (X_F - X_W)/(X_P - X_W). \end{aligned}$$

We shall introduce the concept of relative concentration of isotope ^{235}U in a binary mixture ($^{235}\text{U}, ^{238}\text{U}$), appearing in the input as $R = X_F/(1 - X_F)$; in the product output as $R' = X_P/(1 - X_P)$; and in the waste output as $R'' = X_W/(1 - X_W)$. Then:

the separation factor for the enriched fraction is:

$$\alpha = R'/R = [X_P/(1 - X_P)]/[X_F/(1 - X_F)];$$

the separation factor for the depleted fraction is:

$$\beta = R / R'' = [X_F / (1 - X_F)] / [X_W / (1 - X_W)];$$

enrichment factor: $\epsilon' = \alpha - 1$;

depletion factor: $\epsilon'' = \beta - 1$;

total enrichment factor for one stage :

$$\epsilon = \epsilon' + \epsilon''.$$

Table 2.3 presents some data descriptive of enrichment processes in terms of separation factors and power consumption.

Table 2.3

Separation factors and power consumption specific to enrichment processes

Enrichment process	Separation factor, α	Power consumption, kWh/SWU
Electromagnetic separation	No data	4000
Gas diffusion	1.0043	2300–2600
Gas centrifugation	1,25	100–300
Separation nozzle	1,025	3000–3500
Laser techniques	3–15	10–50
Chemical techniques	1.0025	400–700

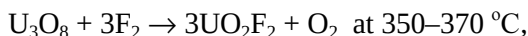
Gas diffusion and gas centrifugation are the two NFC methods most extensively used on a commercial scale. Both of them rely on the difference in mass between molecules of a gaseous uranium compound (UF_6).

Uranium hexafluoride UF_6 is often used as a starting material in uranium enrichment. This compound has a number of attractive properties:

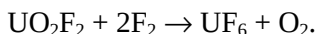
- natural fluorine contains only one stable isotope, namely, ^{19}F ;
- uranium hexafluoride can appear as a solid, liquid or gas at moderate temperatures and pressures;
- uranium hexafluoride can pass from a solid to a gaseous state and back, skipping the liquid phase.

One of the shortcomings of uranium hexafluoride is its high chemical activity. It reacts with air and steam, giving rise to uranium tetrafluoride UF_4 (powder), which deposits in process circuits. That is why circuits and containers should be made leak-tight, should be desiccated and degreased. Ni, Al, Mg, Cu and their alloys as well as teflon show resistance when exposed to UF_6 .

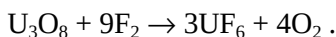
Uranium oxide conversion to uranium hexafluoride. For isotopic enrichment, the concentrate of U_3O_8 has to be turned into UF_6 . This can be done in a two-step process. First, a reaction with fluorine gas yields uranyl fluoride UO_2F_2 :



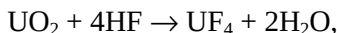
whereupon uranium hexafluoride is formed by a reaction of uranyl fluoride with fluorine at a lower temperature of $\sim 270^\circ\text{C}$:



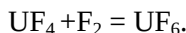
A single-stage process (flame method of direct fluorination) can only take place with excess fluorine and at much higher temperatures ($900\text{--}1000^\circ\text{C}$):



Production of uranium hexafluoride from uranium dioxide (UO_2) is achieved by using another two-step process. First, UO_2 reacts with hydrofluoric acid (HF) at $500\text{--}600^\circ\text{C}$ to form uranium tetrafluoride (UF_4):



whereupon UF_4 reacts with fluorine at 400°C :



1. Uranium enrichment by gas diffusion (GD)

The enrichment GD technology is based on different speeds of thermal motion of heavy and light molecules, and on the ease with which the latter go through thin porous partitions.

In a mixture of two gases with the same temperature, light and heavy molecules have the same average kinetic energy:

$$m_L \cdot V_L^2 = m_H \cdot V_H^2 ,$$

while the average speed of light molecules is higher than that of heavy ones:

$$V_L = V_H \cdot (m_H/m_L)^{1/2}.$$

An ideal separation factor, α_0 , for a mixture of two gases diffusing through a porous partition, is:

$$\alpha_0 = (m_H/m_L)^{1/2} \approx 1 + \Delta m/2m_L.$$

For uranium hexafluorides $^{235}\text{UF}_6$ and $^{238}\text{UF}_6$ ($m_L = 349$, $m_H = 352$), the separation factor α_0 is equal to the enrichment factor ϵ_0 :

$$\alpha_0 = 1,0043; \epsilon_0 = \alpha_0 - 1 = 0,0043.$$

The free path of molecules should be larger than the typical size of pores, so that such molecules could interact mostly with pores in a partition, rather than with one another. The free path of molecules is inversely related to pressure. For UF_6 , the free path at 1 atm. is 1 μm , and at 1 mm Hg makes 700 μm . Fabrication of partitions with pores measured in microns is a fairly complicated task, which requires a low operation pressure.

Partitions should be:

- thin (fractions of millimeter);
- strong (to withstand a pressure drop of ~ 0.3 atm.);
- corrosion-resistant in the atmosphere of UF_6 .

Partitions with micron-sized pores are made of:

- sintered aluminum and nickel oxide powder;
- sintered nickel powder;
- aluminum with pores produced by electric etching;
- teflon.

The uranium GD-enrichment factor at one stage is small (1.0043), wherefore the gas flow has to be repeatedly passed through many enrichment stages. A series of GD stages forms a cascade.

2. Uranium enrichment in gas centrifuges (GC)

It is assumed that a tube rotating at an angular speed of ω contains a mixture of gases with molecular weights of M_1 and M_2 . Their molecules are exposed to centrifugal forces proportional to the mass and radius:

$$F_{1,2} = M_{1,2} \cdot \omega^2 \cdot r.$$

Gas pressure rises steeply from the center to the periphery:

$$P_{1,2} = P_0 \cdot \exp(M_{1,2} \cdot \omega^2 \cdot r^2 / 2RT) \sim \exp(a \cdot V^2).$$

The heavy fraction subjected to the higher pressure is driven to the GC periphery, while the light fraction collects in its central part.

The separation factor in a GC is:

$$\alpha = \exp(\Delta M \cdot \omega^2 \cdot r_0^2 / 2RT) = \exp(\Delta M \cdot V(r_0)^2 / 2RT);$$
$$\varepsilon = \alpha - 1 \approx \Delta M \cdot V(r_0)^2 / 2RT.$$

Calculations suggest that the following enrichment factors can be provided by gas centrifugation as a function of rotation speed:

$$\varepsilon = 0.068 \text{ at } V = 330 \text{ m/s};$$

$$\varepsilon = 0.098 \text{ at } V = 400 \text{ m/s};$$

$$\varepsilon = 0.152 \text{ at } V = 500 \text{ m/s}.$$

Centrifuges are manufactured from the following materials:

- aluminum alloys (for speeds $V \leq 350$ m/s);
- titanium alloys (for speeds $V \leq 450$ m/s);
- alloyed steels (for speeds $V \leq 500$ m/s);
- graphite-reinforced fiber-glass plastics (for $V = 500\text{--}700$ m/s).

3. Separating nozzle

This method essentially relies on different behavior of uranium isotopes in a centrifugal force field. Uranium hexafluoride is fed into a highly curved nozzle where centrifugal forces cause spatial separation of light and heavy isotopes.

The advantage of this method over GC lies in the absence of rotating components, but the small size of separation slots (a fraction of a millimeter) calls for precision assembly. The uranium enrichment factor for the separating nozzle is $\epsilon' = 0.025$.

4. Laser methods

Laser methods of uranium separation are based on the difference in the arrangement of excited energy levels of electrons in atoms of ^{238}U and ^{235}U , which is made possible by use of a monochromatic laser. Excitation of electron shells leads to selective intensification of physical or chemical processes (intensified ionization of excited atoms or intensified dissociation of excited molecules). The conditions for laser-based enrichment include:

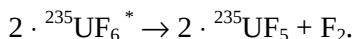
1. Presence of an excited electron level unique to one isotope. This level should be sufficiently far removed from other spectrum lines and from lines of other isotopes.
2. Availability of a laser tuned to an appropriate radiation frequency.
3. Existence of processes separating excited atoms and molecules.

Laser-based enrichment of uranium vapors. This enrichment method consists of the following stages:

- evaporation of U atoms in vacuum (an electron beam knocks out U vapors from the U–Re alloy);
- irradiation by a xenon laser with ensuing selective excitation of ^{235}U atoms;
- irradiation by a krypton laser with ensuing selective ionization of excited ^{235}U atoms;
- collection of ionized ^{235}U atoms on a charged plate.

Laser-based enrichment of UF_6 molecules. This process has three stages:

- cooling of the $\text{UF}_6 + \text{H}_2$ mixture to 30 K for the UF_6 molecules to be mostly in an unexcited state;
- irradiation by an infrared laser with ensuing selective excitation of $^{235}\text{UF}_6$ molecules;
- irradiation by an ultraviolet laser with ensuing selective dissociation of excited molecules:

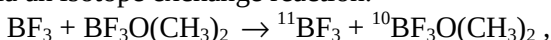


White powder of $^{235}\text{UF}_5$ (“laser snow”) precipitates from the gas mixture.

The enrichment factor of laser methods is as high as 3 to 15. They offer a possibility to use the waste of GD plants (containing 0.2–0,3 % of U) for recovery of uranium suitable for light water power reactors.

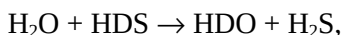
5. Chemical enrichment methods

Chemical methods depend on different stability of isotopes in compounds. A contact between chemical compounds of one element with different valences leads to isotope exchange. Thus, boron can be enriched in isotope ^{10}B via an isotope exchange reaction:



in which ^{10}B builds up in the organic phase.

Heavy water generation results from an isotope exchange reaction between light water and hydrogen sulfide:



with deuterium accumulating in the water phase.

The USA and Japan are developing a uranium enrichment process involving UF_6 and NOUF_6 as contacting compounds. This is essentially oxidation–reduction chromatography achieved by alternation of oxidation reactions (addition of oxygen gas) and reduction reactions (addition of hydrogen gas). In this case it is possible to separate compounds including ions of UO_2^{++} (with 6-valent ^{235}U) and U^{4+} (with 4-valent ^{238}U). The experimentally obtained separation factors reached 1.08 and power consumption proved to be up to 150 KWh/SWU.

6. Plasma method

This method is based on the effect of ion cyclotron resonance.

Charged particles (ions) moving about in a magnetostatic field experience the action of a force

$$F = q \cdot [V \times B],$$

causing them to spiral about magnetic field lines. The orbital radius is found from the following equation:

$$F = q \cdot V \cdot B = mV^2/R ;$$

$$R = m \cdot V / (q \cdot B) = (2m \cdot E)^{1/2} / (q \cdot B),$$

while the rotation frequency $\omega = V/R = q \cdot B/m$ is the ion cyclotron frequency (ICF).

If a variable electric field is applied, with its frequency equal to the ICF of a specific isotope, this will be the only isotope to take up the field energy. A higher energy of ions of a certain isotope will increase the radius of its rotation about magnetic field lines. It is then possible to separate ions of different isotopes and to accumulate ions of ^{235}U and ^{238}U selectively on appropriately arranged collectors.

Uranium enrichment technologies viewed in the context of non-proliferation of nuclear weapons

Gas diffusion:

- a) technically sophisticated process;
- b) high power requirements (2300–2600 kWh/SWU); one GD facility in the USA consumes about 5 GWe;
- c) relatively low enrichment factor ($\epsilon' = 0.0043$);
- d) unlikely secret construction of a GD facility.

Gas centrifugation:

- a) technically sophisticated process;
- b) low power requirements (100–300 kWh/SWU) and high enrichment factor ($\epsilon' = 0.2\text{--}0.3$) make this technology hazardous from the viewpoint of non-proliferation.

Separating nozzle:

- a) less sophisticated than GD and GC processes;
- b) low enrichment factor ($\epsilon' = 0.025$) and high power requirements (3000 kWh/SWU) make this method a lesser proliferation hazard as compared with GD and GC processes.

Laser methods:

- a) the highest enrichment factor ($\epsilon' = 3\text{--}15$) and the lowest energy requirements (10–50 kWh/SWU);
- b) the most sophisticated process; the most promising enrichment technology and the most hazardous process from the non-proliferation point of view.

Fuel fabrication processes

Uranium dioxide is the most extensively used and commercialized nuclear fuel for thermal and fast reactors.

Uranium dioxide advantages:

- high melting temperature (2780°C);
- chemical resistance to the main coolant types (light and heavy water, sodium, carbon dioxide);
- good compatibility with cladding materials (stainless steel, zirconium alloys) at operating temperatures;
- possibility of producing high-density pellets;
- acceptable radiation resistance at neutron fluxes of $\sim 10^{14}$ n/cm²·s and fluences of $\sim 10^{22}$ n/cm², i.e. for 3 years;
- isotropic crystal lattice, which facilitates high-temperature sintering.

Uranium dioxide disadvantages:

- low heat conduction dropping abruptly as temperature increases. This accounts for sharp temperature differentials between pellet center and periphery ($\Delta T \sim 1000\text{--}1500$ °C);
- easy oxidation in air. It needs inert dry environment or vacuum, otherwise the pellet will get saturated with moisture and oxygen will be adsorbed by its surface layer. Moisture on the surface can cause hydrogenation of the cladding and failure of the fuel element;
- presence of oxygen moderates the neutron spectrum in a fast reactor and reduces the breeding ratio.

Steps in production of uranium dioxide pellets

1. Conversion of uranium hexafluoride into dioxide:

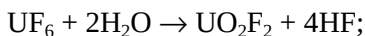
a) “Wet” AUC process:

uranium hexafluoride is passed through aqueous solution of ammonium carbonate $(\text{NH}_4)_2\text{CO}_3$, producing a solid insoluble precipitate of ammonium–uranyl–carbonate (AUC) – $(\text{NH}_4)_4\text{UO}_2(\text{CO}_3)_3$;

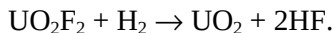
heat treatment of AUC at 550–650°C, resulting in its thermal decomposition with formation of UO_2 as fine powder;

b) “Dry” process:

uranium hexafluoride hydrolysis by steam at 150–300 °C to produce uranyl fluoride UO_2F_2 :



UO_2F_2 pyrohydrolysis by steam and hydrogen at $t \sim 550^\circ\text{C}$ to form fine UO_2 powder and hydrofluoric acid (HF):



The resulting fine powder of UO_2 is made unfit for compaction by its very small particles (less than $0.6\ \mu\text{m}$). To obtain larger particles, the following operations are carried out:

2. Mixing with plasticizing agents;
3. Hydrocompaction: filling of a rubber mould; placement in a container with liquid, which is then pressurized (uniform compression), briquetting;
4. Granulation by briquette milling;
5. Annealing to remove plasticizers;
6. Cold molding to make pellets;
7. Pellet sintering;
8. Pellet quality control and sorting according to size, carbon content (plasticizers), and stoichiometry.

As regards the technology of producing mixed oxide (MOX) fuel, there are three possible blends:

$\text{PuO}_2 + {}^{238}\text{UO}_2$, where Pu is taken from weapons materials;

$\text{PuO}_2 + {}^{238}\text{UO}_2$, where Pu is obtained by irradiated fuel reprocessing; and

${}^{235}\text{UO}_2 + {}^{238}\text{UO}_2$, where ${}^{235}\text{U}$ is taken from weapons materials.

MOX fuel production presupposes availability of two source materials:

${}^{238}\text{UO}_2$ powder made from depleted or natural uranium; and

PuO_2 coming from weapons or reactors, or ${}^{235}\text{UO}_2$ from weapons uranium.

It is impossible to guarantee homogeneity of the $(\text{Pu}, {}^{238}\text{U})$ or $({}^{235}\text{U}, {}^{238}\text{U})$ mixture. Mixing of powder from different sources is the only stage to distinguish the production method of MOX fuel from that of uranium dioxide fuel. Mixture homogeneity is essential to reactor safety. As power rises, fissile isotopes will be the first to heat up. Doppler widening of capture and fission resonances takes place with the ensuing cumulative positive effect of reactivity. A fertile isotope takes more time to heat up, bringing about a negative Doppler effect of reactivity. This delay is the shorter, the higher is the mixture homogeneity. With poor mixing, the

positive effect of reactivity of fissile isotopes can cause power rise to an unacceptably high level, before the negative effect of reactivity of the fertile isotope can have its stabilizing action.

Fuel fabrication stages

1. Preparation of nuclear fuel (conversion of UF_6 into UO_2 ; powder production; pelletization and sintering);
2. Preparation of tubular claddings and end-pieces;
3. Preparation of fuel assembly components.
4. Fitting up of fuel rods: packing of tubular claddings with pellets; attachment of end-pieces; filling with helium; sealing of end-pieces; fuel rod quality control.
5. Putting together of fuel rods into assemblies; quality control; rig tests.

Fabrication of fuel rods and assemblies is:

- a precision process;
- an automated quantity production process;
- an important object of physical protection, accounting and control of nuclear materials.

It takes hundreds of thousands of components and millions of fuel pellets to build a reactor core.

Fuel use in nuclear reactors

A reactor is above-critical before its operation starts, but the reactivity margin is suppressed by special controls, such as absorber rods, boric acid in the coolant, burnable poison in fuel. Fuel burning and buildup of fission products (FP) cause the reactor to go subcritical ($K_{\text{eff}} < 1$). For the reactor to continue operating, K_{eff} should be raised above unity. The primary purpose of refueling is to restore the reactivity margin.

Another purpose is to flatten power density distribution for the highest possible energy generation and uniform fuel burnup.

These purposes may be attained by:

- full or partial refueling;
- rearrangement of fuel assemblies with different burnup in the core;
- combining of the first two approaches.

Refueling of nuclear reactors can take the following forms:

Cyclic refueling, involving uniform fuel distribution and its complete replacement once the reactivity margin is exhausted.

The disadvantages of this approach include:

- non-uniform power density distribution in the reactor;
- quick burnup of the central core, with the reactivity potential of the peripheral fuel retained.

Partial cyclic refueling

It is only the fuel assemblies that have reached their burnup limit that will be unloaded from the reactor and replaced with fresh ones. The core is divided into a number of concentric zones. During each subsequent refueling, the burnt assemblies will be replaced with fresh ones in turns, one zone after another, from the center to the periphery.

The advantage of this approach lies in the same burnup of unloaded fuel.

A disadvantage of this approach is that fresh fuel will take time in moving towards the periphery. This results in impaired power density distribution, with its higher values found in the central zones.

Scattered refueling

The core is divided into groups of fuel assemblies, each including the same number of FAs, e.g., four. The assemblies replaced in the first refueling operation will all be itemized under No. 1. During the second refueling, this procedure will be repeated for assemblies No. 1 and 2, and so on. The distribution of fresh FAs will be uniform throughout the core, resulting in improved global uniformity of power density distribution.

Refueling “from the periphery to the center”

The core is divided into concentric zones containing the same number of fuel assemblies. The first unloading operation will involve the FAs of the central subzone with the highest burnup. They will be replaced by FAs of the second subzone, the place of the latter will be taken by assemblies of the third subzone, etc. The last subzone vacated will be filled with fresh fuel assemblies.

As a result, FAs concentrating in the center will have the highest burnup, i.e. they will be less reactive than the peripheral assemblies. The associated processes are depression of heat release in the center and reduction of the efficiency of reactor controls.

Modified scattered refueling

This method involves the following:

1. The peripheral ring of fuel assemblies is singled out, comprising, e.g., 1/5 of all the reactor’s FAs;
2. The central core area is divided into local groups, four FAs in each;

3. Assemblies No. 1 are removed from each group during the first refueling and are replaced by FAs from the outer ring. The vacated outer row is loaded with fresh FAs.

The advantage of this method lies in uniform power density distribution, without a surge in the center peculiar to “partial cyclic” refueling, or depression in the center characteristic of the “periphery-to-center” process.

Refueling procedures

Refueling may take place:

- after reactor shutdown and cooldown, with its vessel head removed;
- after shutdown, without cooldown and vessel head removal;
- at low or full power.

A full shutdown procedure is practiced at light water reactors. Once a year, a reactor will be shut down for 4 to 6 weeks, its vessel head removed, the irradiated fuel assemblies unloaded, the remaining FAs reshuffled, and fresh fuel loaded. All these operations proceed under water.

In a fast reactor with liquid metal coolant, fuel is reloaded after reactor shutdown, with its vessel head left in place. Use is made of a rotary plug with a reloading mechanism. Two eccentric systems guide the mechanism to an appropriate FA so that it can grip the assembly by its top end-piece and move it into the in-pile storage at the core periphery. Fuel assemblies are kept for some time there to be later removed by a simpler mechanism during reactor operation.

Heavy water reactors, such as CANDU, can be refueled without shutting down the reactor or reducing its power. Fuel assemblies are placed in horizontal channels. The refueling process relies on the “sluice” principle. There is a reloading machine on either side of the reactor. Each machine has a sleeve, which is connected to either end of the fuel channel. Once the channel plug is removed, pressure in the machines and in the channel levels off, fuel is unloaded, and the channel is closed again. One of the machines inserts a fresh assembly at one end, while the other picks up the assembly pushed out at the opposite end.

RBMK reactors also feature on-load refueling. To this end, a reloading machine is used and the “sluice” principle is applied, as is the case with CANDU:

- the reloading machine, filled with condensate, is joined to a channel;
- pressure in the machine box becomes equal to that of the channel;
- the depressurized channel receives cold condensate;
- the spent FA is gripped and retrieved;

- a mockup FA is inserted to check the channel for passability;
- a fresh FA is loaded into the channel;
- the channel is pressurized, pressure in the machine drops, and the machine is disconnected from the channel.

The reactors permitting refueling without power reduction and reactor depressurization, such as heavy-water CANDUs and water-graphite RBMKs, are the greatest proliferation hazards.

Discharged fuel assemblies are kept for 3 to 10 years in the on-site water pool to reduce their activity and residual heat.

The irradiated fuel pools are equipped with:

- a water cooling system;
- an ion exchange facility to remove radioactive substances and to clean the pool water;
- a ventilation system to pass air through filters and to vent waste gas to the atmosphere.

Transportation of irradiated nuclear fuel

Irradiated fuel assemblies are carried in special casks by rail, motor and water transport. Such shipping casks weigh about 80–110 t, of which fuel accounts for merely 2–5 %. The rest is contributed by safety features.

A shipping cask looks as follows:

1. It is a large hollow thick-walled cylinder (with diameter of ~ 2 m; height of ~ 4–6 m, and wall thickness of ~ 40 cm). It may be oriented either horizontally or vertically, and its structural material is steel, cast iron, or concrete.
2. Inside, it is lined with stainless steel for better corrosion resistance, which may have interlayers of neutron moderating material.
3. Its outer surface may be ribbed to increase the heat transfer surface area.
4. It contains metal racks for fuel assemblies. During transportation it is filled with coolant which will remove heat by natural convection or forced circulation.
5. Casks are made tight by strongly sealed lids.
6. Casks are fitted with an interior system for monitoring activity, heat release, temperature, and pressure and with an emergency decontamination system.

Technologies for reprocessing of irradiated nuclear fuel

The purposes of fuel reprocessing are:

- 1) to separate plutonium and uranium for recycling;
- 2) to separate fission products (FP) and transuranic elements as waste.

Irradiated nuclear fuel is generated in the world at a rate of 7000 t per year, while the existing facilities can reprocess annually about 5100 t of INF.

INF reprocessing methods

1. Aqueous (“wet”) methods:

- extraction processes, with uranium and plutonium extracted from solutions by organic compounds;
- precipitation processes, with poorly soluble uranium and plutonium compounds precipitating from solutions.

2. Non-aqueous (“dry”) methods:

- pyrochemical processes, e.g., fluoride gas technology, with its principle lying in different volatility and sorption capacity of uranium and plutonium fluorides and FP;
- pyrometallurgical processes, e.g., electrolytic refining, based on difference in transport of uranium, plutonium and FP in molten metals and salts.

Irradiated nuclear fuel is reprocessed using one of the above processes at a special radiochemical facility. Aqueous extraction processes are the best developed and proven technologies.

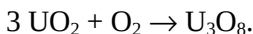
Main stages in the aqueous extraction technology (PUREX)

Disassembly and cutting.

1. Fuel assemblies are taken apart by cutting off end-pieces, cutting shrouds by disk saws, disassembling fuel lattices.
2. Fuel rods are cut, e.g., by guillotine shears or lasers in inert environment (nitrogen or argon).

Pre-oxidation (voloxidation).

Pre-oxidation of irradiated fuel takes place in oxygen at an elevated temperature. Uranium dioxide, UO_2 , transforms into uranium octaoxide, U_3O_8 :



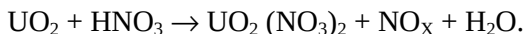
This gives rise to the following effects:

Fuel decompaction. The density of UO_2 is tangibly different from that of U_3O_8 : $\gamma(\text{UO}_2) = 11 \text{ g/cm}^3$, $\gamma(\text{U}_3\text{O}_8) = 8.3 \text{ g/cm}^3$. Fuel increases its volume by 30 %, becoming porous and loose;

Change of crystalline lattice;

Intensive release of fission and tritium gas.

INF dissolution. Fuel is dissolved in boiling nitric acid, HNO_3 :



Zirconium and steel claddings will not dissolve. They are removed from solution and are treated as solid radioactive waste.

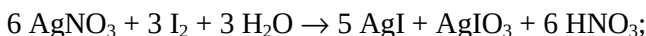
Preparation of INF solution for extraction proceeds as follows.

1. Clarification of solution:

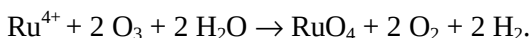
- filtration through cermet or porous polypropylene;
- centrifugation with addition of coagulants.

2. Removal of volatile FP and fission gas from solutions:

- air bubbling to remove iodine present as I^- , IO_3^- , which is then captured at silver nitrate (AgNO_3) filters:



- ozone bubbling to remove ruthenium, Ru^{4+} :



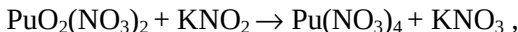
- volatile ruthenium oxide (RuO_4) is removed from gas in a reaction with NaOH ;
- removal of inert Kr and Xe by bubbling with gas sorption at zeolite or activated carbon at low temperatures.

Extraction is breakdown of a substance into two immiscible fractions: light organic fraction (TBP + diluent) and heavy aqueous fraction (acid solution of INF). A significant drawback of extraction is radiolysis of organic agents, i.e., decomposition under irradiation.

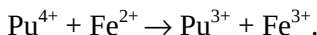
Separation of plutonium from uranium. Plutonium found in an INF solution can be 3-, 4- or 6- valent. Separation of uranium and plutonium relies on the fact that U^{6+} , Pu^{6+} and Pu^{4+} are easily dissolved both in the aqueous phase and in the organic phase, while Pu^{3+} is only slightly dissolved in the organic phase. When plutonium is restored to a condition in which it becomes 3-valent, it will completely pass into the aqueous

solution and will be removed from the process, whereas uranium will remain in the organic phase.

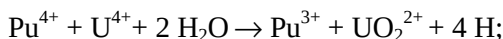
In separation of plutonium from uranium, hexavalent plutonium is first restored to a condition of tetravalency, and then to trivalency. Plutonium is converted from the hexavalent to tetravalent condition in a reaction with potassium nitrite, KNO_2 :



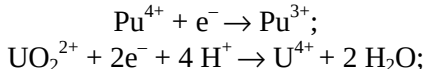
i.e. Pu^{6+} is turned to Pu^{4+} , which is then restored to Pu^{3+} in a reaction with Fe^{2+} compounds:



Iron gives up one valent electron to plutonium in a reaction with U^{4+} :



through electrochemical reduction of plutonium. An electric current is passed through the solution:



and U^{4+} will act as another reducing agent.

When the organic phase is washed with a reducing solution, Pu^{3+} will go into the aqueous phase, while U will remain in the organic phase. In re-extraction of the organic phase with a weak solution of nitric acid, uranium will pass into the aqueous phase (re-extract).

Stages of one extraction–re-extraction cycle

1. Fuel dissolution in nitric acid.
2. Extraction of uranium and plutonium compounds from solution using TBP. Uranium and plutonium pass into the organic phase.
3. Re-extraction with a reducing solution. Hexa- and tetravalent plutonium turns into its trivalent variety and goes into the aqueous phase.
4. Uranium re-extraction from the organic phase with diluted nitric acid. Uranium passes into the aqueous phase.

Control for non-proliferation of nuclear materials at a reprocessing facility

A reprocessing facility is one of the most sensitive components of the nuclear fuel cycle in terms of proliferation resistance. The main problem here is control over plutonium, which is made even more complicated by a number of factors:

Large plutonium quantities. The existing reprocessing facilities are capable of treating about 1000 t of INF per year. One tonne of irradiated fuel from light water reactors contains 6–7 kg of plutonium, which means that 6–7 t of plutonium can be put through the facility in one year.

High accuracy requirements. The Significant Quantity of plutonium, SQ(Pu), adopted by the IAEA is 8 kg. Suppose plutonium needs to be monitored at the reprocessing facility with an accuracy of 1 kg. With 7 t of plutonium passing through the reprocessing facility every year, the monitoring accuracy should be in the order of $\sim 10^{-2}$ %. The realistic accuracy of Pu mass measurements is 0.1–1 %. The permissible imbalance is about 0.1 %, which is close to the limit of measuring capabilities. As a result, inventory has to be taken several times a year, with the facility divided into material balance areas for location of a potential plutonium diversion point.

Plutonium is found in different phase states (solid, liquid, organic); it may be part of compounds with different valences, and is involved in periodic, continuous or semi-continuous processes.

The following factors are considered in assessing the extent to which plutonium compounds may be attractive for theft:

Density factor f_1 defines the Pu content in its compounds. Factor f_1 is treated as a function of NM volume containing 1 g of Pu. For Pu metal, this factor is assumed to be $f_1 = 1$. The density of Pu metal is 19.8 g/cm^3 ; i.e. its specific volume is $I \sim 5 \cdot 10^{-5} \text{ l/g}$. The datum point of function $f_1(V_{y\lambda})$ is 1, given $V_{sp} = 5 \cdot 10^{-5} \text{ l/g}$. Other Pu-bearing materials have larger specific volumes and, hence, smaller values of factor f_1 .

Time factor f_2 accounts for the time it takes for a group of specialists armed with modern equipment to convert a Pu-bearing material into the charge of a nuclear explosive device. It is assumed that plutonium metal can be turned into such a charge in a week's time, i.e. the time factor for Pu metal is $f_2 = 1$ with $t = 7$ days. For other Pu-bearing materials, the charge production time is longer and the f_2 value is smaller.

Radiation factor f_3 describes the radiation hazard of a Pu-bearing material as compared with Pu metal. The radiation factor of plutonium metal is taken to be unity.

The factors of density $f_1(V_{sp})$ and activity $f_3(A)$ account for the difficulty of producing a Pu-bearing material, while the factor of time $f_2(t)$ characterizes the difficulty of converting it to a nuclear explosive device.

The generalized factor of attractiveness of Pu-bearing materials is defined as a product of the three above factors: $f_1(V_{sp})$, $f_2(t)$, and $f_3(A)$. The attractiveness factors for different Pu-bearing materials are given in Table 2.4.

Table 2.4

Attractiveness factors of Pu-bearing materials

Material	$f_1(V_{sp})$	$f_2(t)$	$f_3(A)$	$f_1 \cdot f_2 \cdot f_3$
Pu metal	1	1	1	1
PuO ₂	0.70	0.90	1	0.63
(U,Pu)O ₂	0.40	0.65	1	0.26
Pu(NO ₃) ₄	0.25	0.80	1	0.20
(U,Pu)(NO ₃) _x	0.15	0.70	1	0.10
INF solution	0.06	0.35	0.004	$8 \cdot 10^{-5}$
FA	0.08	0.10	0.004	$3 \cdot 10^{-5}$
Concentrated HLW	0.025	0.35	0.001	$9 \cdot 10^{-6}$
Solidified HLW	0.05	0.02	0.001	$1 \cdot 10^{-6}$

Advanced proliferation-resistant aqueous INF reprocessing technologies

SAFAR process of INF reprocessing. The key proliferation resistance idea of this technology lies in incomplete separation of uranium, plutonium and fission products.

SAFAR process as distinct from PUREX process:

1. Pu is not fully separated from U and FP. Pu and U are separated together only in two cycles of extraction, i.e. U and FP “impurities” are deliberately left in Pu (~1 % of the starting quantity).
2. Pure U and Pu dioxides are not separated. MOX fuel particles are produced by the sol-gel method.

3. High radioactivity of the end product. It is unattractive for diversion and affords easy control over fuel, but additional measures are required for radiation safety of personnel.

Sol-gel process

The starting material is an acid solution of INF after two cycles of FP separation. Subsequent operations are:

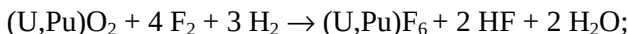
1. Addition of reagents to the solution to reduce acidity.
2. Addition of the solution to an inorganic material, e.g. to ethyl benzoate, for moisture absorption. The nitrite mixture $(\text{U,Pu})\text{O}_2(\text{NO}_3)_2$ is treated to produce $(\text{U,Pu})\text{O}_2(\text{OH})_{0.4}(\text{NO}_3)_{1.6}$, which is a colloid.
3. Colloid injection into an ammonia-based organic mixture which continues removing water from the colloid. The operation produces jelly-like spherical granules (40–100 μm in size).
4. Heat treatment of granules at higher temperatures:
 - at 95 °C – ammonia detachment;
 - at 125–200 °C – water detachment and formation of $(\text{U,Pu})\text{O}_2(\text{OH})_4$;
 - at 300–400 °C – evaporation of organic substances, granulation;
 - at 400–500 °C – baking of MOX fuel granules.

Non-aqueous (“dry”) INF reprocessing technologies

Pyrochemical fluoride-gas process. This process relies on the difference in boiling temperature, volatility and sorption capacity of U, Pu and FP fluorides. The boiling temperatures of U and Pu hexafluorides at atmospheric pressure are 56 °C and 62 °C. At such temperatures, the main fission products form non-volatile or low-volatile fluorides.

The main stages of the fluoride-gas process are:

- 1) thermal stripping of fuel claddings at 1600 °C;
- 2) fuel fluorination at 400 °C:



the bulk of FP fluorides remains in the non-volatile precipitate. The substances released are fluorides of U, Pu and some FP, and as fission gas (Xe, Kr, I);

3) freezing-out of FP fluorides at a desuperheating coil at 27 °C. A gas flow is fed into a cylindrical tank from the top, at an angle to its axis. Solid particles hit its walls and settle out;

4) passing of a gas flow through sodium fluoride (NaF) granules. Use is made of the difference in the sorption capacity of NaF relative to U, Pu and FP fluorides; U, NP and Tc fluorides are sorbed on NaF granules at 100°C and Pu, Ru, Zr and Nb fluorides, at 400°C;

5) desorption of uranium hexafluoride (UF₆) from granule surfaces by a mixture of “fluorine(10 %)-nitrogen(90 %)” at 400°C.

The disadvantages of the fluoride-gas technology lie in the following:

- removal of FP fluorides from UF₆ is incomplete;
- Pu is inferior to uranium in changing into volatile fluorides, and spreads over surfaces;
- this technology is unfit for MOX fuel reprocessing due to a high concentration of plutonium.

Pyrometallurgical reprocessing. One of the options with this technology is the method of electrochemical refining.

The bottom part of an apparatus for electrochemical refining is filled with liquid cadmium (anode), which is overlaid by a molten salt layer (mixed K, Na, Ca and Ba chlorides). An iron cathode is inserted into the salt melt from above.

Electrochemical refining includes the following stages:

1) fuel rods are cut and loaded into a perforated graphite basket, which is then immersed in a layer of liquid cadmium;

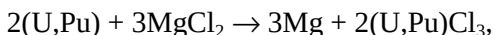
2) fuel dissolves in cadmium, while the claddings remain in the basket;

3) fuel and fission products are distributed between Cd and molten salt:

- fission gas and volatile FP pass from the melt to the gas blanket;
- solid FP pass into molten salt;
- U and Pu are found in both layers;

4) current passing. U, Pu and Zr go from liquid cadmium and molten salt to the iron cathode.

The cathode deposit is removed and remelted to become fresh fuel. Removal of FP from uranium and plutonium is improved by halide slugging. U and Pu are transformed into chlorides:



which return into the molten salt. The coefficients of FP removal from fuel are small (10^2 – 10^3 as against 10^6 – 10^8 in the PUREX process).

DUPIC process. DUPIC (Direct Use of spent PWR fuel in CANDU) is one of the INF reprocessing options which features an improved proliferation resistance.

Its purpose is to reuse INF of light water reactors, such as PWR, in heavy water reactors, such as CANDU. The irradiated fuel of PWRs is enriched in U to 0.9 % (h.a.) and has 0.6 % of Pu, which contains 70 % of fissionable isotopes. So, the content of all fissionable isotopes in INF is about 1.3 % (in terms of h.a.). CANDU reactors can run on natural uranium (with 0.7 % of ^{235}U), i.e. the irradiated fuel of PWRs can be reused in CANDUs.

The DUPIC process includes:

- 1) dismantling of irradiated fuel assemblies, separation of fuel rods;
- 2) lateral cutting of fuel rods into pieces of ~ 20 cm;
- 3) longitudinal cutting of claddings;
- 4) voloxidation, i.e. heat treatment in oxygen environment at 400°C . Uranium dioxide (UO_2) changes to U_3O_8 , the fuel core becomes 30 % larger, and the fuel sheds its cladding. The fuel becomes porous and releases fission gas;
- 5) treatment by the OREOX process. OREOX is a redox process in which oxidation alternates with reduction of uranium oxides:
 - a) air oxidation at 450°C ; UO_2 is transformed into U_3O_8 , as it is in voloxidation;
 - b) reduction in the environment of $\text{Ar}+4\% \text{H}_2$ at 700°C ; uranium octaoxide (U_3O_8) turns into UO_2 ; repeated oxidation–reduction cycles lead to formation of dispersed UO_2 powder and to release of all fission gas;
- 6) UO_2 powder sintering to produce pellets;
- 7) fabrication of fuel rods and fuel assemblies by a standard process.

The DUPIC process is distinguished by the following.

1. Absence of solvents leads to:

- small volume of radioactive waste;
- compact reprocessing facilities, which can share the site with a nuclear power plant.

2. No separation of U from Pu; incomplete removal of FP.

DUPIC offers improved proliferation resistance due to:

- high radioactivity of fuel materials;
- no separation of U from Pu;
- freedom from long hauls, with a reprocessing facility built on the same site with the NPP.

Radioactive waste treatment technologies

All nuclear technologies are associated with radioactive materials either by using or by generating them. Fresh fuel assemblies of nuclear reactors

contain radioactive isotopes of uranium, while irradiated fuel incorporates isotopes of uranium, plutonium, transuranic elements and fission products. Part of these isotopes can be extracted and put to use. The remaining radioactive material, the utilization of which seems unfeasible today, is regarded as radioactive waste (RW).

A feature specific to RW is the impossibility of eliminating it by traditional methods, such as incineration or conversion to another chemical form. Whatever such a form may be, RW retains its radioactivity. The only thing traditional methods can offer is to convert waste to a form suitable for its final disposal in geological repositories.

The greatest hazard for the biosphere comes from RW produced by chemical reprocessing of irradiated nuclear fuel. Fission products are removed from INF during its reprocessing. The content of FP is 30–40 kg/t in INF of thermal reactors and 100 kg/t in INF of fast reactors, with the corresponding FP activity making 6 MCi/t INF and 20 MCi/t INF, respectively.

For comparison:

- the total release of radioactive material during the Chernobyl accident is estimated at 90 MCi;
- the total radioactive release during the Kyshtym accident (explosion of liquid HLW storage facility) is estimated at 20 MCi;
- RW activity on Rosatom sites (in 1990) was 2.3 GCi;
- as of 1995, Russia had about 9400 t of INF with the total activity of 4.65 GCi (its average specific activity being 0.5 MCi/t). Considering that the INF will be reprocessed sooner or later and its activity will be passed on to waste, the potential total activity of RW in Russia is 7 GCi.

Radwaste treatment is undertaken to protect man and environment against its adverse impacts.

RW is classified by its aggregative state into liquid, gaseous and solid waste and by the specific activity into low-level, intermediate-level and high-level waste. Bearing in mind the main purpose of this chapter, discussion will be confined to the specifics of treating high-level and intermediate-level waste.

Treatment of high level waste (HLW) will be discussed in more detail.

There are two major types of HLW:

- HLW resulting from INF reprocessing. This is mainly liquid waste, as industrial fuel reprocessing is based on aqueous processes of NM extraction from solutions;
- irradiated fuel assemblies (IFA) of power reactors.

The key stages of HLW treatment are:

1. Monitored interim storage:

- Liquid HLW is kept in stainless steel tanks; monitoring covers heat release and gas blanket composition (hydrogen resulting from water radiolysis is removed);

- IFAs are kept in water pools on NPP sites;

2. Evaporation of liquid HLW (with its volume reduced by a factor of 150 to 200). This process is accompanied by:

- a rise in specific activity of concentrated HLW;

- intensified gas formation due to water radiolysis, with the ensuing risk of hydrogen–air mixture explosion;

- increase in specific heat release caused by natural decay of nuclides, with the ensuing rise of HLW temperature;

- intensification of corrosive activity of HLW as concentration and temperature rise.

3. Solidification of HLW. The purpose of this stage is to implant HLW into a stable matrix which will prevent waste migration into the environment. Incorporation of HLW into glass (vitrification) is believed to be the most suitable form of its immobilization.

There exist two vitrification processes.

Single-stage process. Liquid concentrated HLW is poured into a crucible, and glass-forming agents are added to it. The mixture heating is accompanied by complete evaporation of moisture, baking of the resultant dry waste, and melting of the glass mass.

Once it is cooled down, the crucible together with its contents will be sent off for disposal.

Two-stage process:

a) calcination of the starting HLW at 300–400°C;

b) mixing of the calcination product and the glass-forming additives, with the resulting mass transferred to a melting furnace;

c) heat-up and vitrification of the mass at 1100–1150 °C;

d) periodic discharge of the glass mass into steel containers;

e) interim storage and disposal of the containers.

There are alternative technologies of HLW immobilization. They consist in incorporation of this waste into other stable materials, such as ceramics, glassceramics, mineral-like materials, e.g., SYNROC.

SYNROC is an abbreviation of Synthetic Rock. Creation of synthetic rock for HLW immobilization is based on the assumption that such material will be as stable and durable as natural rock.

Treatment of liquid intermediate-level waste

Intermediate-Level Waste (ILW) includes solutions from extraction cycles (except for the first cycle), condensate resulting from evaporation of low-level waste, and vapor produced in evaporation of high-level waste.

The main stages of ILW treatment are:

- 1) precipitation and removal of ILW from liquid phases (settling and filtering with the use of coagulants);
- 2) ion-exchange treatment of the remaining liquid;
- 3) evaporation to produce solid residue;
- 4) immobilization by bituminization (the material is mixed with bitumen mass and is left to solidify);
- 5) containerization of the bituminous mass with ILW;
- 6) interim storage and final disposal.

Bitumen as an immobilization material has the following merits:

- low water leaching;
- suitability for all chemical forms of ILW (salts, hydroxides, organic compounds);
- good radiation resistance.

The disadvantages of bitumen are its combustibility (as a product of oil refining) and softening when heated (asphalt).

An alternative to ILW immobilization is its cementation, i.e. incorporation into concrete. Concrete as an immobilization material is appreciated for its:

- low cost and simplicity of handling;
- high radiation resistance;
- high heat conductivity;
- being neither combustible nor softening when heated.

However, concrete does not have sufficient chemical resistance to water. Various rates of water leaching are given below for comparison of several materials:

glass:	$10^{-8} \div 10^{-7} \text{ g}/(\text{cm}^2 \cdot \text{day})$;
SYNROC:	$10^{-6} \div 10^{-5} \text{ g}/(\text{cm}^2 \cdot \text{day})$;
bitumen:	$10^{-6} \div 10^{-4} \text{ g}/(\text{cm}^2 \cdot \text{day})$;
concrete:	$10^{-3} \div 10^{-2} \text{ g}/(\text{cm}^2 \cdot \text{day})$.

That is why glass and SYNROC are predominantly used for immobilization of high-level waste and bitumen and concrete for immobilization of intermediate- and low-level waste.

A fuel cycle ends with final disposal of special casks with RW in deep, stable geological formations. Common candidates for this purpose are: salt deposits, clayey sedimentary and other rocks.

CHAPTER 3

INTERNATIONAL NON-PROLIFERATION SAFEGUARDS

3.1. IAEA activities

The global problem of non-proliferation is being dealt with by the International Atomic Energy Agency (IAEA [1]). Using a well-developed system of measures, referred to as the International Safeguards, the IAEA seeks to ensure that nuclear materials (NM) are used exclusively for peaceful purposes.

The system of International Safeguards is based on the Treaty for the Non-Proliferation of Nuclear Weapons (NPT) and is described in the IAEA document INFCIRC/153. It relies largely on the national systems of safeguards, making it possible to exercise control over all NM in the states – signatories to the NPT.

Organization of international control over nuclear materials

The IAEA, established in Vienna in 1957, is an international intergovernmental institution related to the United Nations Organization through a special agreement and is thereby made part of the UNO system. This agreement states that the Agency acts as an independent international organization having a working relationship with the UNO. The IAEA reports its activities to the UN General Assembly and cooperates with the Security Council by providing it with the information and assistance that may be required for the Council to perform its functions of keeping peace and security in the world.

The Agency's objectives are defined in its Statute:

- It shall seek to accelerate and enlarge the contribution of atomic energy to peace, human health and prosperity throughout the world;
- The Agency shall encourage research and development in the field of peaceful energy uses, and shall provide materials, services, equipment and facilities to this end;
- The IAEA shall establish and apply safety rules in connection with the use of nuclear energy and radiation;
- The Agency shall be authorized to establish and implement safeguards for exclusively peaceful uses of nuclear materials.

As of 2007, the IAEA had 144 states as its members. Its steering entities are the General Conference and the Board of Governors.

The General Conference is the highest authority of the Agency. Its sessions are held once a year. Most of its decisions and resolutions are made by a simple majority vote.

The Board of Governors guides the IAEA work in between the General Conference sessions. Its decisions on the main aspects of the Agency's activities are subject to approval by the General Conference. The Board of Governors has 35 members. Its permanent members are ten states whose nuclear science and engineering are best developed, namely: Russia, China, USA, UK, France, Germany, Japan, Italy, Canada, and India. Besides, every year, three more states most advanced in the field of nuclear technology are appointed to the Board for a term of one year. All other members are elected for two years to represent states, other than the above ten, from seven regions: Latin America, Western Europe, Eastern Europe, Africa, Middle East and South Asia, South-East Asia and the Pacific, and Far East.

Besides, the Board of Governors will periodically set up *ad hoc* committees to address major specific matters. Thus, in view of the NPT coming into force in 1970, the Board appointed a committee for development of a standard safeguards agreement, which came to be referred to as document INFCIRC/153.

All regular practical activities of the Agency are carried out by its Secretariat. The IAEA Secretariat relies on the guidance and leadership of its Director General who is responsible for fulfillment of the Agency's work program. At present, the post of Director General is held by Yukiya Amano from Japan.

The administrative structure of the IAEA is similar to that of a large research center (Fig. 3.1) and is tailored to its purposes. Its six major departments deal with: technical cooperation; nuclear energy; nuclear safety and security; management; nuclear sciences and applications; and safeguards. The departments consist of divisions, each subdivided into sections to address specific subjects.

Main areas of IAEA activities

All the variety of IAEA activities can be divided into three general areas: control over nuclear materials; technical assistance to countries; and scientific programs. Out of the six departments, three are responsible for implementation of scientific programs:

The departments for nuclear energy and for safety and security pursue studies in two directions:

- nuclear power and fuel cycles;
- nuclear safety and radiation protection.

The department of nuclear sciences and applications studies global problems faced by the world, such as food and fresh water shortage, human health problems, etc.

The department of technical cooperation aims to facilitate transfer of nuclear energy knowledge to countries seeking it – primarily to the developing world. The technical assistance program covers:

- personnel training (provision of training allowances, re-training courses);
- consultancy missions to help in solving problems related to nuclear energy uses;
- research contracts. Every year, the IAEA allocates \$ 4 to 5 million for research activities. It supports studies under ~ 1900 contracts and agreements in more than 90 countries, with the majority of them being developing economies.

The department of safeguards is the Agency's largest unit with about 366 employees. This is explained by the fact that the department is entrusted with one of the most important tasks undertaken by the Agency, to wit, implementation of the international safeguards as a system of measures used by the IAEA to make sure that its member-states meet their obligations assumed in connection with the Agency's Statute and the Non-Proliferation Treaty.

To this end, the safeguards department is staffed with about 250 inspectors. Inspection activities include independent measurements of nuclear material parameters on sites and use of containment and surveillance techniques to keep nuclear materials under control during inspection intervals. The IAEA inspectors have at their disposal up-to-date instrumentation and advanced systems. The safeguards-related data are processed by state-of-the-art computers.

The tasks of the safeguards department include inspections at national fuel cycle facilities; development of inspection/monitoring techniques and equipment; evaluation of safeguards information; cooperation with national authorities on matters of safeguards implementation. The safeguards department has six divisions (see Fig. 3.1). Three operations divisions carry out actual inspections in various regions of the world. The functions of the other three divisions are to support the activities of the operations staff.

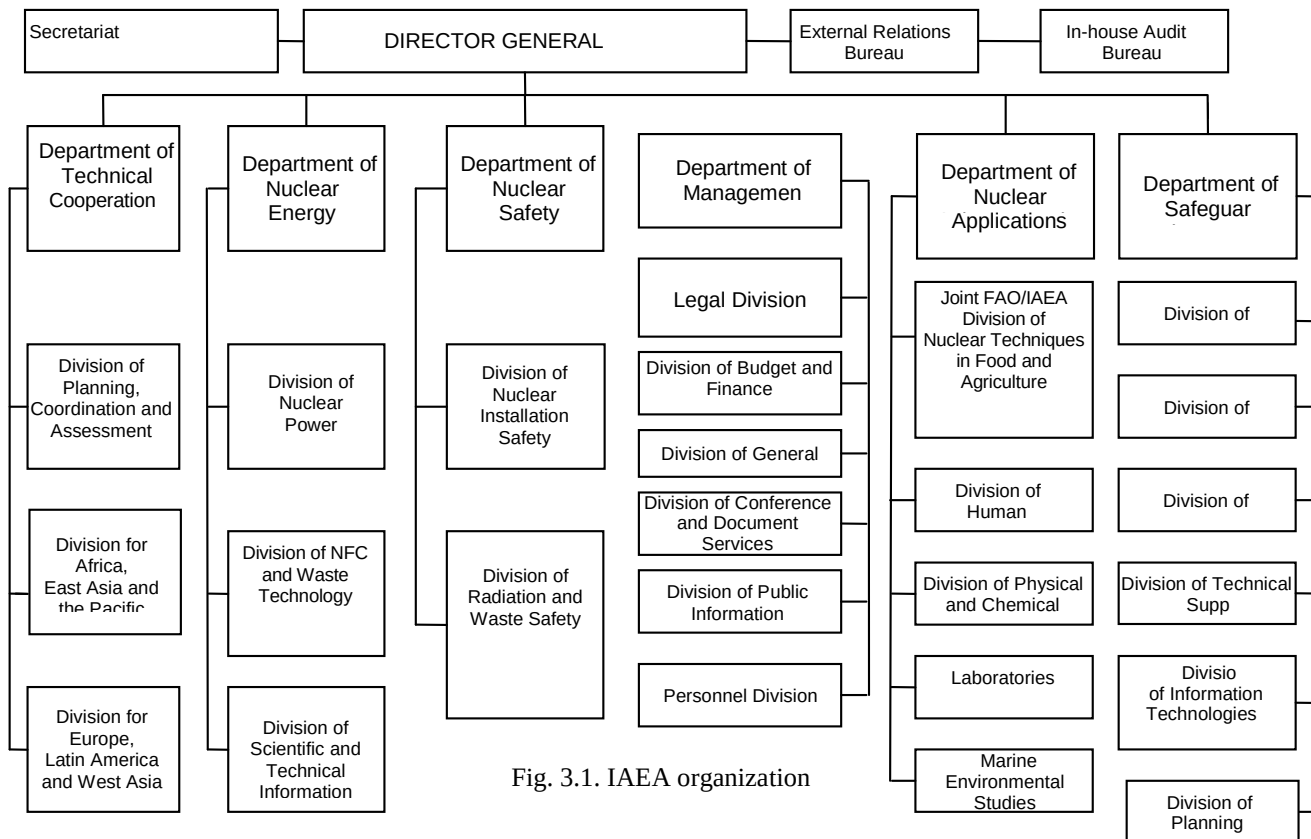


Fig. 3.1. IAEA organization

The division of information technologies analyzes and assesses the safeguards implementation activities by collecting and reviewing reports, questionnaires on design of facilities, and inspection results.

The division of technical services is responsible for development and use of equipment, instrumentation and computers. It provides the inspectors with up-to-date facilities.

The division of concepts and planning develops and improves safeguards implementation procedures and approaches, works out ways for enhancement of their efficiency, and deals with matters of standardization and statistical treatment of inspection results.

International legal framework for development and application of the IAEA Safeguards

Given below are definitions of some terms associated with the practice of international safeguards.

Source material is uranium (natural or depleted) and thorium in the form of metal, alloy, chemical compound or concentrate (other than ore).

Special fissionable material is plutonium-239; uranium-233; uranium enriched in U-235 or U-233; or other material containing one or several of the above substances.

The **IAEA Safeguards** constitute a system of technical measures taken by the IAEA in accordance with its Statute and the NPT for the purpose of non-proliferation of nuclear weapons.

1. The IAEA Safeguards were originally based on the Statute of this organization [2]. The principal requirements and conditions of the safeguards application were defined in Article III.A.5 of the IAEA Statute. Those requirements may be described as minimal. A state was required to make a minimum of efforts for providing access to nuclear materials at individual facilities chosen for inspection on agreement with the parties concerned.

2. In 1961, the IAEA Statute was taken as a basis for development of the initial safeguards system which is described in INFCIRC/26. At that stage, the inspection and verification activities of the Agency were limited to small research reactors and laboratory facilities.

3. As nuclear activities grew in scale, it became clear that the original system of safeguards was in need of extension and improvement. In 1965, the system was revised and extended to include nuclear power reactors, irradiated fuel reprocessing facilities, as well as nuclear materials found at fuel fabrication plants. This system – INFCIRC/66 – amended in 1966 and

1968 is in use up to now as a basis for agreements on safeguards concluded with the states that have no nuclear weapons and are not signatories to the NPT. Like all the earlier systems of safeguards, INFCIRC/66 was aimed at control over individual facilities in a country (such was, for instance, the agreement between the IAEA and Israel).

4. With the Treaty on the Non-Proliferation of Nuclear Weapons having come into effect in 1970, the IAEA acquired new significance in its role of consolidating the non-proliferation regime. It is very important that Article III.1 of the Treaty stipulates that the safeguards should be extended to all peaceful activities of the signatory states. Thus, unlike the safeguards imposed according to the IAEA Statute upon specific facilities, the safeguards arising from the NPT are full-scale and covering the whole nuclear fuel cycle in the states where they are implemented. The system described in the IAEA document INFCIRC/153, was set up 1971 and is still effective.

5. INFCIRC/153 [3] states that the main obligation assumed by a state in the framework of a safeguards agreement concluded in accordance with the NPT, lies in the fact that the safeguards should cover all the source or special fissionable materials involved in peaceful nuclear activities on the state's territory for the exclusive purpose of making sure that such material is not diverted to production of weapons or other nuclear explosive devices.

The system of INFCIRC/153 requires that a state should keep the Agency informed, or, more specifically, that it should:

- supply the IAEA with information on the design features of its facility as well as with other, safeguards-related information;
- keep accounting records for every material balance area;
- submit to the IAEA reports on its nuclear materials as shown by the current accounting documents.

Thus, availability of a national system for accounting and control of nuclear materials is a prerequisite for implementation of efficient international safeguards, but cannot supplant the latter.

Agreements based on INFCIRC/153 will also stipulate that:

- a state should set up and maintain its system for accounting and control of all nuclear materials to be kept under the safeguards;
- a national system for NM accounting and control should be structured according to material balance areas;
- a national system should provide for the availability and use of measurement systems and procedures to determine the actual inventory of nuclear materials (i.e. should allow taking a physical inventory at facilities).

It is required that facilities submit to the IAEA reports of three types, which should be prepared on the basis of accounting documents:

- a report on changes in the NM inventory (a detailed list of all materials received and dispatched);
- a material balance report with indication of the inventory difference and the range of its statistical straggling;
- a list of available nuclear material quantities.

The basis of the IAEA safeguards

The purposes of the IAEA safeguards are clearly stated under paragraph 28 of INFCIRC/153 as “timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection”. The words “for purposes unknown” are of importance for practical application of the safeguards as they imply that the IAEA should not try to find out the nature of the intended use of the diverted material, nor should it determine whether the material was diverted to the “manufacture of nuclear weapons or other nuclear explosive devices”.

The key principle of the Agency’s system of safeguards lies in comparison of the information submitted by the entity under inspection with the results of independent verifications and observations made by the IAEA.

Keeping to this principle in attaining the objectives of the safeguards, the Agency pursues its monitoring activities along the following three lines:

- study of the data submitted by a state as part of the information on the design of national facilities, in its reports to the IAEA, and in preliminary notifications concerning international transfers;
- collection of information during inspections to verify the states’ declarations, during routine and special inspections;
- assessment of the information submitted by a state and collected during inspections to check it for completeness, accuracy and validity.

It should be emphasized that the IAEA safeguards are applied in a way to avoid impediments to the economic and technological development of countries, to their international cooperation for peaceful use of nuclear energy. The Agency avoids unjustified intervention in peaceful nuclear activities of states and operation of their facilities.

Article XII of the IAEA Statute defines the types of activities undertaken to implement the safeguards. According to this article, the Agency has the right:

- to verify the information on the design of nuclear facilities;
- to demand that relevant national authorities keep records as required for NM accounting and provide access to such documents by the Agency;
- to demand submission of the accounting documents to the Agency;
- to send IAEA experts to the states that recognize the safeguards.

As mentioned already, for the purposes of the safeguards to be attained, the IAEA checks on the nuclear materials during inspections. To this end, it is necessary to know, first of all, which and how much material should be checked to allow a conclusion on the absence of NM diversion. Such verification involves three reference parameters:

- significant quantity;
- time of detection;
- probability of detection.

Significant quantity of nuclear material

In the context of a national system of safeguards developed mainly to protect NM from theft or acts of terrorism, the word “significant” may be applied to a relatively small quantity of material, considering, for example, its high toxicity (plutonium). However, the international safeguards are intended primarily to make sure that governments do not procure nuclear weapons or other nuclear explosive devices (NED), and it takes a relatively large NM quantity to produce even one NED.

In practice, the safeguards apply to NM with various Pu and U concentrations and of various isotopic compositions. This fact suggests the need for defining the “Significant Quantity” (SQ) for each material category, so as to indicate how much material should be looked for to determine whether there was a diversion in violation of the safeguards.

In general, the SQ is defined as an approximate quantity of nuclear material large enough to allow producing a nuclear explosive device, whichever conversion process is used.

The SQ varies depending on whether this material may be directly used for NED production, or it needs to be converted first, e.g., by enrichment (in which case it will be referred to as an indirectly usable material).

For directly usable materials, the Significant Quantities are established by experts of the Standing Consultative Group of the IAEA for Implementation of the Safeguards as follows:

- 8 kg of Pu (containing < 80 % Pu-238);
- 8 kg of U-233;
- 25 kg of U-235 contained in HEU.

For indirectly usable materials, the Significant Quantities are:

- 75 kg of U-235 contained in LEU (10 t of natural uranium);
- 20 t for depleted U and Th.

Significant Quantities in inspection practice

The actual purpose of inspections at a specific facility does not necessarily lie in detecting diversion of one SQ (nor is it practicable in some cases). For instance, checking on nuclear materials at reactors consists primarily of counting, identification and measurement of individual accounting items, i.e. fuel assemblies. Once such items are counted, the purpose of inspectors is to find whether at least one FA is missing. Before research reactors of the IRT type were converted to low-enriched uranium (LEU), fuel assemblies contained ~ 300-400 g of highly enriched uranium (HEU). It means that the inspection target in counting such items is smaller than one SQ (25 kg) for HEU.

At large facilities where nuclear material is found in bulk, it may be the other way around. In such cases, inspection will necessitate measuring large quantities of NM found in different physical forms and varying in chemical composition, including such material as waste. It may be tentatively assumed that the NM measurement error is about 1 % of the total measured quantity. It is clear, however, that 1 % of the inventory or throughput of a large facility with NM in bulk may exceed (by far in some cases) 1 SQ.

Let us consider a case where the IAEA safeguards cover several fuel fabrication facilities, with a large quantity of indirectly usable bulk material (LEU) being processed. Measurement errors and other factors make it necessary to set the inspection target at five SQs. In consequence, at such facilities there is no ruling out the possibility (with a credibility level of 90–95 %) of one SQ diversion in the case of LEU. It does not mean, however, that diversion of one SQ is not detectable at all. Detection is possible even in this case, but its probability is lower. Besides, a high threshold of detection is offset by using additional means of control, such as containment and surveillance. Finally, it should be borne in mind that diverted LEU may be discovered at other stages of its conversion into a weapons-grade material.

In countries with a well-developed fuel cycle, it is theoretically possible to divert a significant quantity of material by adding up under-SQ material quantities diverted at each one of many facilities. With such an approach, diversion would involve materials of different types and categories and would necessitate concerted actions of personnel from a large number of facilities. That is why the IAEA regards this scenario as unattractive for a rogue state and highly risky. Besides, an attempt to counteract such hypothetical diversion scenarios would necessitate an inspection regime much too cumbersome for implementation by either a state or the IAEA.

Early detection

Early detection is a notion of importance to the safeguards. The early-detection requirement determines the frequency of inspections at facilities. The system of the IAEA safeguards is based on the assumption that diversion of a significant quantity of nuclear material should be detected at an early stage, irrespective of whether it is committed once or on multiple occasions. The practical implications of early detection depend on the type of the nuclear material covered by the safeguards. In order to determine ‘timely detection’ in quantitative terms it is necessary to have a notion of the ‘conversion time’. The time of NM conversion is the time required in optimal conditions for converting NM in a given form into a component of a nuclear explosive device. The following typical conversion time periods were established on recommendation of the Consultative Group:

Pu, U ($U-235 \geq 20\%$) (in fresh fuel)	7 – 10 days;
PUO_2 , $Pu(NO_3)_4$	1 – 3 weeks;
Pu, U ($U-235 \geq 20\%$) in spent fuel	1 – 3 months;
U ($U-235 < 20\%$), Th	about 1 year.

Besides, following the CG recommendations, the IAEA established the ‘detection time’ to be of the same order of magnitude as that of the conversion time. The ‘order of magnitude’ here is a factor equal to 1–3.

In practice, it is sometimes difficult to stay within a short time of detection. So, at some facilities where nuclear material is found in bulk it is a far from easy business to reconcile a short detection time with the requirements of normal operation. For plutonium and highly enriched uranium (whose conversion takes 7–10 days), inspection targets are set at the upper boundary of the permissible time range (3 weeks). In those cases where acceptable inspection frequency falls short of ensuring early

detection, additional measures are taken to attain the required detectability, such as application of seals and surveillance.

Detection probability

Considering the global scale of the IAEA activities, it is an extremely difficult task to discover NM diversion with a 100 % probability and as early as required. That is why the Agency seeks to build such a system of safeguards that will meet these objectives with a certain probability. This probability should also be specified. Neither INFCIRC/66, nor INFCIRC/153 refers specifically to the level of confidence in detection, but the Agency interprets these documents as if this notion were covered there. From the viewpoint of the Agency, the detection probability should be so high as to keep a state from resorting to diversion and to ensure the required confidence of the international community. The target detection probability was set by the IAEA at the level of 0.9±0.95.

Extent of independent inspections

The effect of the probability of detecting a significant quantity of NM on the extent of IAEA inspection activities can be illustrated by a model case.

Suppose we have as many one-type articles as $N = 12000$. The SQ of the material under consideration (e.g., plutonium) is $M = 8$ kg. The mass of each article is $m = 80$ g. It is necessary to determine the number of articles to be verified during an IAEA inspection, if the probability β of attaining the safeguards purpose should not be less than 0.9.

The number of diverted components x in sample n is taken to be a random quantity whose distribution follows the hypergeometric law. The sample size is then determined by the formula:

$$n = N \times (1 - \alpha^{m/M}), \quad \alpha = 1 - \beta, \quad (3.1)$$

if

$$(M/m) \ll N. \quad (3.2)$$

Condition (3.2) implies that relatively large components are under consideration. Once fulfillment of this condition is checked upon, formula (3.1) will be used to find the number of measurements to be made during the inspection:

$$n = 12000 \cdot (1 - 0,1^{1/100}) = 276.$$

Apparently, the extent of sample measurements is vastly reduced in comparison to the initial scope, if the adopted SQ is largely in excess of the component mass, and the probability of attaining the purpose is noticeably smaller than 1.

Equipment involved in implementation of the safeguards by the IAEA

The complexity and diversity of NM-containing facilities call for use of various techniques and equipment [4]. Table 3.1 presents the main verification procedures carried out by the IAEA at such facilities.

Since the 1980s, inspection activities have tended to involve expanded means of containment and surveillance, as well as non-destructive test methods.

Table 3.1

Main types of facilities covered by the IAEA safeguards (data of 2002)

Facility type	Isotope separation facilities	Fuel fabrication facilities	Power reactors and storage facilities	Irradiated fuel reprocessing facilities
Number of facilities	10	41	239 reactors, 80 storage facilities	6
Materials under control	UF ₆	U and Pu oxides, MOX	Irradiated fuel	U and Pu nitrates
Key control procedures	Weighing, γ -spectrometry	γ -spectrometry, neutron measurements, destructive analysis	Cerenkov effect, gamma and neutron measurements	Destructive analysis, neutron measurements

The scale of equipment uses may be broadly characterized by the following statistics dating to 2002:

- 550 facilities found under the safeguards were equipped with 700 non-destructive testing systems;
- 760 samples were analyzed by destructive testing;
- 400 video surveillance systems were installed at facilities;
- 24500 seals were checked;
- 230 samples were taken near 50 facilities and analyzed.

Some data on the equipment in use by the IAEA in its inspection activities are given in Tables 3.2 – 3.7.

Optical surveillance. Optical (video) surveillance equipment has an important part to play in implementation of the IAEA safeguards. It has found wide application in keeping continuity of the knowledge of nuclear materials in between inspections and has been a strong support to the means of NM accounting. By now, the Agency has installed about 800 operating video cameras (as part of ~ 400 video systems) at 170 facilities all over the world. Table 3.2 lists some of the systems in use by the Agency at present.

The Agency adopted a program for upgrading video equipment in use. The decision was to develop surveillance systems around the electronic DCM14 unit which digitizes images, checks information for authenticity, encodes data and ensures their confidential use, compresses data, controls power of the surveillance system, etc. This unit is the best one to meet the IAEA requirements for surveillance systems. In 1998, work was initiated to create 5 base digital surveillance systems using the DCM14 unit, which would be fully consistent with the specifics of the IAEA inspection activities and immune to possible harsh environmental conditions during their operation.

Table 3.2

Video surveillance systems in use by the IAEA in implementation of the safeguards

System designation	System name and type	Application and features
Single-camera surveillance systems with a tape-recording function		
SIDS	Sample Identification System	System for identification of fuel samples at facilities for MOX fuel fabrication. It has an interface with a neutron flux measuring instrument (HLNC) and is actuated when the neutron flux exceeds an established limit.
STVS	Short-Term TV System	System built around the MXTV equipment and meant for short-term surveillance. It comprises one camera and one recorder.
UWTV	Underwater TV	Portable system meant for underwater video surveillance. Its major application is examination of spent fuel assemblies of CANDU reactors in a storage pool. It has appliances for rotation of the camera and for illumination of the object of surveillance. The camera is enclosed in a waterproof shell, it remains operative at high radiation levels, and allows reading small print under limited lighting conditions. The system has a built-in monitor to scan images in situ.
Digital single-camera surveillance systems		
ALIP	All in One Surveillance Portable	Portable single-camera surveillance system powered from a storage battery or from the mains. It comprises a camera, a video terminal, an electronic unit DCM14, and a set of storage batteries. With the batteries fully charged, the system can operate for up to 100 days. Complete with a 660 Mb card, the ALIP system can record 40÷50 thousand images. It is installed in easily accessible places.
ALIS	All in One Surveillance	Single-camera surveillance system powered from the mains and built around an electronic DCM14 unit. It has an interface with the inspector's terminal. The information storage capacity is the same as that of ALIP. It is installed in easily accessible places.
DSOS	Digital Single-Camera Optical Surveillance	Surveillance system built around a DCM14 unit. The camera may be installed in difficult-of-access places.

Table 3.2 (continued)

System designation	System name and type	Application and features
Multi-camera surveillance system with a tape-recording function		
FTPV	Fuel Transfer Video	Underwater closed-circuit video surveillance system with a camera in a waterproof shell. It is used for monitoring fuel handling in pools.
MOSS	Multi-Camera Optical Surveillance System	The system can comprise up to 16 video cameras. Information is tape-recorded. By 2006, the system was to be replaced by an advanced digital DMOSS system.
MXTV	Multiplex TV Surveillance System	Multi-camera surveillance system (with up to 16 cameras). It will be replaced by a digital server-based system SDIS.
VSEU	Video System Multiplex	Multi-camera surveillance system in use by Euroatom.
VSPC	Video System	Closed-circuit system which can have up to 4 video cameras.
Digital multi-camera surveillance systems		
DMOS	Digital Multi-Camera Optical Surveillance	Digital multi-camera (normally with 6 to 16 cameras) system for unattended operation and remote monitoring. It is built around a DCM14 unit and has a central console. Each camera is polled by the server. Images and data are stored on a portable medium.
SDIS	Server Digital Image Surveillance	Digital server-based multi-camera surveillance system built around a DCM14 unit, which collects images and data from cameras (up to 6). It can be also used for checking electronic seals VACOSS. The server can sort images and data and transmit them to the Agency offices. The system is fitted up with an uninterruptible power supply unit which can support continuous operation of the system for 48 hours in the event of loss of power from the mains.
Data survey systems		
GARS	General Advanced Review Station Software	Advanced software for viewing video-recordings. It is widely used for analyzing recordings of many video systems, such as ALIP, ALIS, DSOS, DMOS, SDIS, etc. It provides a user-friendly interface for examining video-recordings and performs a whole number of auxiliary functions. GARS enables an inspector to make sure that the recordings are authentic, to view simultaneously images from several cameras, to detect changes in the monitored surroundings, to decode data, etc.
MORE	Multi-system Optical Review Station	The station is used by inspectors to examine video-recordings made by MXTV and MOSS systems. Every station of this type includes a computer to start programs of the MORE system, a monitor with functions of automatic detection of changes in the conditions, videotape recorders to examine video material, and a printer.

Means of containment. The purpose of seals is to provide evidence of any unauthorized attempts to get access to the protected material. Seals will also serve for unique identification of protected containers. Disposable metallic, adhesive, fiber-optic, ultrasonic, and reusable electronic seals are used by the Agency personnel, depending on their specific purpose. Seal types are briefly characterized in Table 3.3.

Table 3.3

Sealing devices applied in the safeguards-related activities of the IAEA

Seal designation	Seal type	Application and features
CAPS	Metallic, disposable	Widely used for sealing casks, cabinets and equipment of the Agency. This seal is of simple design, inexpensive; it is easily applied and removed. About 20 thousand such seals are used annually.
VOID	Adhesive, disposable	Made of material destroyed in removal. The seal is used for temporary containment of material (for several hours).
FBOS	Fiber-optic seal, disposable	Unique owing to the random pattern of fibers. This general-purpose seal is examined by an inspector in situ.
ULCS	Ultrasonic seal, disposable	Unique seal checked in situ. Used for sealing casks with CANDU fuel, kept underwater.
USSB	Ultrasonic sealing bolt, disposable	Used for sealing casks with spent LWR fuel, kept underwater.
VCOS	Variable coding seal, electronic, reusable	Its memory unit saves every act of breaking and closing the fiber-optic circuit. Used in conditions of long-term surveillance of periodically accessible objects.

Non-destructive examination of non-irradiated nuclear materials. Most materials covered by the IAEA safeguards are γ -active. Their radiation spectra show distinct lines typical of certain γ -emitting isotopes. The energy characteristics of observed spectrum lines of a material serve as a basis for identification of isotopes and, in combination with line strength measurements, allows estimating the material quantity.

Today, there are commercially available efficient instruments for analyzing γ -radiation spectra. For example, the Inspector's Multi-Channel Analyzer (IMCA) employs the technology of digital signal processing and

can operate together with various detectors made of: high-purity germanium (HpGe), cadmium telluride (CdZnTe), and sodium iodide (NaI), which afford high, medium and low energy resolution. There is also a design option of a Miniature Multichannel Analyzer (MMCA). This instrument is much smaller and lower in weight than the previously employed Portable Multichannel Analyzer (PMCA) and, into the bargain, has three times longer time of continuous operation when powered by storage batteries.

The International Agency uses in its inspections a number of γ -spectrometers which differ mostly in their resolution as well as in the capability for subsequent information processing. Many of these spectrometers comprise the above multichannel analyzers. These instruments are briefly described in Table 3.4.

Table 3.4

Gamma-spectrometers in use by the IAEA in the safeguards-related activities

System designation	System name and type	Application and features
HM-5	Hand-held Assay Probe	Modern hand-held digital gamma-spectrometers allow determining dose rates, finding radiation sources, determining the active length of fuel rods and assemblies, and detecting the presence of U and Pu. The base option of this instrument includes a NaI detector. For special applications, a CdZnTe detector can be hooked up. It can store up to 50 spectra (1024 channels for each), which are entered into a computer for subsequent processing.
IMCN, IMCC, IMCG	Based on the IMCA analyzer	With an HpGe detector (IMCG), it is a spectrometric device of high resolution. It is used for determining U enrichment and isotopic composition of Pu.
MMCN, MMCC, MMCG	Based on the MMCA analyzer	In a combination with a CdZnTe detector (MCC) and a notebook (Palmtop), it is a portable (small enough to be carried in an ordinary briefcase), powerful and flexible spectrometric system suitable for many inspection purposes.

The technique of neutron coincidence counting is a robust and accurate method which is widely used for determining the content of Pu and U²³⁵. Modern well-type systems of neutron coincidence counting can process

pulses in the range of counting rates differing by more than six orders of magnitude.

Passive systems of neutron coincidence counting allow determining the mass of plutonium by logging spontaneous-fission neutrons of mostly even-numbered isotopes (^{238}Pu , ^{240}Pu , ^{242}Pu). With plutonium isotope composition known, the measurement result – $^{240}\text{Pu}_{\text{eff}}$ mass – can be converted to the total Pu mass in the sample.

The fissionable isotope ^{235}U does not go into spontaneous fission readily enough to be logged by passive systems. In this case, instruments will register secondary induced neutron radiation, which arises under exposure to neutrons of an AmLi source (active systems). For low-energy incident neutrons, the induced fission of ^{238}U in a specimen makes an insignificant contribution to the measured rate of neutron coincidences.

Neutron coincidence counting systems have detectors of two major configurations: well-type detectors in which a specimen is fully enclosed and collar-type detectors embracing a specimen from the outside. The geometry of the former detectors is preferable as it is possible in this case to register all emitted neutrons. But the alternative collar-type geometry allows measuring specimens too large to be placed in a well-type detector (e.g., a fuel assembly). In its inspection activities, the IAEA employs neutron instruments of more than 20 types, which have various design features and are usable for specimens of certain sizes and forms and various Pu and U mass ranges. Some of them are presented in Table 3.5.

Table 3.5

Neutron coincidence logging instruments in use for determining the mass of fissionable material

Instrument designation	Instrument name and type	Application and features
Passive neutron coincidence counters		
FAAS	Fuel assembly/Capsule Assay System	Meant for checking Pu mass in non-irradiated MOX fuel assemblies.
HLNC	High-Level Neutron Coincidence Counter	Meant for checking Pu mass (from 20 g to 2 kg) in bulk materials (pellets, powder, scrap, etc.).
INVS	Inventory Sample Counter	Meant for checking Pu mass (from 0.1 g to 300 g) in samples. Instrument options for checking Pu mass in glove boxes.

Table 3.5 (continued)

Instrument designation	Instrument name and type	Application and features
Active neutron coincidence counters		
AWCC	Active Well Coincidence Counter	Meant for checking ^{235}U content in samples with highly enriched uranium.
UNCL	Uranium Neutron Coincidence Collar	Meant for checking ^{235}U content in low-enrichment fuel assemblies.
WCAS	Waste Crate Assay System	Meant for checking waste for presence of nuclear material.

Non-destructive testing of irradiated nuclear material. Methods of checking irradiated nuclear fuel involve logging of neutrons and gamma-quanta, as well as the Cerenkov ultraviolet glow. Fission products found in irradiated fuel set up a very high radiation background. It is mainly this fact that determines the type of instruments employed for verification of spent fuel.

The main sources of neutrons emitted by spent fuel are spontaneously fissionable ^{242}Cm and ^{244}Cm . These isotopes are generated in a reactor when neutrons are successively captured by the nuclei of transuranic elements. There are several approaches to logging spent fuel neutrons under conditions of intensive gamma background. It is possible, for example, to choose such detectors that either will be insensitive to gamma radiation, or will protect a neutron detector from penetration of gamma rays, while letting in neutrons. Table 3.6 lists some measurement systems in use by the Agency for examining reactors' spent fuel.

Table 3.6

Spent fuel testing instruments

Instrument designation	Instrument name and type	Application and features
FDET	Fork Detector Irradiated Fuel Measuring System	The detector head contains neutron detectors insensitive to gamma radiation (four gas-filled proportional fission counters) and two gas-filled ionization chambers to match strong gamma radiation. The ratio between neutron and gamma data together with additional information of another sort allows getting an idea of the fluence received, of the initial content of fissionable material, and of the number of in-pile irradiation cycles.
SFAT	Spent Fuel Attribute Tester	The instrument includes a multichannel gamma-radiation analyzer and a NaI- or CdZnTe-based detector. It can accurately detect irradiated fuel by identifying the characteristic lines from ^{137}Cs and ^{144}Pr fission products and ^{60}Co as an activation product. The instrument is particularly helpful in situations where the Cerenkov effect analyzers are not easily useable.
ICVD, DCVD	Cerenkov Viewing Device, Digital Cerenkov Viewing Device	ICVD is a hand-held instrument employed for identification of irradiated fuel assemblies from, mostly, light water reactors by analyzing the Cerenkov effect. DCVD is a highly sensitive digital device for analyzing the Cerenkov effect. It is particularly suitable for fuel of low burnup after prolonged cooling.

Destructive analysis techniques. Destructive measurements practiced to determine the element and isotope composition are applicable to all forms of bulk material found at nuclear fuel cycle facilities. Such measurements enable the Agency:

- to make sure that there were no long-term diversions of materials covered by the safeguards;

- to verify the quality of working standards in use for calibration of non-destructive analysis instruments;
- to carry out periodic verification of measurement systems at the inspected facility.

In general, destructive verification measurements carried out by the Agency include the following successive stages:

- 1) independent sampling;
- 2) in-situ conditioning of samples to ensure their integrity during transportation;
- 3) packaging, sealing and dispatch of samples to the IAEA laboratories;
- 4) statistical estimation of the analysis results.

The main analytical methods of destructive testing practiced by the Agency during inspections are listed in Table 3.7. This table presents the estimated random and systematic components of errors in measurements of materials of nuclear grade or similar chemical purity. It is obvious that the sampling process itself or the presence of impurities in material can tangibly affect the data of Table 3.7.

Table 3.7

Main destructive analysis methods in use by the IAEA

Method	Measured quantity	Type of material analyzed	Error, (% rel.), random and systematic	
Element analysis				
Potentiometric titration of U (Davis–Gray method)	U	U, U–Pu, U–Th ^{a)}	0.05	0.05
Potentiometric titration of Pu (McDonald-Savage method)	Pu	Pu materials ^{a)}	0.1	0.1
Calorimetry of Pu solutions	Pu	Pure Pu materials	0.1	0.1
Gravimetry with baking	U	Pure U oxides	0.05	0.05
X–K fluorometric analysis	Pu	Pu materials ^{a)}	0.2	0.2
X-ray fluorescence spectrometry	Pu, U	Pure U and Pu oxides and MOX ^{a)}	0.3	0.3
Mass–spectrometry with isotopic dilution	U, Pu	Starting solutions of spent fuel, Pu and U–Pu materials	0.1	0.1

Table 3.7 (continued)

Method	Measured quantity	Type of material analyzed	Error, (% rel.), random and systematic	
Isotope analysis				
Thermal-ionization mass–spectrometry	U, Pu isotopes	All Pu and U materials, starting solutions of spent fuel	0.05 ^{b)}	0.05 ^{b)}
Gamma–spectrometry of high resolution (Ge-based detector)	Pu isotopes, Am, Np	Pure U and Pu materials	0.5–2.0	0.5–2.0
Gamma–spectrometry (NaI-based detector)	²³⁵ U	LEU materials	0.2–0.5	0.2–0.5
Alpha–spectrometry	²³⁸ Pu	Pu materials	0.2	0.3

a) excepting INF;

b) for ratios of the main isotopes.

Safeguards-related activities of the IAEA

The inspection activities of the IAEA depend on the scale of nuclear operations carried out by a state. These operations will be small-scale in states having, e.g., one small research reactor alone, but can be quite extensive in countries with many nuclear fuel cycle facilities. The scope of inspection activities is the greater, the larger is the number of NFC facilities in a country. Table 3.8 presents rough estimates of the nuclear material quantities covered by the IAEA safeguards. It may be seen that the NM quantities under control are steadily growing, and so is the number of facilities under the IAEA safeguards.

This being so, the inspection activities, including independent measurements of nuclear materials and their control by means of containment and surveillance techniques, depend largely on the type of nuclear facilities under the safeguards. Reactors and storage facilities, where materials appear as articles, such as fuel assemblies, call for less inspection effort than do facilities with materials found in bulk, where the greater part of NM is in motion or under processing. Table 3.9 shows the numbers of various facilities covered by the IAEA Safeguards.

Table 3.8

NM quantities under the IAEA Safeguards in states possessing no nuclear weapons
(as of 1996)

Material	NM quantity, t					
	1995		1997		2002	
	INFCIRC /153	INFCIRC /66	INFCIRC /153	INFCIRC /66	INFCIRC /153	INFCIRC /66
Plutonium	388	29	430– 460*)	32–35	540–610	39–44
Highly enriched uranium	10.0	0.4	10.0	0.4	10.0	0.4
Low-enriched uranium	36900	2410	39200 – 41100	2700 – 2800	44900 – 50300	3400 – 3800
Source material	70200	3980	80000 – 84000	4500 – 4700	108200 – 121200	5600 – 6300

*) forecast data.

Table 3.9

Facilities under the IAEA safeguards in states
possessing no nuclear weapons (as of 1999)

Facility type	INFCIRC/153	INFCIRC/66
Power reactors	231	14
Research reactors and critical assemblies	173	11
Conversion facilities	13	1
Fuel fabrication facilities	39	5
Reprocessing facilities	6	1
Fuel enrichment facilities	10	0
Separate storage facilities	64	2
Other facilities (> 1 eff. kg)	76	2
Other facilities (< 1 eff. kg)	481	22
Non-nuclear facilities	0	2
TOTAL:	1093	60

It may be concluded that the system of IAEA safeguards is growing to global dimensions, and there is little material left uncontrolled. Nevertheless, implementation of these safeguards is not free from certain difficulties. The first to be mentioned among them are the problems

associated with existence of the so-called “threshold” states and the efficiency of the safeguards themselves. In recognition of the above, the IAEA is taking steps towards strengthening the safeguards regime. In 1995, the Board of Governors of the Agency set up a committee for enhancing the effectiveness and efficiency of the safeguards and entrusted it with drafting a model additional protocol seeking to improve the Agency’s capability to reveal undeclared nuclear activities. In 1997, the Board of Governors approved the Model Protocol prepared by the Committee as an addendum to the comprehensive agreements for application of the safeguards [5]. The Protocol comes into force after the Agency receives written notification made by a state on acceptability of the Protocol terms, or once it is signed by representatives of a state and the Agency.

At present, the IAEA member-states submit declarations with information on nuclear materials, on the processes these materials are involved in, and on nuclear facilities containing NM. The Protocol stipulates submission of an extended declaration on nuclear activities of a state. Such a declaration together with certain verification work should make the nuclear fuel cycle of a country and its associated activities more transparent. In addition to the data on all nuclear materials, an extended declaration will include information about all other nuclear activities, such as:

- description of all processes and location of all facilities related to nuclear activities (industrial, R&D, personnel training);
- identification of industrial, commercial and military facilities found in immediate proximity to nuclear installations.

Any process to produce nuclear materials or articles containing them is bound to leave some trace in the environment. The extent and nature of such traces depend on a number of factors, including the production technology, materials, loss limitation measures, and possible trails left by NM migrating beyond the nuclear site boundaries. Thus, the results of field tests in Sweden (1993) showed traces of nuclear activities in water and deposit samples up to 20 km away from the facility, depending on the local transport and water mixing conditions. Therefore, the Additional Protocol provides for wide application of sensitive environmental monitoring methods developed to detect traces of nuclear activities.

Provision of inspectors’ access to materials, equipment and installations is a key aspect in implementation of the safeguards. For regular inspections within the framework of the INFCIRC/153 Agreement, access should be provided to the places where such access was recognized as essential for

fulfillment of the obligations undertaken by the Agency in regard to the safeguards. Extended access is a crucial factor in consolidating the system of safeguards. This implies access to any place at the facilities covered by the IAEA safeguards. The extended access approach also applies to the areas included in an extended declaration, which have no NM at all or contain small quantities of materials exempt from the safeguards, but are associated with the nuclear activities mentioned in the extended declaration. Besides, to enhance the transparency of nuclear activities, pursuant to the Additional Protocol, a state should seek to facilitate access to industrial, commercial or military installations located in the immediate proximity to nuclear facilities.

For a state which is a party to a comprehensive safeguards agreement and an effective Additional Protocol, review of all available information should show absence of not only any evidence of diversion of the safeguarded nuclear material, but also of undeclared nuclear materials or activities. Therefore, application of the safeguards is intended to lead to a positive conclusion that all nuclear materials in a state are placed under safeguards, with their use limited to peaceful nuclear activities, or are duly accounted for. For the Agency to be able to arrive at such a conclusion, it has to assess all state-level information resulting from implementation of the comprehensive safeguards agreement and additional protocol, as well as all available and relevant information from other sources.

Confidence of the Agency and member-states in reliability of the conclusions drawn from the results of safeguards application, is directly dependent on the quality of measures taken to collect, analyze and evaluate the relevant information. Such measures should be exhaustive, detailed and effective. Declarations made in accordance with the additional protocol present extensive information on national nuclear programs. Additional information arises from implementation of the extended access approach on the sites. The Agency collects substantial data from a wide spectrum of open sources with simultaneous assessment of their reliability, and applies new technologies, such as use of images from commercial satellites. The IAEA will also use the information voluntarily provided by member-states concerning export of nuclear materials, cases of illegal circulation of materials, etc. Assessment of the nuclear activities of a state is based then on three components:

- assessment of the national nuclear program on the strength of the evidence of non-diversion of declared nuclear materials; this serves as a bases for subsequent assessments;

- assessment made on completion of the additional protocol measures; it covers the information contained in the original extended declarations of states, as well as the results of actions pursuant to the additional protocol; and
- conclusions arising from continuous monitoring of the national nuclear program.

By acting upon the Additional Protocol, the Agency can make national nuclear activities more transparent, while recognizing the right of states to protect their sensitive information.

3.2. Export control system

Export control is one of the key tools of preventing proliferation of nuclear weapons [6]. It embraces a package of measures taken to ensure compliance with the effective international standards and rules for trade in materials, equipment and technologies potentially usable in production of nuclear weapons. The export control system is based on the licensing procedure for exporting the products and technologies covered by specially developed check lists. Export control is brought into effect at two levels: as international regimes and national systems.

The international regime of export control is built by joint efforts of states upon agreements between them, aimed at establishing control over export of products relating to development and production of nuclear weapons. International export control regimes are based on the requirements of the Non-Proliferation Treaty. Article III.2 of the NPT bans transferring to any non-nuclear-weapons state source or special fissionable material and equipment designed for production of special fissionable material, unless they are covered by the IAEA Safeguards.

The requirements of Article III.2 of the NPT are not exhaustive, however, and a number of issues were left unresolved, for example:

- the equipment and materials meant for production of special fissionable material have not been specified;
- the conditions for control over nuclear technology transfer have not been addressed;
- nor have been addressed the conditions for control over repeated NM transfers;
- the Article does not require that the full-scope safeguards of the IAEA be recognized. As a result, international NM transfers to non-signatory non-nuclear states have been regulated for many years by the incomplete IAEA system of safeguards described by INFCIRC/66.

Zangger Committee

The awareness of these outstanding issues led states to set up international organizations, such as Zangger Committee and Nuclear Suppliers' Group (London Club), which developed mechanisms and recommendations for control over international transfers of nuclear materials, nuclear technologies and equipment. The states involved in these international activities are listed in Table 3.10.

Table 3.10

International export control regimes

State	Zangger Committee	NSG	State	Zangger Committee	NSG
Australia	+	+	Luxemburg	+	+
Austria	+	+	Netherlands	+	+
Argentina	+	+	New Zealand		+
Belarus		+	Norway	+	+
Belgium	+	+	Poland	+	+
Bulgaria	+	+	Portugal	+	+
Brazil		+	Russia	+	+
UK	+	+	Rumania	+	+
Hungary	+	+	Slovakia	+	+
Germany	+	+	Slovenia	+	+
Greece	+	+	USA	+	+
Denmark	+	+	Turkey	+	+
Israel			Ukraine	+	+
Ireland	+	+	Finland	+	+
Iceland			France	+	+
Spain	+	+	Czechia	+	+
Italy	+	+	Switzerland	+	+
Canada	+	+	Sweden	+	+
Cyprus		+	SAR	+	+
China	+		Japan	+	+
South Korea	+	+			
Latvia		+	IN ALL	35	39

In the period of 1971 to 1974, a group of states most advanced in the nuclear sphere (15 states at the beginning) held a series of meetings in Vienna. Professor Claude Zangger from Switzerland presided over those

meetings. The purpose of the meetings was to reach agreement on the following:

- more specific definition of the equipment and materials intended for processing, use or production of special fissionable material;
- development of the terms and conditions for regulating export of such equipment and materials in accordance with Article III.2 of the NPT.

The following terms for export of NM and equipment were agreed upon:

- transfer of source or fissionable material is banned unless the material to be supplied is covered by the IAEA safeguards;
- the equipment and materials included in the “Trigger List” and intended for production of special fissionable material, may not be transferred unless the fissile material produced by this equipment is placed under the IAEA control;
- materials and equipment may not be re-exported unless this material (equipment) is placed under the IAEA control.

The Trigger List drawn up by the Committee includes the following equipment and materials:

- source and special fissionable materials;
- reactors and reactor components;
- non-nuclear materials for reactors;
- facilities for reprocessing irradiated fuel and the associated equipment;
- facilities for fabrication of fuel elements;
- facilities for separation of uranium isotopes and the associated equipment;
- facilities for production of heavy water, deuterium and deuterium compounds and the associated equipment.

In 1974, the agreements of the Zangger Committee and the Trigger List of equipment and materials which may only be transferred under international control, was published by the IAEA as document INFCIRC/209.

Nuclear Suppliers’ Group

The nuclear test carried out by India in 1974 made it clear that the Zangger Committee agreements had failed to bar completely the proliferation routes of nuclear weapons. In the same year of 1974, the major countries involved in supply of nuclear materials and equipment, set up the Nuclear Suppliers’ Group (NSG) to supplement and reinforce the

terms and conditions for nuclear export, formulated by the Zangger Committee. Like the latter, the NSG is based on a voluntary collective political agreement between its member-countries. Since 1991, the NSG has had no official relations with the IAEA.

In 1976, the Group developed and published its fundamental document *the Guidelines for Nuclear Export* (INFCIRC/254). The NSG extended the List compiled by the Zangger Committee by adding uranium conversion processes, toughened up the requirements for their transfers to other countries, and introduced restrictions on supply of dual-purpose products.

Conditions for supply of products covered by the NSG list

Part 1 of the NSG Guidelines describes the supply conditions and includes a check list of materials, installations, equipment and components usable for production of special fissionable material. Unlike the Trigger List of the Zangger Committee, the NSG list extends controls to the technologies for production of items mentioned in the Trigger List.

The NSG interprets “technology” as technical data materialized, essential to design, construction and operation of nuclear facilities for enrichment, reprocessing, and heavy water production.

For items of the extended list to be exported, they should have physical protection at least at the level recommended by the IAEA. The NSG Guidelines prohibit export of source and special fissionable materials, of products and the associated processes mentioned in the check list:

- to any non-nuclear country which has no obligations in law in regard to the full-scope IAEA safeguards;
- unless the exporter is sure that the exports will be used for peaceful purposes.

Exceptions may only be made if:

- the export is of importance to safe operation of an existing facility covered by the IAEA safeguards;
- the export follows the agreements made before April 4, 1992 (NSG meeting in Warsaw).

Dual-purpose products and the conditions for their export

Part 2 of the NSG Guidelines contains the conditions for export and a check list of dual-purpose materials and equipment subject to export control.

Materials and equipment are treated as dual-purpose products if they could significantly promote activities aimed at production of nuclear explosive devices.

The list of dual-purpose products includes:

industrial equipment: radial– and linear–rolling machine-tools; numerically controlled tools; vacuum furnaces; presses; robots; vibration testing equipment;

materials: aluminum; beryllium; bismuth; tungsten; zirconium, etc.;

equipment for uranium isotope separation;

equipment of facilities for heavy water production (omitted in the Trigger List);

equipment for development of blasting systems;

equipment for conducting explosions;

components and equipment for conducting NW tests;

other items of export (tritium).

The Guidelines ban export of dual-purpose products and technologies subject to export control (on the list) to any non-nuclear country for use in activities relating to nuclear explosions, or in NFC facilities outside the IEAE safeguards.

Export control in Russia

Involvement of a country in international export control regimes implies:

- provision of a national legal framework consistent with the adopted agreements;
- adherence to the regime principles in the national policy;
- participation in the forums of member–countries.

Export control law

The Export Control Law has been in force in Russia since 1999. It specifies the main methods of legal regulation of foreign-economic activities, such as:

- identification of products and technologies under control;
- licensing procedure for foreign trade in products and technologies under control;
- customs control;
- law enforcement measures applied to persons who have violated the foreign-economic regulations.

A typical feature of this law is broad construction on the notion of export (Article 1). Foreign-economic activities embrace foreign trade, investments and other activities, including cooperation in international exchange of goods, information, services, and intellectual products.

In-house export control programs (IHECP)

IHECP establishment is made incumbent by the law (Article 16) upon all organizations involved in scientific or industrial activities associated with national defense and security of the RF and receiving profits from operations with products and technologies under control. Organizations will set up such programs to ensure compliance with the Russian laws and regulations in their foreign-economic activities in relation to goods, information, services, and intellectual products potentially usable for producing weapons of mass destruction. The National Research Center of the RF Physics and Energy Institute has developed a draft model IHECP for organizations in the Rosatom framework.

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CHAPTER 4

NATIONAL NON-PROLIFERATION SAFEGUARDS. SPECIAL MANAGEMENT OF NUCLEAR MATERIALS AND ITS ASPECTS

Reasons for special handling of nuclear materials

The idea of safe management of nuclear materials (NM) underlies any nuclear enterprise, including nuclear power, and is central to the Law on the Use of Atomic Energy adopted in Russia in 1995.

NM safety is a complex notion of many facets, such as nuclear safety; radiation and chemical safety; security, etc. All these aspects require appropriate conditions for NM handling, i.e. special management. Thus, special management is a combination of measures and means adopted to provide comprehensive safety of NM handling in a way that will be environmentally friendly and acceptable for the general public.

Considerable efforts have been made in the world towards such management of nuclear materials, these efforts aimed not only at NM security but also at the fullest possible knowledge of such materials. Safe NM management has three major aspects, i.e., accounting, control and physical protection of nuclear materials (AC&PP), which lie at the root of the national non-proliferation safeguards in Russia.

There are several factors that call for a special approach to nuclear materials.

1. Nuclear materials – at least some of them – are sufficiently valuable in commercial and energy terms. To illustrate this point, suffice it to mention an agreement signed in 1993, pursuant to which Russia was to supply 500 t of highly enriched uranium to the United States within 20 years, blending it down to a low enrichment level before delivery. The contract stipulates that the United States Enrichment Corporation shall convert the uranium to a form suitable for fueling nuclear reactors and shall sell it on the world market. For the 500 t of uranium, the US was to pay ~ \$ 8 billion, which was tantamount to buying it at about \$ 16 per gram of HEU. It goes without saying that the lower the material quality, the lower its price. World markets offer 1 kg of natural uranium for \$ 60–80 (this figure, naturally, changing with time). Needless to say that nuclear materials are valued for their energy potential – the whole nuclear power of the world relies on this property. The remarkably high calorific value of nuclear fuel is explained by the fact that every fission act liberates energy of about 200 MeV. For comparison, an act of chemical interaction between oxygen and carbon (fossil fuel burning) results in ~ 4 eV.

2. The second factor lies in the fact that nuclear materials – practically, all of them – are radiation and chemical hazards and should be treated with due caution. The accident at the Mayak Facility (Kyshtym, Southern Urals) on September 29, 1957, was caused by a failure in the cooling system of a tank which stored 70 to 80 t of high-level waste from radiochemical processes. The Karachai Lake became a huge radioactive dump, which is still an enormous problem.

3. Nuclear materials are nuclear hazards. Many of them pose a potential threat of above-criticality. Poor accounting and erroneous actions can lead to uncontrollable chain reactions with severe consequences. The catastrophe at Chernobyl Unit 4 may be largely attributed to negligence of this factor.

4. The fourth factor, which is a risk not to be neglected, amounts to the fact that nuclear materials can be used for military or terrorist purposes, for production of nuclear weapons or nuclear explosive devices. This factor is causing increasing anxiety in Russia as well as in the world at large and is the main reason for creating national systems of non-proliferation safeguards to stop the sprawl of nuclear weapons in the world.

National non-proliferation safeguards

At the national level, proliferation resistance is ensured by a number of factors, such as:

1. Legal and regulatory framework of the nuclear sector (laws, rules, decrees, regulations, directives);
2. Systems for accounting, control and physical protection of nuclear materials in use at all nuclear sites of the country;
3. Organizations and systems set up to counteract illegal circulation of nuclear materials.
4. Professional culture of personnel working with nuclear materials and dissemination of the non-proliferation ideas for the broad public to comprehend the importance of this concept. The associated efforts include training of highly skilled specialists, retraining of nuclear personnel, public relations activities, etc. All the above may be referred to as **non-proliferation culture**.
5. Other activities, including international cooperation in the field of non-proliferation.

All these measures, systems and organizations together form the foundation of national non-proliferation safeguards, which are being implemented by states via their atomic energy authorities.

Key components of NM management

NM AC&PP systems are being actively improved and developed at Russian nuclear facilities. This work proceeds along the following lines:

- improvement of the legal and regulatory framework at the federal, departmental and site levels;
- development, manufacture and use of up-to-date equipment and systems;
- development and application of advanced AC&PP analysis and design methods;
- upgrading of the export control system;
- training and retraining of personnel.

Besides, Russia is involved in wide cooperation with the USA and West-European countries, which adds to the AC&PP progress on nuclear sites.

The AC&PP systems are schematically presented in Fig. 4.1. As may be seen, each of the systems embraces many measures and means. Although accounting, control and physical protection are provided by separate systems, their operational interdependence is quite obvious. This dependence is easily discerned from Fig. 4.1, if we assume one of the NM management components to be missing.

For the objectives of the national safeguards to be reliably attained, the ‘defense-in-depth’ principle should be used for NM protection. Protection in depth implies that failure of one of the security measures will not result in a significantly higher risk of NM diversion or theft. The above components of the national non-proliferation safeguards add up to provide such protection. In certain conditions, accounting, control and physical protection of nuclear materials are complementary activities contributing to the NM protection sought.

Such will be the case, for example, if protection is arranged against efforts of various perpetrators acting in conspiracy (e.g., between site personnel and guards), or if there are small NM leaks from the guarded site. Physical protection operates in real time. But detection of small leaks is problematic due to sensitivity thresholds of the NM detectors. In this case, the A&C system will be complementary to physical protection, as small NM diversions over fairly long periods of time will be diagnosed during periodical inventory processes on the site.

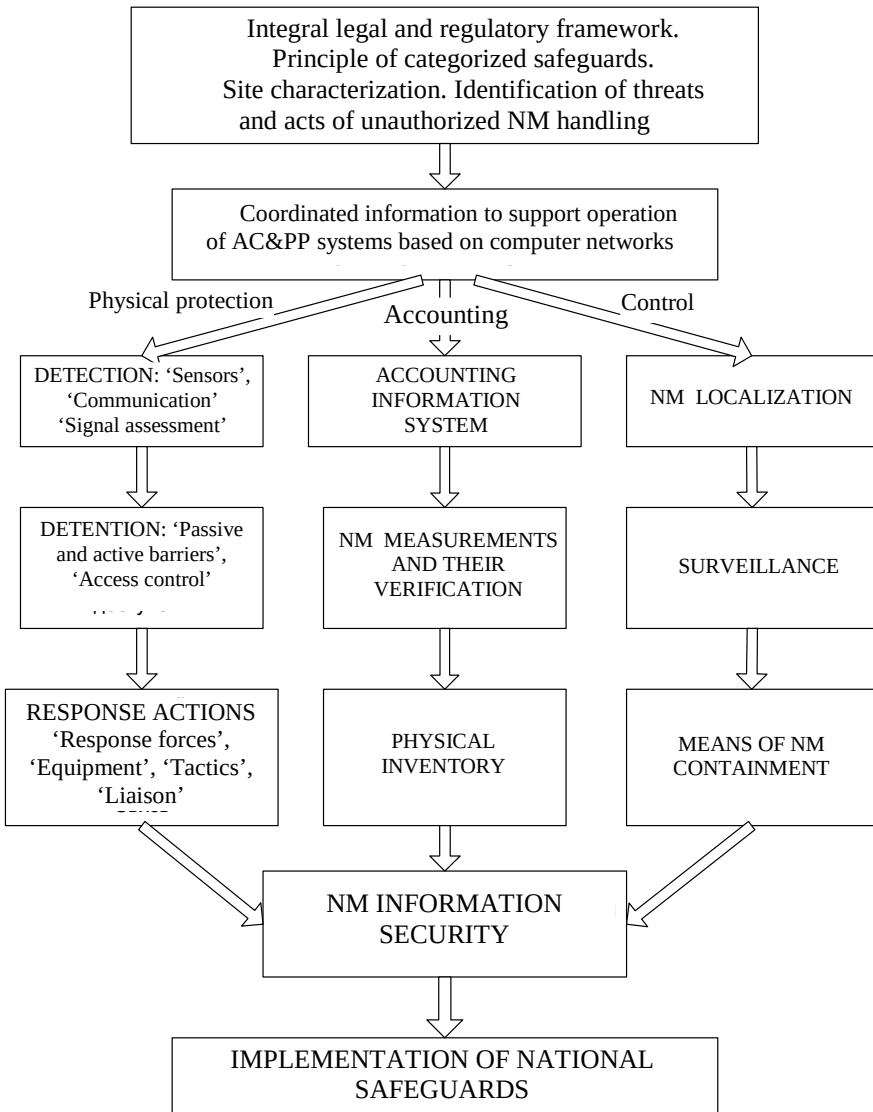


Fig. 4.1. NM accounting, control and physical protection

Operating environment of AC&PP systems

Interfaces between accounting, control and physical protection systems are based on their shared operating conditions. These conditions, governed by the specifics of NM handling processes on the site and of their information support, include:

- attractiveness and quantities of nuclear materials (NM category) found on the site;
- forms of NM localization on the site;
- methods of information support to NM handling on the site;
- site personnel.

It should be noted that AC&PP systems can never be effective unless their operating environment is duly taken into consideration. Operation modes of these systems are dictated by the NM types and quantities, the NM handling processes, and the information support they need.

As mentioned above, the levels of physical protection, accounting and control of nuclear materials depend on the inventory of NM found on the site and on the degree to which they may be attractive for diversion. The highest AC&PP levels are provided for such materials, the loss, theft or diversion of which may be most damaging to national security, human health or environment. Such an approach may be referred to as the principle of categorized safeguards.

The concept of NM localization lies in making NM accommodation as compact as possible and in providing security of these materials by setting up controllable barriers on the paths leading to them. This concept is usually implemented by placing NM in protected areas, access control zones, strong boxes, casks, etc. The higher is the localization degree, the simpler it is to protect and control the materials. The issues of NM localization are discussed at greater length in the second part of this book.

On-site NM handling is carried out in a way consistent with the concept of information security. This concept aims to provide complete information required for control of NM handling processes and, at the same time, to keep the information uses strictly within the limits of its intended purposes – all under conditions of its protection against unauthorized access.

In regard to personnel, both systems stem from the concept of safety culture. In other words, their purpose is to make personnel fully aware of the importance of safe NM handling and willing to achieve this end.

Computer-based information technologies pave the way for more efficient interfacing of accounting, control and physical protection systems on nuclear sites. These systems, with their functions appropriately assigned, interact during operation, adding to the strength of NM protection in depth against actions of potential perpetrators.

CHAPTER 5

REGULATIONS AND LAWS AS A FOUNDATION FOR DEVELOPMENT AND OPERATION OF AC&PP SYSTEMS IN THE RUSSIAN FEDERATION

5.1. Legal framework of the AC&PP activities

This section will deal with the way Russia regulates its nuclear energy uses and the relations arising in such activities, as well as with the place occupied in this sphere by the AC&PP systems.

One of the cornerstones of nuclear activities is the Law on the Use of Atomic Energy adopted in 1995 [1]. The principles set forth in this Law give a good account of the nuclear material management system in the Russian Federation. The Law provides clear guidance for the whole spectrum of nuclear activities (with their associated relations). The concept of rights (and duties, as the dialectical antipode of the former) brings certain order into the activities associated with nuclear energy, including NM management.

This Law reflects the almost 50-year experience of handling nuclear materials in Russia and, therefore, serves as the main regulatory document for safe management of these materials. Central to all articles of this law is the key idea of ensuring safe development of the Russian nuclear industry, with due regard for the human factor (the rights and duties of individuals and organizations, and the responsibilities of officials).

In today's world, NM handling safety dictates that any nuclear material should be protected against unauthorized actions (and should be adequately presented in the relevant information systems of different levels). This purpose is fulfilled by AC&PP measures, which are the key components of NM management and are therefore highlighted in the Law.

This document covers three types of materials: nuclear and radioactive materials, and radioactive waste. For the purposes of this book, the main subject is nuclear material.

Fig. 5.1 shows the NM-related activities regulated by the Law on the Use of Atomic Energy. In one way or another, the Law covers all the major areas of NM management undertaken for peaceful purposes.

The way nuclear activities (including NM management) are regulated in Russia is discussed below.

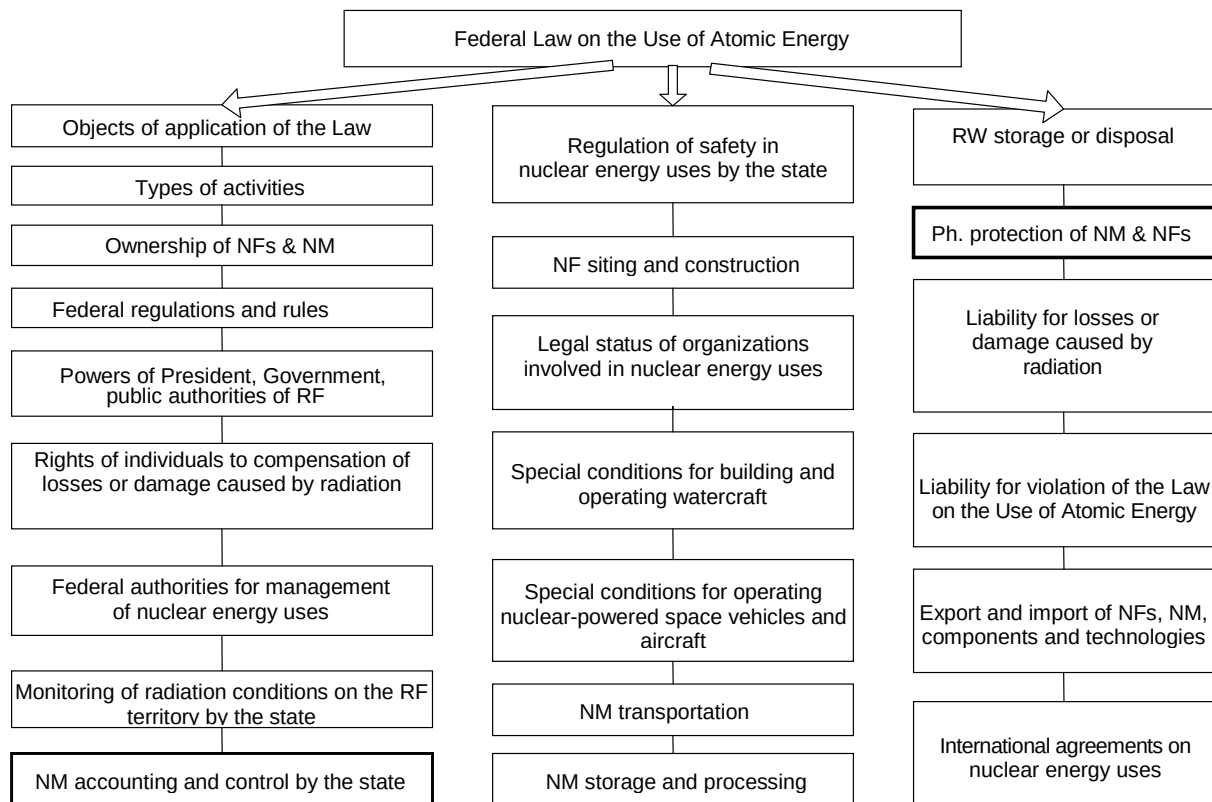


Fig. 5.1. Regulation of nuclear activities in accordance with the Law on the Use of Atomic Energy.

1. Practically all assets of the Russian nuclear industry are subject to this Law, including:

- nuclear installations;
- radiation sources, such as components and equipment containing radioactive material or generating ionizing radiation;
- nuclear and radiation material storage sites, radioactive waste storage facilities; as well as
- nuclear materials;
- radioactive materials;
- radioactive waste.

Considering the above, the Law on the Use of Atomic Energy appears to be all-embracing.

2. The Law regulates nuclear activities in various ways, depending on their nature. For any nuclear activities to be undertaken, they have to be licensed. Some activities are imposed by the Law as duties. This applies, first of all, to ensuring safety in nuclear energy uses. Other forms of activities are regulated using the notion of “rights”.

The Law imposes the following duties:

- physical protection of nuclear installations;
- accounting and control of nuclear and radioactive materials;
- state-level monitoring of radiation conditions;
- monitoring of nuclear, industrial and fire safety;
- training of personnel.

The following activities are regulated by the Law:

- siting, design, construction and operation of nuclear installations;
- nuclear and radioactive material management, including its production, use, processing, transportation and storage;
- research activities;
- export and import of nuclear installations, components, technologies, nuclear materials.

Until recently, all nuclear materials, nuclear installations, radioactive material, radioactive waste, radiation sources, and storage facilities were owned by the state. The only action permitted was their transfer for use by legal entities with licenses for nuclear activities.

The basic legislative acts in force today have changed the terms of ownership pertaining to nuclear materials. To wit, Article 4 of Federal Law No. 13-FZ of February 5, 2007, says that the nuclear materials owned by the RF but being used by state unitary enterprises of the nuclear sector, may

be included in the assets of these enterprises, which are subject to privatization.

Therefore, nuclear materials may be owned either by the state or by open joint-stock companies.

3. Development of general federal regulations and rules is essential for nuclear energy uses in Russia. These regulations and rules set forth requirements for safe applications of nuclear energy. Their fulfillment is mandatory for all nuclear activities.

The procedure for elaboration of regulations and rules should provide for their preliminary publication by an official publishing house for the purpose of their broad discussion.

The rules and regulations should take into account recommendations of international organizations, such as the IAEA. They will appear in print for easier accessibility.

Such documents in force today are: the rules of nuclear and radiation safety, main rules for accounting and control of nuclear materials, rules for physical protection of nuclear installations and materials, etc.

4. The Law defines the rights of authorities, organizations and individuals in regard to nuclear energy uses.

With its appearance, individuals and organizations received some new rights, including the following.

The right to be informed. Organizations and individuals are entitled to request and receive information on the safety of nuclear facilities from relevant executive authorities. Individuals have the right to free information about radiation conditions.

The right to compensation of losses and damage. Individuals who have suffered losses or damage as a result of radiation impacts, have the right to be fully compensated for such losses or damage. Application of this right may be exemplified by the damages awarded after the Chernobyl accident.

The rights of individuals related to medical treatment. When taking medical treatment, an individual has the right to decide on or against use of ionizing radiation.

5. State control over nuclear energy uses is effected by management agencies specially authorized by the RF Government, such as the State Corporation Rosatom and others.

The terms of reference of these agencies include:

- implementation of the national policy in scientific, technical, investment and organizational areas;

- development and implementation of safety measures in nuclear energy uses;
- development of regulations and rules;
- accounting and control of nuclear materials by the state;
- physical protection of nuclear installations, nuclear and radioactive materials, and their storage facilities;
- monitoring of radiation conditions by the state;
- development and implementation of programs for radioactive waste management, and other functions.

6. State-level monitoring of radiation conditions is aimed at early detection of changes in such conditions, at assessment, prediction and prevention of possible adverse effects of radiation on people and environment on the RF territory. The order of arranging and conducting such monitoring is determined by the RF Government. Every operating organization (Operator) that has nuclear and radioactive materials or radioactive waste is responsible for radiation monitoring in the control and surveillance areas. The National Nuclear Research University “Moscow Engineering and Physics Institute” (designated by the Russian acronym MIFI), for instance, has its own radiation safety service, which monitors radiation conditions on the campus and in the surrounding areas.

7. As noted above, all efforts to ensure safe uses of nuclear energy are treated by the Law as mandatory activities. These include, for example, accounting and control of nuclear materials by the state aimed at determining the quantities of these materials in places of their location, at preventing their losses, unauthorized uses or theft, and at reporting these data to the authorities for safety management and regulation (Article 22). Nuclear materials are subject to accounting and control at the federal and departmental levels of the state A&C system.

In view of their importance, the Law treats separately the issues of safety regulation by the state relating to nuclear energy uses. Safety regulation at this level provides for activities of Rostekhnadzor – an agency specially appointed for this purpose by the government. Rostekhnadzor is responsible for safety regulation in all its aspects, including nuclear, radiation, industrial and fire safety. This authority is independent of all other state entities, as well as of the organizations whose activities relate to nuclear energy uses. Rostekhnadzor:

- carries out licensing of activities pursued by various organizations;
- takes part in development of regulations and rules for nuclear energy uses;

- performs surveillance of NM accounting and control systems at organizations;
- oversees physical protection and other aspects of the safety and security of nuclear materials and installations;
- inspects nuclear facilities;
- takes disciplinary actions (injunctions, fines) if licensing conditions or safety rules are violated.

8. In some cases, plans for siting and building nuclear installations caused negative sentiments in certain groups of population. For this reason, the Law has special provisions as to who makes such decisions and on what grounds they are made. In particular:

- a decision on building a nuclear installation is taken by the RF Government;
- a decision on siting a nuclear installation is taken jointly by the RF Governments and the local administration;
- a decision on siting and building a nuclear installation is made considering the need for such a facility and the conditions required for its siting.

9. The Law defines the main requirements to be met by Operators, i.e. the organizations declared fit for handling nuclear materials. An Operator should be licensed to carry out nuclear activities, should have sufficient resources for fulfilling its functions, and is fully responsible for the safety of NM handling, providing:

- records of individual exposure of the site personnel;
- protection of personnel and population in case of an accident at the nuclear facility;
- NM accounting and control;
- physical protection of facilities and materials;
- radiation monitoring;
- recruitment, training and retraining of the site personnel.
- Unauthorized public events, such as meetings or strikes, are banned on nuclear facility sites and in their control areas.

10. In areas of NM handling, e.g., storage and processing, reliable radiation protection measures should be provided for the site personnel, local residents and environment. During transportation of such materials, they are equated to cargo of particular hazard.

11. Physical protection of nuclear facilities is provided by their Operators and specially appointed authorities, or by crews if they are ship-borne.

Security requirements are established by the rules for physical protection of nuclear materials and facilities. Operation of a nuclear installation or use of nuclear materials are prohibited if no measures are taken for their physical protection (Articles 49, 50).

Limited rights of persons found on nuclear sites. For the sake of physical protection of a nuclear facility, the site personnel and visitors as well as their belongings and vehicles may be inspected, for which purpose special equipment may be used.

Admission to work. Persons may be admitted to work on a nuclear site, if they are properly qualified and have a clearance for work associated with state secrets.

Persons with health problems identified in a special list of medical contraindications, will not be permitted to work at a nuclear facility.

12. Operators bear liability for losses or damage caused by radiation impacts within certain limits. The scope of liability should be financially provided for by combination of in-house funds of the organization, its insurance policy, state guarantees, etc. Documentary evidence of such financial provisions is a prerequisite for granting a license to the applicant organization.

Russian Government will pay damages on account of radiation impacts in amounts exceeding the scope of liability of the operating organization.

13. Responsibility of officials. Violation of the RF Law on the Use of Atomic Energy entails disciplinary, administrative or criminal responsibility. Such violations include:

- infringement of requirements for physical protection of a nuclear facility;
- infringement of the order of NM accounting and control;
- theft, illegal purchase, storage and sale of NM;
- infringement of rules and regulations for nuclear energy uses;
- violation of the license terms;
- acceptance of a nuclear facility for operation without taking measures for protection of personnel and local population;
- failure to fulfill their duties by the site personnel;
- unauthorized absence from the workplace at the facility;
- admission to work at the facility granted to personnel without appropriate qualification documents, having certain medical contraindications, and to persons under 18;
- direct or indirect coercion of personnel to break the operating procedure or job instructions;

- assignment of personnel to work in high-exposure areas;
- unjustified release of radioactive substances to the atmosphere, to water or underground environment;
- concealment of the fact of an accident;
- refusal to provide information, or distortion of information concerning the facility safety;
- facts of putting into use products contaminated by radioactive substances;
- infringement of the export and import order.

14. Export and import of nuclear installations, equipment, technologies and materials are carried out in compliance with the international agreements and obligations assumed by Russia for non-proliferation of nuclear weapons. Export and import are subject to special licensing.

Spent nuclear fuel is taken in to the RF territory from foreign countries in a way dictated by the Russian legislation and international agreements of the RF. If such an international agreement establishes rules other than those set by the Law on the Use of Atomic Energy, the rules of this international agreement will prevail (Articles 64, 65).

5.2. Regulatory framework for accounting, control and physical protection of nuclear materials

The regulatory framework for NM management appears in the form of the rules laid down for such activities. Accounting and control of nuclear materials are covered by a series of regulatory documents at the international and national levels.

1. The IAEA recommendations for development of a state's system of accounting for and control of nuclear materials (SSAC) [2].

2. The concept of a state system for accounting and control of nuclear materials (NM A&C) [3].

3. General rules for accounting and control of nuclear materials [4].

The concept of such a system adopted in Russia takes into consideration practically all the international recommendations. It treats NM accounting and control as an important element in management of nuclear energy uses by the state. This document defines the hierarchy of objectives and the key operating principles of the State NM A&C system.

The objectives, arrangement and operation principles of NM A&C systems are discussed at greater length in the general rules for accounting and control of nuclear materials (NP-030-05), which is the key regulatory document where the requirements and criteria for A&C are determined.

These requirements are mandatory to all legal and natural persons involved in NM management.

NP-030-05 contains a list of nuclear materials subject to accounting and control and specifies their threshold quantities. The basic principles of accounting and control identified in this document are those of continuity of knowledge, categorization, and measurable material balance.

Accounting and verifying measurements

It is only objective data, i.e. the results of quantitative measurements, that may serve as a basis for NM accounting and control in the new regulatory system. A principle central to this system is that of regular NM measurements, which naturally leads to a sharp increase in the extent of such operations. That is why measurements are differentiated according to their purpose: they may be aimed either at getting new information, as is the case, for instance, at facilities that fabricate NM-containing articles, or at verifying the existing NM data. Hence, measurements may be either of accounting or of verification nature.

Accounting measurements determine NM parameters in a batch, and their results (together with the measurement error) are entered in accounting documents as certification values. Every subsequent measurement cancels the result of the previous one. Such measurements cover all nuclear materials (100 % sampling).

Verifying measurements determine NM parameters in a batch or NM attributes to confirm the previous accounting data. The accuracy requirements for such measurements may be lowered.

Data verification is regarded as positive if the difference between its results and the accounting data is within the limits of allowable statistical straggling. As a rule, such allowable straggling in measurement results is determined by a 99 % confidence interval. If the discrepancy is found to be outside this interval, a new accounting measurement is to be made.

Access control equipment

The General Rules reflect the trend towards greater reliance on instrumentation in NM control. The Rules emphasize the importance of equipment for control of access to nuclear materials. Such equipment should be used wherever nuclear materials are found. Its purpose is to confirm the validity of previously measured NM quantities and attributes or to detect tampering with the materials. Though not providing NM security *per se*, this equipment will reveal attempted access to materials or will

prove absence of such attempts. In the latter case, the previous measurement results may well be used, with the measurement costs reduced thereby.

Thus, instrumental methods of detecting and deterring attempts at tampering with nuclear materials are indispensable elements of modern NM A&C systems.

Sampling of nuclear materials

Sampling for verification is permitted if a nuclear material has undergone no changes and if it has been kept under instrumental access control. The extent of such measurements should be set to ensure the specified confidence probability of detecting an off-normal condition (anomaly). This probability depends on the extent of access control applications. An anomaly is detected by judging against the following values of threshold NM quantities:

a) for materials of Categories 1, 2 and 3, the threshold quantities are:

- 3 kg for plutonium and uranium-233;
- 8 kg for uranium-235;

b) for uranium enriched to less than 20 % (Category 4), the threshold quantity is 70 kg of U-235.

If nuclear materials appear as encased articles whose integrity is ensured by their design, they may be checked upon by sample measurements. The sampling extent is determined in a way similar to that of materials fitted up with tampering indication devices.

In-house measurement programs

Every organization develops a measurement program for the purpose of NM accounting and control, including:

- measurement procedures, which are subject to governmental qualification. Measurements are made by destructive and nondestructive methods, each having its intrinsic advantages and disadvantages. Every method has its own preferred applications and, on the whole, they are complementary to one another;
- a list of key measurement points, with instrumentation employed at each;
- arrangement and description of measurement procedures;
- measurement accuracy requirements, etc.

Measurement quality control

If an organization has good instrumentation at its disposal and its own metrological service, it does not necessarily mean that the NM measurements it makes are of a high quality. Practice has shown that good measurement quality necessitates a special quality control process and appropriate record keeping. These may be summed up as a measurement quality control program. Such a program provides for steps to determine the capabilities of measurement instrumentation in terms of attainable accuracy and to develop procedures for keeping its performance within tolerance limits.

The General Rules for Accounting and Control call for setting up such a measurement quality control program that will allow using measurement results in the A&C system. Such programs are being introduced and operate already at many organizations and companies in Russia.

A principle central to measurement quality control is that of continuous checking for errors caused by instrumentation and measurements techniques. Such continuity is made possible, first of all, by regular (weekly, daily or several times a day) calibration of equipment against various reference specimens: mass specimens containing uranium of known enrichment, plutonium specimens of known isotopic composition, etc. Thus, a measurement quality control program includes, as its essential components, certified NM specimens to be used for calibration and verification of secondary standards, and measurement control methods.

Measurements against reference specimens allow:

- estimating errors in individual measurements;
- calculating random and systematic components of measurement errors and, if possible, correcting the latter;
- calculating the control limits of instrumentation performance; if measurement results exceed a certain emergency limit, the instrument is taken out of operation.
- In order to speed up introduction of measurement quality control programs on nuclear sites, it is recommended:
 - to use programs requiring a minimum extent of measurement verification;
 - to set tolerances at a level of practical necessity;
 - to integrate measurement control procedures into measurement procedures.

Accounting procedures

Special attention is paid in the General Rules to the main accounting procedures including NM measurements, i.e., to NM transfer and physical inventory-taking. Their proper fulfillment (following the Rules, among other things) can largely ensure successful operation of an A&C system.

The requirements of the General Rules apply also to the A&C information system, including accounting and reporting documents. These requirements unify the information formats and facilitate transition to computerized information support of A&C, which is known to enhance hugely the A&C capabilities.

In subsequent chapters of this book, we shall repeatedly refer to the General Rules with the aim of more detailed discussion of various requirements placed on nuclear material accounting and control systems.

A regulatory framework is of great importance to physical protection of nuclear materials. It embraces documents of various levels.

1. International level:

- INFCIRC /225/ rev. 4, The Physical Protection of Nuclear Material and Nuclear facilities (IAEA);
- INFCIRC /274/ rev. 2, Convention on Physical Protection of Nuclear Material (IAEA).

2. Russian documents of the federal level:

Rules for Physical Protection of Nuclear Materials, Nuclear Installations and Nuclear Material Storage Facilities, approved by Governmental Decree No. 264, of 07.03.97.

3. Russian documents of the departmental and interdepartmental levels (a package of documents).

4. Russian documents of the site level (a package of documents).

Physical protection of nuclear installations is provided by operating organizations and specially authorized governmental agencies, following the requirements laid down in the Rules for Physical Protection of Nuclear Materials, Nuclear Installations and Nuclear Material Storage Facilities. These rules are based on the RF legislation for safety management in nuclear activities and were drawn up with regard to the international obligations of Russia and to the IAEA recommendations for physical protection of nuclear materials, nuclear installations and nuclear material storage facilities. The Rules apply to nuclear sites on the whole territory of the RF and are binding upon all legal entities involved in nuclear activities irrespective of the forms of ownership, funding sources and departmental affiliation, as well as upon

the federal executive bodies responsible for coordination and supervision of nuclear activities.

This document regulates the relations arising in the process of safety management during nuclear activities. In accordance with these Rules, no nuclear activities may take place unless physical protection is provided for nuclear materials, nuclear installations and nuclear material storage facilities.

The subjects covered in this document include: the functions of federal executive bodies and physical protection organizations; the key requirements for organization of physical protection during transportation of nuclear materials and nuclear installations; state supervision of and departmental control over provision of physical protection; the procedure for bringing facts of unauthorized actions to the notice of appropriate authorities. It is a most important objective today to make the key ideas of those documents clear to each employee of a nuclear enterprise so that they become an effective and reliable link in the system of special management of nuclear materials.

The issues of physical protection on nuclear sites were comprehensively addressed in Minatom Order No. 550 of 01.09.2001 on Approval of the General Requirements for Physical Protection Systems on Nuclear Sites of Russian Minatom. This departmental regulatory document defines the order of arrangements made for physical protection of nuclear materials, nuclear installations and nuclear material storage facilities within the Minatom framework, and sets forth the basic functional requirements for physical protection systems and their structural elements.

The General Requirements were developed in line with the Federal Law on the Use of Atomic Energy and other federal laws clarifying the issues of site safety and security; with the Rules for Physical Protection of Nuclear Materials, Nuclear Installations and Nuclear Material Storage Facilities, approved by Governmental Decree No. 264 of 07.03.97; with the Regulation on the Ministry of the Russian Federation for Atomic Energy, approved by Governmental Decree No. 392 of 05.04.97. Besides, this document was developed with due regard to the international obligations arising from the Convention on Physical Protection of Nuclear Material, and other regulatory acts dealing with physical protection.

The General Requirements for physical protection of nuclear sites establish:

- the order of organizing and supporting physical protection activities at the departmental level;

- the directions of work to develop the regulatory framework for physical protection at the departmental level;
- the list of the main regulatory documents on physical protection at the site level;
- the goals, objectives and principles of PPS arrangement;
- the criteria for and the order of categorization of nuclear sites and objects of physical protection;
- the procedure for analyzing the vulnerability of nuclear sites;
- the PPS structure;
- the functional requirements for structural elements of PPS equipment and utilities;
- the general requirements for the equipment of areas guarded by a PPS;
- the requirements for building and upgrading a physical protection system;
- the requirements for planning and management of physical protection activities;
- the requirements for operation and maintenance of PPS equipment and utilities;
- the requirements for physical protection of NM during transportation;
- the requirements for organization and conduct of exercises to try out and practice interactions within the PPS framework;
- the requirements for the PPS personnel, their training and retraining.

The General Requirements for physical protection of nuclear sites specify the provisions of the Rules for Physical Protection of Nuclear Materials, Nuclear Installations and Nuclear Material Storage Facilities, as applied to management of physical protection activities within the Minatom framework, the physical protection systems of nuclear sites and their structural elements.

The site-specific requirements for PPSs and their structural elements are based on the General Rules for physical protection of nuclear sites, taking into consideration the results of site vulnerability analyses, the category and operating features of specific sites, and the PPS efficiency assessments. These requirements serve as a basis for PPS development, operation and upgrading.

The requirements for quantitative characteristics of PPS equipment and utilities are set in regulatory standardization documents of the federal or departmental level.

The General Requirements are meant for use by the management and personnel of nuclear sites, as well as by other departmental organizations involved in the following activities:

- organization of work on physical protection;
- development and upgrading of a PPS;
- support of PPS operation;
- control of PPS compliance with the official requirements.

The requirements of this document apply to physical protection of nuclear sites belonging to Minatom of Russia, as well as to physical protection of nuclear materials and articles containing them during transportation. The requirements and provisions of this document are used as a basis for developing new or updating the current regulatory documentation on physical protection of the departmental and site levels.

Regulation No. 3 of the Federal Agency for Supervision of Nuclear and Radiation Safety (Gosatomnadzor), dated 16.01.2002 deals with approval and enactment of the federal regulations and rules in the field of nuclear energy uses, referred to as the Rules for Physical Protection of Radiation Sources, Storage Facilities, and Radioactive Material.

This regulatory document was prepared on the basis of Federal Laws on the Use of Atomic Energy and on the Radiation Safety of Population; on the General Rules for Radiation Safety; Rules for Physical Protection of Nuclear Materials, Nuclear Installations, and Nuclear Material Storage Facilities, as well as on the IAEA Recommendations for Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Rev/4).

The Regulation explains: the requirements for physical protection of radiation sources, storage facilities, and radioactive material; the procedure for determining the composition of and requirements for the system of physical protection of radiation sources, storage facilities, and radioactive material; the procedure for reporting unauthorized actions involving radiation sources (RS), storage facilities (SF), and radioactive material (RM).

The Regulation addresses: the organizational aspects of physical protection; the documents dealing with organization and provision of physical protection for RS, SF, and RM; the requirements for utilities and equipment of a PPS; the requirements for actions of the guard forces; the RS, SF and RM classification according to their potential hazards.

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CHAPTER 6

HUMAN FACTOR IN NUCLEAR MATERIAL ACCOUNTING, CONTROL AND PHYSICAL PROTECTION. AC&PP CULTURE

6.1. Present-day threats to safe management of nuclear materials and systems of counteraction

The main threats to a nuclear facility analyzed are:

- theft of nuclear materials and NM-based products, or of information about nuclear materials and technologies;
- acts of terrorism or sabotage at a nuclear installation or a NM storage facility;
- nuclear blackmail;
- anomalies in the processes of onsite NM handling or storage.

An anomaly is a discovered discrepancy between the physical material inventory and the accounting records in a material balance area. Anomalies include:

- NM shortage (excess);
- mistakes in accounting or reporting documents;
- damage to NM-containing products or tampering indication devices (TID);
- infringement of NM use or handover procedure;
- inventory difference (ID) values gone beyond the permissible limits.

The above threats may be carried into effect by various perpetrators. A perpetrator is a person who has committed or is trying to commit an unauthorized action, or an accomplice to such an action. Nuclear sites will normally be protected against perpetrators of two types: outsiders and insiders. The latter are particularly dangerous as they may not only know the vulnerable points of a facility and its physical protection system, but may also have access to such points and to the related information.

The above threats can have severe consequences, including production of nuclear explosive devices and their unpredictable subsequent uses. NM AC&PP systems are means of counteracting threats coming from both outside and inside perpetrators. The importance of such systems on nuclear sites has grown dramatically in the face of the rising activity of terrorist organizations in the world.

A special case is a perpetrator unaware of the offense he commits. This category includes:

- nuclear site personnel negligent of their duties;
- employees who are not competent enough to fulfill their duties, etc.

Such perpetrators are not motivated for unauthorized action, the adverse effects of which may be none the less serious.

Human factor and site security

The notion of ‘human factor’ refers to the integral characteristics of man and machine manifested under specific conditions of their interaction in the form of man–machine interface, which will function as dictated by the objective set for it. Personnel are responsible for operation of systems, they tend and control them, respond to the signals generated by them, and make decisions on allocation of resources for NM AC&PP. Such strong dependence on human factor leads to certain risks. Analysis of the reasons for failure at the man-machine interface shows 30 to 60 percent of all malfunctions to be caused by site personnel. Moreover, it is an unquestionable fact that the probability of an operator’s error will grow once an off-normal situation or an emergency arises.

Even specialists will not always realize the extent of incidents and problems accounted for by human factor. The truth of this statement, though, is supported by statistics. In 2001, 16 cases of failure caused by human errors were reported by Russian NPPs. Analysis of the events at nuclear plants in 2001 showed inadequate safety culture to underlie all those occurrences. The failures were attributed to:

- flaws in or absence of administrative and operating regulations;
- unsatisfactory distribution of duties and responsibilities;
- imperfect site systems for personnel training and retraining.

6.2. The concept of nuclear safety culture

Analysis of the Chernobyl catastrophe led to a revised attitude towards the issues of safe operation of nuclear plants all over the world. Human factor was pointed out by the IAEA experts as the most important one among all possible risks. That is why the IAEA names safety culture as the crucial condition for nuclear power development [1]. The principles of safety culture are applicable to all nuclear facilities.

According to the IAEA definition, “Safety Culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance”.

Safety culture manifests itself, first of all, in such a working atmosphere in which assurance of nuclear facility safety becomes the key purpose as well as an inherent need of every individual, leading to self-control, concentration and a feeling of responsibility for any safety-related activities.

Thus, safety culture as applied to every employee of a nuclear site implies:

- qualifications and psychological fitness for handling nuclear material and equipment;
- strict compliance with operating rules (working discipline).
- As applied to site personnel as a whole, safety culture implies creating:
- an atmosphere of attention to safety issues and support of related initiatives (safety awareness);
- an atmosphere in which personnel will not be afraid to speak openly about their mistakes and will be encouraged to report the facts that may impair safety (critical attitude);
- an atmosphere of outspokenness owing to which any information related to the facility safety will be easily accessible to all (communicativeness).

Safety assurance in operation of a nuclear facility is the primary objective shared by all specialists involved in the activities on the site. This means that safety culture should be shown at all levels, i.e., at organizations with different positions in the administrative hierarchy, such as ministry/department, operating organization, enterprise/company, etc., as well as in behavior of every individual.

6.3. Development of the NM AC&PP culture

To study the culture of NM AC&PP as a specific aspect of safety culture, it is necessary first to have it defined in a way consistent with the above.

NM AC&PP culture may be interpreted as a combination of attitudes and values of organizations and individuals, which demands that NM AC&PP issues, as those of high priority, should receive the attention dictated by their significance.

The IAEA experts suggested that the final document of the associated Technical Meeting should include a definition to the effect that:

Safety culture is a combination of qualities, principles, relations and behavior of individuals, organizations and institutes that serves to support and improve nuclear safety.

The concept of culture embraces a whole number of factors, such as availability of highly qualified personnel; a well-developed organizational framework, etc. The objective of culture development (with the role of human factor reduced) is only attainable by taking a comprehensive approach, including, *inter alia*, formation of an organizational infrastructure, education and training.

Principles of nuclear safety culture

- **Responsibility** – AC&PP activities are most effective if every specialist assumes personal responsibility for the system operation, as well as for his/her actions in fulfilling working duties.
- **Guidance** – AC&PP activities are most effective if management of all levels daily manifest in word and deed their commitment to ensure security of nuclear materials.
- **Motivation** – personnel will show high performance if they see reasons for excellence, including motives introduced by management and colleagues.
- **Professionalism and competence** – AC&PP systems show optimal performance where personnel are highly qualified and have knowledge and skills sufficient for good work in all its aspects, for correct and prompt response to all off-normal occurrences and emergencies.
- **Training and improvement** – the probability of incidents may be reduced and high performance attained by improving the personnel qualifications, their general education level and intellectual abilities, by applying advanced practices and the knowledge previously gained.

Improvement of the national legal framework for nuclear material management

Practically all articles of the Law on the Use of Atomic Energy are based on the idea of safe development of the Russian nuclear industry. The effect of human factor on the safety of nuclear facilities is expressed by the Law in its provisions for the rights and duties of individuals, organizations and office bearers.

The Law provides legal regulation of nuclear activities in various forms, with some of them imposed as mandatory actions. These include physical protection, accounting and control of nuclear materials.

Improvement of the national regulatory framework for nuclear material management

The Law provides for development of general federal regulations and rules to establish requirements for safe nuclear energy uses. Based on this law, federal rules for accounting, control and physical protection of nuclear materials were elaborated and brought into effect. This framework allows regulating NM management activities in a way safe for the public.

It is highly important today to make every employee of a nuclear site aware of the key ideas of the above documents so that they could become an effective and reliable link in special management of nuclear materials and in implementation of the non-proliferation safeguards.

Education of specialists in the spirit of high professional culture

The philosophy of safe NM handling should be an integral part of professional culture shared by all workers of the nuclear sector. Such conscientious attitude leaves no room for complacency in matters of NM security and suggests willingness to contribute to improvements in NM handling procedures.

Training of specialists taught to seek safety as a first priority is an objective to be attained by the national education system as well as by special instruction programs.

Promotion of the non-proliferation ideas among the public

The effectiveness of non-proliferation measures in a country depends on the awareness of this vital problem in all social strata. Such awareness in society, including the authorities, sets the problem high on the list of public priorities and dictates the level of resources allocated for its resolution. It is therefore highly important to promote the non-proliferation ideas among the country's population.

Activities along these lines are carried out by a number of organizations, including the Nuclear Society of Russia and the Center of Political Studies. They publish magazines and books, hold scientific conferences and workshops, inviting representatives of broad public circles to take part in these events.

NM AC&PP culture at Rosatom enterprises

The program for accounting, control and physical protection of nuclear materials has made significant progress in reducing the risk of proliferation

of nuclear weapons. All Russian nuclear facilities are equipped with physical protection systems and use new technologies of accounting for nuclear materials. However, the required security level will not be maintained by equipment and technology alone. The availability and effectiveness of NM AC&PP systems depend largely on human factor.

The importance of human factor is universally recognized and there are a number of programs aligned for instruction of personnel in subjects of safety improvement in NM handling, including enhancement of professional culture of NM AC&PP personnel.

An important part in the Russian program for NM AC&PP development belongs to the NM AC&PP Culture Project, aimed at the greatest possible reduction of the risks attributable to human factor in NM handling and at improving the NM AC&PP culture at enterprises and organizations of the nuclear industry.

This project pursues the following objectives:

- to improve the awareness of the NM AC&PP implications among site personnel as well as their understanding of the responsibility for maintaining high standards of culture in this sphere;
- to enhance the attention of management to NM AC&PP issues and to the contribution their organization can make in this area;
- to minimize the events and problems in NM AC&PP attributable to human factor.

One of the main problems associated with the NM AC&PP culture is the absence of special infrastructure (organization, personnel, technologies, or well-established practices) for enhancement of this culture on the sites. This fault is planned to be corrected by the NM AC&PP Culture Project. Employees (coordinators) responsible for NM AC&PP culture will act as links in the said infrastructure.

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Part II

NUCLEAR MATERIAL ACCOUNTING AND CONTROL SYSTEMS

CHAPTER 1

STATE SYSTEM OF ACCOUNTING FOR AND CONTROL OF NUCLEAR MATERIAL (SSAC)

Accounting of nuclear material is determination of NM quantities, as well as preparation, filing and operation of accounting records and reports. Accounting relies on results of measuring NM quantitative characteristics. NM accounting allows:

- use of earlier NM measurement results where confidence thereof has been confirmed by the appropriate condition of the access controls employed and respective changes;
- use of calculation techniques based on prior measurement and experimental research results.

Therefore, quantitative characteristics of NM at respective locations and of NM flows both within and between enterprises are subject to careful accounting. This is so because information on NM forms the basis for up-to-date control and security systems at all levels of nuclear material handling.

This chapter looks into how state accounting for and control of NM is organized and is evolving in Russia.

1.1. Objectives, tasks and structure of the SSAC

The state system of accounting for and control of nuclear material is part of the state system for management of atomic energy and is intended to:

- a) ensure control of nuclear material handling;
- b) ensure integrity, early detection and avoidance of loss, unauthorized use and theft of nuclear material;
- c) provide the Russian Federation state authorities, atomic energy management bodies, government nuclear power safety regulation agencies and other federal executive power bodies concerned with information on the presence and movements of nuclear material, including transborder shipments into or out of the Russian Federation, these may require for exercising their respective powers;
- d) determine the quantities of nuclear material at respective locations;
- e) ensure necessary conditions for employing the safeguards of the International Atomic Energy Agency, as well as for implementing bilateral agreements on control of nuclear material.

The state system of accounting for and control of nuclear material includes:

- Systems of accounting for and control of NM at three levels. These are primarily control authorities that support its operations at the federal national level. The second level is formed by operators which handle nuclear material. The third level is formed by the NM balance areas within the operator sites;
- legal regulatory support for accounting and control of nuclear material;
- informational and analytical support for the system operations, as well as for processing and transfer of information on the presence and movements of nuclear material;
- nuclear material accounting and control systems of organizations which handle nuclear material;
- control and supervision of the state of the art in accounting and control of nuclear material.

The state system of accounting for and control of nuclear material should ensure:

- a) update of the system of measurements that supports obtainment of data on the quantity and composition of nuclear material;
- b) occupational training and retraining of personnel in the field of accounting and control of nuclear material;
- c) restrictive access to the information in the field of state accounting and control of nuclear material for ensuring the protection of national security and restricted official information.

Regulatory, legal and organizational basis of state nuclear material accounting

Legal framework of state NM accounting. Russia adopted the atomic energy law in 1995. We did not have an earlier atomic energy law so, before the law was adopted, all aspects had been governed subject to resolutions of the Ministry for Medium Machine Building (now Rosatom). Since 1995 therefore, the atomic energy law (Part I, Chapter 5) has been the underlying document in Russian nuclear energy with all nuclear material handling based on the articles thereof.

Organizational framework of state NM accounting. The atomic energy law calls for a state system of accounting for and control of nuclear material (SSAC) to be formed to enable accurate and highly reliable accounting of NM disposition and transfer data. To this end, the Russian Government shall define the manner in which SSAC to be established, as

well as the bodies to implement state accounting for and control of nuclear material.

By and large, accounting and control of nuclear material is an essential part of state NM administration and, therefore, the compositions of state NM administration and control systems have much in common.

Rosatom is the major state corporation carrying out administration of nuclear material in Russian nuclear energy. Rosatom has also been assigned to the task to develop and maintain state system of accounting for and control of nuclear material.

Within the limits of its authority, Rosatom State Atomic Energy Corporation:

- Effectuates state policy in state accounting for and control of nuclear material;
- Implements state accounting for and control of nuclear material in the Russian Federation, notwithstanding the form of ownership for this;
- Implements procedural guidance for and coordinates the activities by federal executive power bodies implementing control with respect to atomic energy uses in state accounting for and control of nuclear material;
- Operates the state register of federally owned nuclear material;
- Keeps the listing of nuclear material in possession of Russian legal entities, as well as of that owned by foreign states and foreign legal entities and held for the time being in the Russian Federation;
- Keeps registers of material balance areas and areas to report on;
- Supplies, on requests from Russian government agencies, state atomic energy administration authorities and state atomic energy regulation bodies, such information on inventories and transfers of nuclear material as they may require to discharge their functions;
- Supports the design, development and operation of the federal computerized information system for accounting and control of nuclear material and establishes information and analytical organizations and/or information acquisition and processing centers;
- Develops and approves forms of reports in state accounting for and control of nuclear material, as well as the manner and frequency in which these shall be submitted;
- Develops and approves the form of the state register for federally owned nuclear material and the form of the listing for nuclear material in possession of Russian legal entities, as well as for that owned by foreign

states and foreign legal entities and held for the time being in the Russian Federation;

- Develops federal standards and regulations for carrying out state accounting for and control of nuclear material;
- Establishes nuclear material accounting and control training and retraining centers in such manner as specified by Russian law, and supports operation of these;
- Implements control with respect to the status and operation of state system of accounting for and control of nuclear material in Russian Federation, notwithstanding the form of ownership for this;
- Implements control of nuclear material handling;
- Supports, jointly with the Federal Agency for Technical Regulations and Metrology, certifications and qualifications of nuclear material characterization equipment and techniques.

Regulatory framework. In the body of the tasks the state agencies authorized to control the use of atomic energy have been assigned to by the Government, emphasis is placed on the development of regulations and rules for state accounting and control of nuclear material. Most of these documents have been developed and put into effect to date. The underlying document is the General Rules for Accounting and Control of Nuclear Materials (NP-30-05 [1]). This was discussed in brief in Part I, Chapter 5.

Composition of information flows. As required by the Federal Rules for Accounting and Control of Nuclear Materials (NP-030-05), a consolidated system of reports is established for different levels of state accounting and control of NM. Within this system, information flows are formed as described below. The material balance area (MBA) level involves all measurements, booking of all NM receipts, shipments and measurement results, and closing of nuclear material balances. Each MBA accumulates therefore primary and the most accurate information on all NM inventories, as proved by the balance closing. All this information makes an elementary autonomous subsystem of the federal NM accounting and control information system. This information is subsequently reviewed, handled and submitted in a consolidated form.

The operator level does not already require all measurement data and all balance area input. Still, there is a need for some consolidated data. Thus, one needs to be aware of all fresh fuel receipts and irradiated fuel shipments, as well as of the fresh and irradiated fuel quantities in storage, to account for the NM at an NPP. So, accordingly, only such data is sent from the MBA.

Further on, all this data, in a still more concise form, is concentrated at the federal level, i.e. within Rosatom. Details on how the material is distributed among the material balance areas are unlikely to be needed by government leaders. However, if all details on NM are required, this may be requested for directly from the respective MBA.

1.2. Operator-level accounting of NM

Each agency has operators, that is, integrated mills, nuclear centers or concerns that are immediately in charge of nuclear plant operations. These fabricate, process and use nuclear material. So, “Mayak”, an integrated mill in the Urals, includes a plant for chemical processing of spent nuclear fuels (RT-1). There is also a facility for storage of the plutonium extracted from WWER-440 reactor fuel at RT-1. It is also used to store plutonium extracted at RT-1 from spent fuel assemblies of nuclear power plants. These are complex and rather large installations.

Rosatom also has major research centers. One of these is State Research Center “Institute of Physics and Power Engineering” in Obninsk, a large nuclear research establishment that operates a number of large-size facilities, including the world’s first nuclear power plant, the BOR-10 reactor and BFS-1,2 critical assemblies.

Another major research center is National Research Center “Kurchatov Institute”, Russia’s oldest and largest nuclear center. The center’s R&D works have been a great contribution to the development of Soviet and, subsequently, Russian nuclear industry. Over its history since the formation time back in the 1940s, the center has had large nuclear material inventories of all grades, forms and enrichments accumulated therein. The Kurchatov Institute has over 30 nuclear facilities, including nuclear reactors, critical and subcritical assemblies, and so on.

An operator of Rosatom is FGUP “Atomflot”. This has in control all of the civilian icebreaker fleet formed to guide cargo ships through Arctic ice. Now, the active fleet consists of four nuclear-propelled icebreakers with a two-reactor nuclear power plant of 75,000 hp. These are the *Rossiya*, *Sovetskiy Soyuz*, *Yamal* and *50 let Pobedy* nuclear-powered ships; two icebreakers, *Taymyr* and *Vaygach*, with a single-reactor plant of 40,000 hp; and *Sevmorput*, a nuclear-propelled container ship with a reactor facility of the same power. There are also four nuclear fleet maintenance and repair ships, including two repair ships, *Imandra* and *Lotta*, the *Serebryanka* LRW tanker and the *Rosta-1* radiation monitoring ship. Three nuclear

icebreakers, *Lenin*, *Arktika* and *Sibir*, and two repair ships, *Lepse* and *Volodarskiy*, have been decommissioned and are non-operational.

Another operator of Rosatom is OAO “Rosenergoatom Concern”. This controls all Russian NPPs, including Balakovo, Beloyarskaya, Kola, Kalinin, Smolensk, Novo-Voronezhskaya and other nuclear power plants with a large number of power units.

Until recently, the NM accounting and control system had its operations limited to the facility level. All NM data was sent from facilities. However, as the new material balance accounting system requires, also material balance areas are introduced where all necessary NM data is generated by measurements.

Enterprise NM accounting: organizational, scientific and technical arrangements

There are many organizations in Russia using nuclear material in different forms, including nuclear power plants, integrated mills, research centers and others. It is exactly these organizations that bear most of the burden in the development of accounting systems. While general state NM accounting and control systems have been mostly prepared and commissioned by now, a great deal of exertion is needed to have practical NM accounting and control systems developed for enterprises. By and large, things with NM should be shaped so that to meet the requirements of the present day and the respective regulations and rules. In the context of NM, this requires the following:

- organizational efforts (including the appointment of administrative staff to be responsible for keeping records of nuclear material);
- NM accounting procedures should be developed in accordance with the site specifics;
- the site should be further equipped with the advanced technology to implement top-level accounting. This primarily suggests that computer systems for NM accountancy and instrumentation for NM measurements should be introduced;
- finally, personnel should be trained in the new rules, based on which the accounting system is built, and the equipment handling rules.

Major components of enterprise NM accounting systems

The NM accounting system of a nuclear enterprise shall include three major components:

- the NM accounting system proper (information system);
- NM measurements and control of measurements;
- physical inventory takings.

As noted above, the accounting system ensures the knowledge about NM (state, location and movements), this knowledge to be complete, confident and timely. These characteristics of our knowledge of NM are achieved, *inter alia*, using the above NM accounting means. Thus, confidence is achieved through measurements of NM and control of the measurement quality. The completeness of knowledge is achieved by physical inventory takings for all existing NM. Timeliness is achieved with the aid of a computerized information system.

1.3. Evolution of nuclear material accounting systems

NM bookkeeping system

Nuclear material accounting systems have quite a long history of evolution. Early systems were based on the so-called bookkeeping. This is a universally employed approach to accounting of tangibles. In the context of NM, bookkeeping has many things specific to it.

1. Nuclear material was measured when the process required so. When this was not required by the process, only paper records were kept. If a material had not been changed technologically or was not involved in the process and was simply moved, this NM was accounted for solely based on the documents that were enclosed and handed over therewith.

2. This is a deterministic accounting system. No NM measurement errors were included in the NM certificate data so the confidence of this NM data was unknown. New measurements often led to discrepancies between the existing and newly obtained data. The NM data nonconformity was eliminated using the concept of the technological loss standard. That is, processing and handling of NM was regarded to involve some discard of it. This discard was determined in a directive manner based on the experience of operators in the nuclear industry.

The 50-year history of operations with NM has led to a great deal of discrepancy between the documentation on NM and the reality.

NM measured material balance system

There is another NM accounting system that has none of the above deficiencies and has been receiving, recently, an increasingly growing recognition. This is the system of the so-called measured material balance

[2–4]. Unlike the NM bookkeeping system, this material balance system is based on NM measurements. Nuclear material is measured every time a major operation involving NM takes place, including, for example, transfers. This makes an allowance for the statistical nature of all NM measurements results. The basis of this NM accounting system will be looked at in the subsequent chapters hereof.

Computerization of NM accounting

There are different versions of computerized nuclear material (NM) accounting and control systems used nowadays by many nuclear industry entities in Russia. The explanation for computerized information technologies having been extensively introduced in accounting and control of NM is fairly simple. Lack of computers makes it rather difficult for large enterprises to determine highly accurately and rapidly where and in what quantity and state their nuclear material is. Furthermore, the requirements of the Federal Information System call for a phased transition to a system of reports based on material balance areas. Such volume of data cannot be acquired and handled with no computerized systems in place. It is exactly the absence of the sufficient choice of proven computerized NM accounting and control systems that leads to a simplified form of reports, that for the whole of the enterprise, being used nowadays. Finally, alienation and socialization of data on NM inventories and transfers, in the centralized database form, from the immediate operators, independent balance closings and other characteristics restrain to a great extent potential unauthorized use of NM and information on these. While contributing to achieving high-level continuity and confidence of knowledge about NM, all these factors give a major impetus to a broad-scale introduction of computerized NM data handling technologies at enterprise, departmental and federal levels.

Continuity of knowledge about nuclear material

The requirement of controlling weapon-grade material necessitates continuous monitoring thereof. The key issue here is continuity of knowledge about inventories of NM, primarily, of weapon-grade NM. Solutions to this have been searched for technologically.

The ideal answer in the context concerned will be to keep NM continuously subjected to visual and instrumented monitoring. For NM at rest, this monitoring is achievable through access controls. Access controls have been heavily involved in accounting and control of NM. These include containment and surveillance measures (seals, TV monitors).

Access control have been intensively developed and perfected in recent years. Aspects of access controls applications will be given a closer look in Chapter 10 hereinafter.

However, where NM is not at rest, no continuity of knowledge about NM can be achieved with the aid of access controls. There may be nuclear material thefts by personnel with access to NM. Such thefts may long be undetected not until the next physical inventory is taken. Still, a physical inventory taking may also fail to detect minor thefts because of an unavoidable uncertainty in the nuclear material balance.

It is exactly lack of secure technologies enabling continuity of NM monitoring in the conditions of operations that renders NM vulnerable to misuses by personnel. In this respect, facilities with a great deal of nuclear material in the form of small-size elements (e.g., the BFS with its large number of disks) are the point of the greatest concern.

A realistic technological solution to making continuity of knowledge about NM transfers substantially achievable is computerized near-real-time accounting of operations with NM involving as extensive use of containment and surveillance features as it can be.

The first ever realization of the near-real-time NM accounting concept was brought into being by Los-Alamos National Laboratory in 1991. This had the form of a standardized computer-aided NM accounting and control system called LANMAS (Local Area Network Material Accountability System). Near-real-time computer-aided NM accounting and control systems are also being created or have already been put into operation by a number of organizations in Russia.

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CHAPTER 2

BASIC CONCEPTS OF THE MEASURED NUCLEAR MATERIAL BALANCE SYSTEM

2.1. Basis for categorization of NM

Accounting category of nuclear material is one of the basic NM-related concepts. A material falling into an accounting category is subject to certain accounting, control and physical protection regulations. A material that fails to fall into an accounting category does not have any stringent regulations it is subject to. The question of which material shall be categorized as accounted for arises so in connection with NM accounting categories.

Nuclear material subject to accounting and control

As defined by the General Rules for Accounting and Control of Nuclear Materials, the following material shown in Table 2.1 below shall be subject to accounting and control procedures.

Table 2.1

List of nuclear and special non-nuclear material subject to accounting and control

Material	Description
Nuclear	Plutonium Uranium Uranium-233 Uranium-235 Thorium Neptunium-237 Americium-241 Americium-243 Californium-252
Non-nuclear, special	Lithium-6 Tritium Deuterium, excluding deuterium contained in heavy water used for nuclear reactor moderator

Apart from major elements of uranium-plutonium and thorium cycles, this list includes transuranium elements. Also, the list includes a range of

special non-nuclear materials which have significance and can be used to produce weapon-grade material and nuclear explosives. Some of the examples are deuterium, lithium-6 and tritium used to make thermonuclear charges. Coming under international safeguards, as defined by the IAEA, is a list of nuclear material which is close to that given above.

Quantitative criteria for nuclear material to be put on and withdrawn from records

Nuclear material shall be subject to state accounting and control if the values of the masses held at the enterprise or carried by one vehicle are equal to or exceed the minimum quantities given in Table 2.2. For major elements of uranium-plutonium and thorium cycles, as evidenced by the data in the table, the minimum quantities thereof to be accounted for make 15 g. For uranium and thorium of a natural isotopic composition, the least quantity from which accounting starts is 500 kg.

In the event of an enterprise with more than one nuclear material, products or articles containing a mix of nuclear material presented in Table 2.1 are not subject to regulations unless exceed the limits given in Table 2.2.

State accounting and control are not applied to:

- uranium contained in ore, as well as in intermediate products in mining or metallurgical processes,
- thorium contained in ore, as well as in intermediate products in mining or metallurgical processes;
- nuclear material in sealed ionizing radiation sources;
- neptunium-237, americium-241, 243 and californium-252 in irradiated products;
- lithium-6 if its content in lithium is not more than 7.5 at. %;
- deuterium contained in hydrogen-containing material where deuterium's relative isotopic content does not exceed 50 at. %;
- nuclear material in radioactive waste (RW) at RW storage points.

Where the mass of the nuclear material at an enterprise is less than specified in Table 2.2, material is accounted for and controlled subject to radioactive material accounting requirements.

Table 2.2

Minimum quantities of nuclear material from which these are subject to state accounting and control

No.	Nuclear material	Minimum quantity	Last significant digit of NM mass as reported
1	Plutonium	15 g	1 g
2	Uranium-233	15 g	1 g
3	Uranium with enrichment in U-235 of more than 0.72%	15 g in U-235 isotope	1 g
4	Neptunium-237	15 g	1 g
5	Combination of nuclear materials as shown in pp.1-4	15 g by total mass of Pu, U-233, Np-237 and U-235	1 g
6	Americium-241	1.0 g	0.1 g
7	Americium-243	1.0 g	0.1 g
8	Californium-252	0.001 g	0.000001 g
9	Uranium with U-235 isotope content of not more than 0.72%	500 kg	1 kg
10	Thorium	500 kg	1 kg
11	Lithium-6	1.0 kg	0.1 g
12	Tritium	0.2 g	0.01 g
13	Deuterium, excluding deuterium in heavy water	2 g	0.1 g

Categorization of nuclear material and facilities

A question arises, why one needs to categorize nuclear material? The answer is that NM is categorized to enable a differentiated approach to identifying techniques and instruments for accounting, control and protection of NM. In the first place, this makes it possible to focus on the nuclear material which is easy to convert to weapon-grade material.

We shall consider the principles to which nuclear material is categorized internationally with a nuclear material categorization system taken for illustration.

Categorization of nuclear material in Russia (NP-030-05 [1])

Categories of nuclear material are defined depending on the NM mass, the form of the NM-containing product and the NM type (Tables 2.3 – 2.6). Depending on the quantity of nuclear material, the MBA facility may fall into category I, II, III or IV. The next parameter is the form of the NM-containing product. As evidenced by Tables 2.3-2.6, this demonstrates the attractiveness of nuclear material. Attractiveness is assessed by how rapidly a nuclear material can be converted to a form fit to produce nuclear weapon.

Noteworthy is that irradiated fuel is the least attractive. The reason is simple. Such fuel is inherently safe which makes it an essentially unlikely target for theft or misuse. Same is true for low-enrichment uranium that needs to be highly enriched to be used directly in nuclear weapons production.

Cases are possible when the area of interest contains different products and diverse NM. To categorize the existing NM in these conditions, one is expected to proceed from the total mass of NM in each product and the quantitative mass limits, as specified in Tables 2.3 – 2.6, for the nuclear material in products falling under a higher category.

Russia defines NM physical protection, accounting and control requirements subject to the following categorization of nuclear material.

Table 2.3

Nuclear material of category I

Products	Nuclear material	Mass of nuclear material, kg, not less than
Metal products: metal articles, billets; ingots, grit, alloys and mixtures; fuel elements and assemblies with a content of metallic and intermetallic fuel; reject articles and waste processed by remelting without dissolution	Pu, U-233	2 by total mass of Pu and U-233
	HEU	5 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	2 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
Products	Nuclear material	Mass of nuclear material, kg, not less than
Products with high content of nuclear material: carbides, oxides, chlorides, nitrides, fluorides, alloys and mixtures thereof; fuel elements and assemblies containing fuel out of above compounds, as well as other products with NM concentration (content) of not less than 25 g/l (25 g/kg)	Pu , U-233	6 by total mass of Pu and U-233
	HEU	20 by U-235 isotope

Table 2.4

Nuclear material of category II

Products	Nuclear material	Mass of nuclear material, kg
Metal products: metal articles, billets, ingots, grit, alloys and mixtures thereof; fuel elements and assemblies with a content of metallic and intermetallic fuel; reject articles and waste processed by remelting without dissolution	Pu, U-233	≥ 0.5 but < 2 by total mass of Pu and U-233
	HEU	≥ 1 but < 5 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	≥ 0.5 but < 2 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
Products with high content of nuclear material: carbides, oxides, chlorides, nitrides, fluorides, alloys and mixtures thereof; fuel elements and assemblies containing fuel out of above compounds, as well as products with NM concentration (content) of not less than 25 g/l (25 g/kg)		≥ 2 but < 6
	Pu, U-233	by total mass of Pu and U-233
	HEU	≥ 6 but < 20 by U-235 isotope
Products with low content of nuclear material: products requiring complex treatment; products with NM concentration (content) of 1 to 25 g/l (1 to 25 g/kg)	Mixture or combination of Pu, U-233, HEU and other nuclear material	≥ 2 but < 6 by total mass of Pu, U-233, U-235, Np-237, Am, Cf
	Pu, U-233	≥ 16 by total mass of Pu and U-233
	HEU	≥ 50 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	≥ 16 by total mass of Pu, U-233, U-235, Np-237, Am and Cf

Table 2.5

Nuclear material of category III

Products	Nuclear material	Mass of nuclear material, kg
Metal products: metal articles, billets, ingots, grit, alloys and mixtures thereof; fuel elements and assemblies with a content of metallic and intermetallic fuel; reject articles and waste processed by remelting without dissolution	Pu, U-233	≥ 0.2 but < 0.5 by total mass of Pu and U-233
	HEU	≥ 0.5 but < 1 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	≥ 0.2 but < 0.5 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
Products with high content of nuclear material: carbides, oxides, chlorides, nitrides, fluorides, alloys and mixtures thereof; fuel elements and assemblies containing fuel out of above compounds, as well as products with NM concentration (content) of not less than 25 g/l (25 g/kg)	Pu, U-233	≥ 0.5 but < 2 by total mass of Pu and U-233
	HEU	≥ 2 but ≤ 6 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	≥ 0.5 but < 2 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
Products with low content of nuclear material: products requiring complex treatment; products with NM concentration (content) of 1 to 25 g/l (1 to 25 g/kg)	Pu, U-233	≥ 3 but < 16 by total mass of Pu and U-233
	HEU	≥ 8 but < 50 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	≥ 3 but < 16 by total mass of Pu, U-233, U-235, Np-237, Am and Cf

Table 2.6

Nuclear material of category IV

Products	Nuclear material	NM mass, kg, not more than
Metal products: metal articles, billets, ingots, grit, alloys and mixtures thereof; fuel elements and assemblies with a content of metallic and intermetallic fuel; reject articles and wastes processed by remelting without dissolution	Pu, U-233	0.2 by total mass of Pu and U-233
	HEU	0.5 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear materials	0.2 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
Products with high content of NM: carbides, oxides, chlorides, nitrides, fluorides, alloys and mixtures thereof; fuel elements and assemblies containing fuel out of above compounds, as well as other products with NM concentration (content) of not less than 25 g/l (25 g/kg)	Pu, U-233	0.5 by total mass of Pu and U-233
	HEU	2 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	0.5 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
Products with low content of NM: products requiring complex treatment; products with NM concentration (content) in a range of 1 to 25 g/l (1 to 25 g/kg)	Pu, U-233	3 by total mass of Pu and U-233
	HEU	8 by U-235 isotope
	Mixture or combination of Pu, U-233, HEU and other nuclear material	3 by total mass of Pu, U-233, U-235, Np-237, Am and Cf
All other products including: a) products containing Pu, U-233 and HEU with a concentration (content) of below 1 g/l (1 g/kg); b) any uranium compounds with a U-235 content in uranium of below 20%; c) any products with an absorbed dose rate of not less than 1 Gy/h = 109 rad/h at a distance of 1 m; d) any compounds of: plutonium with a plutonium-238 isotope content of over 80%; thorium, neptunium-237, americium-241, americium-243 and californium-252; e) special non-nuclear material and any compounds thereof		Total mass of all nuclear material is not less than the minimum quantities

NM categorization practice

The existing material should be categorized if the core contains:

- fresh FAs of a research reactor core (the reactor grid is composed of 16 FAs, each FA containing 90% of uranium in the form of a uranium and aluminum alloy. One FA contains 300 g of uranium-235);
- one fresh FA of a research reactor;
- fresh FAs of a light-water power reactor numbering a third of the overall reactor load (a 4.4%-enriched UO_2 fuel is used, one FA contains 19 g of uranium-235. There are 160 FAs in the reactor. The overall reactor load is 80 t of UO_2);
- one spent FA;
- metal waste with 250 g of plutonium and a container with PuO_2 of the net weight 6.5 kg;
- 450 kg of natural uranium.

2.2. Forms of nuclear material. Batch of nuclear material

Forms of nuclear material

All nuclear material may have one of the following two forms.

Item NM in the form of canned material. This has a unique identification number of its own. Examples of item NM are fuel elements and fuel assemblies.

Bulk-form NM is any NM other than canned NM, i.e. having an unclad form (gases, liquids, powders, pellets). This material cannot be permanently identified as its quantity and composition in containers can be changed.

Depending on the existing NM form, various instruments and identifiers are used to account for this NM. So, bulk nuclear material can be tested destructively with sampling and subsequent sample analysis. These methods are not applicable to item NM. On the other hand, this NM is often measured nondestructively.

Batch of nuclear material

An exclusively important concept used in the new system (as, though, in the old system as well) is nuclear material batch. This concept is used to record item and bulk NM.

A batch of NM is a collection of uniform items that contain NM the parameters whereof are determined in a single series of measurements.

Uniformity means that, e.g., one batch cannot contain items of different enrichments.

Each NM batch has five data elements:

- name of NM batch. Batch name is the identifier composed of a number of symbols. The identifier shows the manufacturer code, the batch serial number and so on. Therefore, name is used as the unique identifier of NM batch;
- number of uniform items in batch. The number of items is often equal to 1. “Item” is the term often used to denote an NM batch. Examples of batches: fuel element (the number of items in batch is 1), container with UF_6 (the number of items in batch is 1), five containers with UO_2 powder (a batch is understood as the given set of containers of which each is viewed as an item);
- NM ligature mass (M_{lig}) which is the mass of a material that contains a chemical or physical NM composition with some inert substance. For example, the mass of the U–Al alloy is understood as the ligature mass of NM in the U–Al alloy used as fuel in some research reactors (of the IRT type). The ligature mass of NM in the form of a chemical compound of uranium dioxide (fuel of light-water power reactors) is understood to be the mass of the UO_2 compound;
- element mass (M_{el}). For example, for the UO_2 compound we have the element masses of $M_{\text{el}} = M_{\text{U}}$, $M_{\text{el}} = M_{\text{O}}$;
- isotope mass (M_{is}). Accounting deals primarily with fissile isotopes: U–235 isotope for uranium and Pu–239, 241 isotopes for plutonium. Enrichment, a similar parameter, is considered occasionally instead of the U–235 mass.

The five noted NM batch parameters are central to NM accounting and balancing closing. These parameters are applicable both to item and bulk NM. For material in the form of items, however, all data that accompanies unirradiated material is the manufacturer data, while data for bulk material normally change over time.

2.3. Material balance area (MBA).

Organization of accounting and control of NM in MBAs

Material balance area

Material balance area (MBA) is the central concept to the new NM accounting and control system. MBA is an elementary structural unit of the state NM accounting and control system.

There is no such notion in bookkeeping where NM balances are operated for the whole of the enterprise. As a concept, MBA was introduced in 1959 by US experts and “legalized” by the IAEA in the Guidelines for States’ Systems of Accounting for and Control of Nuclear Materials (1980 [2]) going later into the Concept of the State Nuclear Material Accounting and Control System as approved by the Russian Federation Government in October 1996 [3].

Definition of MBA: A territorially and administratively area established within a nuclear facility or an NM storage point to account for and control nuclear material, the quantity of nuclear material therein determined by measurements each time it is transferred into or out of the given area with the nuclear material balance closed for the respective time period.

Therefore, controlled inputs and outputs are defined clearly in an MBA, and the NM inventory is periodically subject to determination by NM physical inventory takings (PIT).

Construction of MBA. Proper selection of the NM balance area structure is essential to ensuring sound operations of the corporate NM accounting and control system. However, MBAs are often hard to size and set boundaries for. For example, Figure 2.1 shows a simplified flowchart of a power reactor fuel fabrication plant.

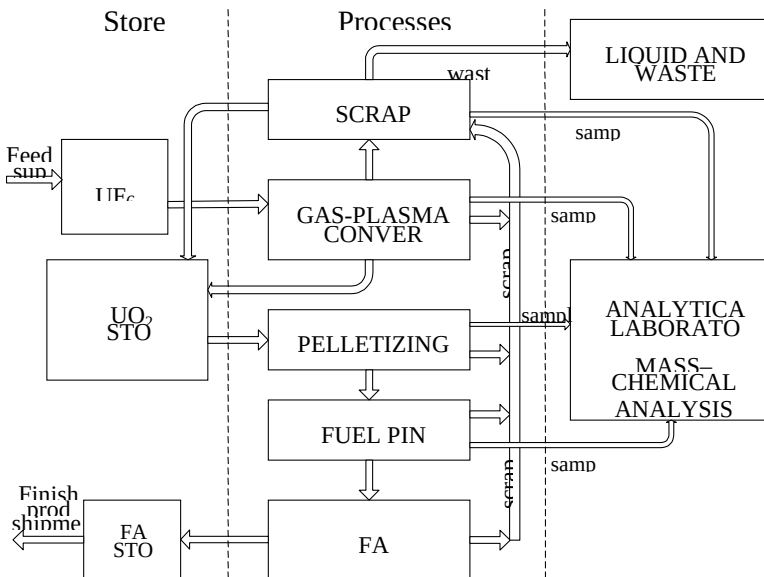


Fig. 2.1. NPP fuel fabrication. Flowchart of major processes

It includes many processes. MBAs, however, should be such that to make it easy to measure incoming and outgoing NM flows and take physical inventories with no great economic loss due to suspension of production.

Sizing of MBAs is so a matter of optimization since the decision is made based on a number of contradictory requirements. Examples:

a) if an MBA is large, there is less corporate documentation and it is easier to report. Physical inventories are however harder and more expensive to take in the MBA as this requires the production process to be stopped;

b) if an MBA is small, physical inventories are easier to take. Still, a great deal of reporting is required for the whole of the enterprise.

To choose the MBA structure, each enterprise proceeds from this kind of contradictory conditions and follows a number of generic MBA selection guidelines. Here are some of such guidelines:

- the number of MBAs at the enterprise is chosen such that they be enough to ensure accounting and control of all NM. Each MBA is documented and subject to approval from a superior organization. Ultimately, the number and boundaries of MBAs are approved by Rosatom that implements federal-level accounting and control of NM;
- each MBA shall form a single indivisible area (a simply connected region);
- MBA structuring requires MBAs to have their boundaries well-defined and matching (other than crossing) those of guarded areas. MBAs and guarded areas may have coinciding boundaries;
- if an MBA has boundaries failing to make material in different MBAs less likely to be intentionally or unintentionally mixed, this renders control of this area senseless;
- determination of the MBA boundaries shall take into account the existing physical barriers. Physical barriers are structural elements (walls, ceilings, gates, doors) and dedicated structures (fencing, anti-ram facilities, meshes, reinforced doors, containers);
- operational divisions, such as plant laboratories, warehouses, as well as departments requiring special protection of information, form separate MBAs.

The IAEA and some organizations in Russia have developed and use dedicated techniques to structure MBAs based on design data. Data on how every facility is designed is arranged as a questionnaire. Answers to the

questions in this enable one to get a set of data required to define the MBA boundaries.

Determination of NM flows and inventories in MBAs

Incoming and outgoing NM flows, as well as NM inventories in MBAs are determined at key measurement points (KMP).

Key measurement point (KMP) is where nuclear material can be measured to have NM flows and inventories determined.

Inventory determination methods for canned articles (FAs, individual fuel elements (FE) and others) are accounting of items (identification of items plus counting thereof) and nondestructive NM measurements.

For bulk material these are a set of measuring procedures used to determine the inventory with potential sampling taken into account. Chemical and isotopic compositions are measured on the samples taken. This gives significance to making so that NM samples to be representative.

Figure 2.2 demonstrates measurements for different NM forms (bulk and items) at key measurement points for the fuel element loading department in an NPP fuel fabrication cycle. It can be seen that both destructive (for incoming NM flow) and nondestructive NM analyses are used to account for NM.

Attributes are the data that determines unambiguously if NM has any feature.

Examples of attributes:

- Is there NM in the given item or not?
- Does the tamper indication device verify to the absence of unauthorized access to NM or not?
- Is NM of the type shown in certificate data or not?
- Does the NM gross weight differ from certificate data in the measurement error limits or not?
- Does the number of items in the container coincide with documented data or not?
- Is the item with the given identifier at its specified location or not?

Attributes are particularly useful with basic accounting procedures. This is the case, say, when an NM transfer requires incoming material to be rapidly received. Incoming tests of material are based predominantly on attributes.

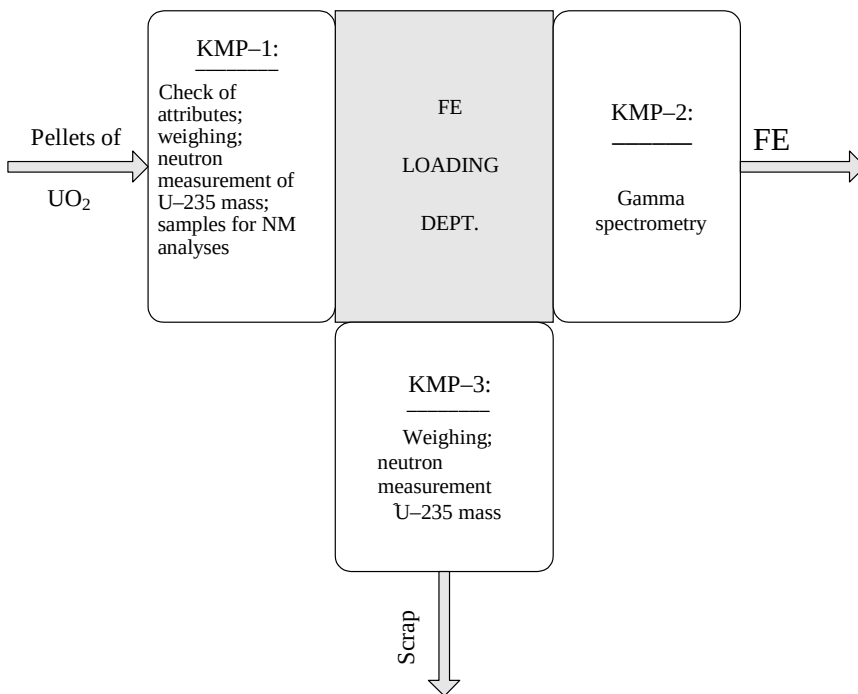


Fig. 2.2. Measurements of NM flows at KMPs

Another example of attributes used efficiently is the procedure of the NM physical inventory taking in MBAs. This procedure determines all NM inventories in an MBA through:

- checks of NM for presence and integrity;
- checks of seals for integrity and identification of same;
- counting of existing items;
- weighing of items;
- accounting and verifying measurements.

A physical inventory taking involves examination of accounting records and the listing of the existing NM (inventory listing (IL)). Nuclear material is measured and the physical inventory of NM in the MBA is determined (physical inventory listing (PIL)).

The NM integrity and accounting quality are determined from the conformity of the NM physical inventory and the NM documented for the MBA. The establishment of this conformity is called NM balance closing

for the MBA. Formally, the NM balance in the MBA can be written as the following equation:

$$ID = PI - BI = PI - IN + DE - I, \quad (2.1)$$

where ID is the inventory difference; PI is the physical inventory of NM in the MBA as determined in the given PIT; BI is the book inventory of NM in the MBA as of the physical inventory taking start point; IN is the determined and documented NM quantity increase over the given material balance period (MBP); DE is the determined and documented NM quantity decrease over the given MBP; I is the inventory of NM in the MBA as determined and documented as of the given MBP start point. More details on the NM physical inventory taking and balance closing procedures are discussed in Chapter 6.

Basic requirements to organization of NM accounting and control in MBAs

When an MBA is established, one shall specify:

- the types, forms and quantities of NM as may be therein (that is, the NM category);
- the system of authorized NM locations. Each location should have a unique identifier;
- personnel with access to NM in the given MBA;
- the MBA has NM key measurement points defined to be provided with required instrumentation;
- the physical inventory taking procedure is developed;
- the forms of and the keeping procedures for accounting records are determined;
- the responsibility for storing all NM inside the MBA shall be placed on a custodian with whom a contract is made as to accountability under the Russian Federation Labor Code.

The custodian's major responsibilities are:

- execution of documents for NM shipments/receipts and all NM transfers into and out of the MBA;
- the keeping of accounting records and preparation of reports to superior organizations;
- participation in physical inventory takings;

- making the enterprise executive staff aware of all NM deficiencies detected.

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CHAPTER 3

INFORMATION SYSTEMS OF NM ACCOUNTING

Information systems are central to accounting and control of NM. It is exactly where all data is generated as required to plan activities with NM at all (state, agency and operator) levels.

This chapter looks into how NM accounting information systems are built at the federal and operator level.

3.1. Tasks of NM accounting information systems

An NM accounting information system addresses a spectrum of tasks involved in NM handling.

1. Management tasks. The first point to note is that no activities can be planned efficiently and no NM can be managed in the process of these activities without credible NM data in hand. So NM data is fundamental to an advanced NM management system at state, agency and operator levels.

2. NM control tasks. An information system provides data for control activities undertaken both by internal departments (e.g. corporate administrative control of NM) and by outside organizations (e.g. control by Rostekhnadzor of Russia).

3. Protection tasks. An information system that is accurate and responds rapidly to changes in the NM condition also has a protection role since it is what helps detect NM-related anomalies. Besides, computerization of data handling processes and generalization of information on inventories and movements of nuclear material in the form of a server-based centralized database are factors that contribute to prevention of unauthorized transactions with NM. The centralized database is accessible to persons in charge who can check what is taking place at the facility against database-contained custodians' reports. This, therefore, gives NM an improved traceability.

3.2. Basic requirements to NM accounting information systems

Quality of reported NM data. NM data provided by an accounting information system at any level is expected to meet the requirement of credibility, completeness and timeliness. The current approach to accounting and control of NM is based on the measured NM balance and is intended to ensure the above requirement. It is exactly based on these measurements that NM data is generated. All NM in each MBA shall be totally checked at regular intervals (the physical inventory taking

procedure). NM is presently accounted for using up-to-date computer-based data processing technologies.

Data security. NM data security, accessibility and access partitioning are the major requirements to NM accounting information systems contained in the General Rules. Means to support these and other regulatory requirements to the NM accounting information systems are developed intensively as part of advanced computerized accounting systems.

3.3. Enterprise-level structure of NM accounting information systems

MBA is an elementary autonomous structural unit having a corporate information system operating as part of it. It is exactly MBA that the primary and most complete NM information is generated in. This information is further analyzed, processed and consolidated for the area reported on to form a single report. The consolidated data is then forwarded to superior levels. Therefore, an enterprise NM accounting data system integrates consolidated data on each MBA.

Structure of the information description of NM in MBAs

The attributes and essential parameters of all NM within the MBA are documented, including NM types, forms and quantities. Identifiers are used to document expressly NM and the authorized locations thereof in the MBA. All NM measurements done and data of the instrumentation used are recorded. Absence of unauthorized access to NM is characterized by identification tags of TIDs. All significant operations done with NM are also documented.

All accounting operations in the MBA lead ultimately to as detailed information as it can be generated for each item with NM. The maximum of information description detailing, as combined with the localization up to the MBA level, enables balance closing for these regions and detection of a significant difference between the documented quantity of NM and its physical inventory at the MBA level, while controlling the quality of the NM handling information description within each MBA.

The data noted above is booked in special journals of NM handling operations and in NM accounting registers (a general ledger and several auxiliary ones) for MBAs in the form of electronic databases. The information system is so realized in paper and electronic forms. These two accounting data keeping forms are mutually complementary and enable online and reliable storing and handling of NM data.

Two types of information: accounting data (original and book records) and reports on NM, are stored and generated in the information system with respect to NM in the MBA.

System of MBA accounting records

An information system for NM accounting in an MBA is operated in accordance with generic requirements to NM accounting records (in accordance with the general rules, NP-30-05). The accounting documents kept for an MBA contain data on each NM type, including the NM inventories in the MBA, changes in NM quantities in the MBA and updates to entries in accounting records. Respective documents also contain additional data, including calibration, test and check data for all instruments; sampling data and sample analysis results; measurement quality check data and more.

No information in accounting records is subject to elimination. It should be at all times accessible to be further examined. Erroneous entries and later entries given new accounting numbers shall be kept in accounting records.

The system of MBA accounting records is a set of:

- initial NM records;
- books;
- an MBA bookkeeping subaccount on the enterprise account.

Initial MBA documentation

Initial documentation is formed by the combination of all accompanying documents for the MBA NM inputs and all NM measurement data (e.g. from physical inventory takings). This documentation is an essential and important part of the entire information system. The so formed initial data is further logged, processed and analyzed. Therefore, credibility checks of the data in initial documents and the secured keeping thereof are the prime tasks with respect to this.

MBA and enterprise books

The NM in an MBA is booked in journals of daily NM operations, in the general ledger and auxiliary ledgers for the MBA NM accounting purposes and so on. The operations that change the balance of the material at the enterprise are booked in the general ledger. This data gives a general

notion of the enterprise NM condition and is kept by the NM A&C department.

These accounting records were kept earlier as well, still conditions have changed and now require:

- mandatory regular NM measurements to show not only measurement data but also the accuracy thereof;
- operation of electronic accounting data as server-based databases. Changes in NM in the form of transactions are logged in databases.

One important note is that multiple entries on NM in records at different levels make it easier to detect errors (by checking various ledgers and listings of NM inventories) while, at the same time, make it more difficult to falsify entries on NM handling operations.

NM accounting on bookkeeping account

Each organization having nuclear material shows it on its bookkeeping account. Enterprise accounts may be arranged differently as depends on a great deal of factors. Normally, an MBA has a subaccount on the corporate bookkeeping account to enter the following for each NM type: NM inventories, NM receipts and shipments, as well as NM accounting measurement data. Taken together for all MBAs, these subaccounts make the enterprise account for the given type of the enterprise NM. The subaccount, however, enables one to have more detailed data on NM, makes it easier to retrieve this and is subjected to internal NM audits.

Internal audits of accounts and records are essential to maintaining the operability of the entire NM accounting information system. This includes:

- a well structured system of existing records in accordance with the enterprise bylaws and the division of document handling powers and responsibilities among personnel;
- periodic revisions of documents and respective check procedures;
- evaluation of the current system condition;
- check of incoming NM data for being logic;
- data access control.

Enterprise reporting system

Enterprise information is put out as paper and electronic reports. Each MBA should have an inventory listing (IL) and an inventory change report (ICR) prepared based on which an IL for the reported area (IL RA) and an ICR for the reported area (ICR RA) are generated to be subsequently

forwarded to a superior organization (and further to Rosatom, Rostekhnadzor and so on).

Presently, data is commonly reported as:

- an NM inventory change report for the reported area (ICR RA) (reports are submitted to the information and analytical center of the Federal Information System (IAC FIS) each time the inventory changes or quarterly);
- an inventory listing for the reported area (IL RA) (the complete list of all material showing quantitative characteristics thereof).

The IL RA and ICR RA reports are generated with information on the nuclear material holder and conditions of use taken into account.

Tables 3.1 and 3.2 give examples of the IL RA and ICR RA forms. Since 2007, these consolidated forms have been used by Rosatom operators to report to state on the NM status as part of the federal NM accounting information system.

Apart from this, the operator forwards consolidated NM data to superior organizations on a periodic basis (say, once per year) by way of financial accountability to state.

3.4. Transaction as the key component of electronic NM logging

Transaction, as a notion, is central to electronic NM accounting in MBAs. Transaction is a database entry with respect to a change in the NM status or a change in NM data. Such changes (say, in the inventory, in the NM chemical or physical form or in NM data) are consistent with the operations (processes) material or NM data undergoes. Therefore, out of a great deal of operations done, it is the most significant ones that are logged.

One example of important characteristics is the total quantity of NM in the MBA as of a point in time (called the NM inventory). All operations leading to an NM inventory change in the MBA are logged as transactions. This includes all NM shipments from the given MBA and NM receipts in the MBA, wastes with NM that have been written off, NM loss, nuclide generation and burn-up, NM changes in enrichment and others. Another example of transactions is an NM measurement data entry. Operations with material information, e.g. NM schedule adjustments, are also logged as transactions.

For easier statement, we will not differentiate hereinafter between a transaction and the respective operation leading to a change in the noted characteristics of NM in the MBA.

Table 3.1

Tabulated part of regulatory ICR RA report

Inventory change No.	Change type	Code of partner organization / RA	Reference to accompanying document	Inventory change date	Rep. batch No.	Reported batch name	Holder code	Use mode	Number of items in batch	Code of material type
1	2	3	4	5	6	7	8	9	10	11

Rated enrichment, %	Material description			Ligature mass		Element		Isotope		Unit
	PF	CF	P&RS	Mass	Unit	Code	Mass	Code	Mass	
12	13	14	15	16	17	18	19	20	21	22

Note: PF – physical form, CF – chemical form, P&RS – purity and radiological status

Table 3.2

Tabular part of the IL RA regulatory report

No. of rep. batch	Name of reported batch	Holder code	Use mode	Number of items	Code of material type	Rated enrichment, %	Description of material			Ligature mass		Element		Isotope		Unit
							PF	CF	P&RS	Mass	Unit	Code	Mass	Code	Mass	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Note: PF – physical form, CF – chemical form, P&RS – purity and radiological status.

All transactions are documented in respective databases. In practice, the entire variety of transactions is reduced to three types:

offsite transfers – an NM shipment or receipt from another enterprise;

onsite transfers – NM transfers between MBAs within one enterprise. Onsite transfers normally require less accompanying documents and permits than offsite transfers. Thus, no prior notice of the planned material transfer is needed;

other inventory changes other than involving relocations of material. This type of transactions differs from the first two as it means “one-side” operations when there is neither shipper nor receiver and an entry is made as to an NM status change solely within one MBA.

These are:

- nuclear production and burn-up;
- isotopic enrichment;
- changes in chemical and physical form;
- measured waste dumps;
- incidental losses and detections of an NM surplus;
- NM schedule adjustments;
- approval of the NM inventory following replicated measurements, accounting of NM deposits and approval of the inventory difference written off.

Documentation of transactions matching “one-side” operations needs the NM inventory change estimate model, e.g. the reactor fuel burn-up model, to be shown.

Therefore, NM electronic accounting means consecutive databasing of transactions. The following data is documented for any transaction:

- identifier of the item to undergo the operation;
- type of relocated material (U, Pu and so on);
- total weight or volume of material;
- weight of elements (U, Pu and so on);
- weight of fissionable isotope (for uranium);
- physical form of material;
- chemical form of material;
- destination (if transferred);
- type of operation to be done;
- date of operation;
- date of material relocation;
- last name of the person logging the operation;

- last name of the person approving the operation.
This data can be seen to include all NM batch parameters.

Documentation of transactions in the above form enables closing of the NM balance in the MBA, estimation of the NM shipper/receiver difference and adherence to regulatory NM accounting and control requirements

3.5. Federal automated NM accounting and control system

The federal automated information NM accounting and control information system (FIS) was established to provide information support to management of nuclear material for peaceful uses and counter illegal circulation thereof. The FIS software was developed by FSUE “TsNIIatominform”.

The FIS is a component of the SSAC and is intended to give information support for governing authorities in charge of planning and management of nuclear material. Among other things, the FIS is intended to:

- give information support to Rosatom of Russia having powers in implementation of federal-level NM accounting and control;
- communicate with agency information systems.

The FIS is tasked to:

- create and operate the state NM register;
- deliver NM data to consumers concerned;
- give information support to NM exports and imports;
- give information support to NM transportation tasks.

The FIS is currently based at Rosatom’s Crisis Management Center (CMC) that includes an information and analytical center (IAC).

The IAC supports continuous communication with operators delivering data to FIS. It is exactly to the IAC that corporate information systems report on quantities and movements of NM. The IAC gathers reports on NM, checks these for conformity to specified requirements and regulations, tests data using all kinds of techniques, and, if found conforming to specified requirements, adds data to database. The IAC therefore forms the array of reporting data on NM, operates reference arrays, operates relevant versions of classifiers and communicates actively with data suppliers.

The current stage of the FIS evolution limits the range of data suppliers to Russian operators. To be able to deliver data, operators establish automated NM A&C systems to ensure corporate NM accounting, generation of regulatory NM reports and delivery of these to the FIS.

The IAC is also responsible for giving information support to the FIS users. It interacts with the FIS information suppliers and defines the required volume and quality composition of data submitted. Most of the information provided by the FIS is consumed by Rosatom executive staff and departments. No interactive user access to the FIS database is presently provided. However, this capability is expected to be made available at subsequent FIS evolution stages, provided information security features are in place.

Initially, the FIS was evolving towards gathering reports on material balance areas. So NM data transmission in the FIS was accordingly based on presentation of data from all MBAs at each enterprise. Operators reporting to the FIS sent in NM inventory listing for MBAs made out as of the reported period ending point and the NM physical inventory reports. This reporting pattern was looked upon as complete. In 1999-2004 the FIS had over 60 MBAs from more than 20 operators connected thereto using this reporting pattern. However, for all attractiveness thereof, this pattern should be understood to be feasible only if a number of conditions are fulfilled, including if corporate automated NM A&C information systems are in place. Besides, it takes quite a time to connect corporate NM A&C systems to the FIS. So, in 2000, a simplified (consolidated) pattern was implemented by Rosatom to connect operators to reports in the FIS. All operators circulating NM were sending annually to the FIS NM Inventory Listings (IL) and NM Inventory Change Reports (ICR) in the form consolidated for respective enterprises.

This dual-form (integrated and consolidated) reporting system had drawbacks (including duplication of NM data flows, loss of time to prepare reports and others), so in 2006 it was decided to switch to a “common reporting system”. As the result, the common corporate reporting system was launched into pilot operation in 2007 to replace, subsequently, the integrated and consolidated reporting systems. Common reporting of NM-handling operators hinges on reports based on presentation of data from MBAs merged into so-called reported areas (RA). The reported area is an area administratively established within an organization and formed by one or more MBAs to generate and deliver reports on the MBAs concerned to the SSAC federal level.

The IL RA and IRC RA reports from the area reported on are generated based on IL and ICR reports from the MBAs forming the RA with regard for the material holder and usage mode data.

IL RA/ICR RA reports should be prepared by the operator as a paper document or as its electronic version. An organization’s report coming into

the FIS IAC is handled at input to result in a data acceptance and error report which is forwarded to the organization concerned. If there are no errors in the organization's report, the reported data are downloaded into the FIS database. In the event of errors, the IL RA/ICR RA data is subject to adjustment by the operator's personnel or the FIS IAC personnel as approved by the operator and Rosatom's respective department.

CHAPTER 4

STATISTICAL BASIS OF NM ACCOUNTING AND CONTROL

If formulated in brief, the prime objective of an evolving NM physical protection, accounting and control (PPA&C) system may be said to consist in ensuring confident traceability of NM at all nuclear fuel cycle stages. Ensuring confidence is surely a problem of mathematical statistics [1].

We shall look at how the triad of accounting, control (A&C) and physical protection (PP) of nuclear material (NM) is organized to help achieve the objective in view (Fig. 4.1).

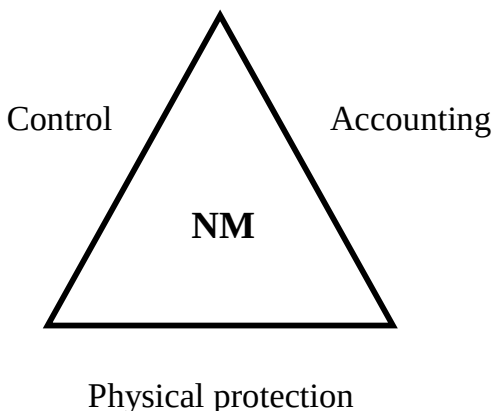


Fig. 4.1. The NM PPA&C triad

It is perfectly obvious that an efficient solution of the NM nonproliferation and confident traceability task depends on how effective and sufficient each of the triad components (physical protection, accounting and control of NM) is. A number of questions arise, which can be answered only by those who are knowledgeable in probabilistic and statistical methods:

- how to quantify the efficiency of a nuclear-hazardous facility and nuclear material physical protection system;
- how often and permissibly accurately a nuclear material shall be controlled;

- how NM accounting measurements shall be properly and sufficiently arranged for?

Use of statistical procedures in inspections and physical inventory taking is dictated by limited time and funds. It happens sometimes that one cannot or finds it economically unreasonable to check all items or all nuclear material in the given material balance area. Statistical methods may however help plan the scope and sequence of sampling so that one could be confident about the characteristics of all material measured from a portion of it.

The prime objective of ensuring traceability of NM is achieved by analyzing and estimating measurement uncertainties and searching for how to bring these down, planning the scope and sequence of sampling, and estimating the statistical significance of measurement discrepancies.

Normally, indeed, the control measurement result deviates from the value declared for the measured characteristic of the nuclear material subject to control. The deviation may be caused either by a measurement error which is determined statistically or by the actually observed difference between the values measured and declared. No final conclusion can be made without the respective statistical analysis done.

Probabilistic and statistical methods do not only enable the efficiency of an accounting and control system to be estimated in quantity terms, but also offer the only means to quantify NM vulnerability, a major characteristic of the physical protection system efficiency, which may be undoubtedly identified as probabilistic.

A large-scale program currently under way to upgrade and improve the state system of accounting for and control of NM envisions to give the state NM A&C system such important feature as extensive use of mathematical statistics methods.

4.1. Basic determination and reduction concepts of probability theory and statistics

Probability theory (PT) and mathematical statistics (MS) stand as a single branch of mathematics. This deals with procedures to solve direct and inverse prediction and decision-making problems. What is the subject matter of MS? One of the simplest definitions is based on the comparison relating to the concept of sampling from a finite universe. Knowing the composition of a universe, one can get a distribution for the composition of a random sample. This is a generic direct PT problem.

Commonly, however, one has to deal with inverse problems when the sample composition is known and it is to be found from this what the

universe was. Problems of the kind form the subject matter of MS. It may be said: use of PT, with the nature of a phenomenon being known, helps us find out how some characteristics of interest observable in an experiment will behave (are distributed). It is vice versa in statistics where the input is experimental data (these are normally observations of random quantities), and the requirement is to derive a statement (or decide) on the identity of the phenomenon under study.

Probability

Probability of event is generically comprehended as an abstraction that originates in the idea of the relative frequency at which an event occurs in the sequence of a replicated experiment (test) with the “given set of conditions”.

Imagine a relative frequency of an event in an unlimitedly protracted series of a replicated experiment, and you will get close to giving a reasoned interpretation of the probability of an event. Complexities will however arise if you try to base PT on strictly formalizing such interpretation. A simpler and deeper formulation was proposed by A.N. Kolmogorov [2]. It relies on the following assumptions:

- interval numbers $[0,1]$ may be chosen as the probability of an event in a certain initial class of relatively simple events;
- these initial probabilities, along with the axioms and rules to determine the probabilities of more complex events, help determine the probability of any event.

Note. Therefore, choosing the probability of an event is normally governed by hypothetical data based on predictions of relative frequencies. One may ask if we have chosen correctly the probability in a given problem. Formally, this question leads us to a problem in theory of testing statistical hypotheses. If solved, this problem brings us to an answer on how to choose probability. Let us introduce these axioms and rules.

1. For every event A there is a given number $P(A)$ satisfying the condition $0 \leq P(A) \leq 1$, which is called probability.
2. The probability of a credible event is equal to unity.
3. The probability of the sum of mutually exclusive events is equal to the sum of the probabilities thereof (the so-called axiom of addition of probabilities).

Let us note again that the system of axioms does not determine the principle of choosing the probability's numerical value. It is found such

that all axioms be fulfilled and the laws to which the event occurs be described.

Probability is an objective measure and exists (can be known!) a priori, while relative frequency is always empirical.

We will treat event A as not dependent on event B if the probability of event A does not change when event B occurs. So the pairwise independence we have introduced can be generalized to an independence in a set for a reasonably broad series of events.

Total probability formula and Bayesian formula

The probability of event F that occurs only with each of the events $A_1, A_2, \dots, A_n$, forming a complete system, provided one knows the probabilities thereof and the conditional probabilities of event F relative to each of them $P_{A_1}(F), P_{A_2}(F), \dots, P_{A_n}(F)$ and so forth, is calculated by the total probability formula:

$$\begin{aligned} P(F) &= P(A_1)P_{A_1}(F) + P(A_2)P_{A_2}(F) + \dots + P(A_n)P_{A_n}(F) = \\ &= \sum_{i=1}^n P(A_i)P_{A_i}(F). \end{aligned}$$

One can obtain a Bayesian formula (a hypotheses formula) by generalizing the product rule so considering that if $P(AB)=P(A)P_B(A)=P(B)P_A(B)$, then $P_A(B)=P(B)P_B(A)/P(A)$, or by generalizing for n events, and by using the total probability formula, we have:

$$P_F(A_i) = \frac{P(A_i)P_{A_i}(F)}{\sum_{j=1}^n P(A_j)P_{A_j}(F)}.$$

Bayesian formula is often referred to as formula of hypotheses because it can be used to re-estimate the probability of hypotheses as to the occurrence of the events $A_1, A_2, A_3, \dots, A_n$ after it became known that event F had occurred.

Random quantities, distribution and characteristics thereof

We will hold random quantity as a variable that is capable of taking any such value as the case may require. Random quantity is any variable x having values that form a set of elementary events or denote points in a sample space.

The respective distribution of probabilities is called probability of the random quantity x . All random quantities are intrinsically divisible into discrete and continuous quantities.

A discrete random quantity has the set of its values finite or countable (number of items in storage, number of fuel elements, number of containers with NM, etc.).

The function $p(x)$ that relates the value of a random quantity to the corresponding probabilities is called random quantity law. Distribution law can be presented in a tabulated or graphic form. However, it is rather difficult to get a complete idea of random quantity from its law. So certain constants of its law are used. These are the so-called moments of various orders. They provide as complete characterization of random quantity as possible. The most important moments are mathematical expectation (first-order moment about zero) and variance (second-order moment about mean) [3].

Mathematical expectation of discrete random quantity

Mathematical expectation of a discrete random quantity is the total of the products of all its values by corresponding probabilities:

$$M(X) = x_1 p_1 + \dots + x_i p_i + \dots = \sum_{i=1}^n x_i p_i. \quad (4.1)$$

Mathematical expectation of a random quantity is a constant showing what value of the random quantity should be expected (on the average) during tests or observations.

We shall discuss the most important properties of mathematical expectation.

1. Mathematical expectation of a constant is equal to this constant: $M(k) = k$, where $k = \text{const}$.

2. Mathematical expectation of the sum (the difference) of a finite number of random quantities is equal to the sum (the difference) of the mathematical expectations thereof:

$$M(X \pm Y) = M(X) \pm M(Y).$$

3. Mathematical expectation of the product of a finite number of independent random quantities is equal to the product of the mathematical expectations thereof:

$$M(XY) = M(X)M(Y).$$

4. Reducing (increasing) all values of the random quantity X by $K = \text{const}$ gives the mathematical expectation a decrease (an increase) by K :

$$M(X - K) = M(X) - K.$$

Variance of random quantity

The most commonly encountered measure (characteristic) of a deviation or spreading (scatter) of a random quantity is variance and the root-mean-square deviation (RMSD) obtained from this.

As the scatter (deviation) of a random quantity's values from the mathematical expectation cannot be evidently characterized by linear differences, the adopted practice is to estimate deviation squares.

Therefore we will call the variance of the random quantity X the mathematical expectation for the square of its value deviation from the mathematical expectation:

$$D(X) = y^2(X) = M[X - M(X)]^2, \quad (4.2)$$

for discrete random quantities we have:

$$D(X) = \sum (x_i - a)^2 p_i, \quad (4.3)$$

where $a = M(X)$.

The RMSD is equal to:

$$y(X) = \sqrt{D(x)}. \quad (4.4)$$

The variance of a random quantity is a constant. If the variance is small, all numbers of the sum are also small (4.3). So if x_i exists that deviates widely from a , these are unlikely. If the variance is great, this indicates to a big probability of the random quantity values being very remote from a .

The average root-mean-square deviation $\sigma(X)$ is convenient in that, while characterizing the deviation (spreading) degree, it has the dimension of the quantity measured.

Let us look into the basic properties of variance.

1. The variance of a constant is equal to zero: $D(k) = 0$; $k = \text{const}$.

2. $D(kx) = k^2 D(x)$, where $k = \text{const}$.

3. The variance of a random quantity is equal to the mathematical expectation of its square with no mathematical expectation square:

$$D(X) = M(X^2) - M^2(X). \quad (4.5)$$

4. The variance of a sum (a difference) of independent random quantities is equal to the sum of the variances thereof:

$$D(X \pm Y) = D(X) + D(Y). \quad (4.6)$$

It follows from 4 that the average standard deviation of the sum of independent random quantities is equal to the root of the sum of squares for the RMS deviations thereof:

$$\sigma(x) = \sqrt{\sum_{i=1}^n \sigma_i^2}. \quad (4.7)$$

Consider n similarly distributed random quantities:

if $x_1, x_2, x_3, \dots, x_n$ are similarly distributed random quantities, the mathematical expectation for each of these being equal to a , the mathematical expectation for the sum thereof is equal to na , and the mathematical expectation of the arithmetic mean is equal to a :

$$M\left(\frac{x_1 + x_2 + \dots + x_n}{n}\right) = \frac{1}{n} M(x_1 + x_2 + \dots + x_n) = \frac{1}{n} na = a;$$

if $x_1, x_2, x_3, \dots, x_n$ are similarly distributed independent random quantities, the variance for each of these being σ^2 , the variance of the sum thereof is $n\sigma^2$, and the variance of the arithmetic mean is $\frac{\sigma^2}{n}$:

$$D(x_1 + x_2 \dots + x_n) = D(x_1) + D(x_2) + \dots + D(x_n) = n\sigma^2, \quad (4.8)$$

$$D\left(\frac{x_1 + x_2 \dots + x_n}{n}\right) = \frac{1}{n} D(x_1 + x_2 \dots + x_n) = \frac{\sigma^2}{n}. \quad (4.9)$$

Distribution function

A random quantity can be considered to be fully characterized if for any value x the distribution function $F(x)$ is known:

$$F(x) = P(X < x). \quad (4.10)$$

Unlike the distribution law that unambiguously relates the values p and x , the distribution function gives a random quantity a somewhat different and more general characterization. The probability that a random quantity will assume any value satisfying the inequality $x_1 \leq x < x_2$, is equal to the increment of its distribution function on this interval:

$$P(x_1 \leq x < x_2) = F(x_2) - F(x_1).$$

Continuous random quantity

We shall introduce the concept of continuous random quantity.

Random quantity is called continuous if its distribution function is everywhere continuous with its derivative (to the exclusion of the finite number of points on a finite interval).

Probability density of continuous random quantity

Probability density $\varphi(x)$ for a continuous random quantity is its distribution function derivative:

$$\varphi(x) = F'(x). \quad (4.11)$$

The probability of a continuous random quantity X to assume any value in the interval (a, b) is equal to a certain integral of its probability density in the limits of a, b :

$$P(a < X < b) = \int_a^b \varphi(x) dx = F(b) - F(a),$$

$$\int_{-\infty}^{+\infty} \varphi(x) dx = 1. \quad (4.12)$$

The probability density $\varphi(x)$ for a random quantity X and its distribution function $F(x)$ mutually determine each other. Actually,

$$F(x) = P(-\infty < X < x) = \int_{-\infty}^x \varphi(x) dx. \quad (4.13)$$

The geometrical interpretation of the formulas at hand is fairly obvious. The distribution curve for a continuous random quantity is called its probability density plot.

The mathematical expectation $M(X)$ for a continuous random quantity:

$$M(X) = \int_{-\infty}^{+\infty} x \varphi(x) dx. \quad (4.14)$$

The variance $D(X)$ of a continuous random quantity:

$$D(X) = \int_{-\infty}^{+\infty} (x - a)^2 \varphi(x) dx, \quad \text{где } a = M(X). \quad (4.15)$$

All earlier found mathematical expectation and variance properties are also just in the event of a continuous random quantity. One example is the property (4.5) for a continuous random quantity:

$$D(X) = \int_{-\infty}^{+\infty} x^2 \varphi(x) dx - [M(X)]^2.$$

Apart from mathematical expectation and variance, other numerical measures are used that reflect various distribution peculiarities. Consider the following major measures of distribution.

Moments

Special numerical measures of a random quantity are moments around zero and moments around mean. Mathematical expectation and variance are known to be moments, and more precisely, mathematical expectation is the first-order moment around zero, and variance is the second-order moment around mean. All basic distributions relate to the moments of the

first two orders (these are parameters of these distributions). If, however, one has to give a detailed characterization to a random quantity, moments of higher orders can be used.

By the moment around zero of the order k we shall mean:

$$\nu_k = M(X^k), \quad (4.16)$$

and by the moment around mean of the order k we shall mean

$$\mu_k = M[(X - M(X))^k]. \quad (4.17)$$

Median

This is used to indicate to the center for the grouping of a random quantity's values alongside with mathematical expectation. For a continuous random quantity, median is the boundary left and right of which the random quantity values are with a probability 0.5. For a normal distribution: $Me(X) = M(X) = a$.

Mode

For a continuous random quantity, mode is the point of the probability density function local maximum. For a normal distribution, $Mo(X) = M(X) = a$.

Quartiles

Quartiles are boundaries that divide the whole of the distribution into four equally probable parts. There are three quartiles in all. It is obvious that the central quartile is the median.

Quantiles

By the quantile of the level q (or q -quantile) they mean such value x_q of a random quantity with which the distribution function thereof assumes the value equal to q :

$$F(x_q) = P(X < x_q) = q. \quad (4.18)$$

Some quantiles have special names. It is obvious that the above introduced median is the quantile of the level 0.5, that is, $Me(X) = x_{0,5}$.

The concept of quantile has a close link to the concept of percentage point.

A $100q\%$ point is understood as quantile x_{1-q} , i.e. as such value of the random quantity X that makes the following condition just:

$$P(X \geq x_{1-q}) = q. \quad (4.19)$$

Binomial distribution law

The distribution law for the occurrence x of the event A in n independent tests, in each of which this can occur with the constant probability p , obeys to binomial distribution law, the expression of which is Bernoulli's formula:

$$P(x = m) = C_n^m p^m q^{n-m}, \quad m = 0, 1, 2, \dots, n. \quad (4.20)$$

The mathematical expectation of a binomially distributed random quantity is equal to np , and the variance is equal to npq :

$$M(X) = np; \quad D(X) = npq.$$

Typically, binomial distribution is interpreted as:

- the probability of an event to occur exactly m times in n independent tests (Bernoulli case) provided the probability is constant and equal to p ;
- (with a test regarded to be sampling) the probability that a replicate random sample of the size n contains exactly m elements of the given type, given the universe of the size N contains pN elements of the given type.

Hypergeometrical distribution law

A generalization of binomial law is hypergeometrical distribution law:

$$P(X = m) = \frac{\binom{N_1}{m} \binom{N - N_1}{n - m}}{\binom{N}{n}} = \frac{C_{N_1}^m C_{N - N_1}^{n - m}}{C_N^n}, \quad (4.21)$$

where $N \geq n$, $N \geq N_1 = pN$;

$$M(X) = \frac{nN_1}{N^2} = pn; D(X) = \frac{nN_1(N - N_1)}{N^2} \left(1 - \frac{n-1}{N-1}\right) = np(1-p) \left(1 - \frac{n-1}{N-1}\right).$$

A typical interpretation of hypergeometrical distribution law: $P(X = m)$ in (4.21) is the probability that a non-replicate random sample of the size n contains m elements of the given type, if this sampling is done from a universe of N elements in which $N_1 = pN$ elements of the given type.

The following passage to the limit is just: it is obvious that if $N \rightarrow \infty$ while n and $p = N_1/N$ remain fixed, the geometrical law tends to binomial. In fact, a non-replicate sample differs little from a replicate sample if the ratio n/N is small. The given approximation is just if $n/N < 0,1$.

Note that the mathematical expectation for the relative frequency of the event A in n independent tests, in each of which it may occur with the probability p , is equal to this probability and the variance is equal to pq/n .

Thus, $M(X/n) = p$, $D(X/n) = pq/n$. So:

$$\sigma = \sqrt{\frac{pq}{n}}. \quad (4.22)$$

Therefore, an increase in the number of tests makes the relative frequency of an event decreasingly less dispersed about this probability.

Poisson's law

If a random quantity X is capable of assuming only integer nonnegative values $m = 0, 1, 2, 3, \dots$ with the probability:

$$P(X = m) = \frac{\lambda^m e^{-\lambda}}{m!}, \quad (4.23)$$

where λ is the parameter, it is said to be distributed by Poisson law.

This is the law of rare events, the probability of which (p) is small and the number n is large, say, severe accidents, birth of triplets and so on.

Poisson distribution approximates hypergeometrical and binomial when $pN \rightarrow \infty$; $n \rightarrow \infty$; $p \rightarrow 0$ given pn has the finite limit $pn = \lambda$. This approximation is normally used if $p < 0,1$.

The mathematical expectation and the variance for a random quantity distributed by Poisson's law coincide and are equal to the value of the parameter $\lambda = pn$.

Normally distributed random quantities

Most of the experimentally obtained, measured or observed continuous random quantities are distributed by normal law:

$$\varphi_n(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-a)^2}{2\sigma^2}\right). \quad (4.24)$$

The quantities σ and a are normal distribution parameters. The plot for this distribution is a normal curve or a Gaussian (Fig. 4.2).

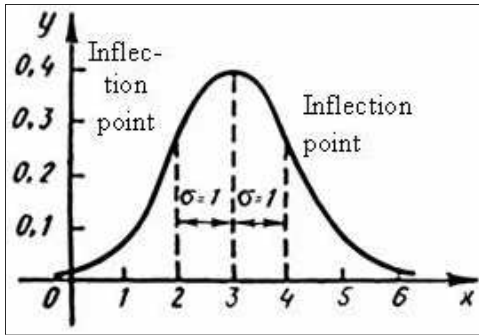


Fig. 4.2. Normal curve

A normal curve with the parameters $a = 0$ and $\sigma = 1$ is called standard. The function $\varphi_n(x)$ has the following properties:

- it exists at all actual values of the argument;
- has the extreme point at $x = a$, $\varphi_n(a) = \frac{1}{\sigma\sqrt{2\pi}}$;
- is symmetrical about the axis through $x = a$;

- has two knee points, left and right of $x = a$ with abscissas, respectively, $x = a - \sigma$ and $x = a + \sigma$.

It is easy to verify that normal distribution parameters have the meaning of the mathematical expectation and the RMS deviation:

$$a = M(X) \quad \text{и} \quad \sigma = \sqrt{D(X)}.$$

It can be shown that normal curves with coinciding σ are identically shaped and differ just in the maximum coordinate shift. The value of the variance, and more exactly, σ (RMSD), influences greatly the normal curve shape. With a decrease of σ , the curve tends to become “narrower”, extends upwards and gets needle-like; if σ increases, the curve lowers, gets “wider” and approaches the abscissa axis.

If a random quantity X is distributed normally, then

$$P(x_1 < X < x_2) = 0,5 \cdot \left[\Phi\left(\frac{x_1 - a}{\sigma}\right) - \Phi\left(\frac{x_2 - a}{\sigma}\right) \right], \quad (4.25)$$

where $\Phi(x) = \frac{2}{\sqrt{2\pi}} \int_0^x \exp\left(-\frac{t^2}{2}\right) dt$ is the integral of the probabilities, the values thereof being tabulated.

The formula (4.25) is simplified if the interval limits are symmetrical about the mathematical expectation:

$$P(|X - a| \leq \Delta) = \Phi\left(\frac{\Delta}{\sigma}\right). \quad (4.26)$$

Lognormal distribution

A continuous random quantity X has a lognormal distribution if its logarithm obeys to normal law. The probability density for lognormal distribution is:

$$\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}x} \exp\left(-\frac{(\ln x - \ln a)^2}{2\sigma^2}\right). \quad (4.27)$$

It can be proved that numerical characteristics of a lognormally distributed random quantity have the following form:

$$\begin{aligned}
M(X) &= a \exp(\sigma^2 / 2), \quad Me(X) = a, \\
D(X) &= a^2 \exp(\sigma^2) (\exp(\sigma^2) - 1).
\end{aligned}
\tag{4.28}$$

Lognormal distribution is rather commonly used to describe a distribution of profits, a distribution of impurities in alloys and minerals, the longevity of products in wear and aging conditions and so on.

Distributions relating to normal distribution

In mathematical statistics, the most common distributions are χ^2 (Pearson), t (Student) and F (Fisher) distributions. All these distributions relate to normal distribution. In turn, common use of normal distribution is determined, as we will see, exclusively by the central limit theorem (CLT) (see Section 4.6). Due to being specially important, all above-mentioned distributions are tabulated and contained in various manuals and reference books [3].

Hereinbelow, we have introduced one-dimensional standard normal distribution as a distribution with the mathematical expectation $a = 0$ and the variance $\sigma^2 = 1$, its density being

$$\varphi(x) = \Phi'(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}. \tag{4.29}$$

In a general case, one-dimensional normal distribution is characterized by the mathematical expectation a and the variance σ^2 . Then, any one-dimensional normal distribution can be treated as a distribution of a random quantity:

$$\eta = a + \xi \sqrt{\sigma^2},$$

where the random quantity ξ obeys to standard normal law.

Pearson distribution. Let $\xi_1, \dots, \xi_n$ be independent random quantities distributed by standard normal law. The distribution of the random quantity:

$$\chi^2 = \xi_1^2 + \dots + \xi_n^2$$

is called χ^2 -distribution (Pearson distribution) with n degrees of freedom. χ^2 -distribution has the density

$$h(x) = H'(x) = \frac{1}{2^{\frac{n}{2}} \Gamma\left(\frac{n}{2}\right)} x^{\frac{n}{2}-1} e^{-\frac{x}{2}} \quad (x > 0), \quad (4.30)$$

where $\Gamma(n)$ is a gamma function.

Further, the following property will be useful to us. Let $\xi_1, \dots, \xi_n$ be independent normally distributed random quantities with the identical parameters a and σ^2 . We shall assume that

$$\eta = \frac{1}{n}(\xi_1 + \dots + \xi_n).$$

Then the random quantity

$$\chi^2 = \frac{1}{\sigma^2} [(\xi_1 - \eta)^2 + \dots + (\xi_n - \eta)^2] \quad (4.31)$$

has the χ^2 -distribution but with $n-1$ degrees of freedom.

There is one more interpretation (case) of Pearson distribution. Let n independent tests be conducted (polynomial case or Bernoulli case), in each of which one of the events A_i ($i = 1, \dots, L$) may occur with the probability p_i . Let us denote the number of the occurrences of the event A_i by m_i . Then it follows from the multidimensional analog of the Moivre-Laplace integral theorem that the random quantity:

$$\chi^2 = \frac{(m_1 - np_1)^2}{np_1} + \dots + \frac{(m_L - np_L)^2}{np_L},$$

with $n \rightarrow \infty$, is asymptotically distributed by χ^2 law with $L - 1$ degrees of freedom.

t-distribution. Let ξ and χ^2 be independent random quantities, ξ being distributed by standard normal law, and χ^2 having a Pearson distribution

with n degrees of freedom. The distribution of the random quantity $\tau = \xi / \sqrt{\chi^2 / n}$ is called a t -distribution with n degrees of freedom (Student distribution).

This distribution has the density

$$t(x) = T'(x) = \frac{1}{\sqrt{\pi n}} \frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{n}{2}\right)} \left(1 + \frac{x^2}{n}\right)^{-\frac{n+1}{2}}, \quad (4.32)$$

where $\Gamma(m)$ is the gamma function.

Let $\xi_1, \dots, \xi_n$ be independent random quantities similarly distributed by normal law with the average a . Let us assume that

$$\eta = \frac{1}{n}(\xi_1 + \dots + \xi_n), \quad \varsigma = (\xi_1 - \eta)^2 + \dots + (\xi_n - \eta)^2.$$

Then the random quantities ζ and η are independent and the random quantity

$$\tau = \frac{\sqrt{n}(\eta - a)}{\sqrt{\frac{\varsigma}{n-1}}}$$

has a t -distribution with $n - 1$ degrees of freedom.

F -distribution relates to Pearson distribution as follows. Let χ_1^2, χ_2^2 be two independent random quantities having an χ^2 distribution with n_1 and n_2 degrees of freedom respectively. The distribution of the random quantity

$$\varpi = \frac{n_2 \chi_1^2}{n_1 \chi_2^2}$$

is referred to as F -distribution (Fisher distribution) with the parameters n_1 and n_2 . The density of the F -distribution is:

$$\psi(x) = \Psi'(x) = \frac{\Gamma\left(\frac{n_1 + n_2}{2}\right)}{\Gamma\left(\frac{n_1}{2}\right)\Gamma\left(\frac{n_2}{2}\right)} n_1^{\frac{n_1}{2}-1} n_2^{\frac{n_2}{2}-1} x^{\frac{n_1+n_2}{2}-1} (n_2 + n_1 x)^{-\frac{n_1+n_2}{2}}, \quad (4.33)$$

$x > 0.$

Covariance and correlation ratio

If the random quantities X and Y are dependent (or we know nothing about the dependence of these), the variance of the sum or of the difference should be written as follows:

$$\begin{aligned} D(X \pm Y) &= D(X) + D(Y) \pm 2M((X - M(X))(Y - M(Y))) = \\ &= D(X) + D(Y) \pm 2M(XY) - M(X)M(Y). \end{aligned}$$

It is obvious that for independent quantities: $M(X - M(X))(Y - M(Y)) = M(XY) - M(X)M(Y) = 0$.

For dependent quantities, we introduce the concept of covariance (joint variance) for the random quantities X and Y :

$$\text{cov}(X, Y) = M((X - M(X))(Y - M(Y))) = M(XY) - M(X)M(Y). \quad (4.34)$$

And the variance in this case is determined as

$$D(X \pm Y) = D(X) + D(Y) \pm 2\text{cov}(X, Y). \quad (4.35)$$

Note that, essentially, covariance is the joint first-order moment about mean.

It follows from (4.34) that covariance has the following property:

$$\text{cov}(X, X) = M((X - M(X))(X - M(X))) = D(X).$$

In fact, covariance (covariance ratio) is to a certain degree a measure of the relationship (dependence) between some random quantities since it possesses the following properties:

- for independent random quantities, the covariance is equal to zero;
- it is positive for the random quantities X and Y tending to vary unidirectionally, and it is negative for those showing the opposite trend.

However, this ratio is capable of assuming values across the number axis so it is not quite good and convenient for measuring the dependence degree. More convenience in this sense is provided by standardized covariance ratio (the so-called correlation ratio) which is normally introduced as

$$\rho(X, Y) = \frac{\text{cov}(X, Y)}{\sigma(X)\sigma(Y)}, \text{ where } \sigma(X) = \sqrt{D(X)}. \quad (4.36)$$

In fact:

- for the independent random quantities x and y , $\rho(x, y) = 0$, because the covariance is equal to zero;
- for linearly dependent random quantities $|\rho| = 1$;
- for the rest, the correlation ratio varies in a range of -1 to $+1$ ($-1 < \rho < +1$).

Let us note that the closer $|\rho|$ is to 1, the more reasons one has to treat X and Y as linearly dependent.

Strictly speaking, if the correlation ratio is zero, this does not always mean independence of random quantities. In this case, they say the quantities are uncorrelated (or do not correlate). Independence implies strictly lack of correlation and it is not always the case vice versa. However, it has been strictly shown that the properties of lack of correlation and independence are equivalent for normally distributed random quantities.

Therefore, one can characterize the function of random quantities or a multidimensional random quantity only by a covariance matrix, say, for the case X_1 and X_2 :

$$\begin{pmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 \\ \rho_{21}\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix} = \begin{pmatrix} \sigma_1^2 & \text{cov}(x_1, x_2) \\ \text{cov}(x_2, x_1) & \sigma_2^2 \end{pmatrix}, \quad (4.37)$$

where $\sigma_1^2 = D(X_1)$ and $\rho_{12} = \rho(X_1 X_2)$.

Law of large numbers

It has long been observed that the arithmetic-mean value for numerical characteristics of random events (relative frequency) in a great number of

such similar events tends to vary to a certain extent. On the average, a dependence shows itself which is inherent in the essence of phenomena, this having the influence of some factors that randomized single observation results cancelled therein.

Chebyshev inequality

Chebyshev inequality is a mathematical from of the law of large numbers: the probability that a deviation of random quantities from its mathematical expectation will exceed $\varepsilon > 0$ in the absolute magnitude, and will be no greater than the relation of its variance to ε^2 .

Let X be a random quantity, a its mathematical expectation and $D(x)$ the variance, then

$$P(|X - a| > \varepsilon) \leq \frac{D(X)}{\varepsilon^2},$$

or

$$P(|X - a| \leq \varepsilon) \geq 1 - \frac{D(X)}{\varepsilon^2}. \quad (4.38)$$

Chebyshev inequality gives a nontrivial estimate to the probability of the event $|X - a| \leq \varepsilon$ only where $D(X) < \varepsilon^2$, the estimate being trivial and not informative in other cases.

Conclusion. Where independent random quantities have identical mathematical expectations equaling a , the variance is limited to one and the same constant c , and the number is great, then for $\forall \varepsilon > 0$, the probability that the arithmetic mean of these random quantities will deviate from a is arbitrarily close to unity:

$$P\left(\left|\frac{x_1 + x_2 + \dots x_n}{n} - a\right| \leq \varepsilon\right) > 1 - \delta. \quad (4.39)$$

This conclusion makes the simplest law of large numbers. Practically, this means that the arithmetic mean of the measurement results is taken for the approximated value of an unknown random quantity. Given that the number of measurements is rather great, this will prove the practical reasoning which is important in terms of (4.39). The equality of the mathematical expectation for the same quantity a is required to show the absence of the so-called systematic component of measurement error.

Limit theorems

If random quantities are many and satisfy some quite general conditions, then, whatever distribution these have, it is practically certain that the arithmetic mean thereof has an arbitrarily small deviation from the constant or the arithmetic mean of the mathematical expectations thereof, i.e. is practically a constant.

Thus, a common sampling technique making it possible to conclude on the universe based on the limited sample test findings, gets a rationale from the law of large numbers:

the number of grains in a sample (measure), n , is enough to infer the size of the whole grain batch, N , from; the number of the tested items (e.g. fuel assemblies), n , is enough to infer the size of the whole FA batch, N , from; i.e. enough for the law of great numbers to manifest itself with a satisfactory accuracy, though $n < N$, but n is rather great and the law works.

It can be shown that the sum of any finite number of normally distributed random quantities is normally distributed. Then, if independent random quantities are not distributed normally or are actually distributed in an unknown fashion, then it turns out that they may have some rather soft restrictions imposed on them such that **the sum thereof will be distributed normally**. This makes the essence of the so-called limit theorems. A form of central limit theorems is Lyapunov theorem [3].

4.2. Basic statistical requirements to NM A&C systems

Upgrades to and evolutions of NM accounting and control systems suggests a greater role of measurements in determining and verifying NM inventories. One can conclude on NM inventories against the background of uncertainties, that are inherent in measurements, only through using statistical methods and employing statistical criteria [4].

We shall consider the major uncertainties inherent in accounting and control of NM:

- uncertainty inherent in applicable measurement methods;
- uncertainty inherent in items to be measured;
- uncertainty inherent in calculation techniques;
- uncertainty due to the sampling procedure used;
- uncertainty inherent in “documented” NM data.

Let us underline again that measurements are decisive to all operations on checking the presence and integrity of NM. Of crucial importance in this is to achieve the needed level of measurement accuracy to ensure the level

of nuclear material control one desires. One of the most important tasks of MS is to analyze uncertainties, estimate measurement errors and search for ways to reduce these. Test measurement results normally deviate from the value declared for the measured characteristic of the NM under control. The cause of a deviation may be a statistically estimated uncertainty (measurement error) or the actually observed difference between the value measured and the one declared. The final conclusion with respect to the cause of the deviation can be made only using a statistical analysis based on accepted statistical criteria.

The need for statistical criteria to be used in inspections also arises due to limited time and funds. Production processes have to be stopped for the inspection, this leading to an economic loss. So, in such cases, sampling checks are done with only some of the items measured. MS is also employed to have the sample size and sequence rationally planned.

The prime objective of NM accounting and control (confident traceability of NM) may be achieved only through an extensive use of statistical and probabilistic methods.

The framework for both determining the inventory of NM in an MBA and detecting anomalies in using NM is formed by NM physical inventory takings. NM physical inventory takings involve audits of accounting data and measurements of the NM quantities in the material balance areas, material balance closing, determination of inventory difference (ID) and estimation of the ID error for each NM.

Absence of anomalies in using NM and of deficiencies in the NM accounting and control system is concluded on based on statistical criteria, that is, statistical guidelines for making decisions from the ID quantity obtained, the ID error and the quantities of the probabilities as set by the guidelines, and detection of a shortage/surplus in NM threshold quantities. We shall highlight again the principles of NM accounting and control that define the statistical requirements:

- NM shall be subject to state accounting and control starting with the smallest quantities;
- NM classification depends on the quantity, type and form of the NM-containing product;
- onsite MBAs are organized;
- key measurement points (KMP) are identified in each MBA;
- NM has access controls (AC) applied thereto to extend the confidence of earlier measurements;

- NM is accounted for based on measurements of NM quantity data and attributes;
- there may be accounting and verifying measurements.
- Statistical criteria are used to:
- find anomalies by verifying measurements;
- perform sample checks of access indicating devices in between inventory takings;
- find anomalies in NM accounting via analyzing the inventory difference;
- find anomalies in NM transfer operations;
- set the upper limit for the uncertainty of verifying measurements of NM samples;
- verify the confidence of accounting records.

Let us specify and define respectively some of the special concepts.

Rule of practical certainty and confidential probability

If an event is unlikely in some conditions, then, given these conditions are fulfilled once, one can be certain that the event will not occur. So, in practice, the event in question can be considered impossible. Practically, however, one cannot derive such upper boundary of the probability, at which some events can be believed to be impossible. The scale of the effects from the events of interest is also an important factor to note. We will refer to the probability, we have decided to neglect herein, as the significance level.

Statistically, the significance level is normally assumed as:

~ 0.05 in pre-estimates;

~ 0.001 in final conclusions.

The concept of significance level has a close link to the concept of confidential probability: by confidential probability we will mean such probability α at which events with the probability $1-\alpha$ can be considered impossible.

Confidence interval

We shall introduce the concept of confidence interval which is closely associated with the concept of confidential probability we have introduced hereinabove.

Due to the randomness of measurement data, one cannot set fairly narrow limits, the estimation error (i.e. the deviation of the estimate from

the characteristic under estimation) would securely remain in. This leads to a problem of defining such limits beyond which estimation error would fail to fall with the specified probability. For example, if P is the estimated probability of the event p , one needs to set, based on the same measurement data, such boundary for the potential deviations of P from p that would not be exceeded by the error modulus $|P - p|$ with the specified preset probability α . This boundary will be also random due to the randomness of measurement data.

So the point is to find, from measurement data, such random interval (i.e. an interval with random boundaries) that would contain with the specified probability α an unknown value of the probability p . Such random interval, as determined in full by the measurement results, is referred to as the confidence interval for the given characteristic, this corresponding to the confidential probability α . The quantity $1 - \alpha$ is referred to as the estimate deviation significance level.

For every quantity, NM weights are found by accounting measurements (or, if these cannot be done, using experimental estimates based on the earlier experience of operation) with documenting the recorded average NM weight values, the confidence interval value for the random error of the NM weight measurement and the boundaries of the residual systematic measurement error based on the confidential probability of 0.99.

These values can be used in accounting procedures (physical inventory takings, NM transfers and so on) only where the confidence thereof from the time of determination to the application time was extended through a proper use of ACs and verified in the process of the accounting procedure by measurements of the NM quantitative parameters and/or the NM attributes (i.e. verifying measurement data).

Error confidence boundaries for the measurement data will be referred to by us as the highest and the lowest measurement error values that confine the interval within which the sought-after measurement error remains with the specified probability interval.

Accounting measurements are measurements of the quantitative characteristics and attributes of NM, items and products, the data from which, including measurement errors, are entered on accounting records as certified values. The subsequent accounting measurement invalidates the preceding measurement result.

Verifying measurements are measurements the data of which is used to verify all or some of the quantitative characteristics and/or attributes of NM, items or products as obtained in earlier accounting measurements and

stored confidently thereafter by way of applying NM access controls. Where the difference in the quantities of the measured quantitative characteristic for the verifying and the accounting measurement is not in excess of its standard measurement errors, the certified value of the characteristic is accepted. Otherwise, the discrepancy is investigated and accounting measurements of this NM are done. Verifying measurements can be done by sampling or for all NM.

The extent to which verifying measurements shall be applied is determined depending on the extent to which ACs are used and on the AC status check data, given the probabilities of detecting a shortage/surplus in the threshold amounts of each NM.

The statistical significance of the difference in the accounting and verifying measurement data for the quantitative variables of NM, items and products is determined given the confidential probability of 0.99. If a statistically significant difference is found between the accounting and verifying measurement data, this is reported to the MBA and nuclear facility administration with special investigations undertaken to find out the cause for the difference. As required, new accounting measurements are done and the accounting records are updated respectively.

Statistical criteria for anomaly detection

Each measurement of the NM quantity involves a certain error which leads to a discrepancy between the shipper and the receiver data, and between the results obtained by the inspector and the existing accounting records. A decision on if the discrepancies detected shall be accepted or not is made based on a statistical analysis thereof.

If the material balance period (MBP) preceding the given inventory taking had accounting measurements done in the MBA for the given nuclear material in production, receipt, processing or shipment, or done in the course of the inventory taking, the criterion for detecting anomalies in using the given NM shall be a modulus that exceeds the inventory difference or its threefold root-mean-square error, or *any* of the following quantities with the confidential probability of 0.95:

- 2% of the total quantity of the given NM booked and of all increases in the quantity thereof over the MBP – for commercial nuclear facilities;
- 3% of the same quantity – for test nuclear facilities;
- 3 kg – for plutonium and uranium-233 for the MBAs that contain NM of categories I and II;

- 8 kg – for uranium-235 for the MBAs that containing NM of categories I, II and III;
- 70 kg for uranium-235 – for uranium enriched at below 20%.

If no accounting measurements for the given NM were conducted in the course of the inventory taking during the MBP and the confidence of the preceding accounting measurement data was ensured through the use of ACs, the conclusions with respect to the absence of accounting and control anomalies shall be made based on the sampling verifying measurement data, the volume of this verifying measurement to be determined from the following values of the NM threshold quantities for detection of an NM shortage/surplus and the probabilities of detecting a shortage/surplus of the given threshold quantity.

For NM of categories I, II and III, the threshold quantities are:

- 3 kg – for plutonium and uranium-233;
- 8 kg – for uranium-235;
- in the case of uranium enriched at below 20% (category 4), the threshold quantity is 70 kg for uranium-235.

The probability of detecting a shortage/surplus of the NM threshold quantity for calculating the verifying measurement sample size is presented in Table 4.1.

Table 4.1

Probability of the NM threshold quantity shortage/surplus detection

Extent of NM AC application	Probability of detection, %	
	NM categories I,II,III	NM category IV
TIDs only	50	30
Surveillance system only	50	30
Two types of various ACs at a time	25	10
<i>n</i> types of various ACs at a time	100 (0,5) ^{<i>n</i>}	100 (0,3) ^{<i>n</i>}

The operator-level physical inventory taking procedures are based on a series of actions:

- comparison of accounting records and reports;
- check of the AC status;
- accounting and verifying measurements of the Nm physical inventory;
- determination of the shipper/receiver data difference;
- estimation of random and systematic measurement errors, including in receipts and shipments;
- estimation of process discards;

- determination of the ID and its random and systematic error for each NM.

The NM parameter measurement data as obtained at earlier process stages can be used for the physical inventory taking only where auxiliary engineered controls (ACs, seals, etc.,) are applied to NM. If NM exists in broad varieties and/or large quantities, one may use statistical samplings to verify the data of online process records and reports respectively. To determine the size of a random sample, one needs to proceed from the requirement of detecting a defect (damage, removal or substitution) in at least one of the above means with the probability of below 0.95.

If no NM accounting and control anomaly is found in an NM balance analysis, the booked inventory of NM in the MBA is accepted as the NM inventory in the MBA as of the beginning of the next material balance period.

4.3. Errors, their models and sources

The knowledge about physical inventories, receipts and shipments of NM requires weight, volume, uranium concentration and enrichment data. One can get this knowledge only by measurements.

Types of measurements

Fig. 4.3 gives a classification of measurements.

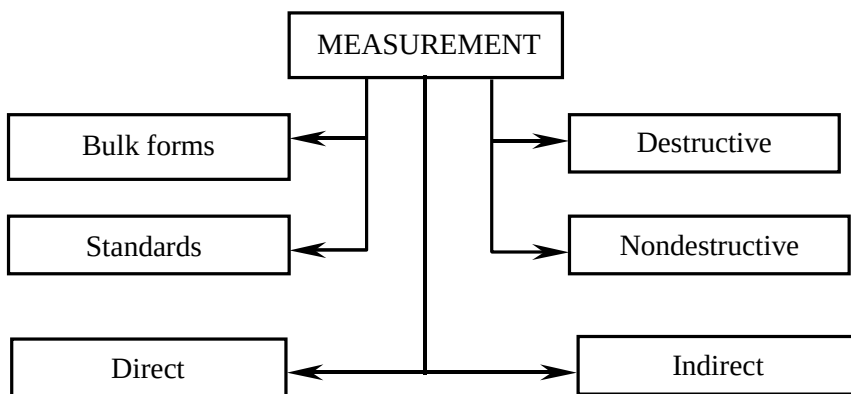


Fig. 4.3. Classification of measurements

The following types of measurements are identified for accounting and control systems:

depending on the objects measured: measurements of bulk forms (bulk samples) to determine the weight and volume and measure material samples (to find out isotopic and/or element composition);

depending on how the measured material is handled: destructive measurements (involve normally destruction of either the chemical or physical form of the material sample) and nondestructive measurements (quantitative or qualitative determination of the type and/or quantity of NM in a sample without producing significant changes to or getting into the sample);

depending on the technique employed to determine the measured quantity: direct and indirect measurements.

Any measurement, as mentioned earlier, involves a certain error. Therefore, formulating the decision to be made based on accounting data needs these errors to be taken into account. What are these and what are their potential sources will be discussed hereinafter.

Direct measurements have the measured and determined quantity compared to the measurement unit directly or using an instrument graduated in respective units.

Indirect measurements have the measured quantity determined (calculated) from direct measurements of other quantities that relate to the measured quantity through a functional dependence.

Measurement error

We will treat error as a deviation of an estimate from the true value of the characteristic estimated for. Then, as applied to measurements, this is a deviation of the measurement result from the true (actual) values of the measured quantity. Note that we do not normally know the true value since uncertainties exist, and properly describing and estimating errors requires that a suitable mathematical model of the error should be selected. Therefore, the actual error is the estimate of the respective uncertainties we have obtained (see p. 4.2.).

The simplest model for a single measurement is

$$X = T + E, \quad (4.40)$$

where X is the measurement result; T is the true value and E is the measurement error [5].

We have already talked about numerous sources of errors as may affect measurement data. All errors are categorized into random errors and systematic errors (also the so-called short-term systematic errors are occasionally introduced).

Indeed, the quantity E can be presented as random and having the mathematical expectation $M(E) = S$. Then (4.40) will be written as

$$X = T + S + R, \quad (4.41)$$

where R is the random quantity with the zero mathematical expectation $M(R) = 0$ conventionally referred to as random error; and S is the so-called systematic error often treated as an unknown constant shift of the measured quantity about the true value.

Here are several examples to consider for a better conception of this division.

Random error relates to the action of a series of random factors per each individual measurement, e.g. random nature of the nuclear decay process, air motion, sample position and so on.

Consider six UO_2 pellets of nominally one composition to be tested for the uranium concentration. Let us denote: x_{ij} is the result of j -th uranium concentration measurement in the i -th pellet; μ is the nominal (declared) uranium content in the pellets; ρ_i is the uranium content deviation from the declared quantity in the i -th pellet; and ε_j is the deviation conditioned by the analytical error of the j -th measurement. With the aid of a multiplicative model we will arrive at

$$\begin{aligned} x_{11} &= \mu + \rho_1 + \varepsilon_1, \\ x_{22} &= \mu + \rho_2 + \varepsilon_2, \\ &\dots\dots\dots \\ x_{66} &= \mu + \rho_6 + \varepsilon_6. \end{aligned}$$

As ρ_i and ε_j differ for each of the six results, these are random errors. According to the classification we have introduced, ρ_i is the random error of the statistical sampling. If to consider this as a random variable with the average value equal to zero and the variance σ_ρ^2 , then σ_ρ^2 is called the variance of the statistical sampling random error. Similarly, ε_j in the classification in question is an analytical random error, and σ_ε^2 is called the variance of the analytical random error.

First, since only one measurement was done for each pellet, and ε and ρ have become parts of the equation with one index, then, in the given case, these two errors cannot be separated. In such situation, one can consider them to be a single “random measurement error”. In the event of two or more measurements done for each pellet, errors are separable. Second, a feature of the random error model is that its index varies with each measurement, its influence on the eventual result decreasing with each new measurement. For this reason, random errors are relatively easy to control.

Systematic error is an error caused by the limited accuracy of the instrument, an improper installation of the instrument, the technique used to process data and the effects of external factors. Systematic errors determine the measurement group. Systematic errors are errors caused by the improperly reset scale and the rounding of numerical values.

Let us expand a bit the presented model by giving it one more summand: Δ - a deviation from the nominal value conditioned by the analytical method. It will be the same for all measurements done by the given method. Then

$$\begin{aligned}x_{11} &= \mu + \Delta + \rho_1 + \varepsilon_1, \\x_{22} &= \mu + \Delta + \rho_2 + \varepsilon_2, \\&\dots\dots\dots \\x_{66} &= \mu + \Delta + \rho_6 + \varepsilon_6.\end{aligned}$$

The quantity Δ that does not have an index and is common for all measurements is called systematic error or bias. These terms are normally used as equals, still they have a small difference. If measurement data is adjusted for the known, somehow estimated quantity Δ , then Δ is called bias. However, if Δ is not known exactly and can be estimated only roughly, then measurement data cannot be adjusted precisely by Δ . A residual bias so occurs, this being equal to the difference between the quantity Δ and its estimate. It is this residual bias that is called systematic error. Not everyone differentiates so between systematic error and bias, still it is important to understand what do you mean exactly by Δ .

If Δ is a random variable with the average value equaling zero and the variance σ_Δ^2 , then σ_Δ^2 will be called the systemic error variance.

Many aspects of accounting and control are more influenced by systematic errors than by random ones. The explanation is that, unlike random error, the systematic error effect does not decrease with each new measurement, thus reducing the efficiency of the NM accounting measures.

Sources of errors

An error in a given measurement results from several errors overlapping (superimposed). Consider some of the error sources that may affect measurement data.

1. *Statistical sampling error*. Consider a set of N items, e.g. containers with NM, each of these having a true value of a characteristic (net weight, uranium mass, enrichment, etc.). If several items have been selected randomly from the set (sample), then the average value of a characteristic calculated for these items will differ from the average value of the given characteristic for the whole set (say, from the average enrichment value). Let us determine the statistical sampling error as the difference between the average value of a characteristic for a randomly taken sample and the average value of the characteristic for the entire set.

This error is neglected in some cases, say, inventory taking has the inspector-obtained measurement data for an item compared against the operator data, so the true value of the measured characteristic does not matter and it is reduced in the difference.

In the event of attributive (quality) inventory taking, the true value for each item is equal either to 1, if there is a defect, or to 0, if there is none. And the average value for the group of interest is equal to the relation of the number of defective items in the group to the total number of items: $0 < N_{\text{def}}/N_{\text{tot}} < 1$. In the given case, therefore, there is a statistical sampling error in each selected item. The influence of this error on the inventory taking data (and so the necessity of taking this into account) will vanish only if all items are checked.

Depending on whether we do measurements for all nuclear material (a universe) or just for a portion of same (a sample), material is accounted for based on three measuring operations:

1) determination of the material net weight or volume (bulk measurements);

2) material sample taking;

3) analysis of the material sampled to find out its element and/or isotopic composition. So, normally, it will be convenient to divide the total measurement error into such components as will match the three measuring operations.

2. *Error of measurements in bulk form* (bulk measurements) will be defined by us as the difference between the true weight (or volume) of an item and its measured value. With only this definition considered, a bulk measurement error appears to be a directly obtainable simple value.

However, it may and even is most likely to result from a great deal of bulk measurement errors superimposed, some of these being capable to compensate each other.

3. *Material sampling error* is found from the relation to characteristic measured. This may be uranium or plutonium concentration, enrichment and so on.

A material sampling error is the difference between the average values of a characteristic for the sample taken and the respective average value of the given characteristic for all material. It is important to understand what “all material” means. If we are interested in the uranium concentration to be found for the given container, then the sampling error is the difference between the uranium concentration in a small sample taken from this container, and the uranium concentration in the container. This may be referred to as the “sampling error for one container”. If the measurement data for a sample taken from the given container with the given uranium concentration needs to be extended to other, nominally the same containers, then the change in the concentration between containers is incorporated in the sampling error together with the “error for one container”.

4. *Analysis error*. As is the case with the material sampling error, the analytical error (analysis error) is determined for the characteristic of interest. An analytical measurement error is the difference between the true value of the sample characteristic in question and the measured value of this characteristic. Note that this error relates to the sample rather than to all material it characterizes. An error of determining the value of a characteristic for all material will be a combination of the analytical error and the material sampling error.

Where nondestructive measurements are used with no sampling involved, it is the error of measuring a characteristic that will be the analytical error of measurement; with nondestructive measurements done not for the whole of the item but for a sample of it, the sampling error should be also accounted for.

As noted earlier, the given error under determination results from many errors superimposed. For example, a weighing error may depend on how the item is placed on the scale, the type of the scale, the particular scale of the given type, the operator and the environment (air temperature, humidity and so on). The extent to which attention is to be given to the search for and estimation of factors that affect the error depends on a number of circumstances. For instance, if a weighing error at the measurement point of interest does not influence greatly the accounting data quality, there is no special need for identifying and evaluating every source contributing to this

error. And, vice versa, if the weight values observed at a measurement point turn out to have an error in excess of the level desired, a special study is required to find out why this has happened. And such a study needs at least some of the above-mentioned error sources to be identified, and individual contributions thereof to the error estimated. By a “special study” we mean, say, calibration.

Models of errors

We have discussed just some of many error sources. Though it is their cumulative effect that we are interested in the most, it is often convenient or even necessary to form a reasonable mathematical model to identify errors as such and find out how these are interlinked. Therefore, a model helps combine errors correctly, find their cumulative effect and identify sources of errors, and provides safeguards against potential skips of certain sources. Let us discuss this in more details and introduce two basic models: an additive model and a nonadditive (so-called multiplicative) model of error.

Additive model. This is the simplest model (4.40) we have already made use of. Despite being simple, additive models are often used in practical activities and, in many instances, give a nearly real result. A note should be made that any model is a mathematical description of reality. Experience shows that humans tend to employ simpler models in practice, occasionally even at a sacrifice of detailed and adequate description of reality. Simple models are therefore commonly used.

Let, say, x be the measured gross weight value of a container with UO_2 powder, g ; μ the true value of this quantity, and ε the error, so then $x = \mu + \varepsilon$.

Therefore, if summed up, the true value and the error would give the measured value. If measurements are done on standard samples of the known weight μ with their measured value x recorded, then the distribution function ε can be constructed based on the measurements.

Multiplicative model. Describing a measurement result by a simple sum of the true value and the errors often gives an acceptable description of the real situation, though not altogether universally. If the absolute error of measurement grows with the measured value, the so-called multiplicative model is employed.

Assume that y is the measured value of the uranium concentration in UO_2 , α is the true quantity and η is the measurement error.

Then $y = \alpha + \eta$. Let us be interested in the net weight of uranium in the container from the previous instance rather than in the weight of oxide. By multiplying x by y , we get $xy = \mu\alpha + \mu\eta + \alpha\varepsilon + \varepsilon\eta$, which no longer makes a simple additive model.

In this case, it will be more convenient to use a multiplicative model:

$$x = \mu(1+\varepsilon), \quad y = \alpha(1+\eta).$$

Then the expression for the uranium weight will look as follows: $xy = \mu\alpha(1+\eta)(1+\varepsilon)$. The latter expression is apparently much simpler, more graphic and more convenient in terms of error estimates. So, though additive models are frequently convenient to use, one should avoid using these in all cases as the net effect of several errors is not always a simple sum thereof.

Estimation of NM measurement errors

Confident estimates of nuclear material measurement errors are required to estimate the significance of the inventory differences detected. These estimates depend on the models adopted to calculate errors and interpret «random» and «systematic» errors.

Test measurement data is expected to satisfy to accuracy and precision requirements. Precision is characterized by *repeatability* and *reproducibility* of measurement data.

Repeatability is determined by the variance (spread) of the data obtained by one operator when measuring one sample in similar conditions. *Reproducibility* is determined by the variance of the measurement data for a sample measured by more than one operator for several days in various conditions.

Accuracy of data depends on the quantity of the systematic measurement error. The systematic quantity error can be estimated as the average difference (in the sense of mathematical expectation) between the values measured and the true value (4.40). A small quantity of the systematic error in data is equivalent to a high accuracy thereof.

Basic principles of measurement error calculations:

1) the total measurement data errors are computed as the sum of the random error and the systematic error as reduced to the same confidential probability;

2) the values of all errors are normally reduced to the confidential probability of 0.95;

3) when computing the random error in data, one should treat the respective quantities as normally distributed;

4) one should consider the systematic error of a measurement result on the assumption of uniform (equally probable) law of distribution of constituent quantities.

Agreed notation.

1. According to GOST State Standards, the following designations should be used to denote errors of the quantity x as reduced to the confidential probability of 0.95: random error – $S(x)$, systematic error – $\theta(x)$, total error – $\delta(x)$.

2. When choosing the confidence probability p other than equal to 0.95, one should use the record ${}^pS(x)$, ${}^p\theta(x)$, ${}^p\delta(x)$.

3. The absolute measurement error should be designated as Δ_s , Δ_θ , Δ .

4. The ultimate measurement result should be presented as $x = X$, $\delta = \dots \%$, $\theta = \dots \%$, $p = 0,95$, where X is the root-mean-square value of the measured quantity x , and θ is the maximum boundary of the nonexceptional residue for the systematic error of the quantity x under determination.

Direct measurements

1. Estimation of the result with a large number ($n > 3$) of measurements for the quantity x :

$$X = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i}, \quad (4.42)$$

where $w_i = \frac{1}{S^2(x_i)}$ is the weight of the i measurement's result;

$$S(x) = \frac{1}{x} \sqrt{\frac{\sum_{i=1}^n w_i (x_i - X)^2}{(n-1) \cdot \sum_{i=1}^n w_i}}, \quad (4.43)$$

where ${}^pS(x) = {}^p t_s \cdot S(x)$ is the factor of reduction to the confidential probability P , Student's coefficient (Table 4.2), [3] and [8].

Table 4.2

Student's coefficients

N	P				
	0.9	0.95	0.98	0.99	0.999
2	6.31	12.71	31.82	63.66	636.62
3	2.92	4.30	6.96	9.92	31.60
4	2.35	3.18	4.54	5.84	12.94
5	2.13	2.78	3.75	4.60	8.61
6	2.02	2.57	3.36	4.03	6.86
7	1.94	2.45	3.14	3.71	5.96
8	0.90	2.36	3.00	3.50	5.40
10	1.83	2.26	2.82	3.25	4.78

2. Estimation of the result with single measurements of the quantity x ($n \leq 3$). Single measurements of the quantity x should be preceded by a metrological test of the instrument to be used. Such test involves multiple ($N > 20$) measures of a certain quantity a similar to the quantity x , and determination of σ for the obtained value set a_i :

$$\sigma = \frac{1}{A} \sqrt{\frac{\sum_{i=1}^N (a_i - A)^2}{N-1}}, \quad (4.44)$$

$$\text{where } A = \frac{\sum_{i=1}^N a_i}{N}.$$

In further measurements of the quantity x , the result is estimated as follows:

$$X = \frac{\sum_{i=1}^N \omega_i x_i}{\sum \omega_i}, \quad S(x) = \frac{\sigma}{\sqrt{n}} K_{\sigma}, \quad (4.45)$$

where K_σ is the coefficient that allows for various statistical significances of results when the instrument is tested and the quantity x is measured

$$K_\sigma = \sqrt{\frac{\omega_\sigma}{\omega_x}}, \quad \omega_\sigma = \frac{1}{\sigma^2}, \quad \omega_x = \frac{1}{\sigma_x^2} \text{ are the weights of the measurement}$$

results when the instrument is tested and x is determined

Indirect measurements

1. Estimation of the result in measuring the quantity $y = f(x_1, x_2, \dots, x_n)$ in a single experiment:

- the input is measured values x_i , as well as the random error and the systematic error of the constituent quantities $S(x_k)$ and $\theta(x_k)$;
- the errors of the constituent quantities that are part of the formula to determine the quantity y , but not measured in the given experiment (constants, coefficients, certification results) shall be treated as $\theta(x_k)$;
- the result Y is estimated by the following formula:

$$Y = y,$$

$$S(Y) = \sqrt{\sum_{k=1}^m S_y^2(x_k)}, \quad (4.46)$$

where

$$S_y(x_k) = \frac{x_k}{Y} \cdot \frac{\partial f}{\partial x_k} \cdot S(x_k), \quad (4.47)$$

$\frac{\partial Y/Y}{\partial x/x}$ is the coefficient of the function Y sensitivity to the variation of the quantity x_k ;

$$\theta(Y) = 1,1 \sqrt{\sum_{k=1}^m \theta_y^2(x_k)}, \quad (4.48)$$

where

$$\theta_y(x_k) = \frac{x_k}{Y} \cdot \frac{\partial f}{\partial x_k} \cdot \theta(x_k). \quad (4.49)$$

The total measurement data error is $\delta(Y) = S(Y) + \theta(Y)$.

Often either $S(Y) \gg \theta(Y)$ or $\theta(Y) \gg S(Y)$. In these cases, the error calculation formula becomes simpler.

2. Estimation of the measurement result for the quantity $y = f(x_1, x_2, \dots, x_n)$ in a multiple experiment:

- the input to estimate the quantity Y is the values y_i obtained by measurements, as well as random errors $S(y_i)$ and the systematic error $\theta(Y)$ calculated in one of the experiments;
- the result of determining the quantity Y shall be estimated as follows:

$$Y = \frac{\sum_{i=1}^n \omega_i \cdot y_i}{\sum_{i=1}^n \omega_i}, \text{ where } \omega_i = \frac{1}{S^2(y_i)}, \quad (4.50)$$

$$S(Y) = \frac{1}{Y} \sqrt{\frac{\sum_{i=1}^n \omega_i (y_i - Y)^2}{(n-1) \sum_{i=1}^n \omega_i}}, \quad (4.51)$$

$$\delta(Y) = S(Y) + \theta(Y),$$

in the latter equality $\theta(Y)$ being calculated as in the previous case.

Calculation of ID errors

A system to account for NM as any other material and articles of value is based on balance closing, the major tasks in which are inventory taking, handling and statistical analysis of the data obtained (determination of the statistical significance). The basic assumptions one needs to analyze the ID significance are as follows:

- it can be assumed fairly credibly that the ID obeys to normal distribution law with a zero mathematical expectation and the variance of σ_{ID}^2 ;
- the confidence interval is to be selected subject to regulations and requirements [4]. Therefore, estimating the ID value and the variance σ_{ID}^2 is enough to conclude on potential anomalies.

Since this is essential, let us discuss in more details the procedures and methodology to estimate the ID statistical significance for detecting anomalies during the material balance closing for an MBA.

The ID is determined and its statistical significance is estimated based on the physical inventory taking data so, as to anomalies, in the given case

we will deal only with an anomaly showing itself in the ID modulus exceeding the threshold values set in the General Rules [4].

To calculate the ID variance, the equation is expressed as the function of:

- the input quantities – direct and indirect measurements (calculation or another determination) data for nuclear material parameters (concentrations, volumes, contents, weights, masses and so on) $x_1, \dots, x_n$;
- the random deviations of the given parameters $r_1, \dots, r_n$ as conditioned by the random errors of parameter measurements;
- the systematic deviations of the parameters $s_1, \dots, s_n$ as conditioned by the residual components of the systematic errors of parameter measurements:

$$ID = f(x_1, \dots, x_n; r_1, \dots, r_n; s_1, \dots, s_n).$$

The ID variance will be found by the following expression:

$$\sigma_{ID}^2 = \sum_{i=1}^n \left(\frac{df}{dr_i} \right)^2 \sigma_{r_i}^2 + \sum_{i=1}^n \frac{df}{ds_i} \sigma_{s_i} \sum_{j=1}^n \frac{df}{ds_j} \sigma_{s_j} \rho_{s_i s_j}.$$

The ID variance or the total root-mean-square error is obtained by expanding the ID function into a Taylor series about the mathematical expectations of input quantities with the terms of the given expansion being limited only to linear terms. Individual derivatives are taken at the point $x_1, \dots, x_n$ while no allowance is made for the deviations and variances of parameter measurements for the NM inventory as of the inventory taking time in the products not changed since the preceding inventory taking and not measured for the accounting purposes in the given material balance period. Estimation of the ID statistical significance consists in finding out if the following two conditions are fulfilled [4]:

- the ID modulus does not exceed the threefold root-mean-square ID error value;
- the ID value does not exceed the found threshold quantities (G) with the confidential probability of 0.95.

The ID modulus exceeding the threefold ID root-mean-square error:

$$|ID| > 3\sigma_{ID},$$

testifies that there are anomalies present in the accounting and control system. The failure to fulfill the second condition:

$$|ID| > G + 2\sigma_{ID},$$

evidences of an anomaly present in the accounting and control system, this manifesting itself in the threshold quantities of nuclear material being exceeded.

4.4. Tests of hypotheses and sampling studies

A measurement process occasionally requires decisions to be made on the significance of the measurement data obtained, say, to find out if data from several series of measurements are consistent, if measurement data from several laboratories agree, or if the ID value has significance.

The final decision with respect to the significance can be made following a hypothesis test. For example, if the ID is significantly above zero in a given period at a given facility.

Let H_0 be a zero hypothesis that consists in that $ID \leq 0$; and H_1 is an alternative hypothesis consisting in that $ID > 0$.

As such, testing a hypothesis about a set of experimental data statistically fails to give any proofs as to whether this hypothesis is true or false. A detailed test simply indicates to what degree the hypothesis agrees with the experiment result.

A hypothesis test consists in calculating a certain criterion and comparing the value of this to the tabulated one. Therefore, a test of the zero hypothesis H_0 may suggest the following cases:

- 1) the hypothesis H_0 is just and the criterion permits H_0 ;
- 2) the hypothesis H_0 is just but the criterion discards H_0 ;
- 3) the hypothesis H_1 is just and the criterion discards H_0 ;
- 4) the hypothesis H_1 is just but the criterion permits H_0 .

It is only in cases 1 and 3 that the hypothesis test leads to a correct result. The probability of a type I error (case 2) is numerically equal to the significance level α set for the hypothesis test. If the probability of a type II error (case 4) is equal to β , then the quantity $1-\beta$ is called the strength of the test. One often succeeds in giving a test more strength just by increasing α . In other words, a compromise is possible between the level of

significance and the test strength, a high strength occasionally turning out to be greater than small α .

Several basic hypothesis types are normally tested.

1. Is the measurement data described by the given distribution?
2. Is the difference between two average values significant?
3. Do the variances of several measurement series differ significantly?

Criterion χ^2

It happens sometimes that for the preset random sample x_i ($i = 1, 2, \dots, n$) of the random quantity X one needs to test the hypothesis that the function $f(x)$ is the probability density for X . To get the measure of the available data deviation from the anticipated data as per a hypothetical distribution, the quantity χ^2 is used. The criterion for testing the hypothesis is the comparison of χ^2 against the tabulated value χ^2_p , which meets the preset p -percent significance level.

First, the whole range of the values X in the given sample is broken down into m nonoverlapping intervals; m is found by one of the following formulas:

$$m = \log_2 n + 1;$$

$$m = 5 \lg n;$$

$$m = \sqrt{n};$$

$$m = 1.9 n^{0.4},$$

or from Table 4.3.

Table 4.3

Recommended number of breakdown intervals depending on the number of events

N	50	100	500	1000	10000
M	8	10	13	15	20

Interval length: $d = 1.02 \frac{X_{\max} - X_{\min}}{m}.$

The boundaries of the intervals are determined as follows:

$$X_{\min} - D; \quad X_{\min} + d - D;$$

.....

$$X_{\min} + (j-1)d - D; \quad X_{\min} + jd - D;$$

$$X_{\min} + (m-1)d - D; \quad X_{\min} + md - D,$$

where $D = 0.01d$.

The number of the values falling into the i interval is equal to v_i . If $v_i < 5$, the intervals merge. Let p_i be the hypothetical probability that X takes a value that falls into the i interval. Then

$$\chi^2 = \sum_{i=1}^m \frac{(v_i - np_i)^2}{np_i}, \quad (4.52)$$

where n is the sample size and

$$\sum_{i=1}^m (v_i - np_i) = 0. \quad (4.53)$$

If the assumed number of values in each interval is more than 10 (i.e. $np_i > 10$), then the quantity $\frac{v_i - np_i}{\sqrt{np_i}}$ is distributed asymptotically normally.

Let there be some χ_p^2 , for which $\chi^2 > \chi_p^2$ with the probability p in the event of $n-1$ degrees of freedom, then it should be taken that the given sample exhibits a significant difference from the hypothetical distribution, and then the hypothesis H_0 is rejected. Otherwise ($\chi^2 < \chi_p^2$), the hypothesis is accepted. According to this rule, the probability of a correct hypothesis to be rejected is equal to p .

t-criterion (Student's)

This criterion is normally used to check if a calculated average value differs from the quantity preset ($\bar{X} = \mu$).

To this end, the following criterion is used:

$$t = \frac{|\bar{X} - \mu|}{\sigma/\sqrt{n}}. \quad (4.54)$$

If the hypothesis is just, then the quantity t obeys to Student's distribution with the $(n-1)$ degree of freedom.

Example. Let there be a group of people growing as follows: 160, 160, 167, 170, 173, 176, 178, 178, 181 and 181.

Let hypothesis H_0 consist in that these values are distributed by normal law with the average value of 167 cm and the hypothesis H_1 in that $\bar{X} > 167$.

Solution:

$$\bar{X} = \frac{\sum_{i=1}^{10} x_i}{10} = 172.4 \text{ cm};$$

$$\sigma^2 = \frac{\sum_{i=1}^{10} (x_i - 172.4)^2}{9} = 62.9; \quad \sigma = 7.93 \text{ cm};$$

$$\frac{\sigma}{\sqrt{n}} = \sqrt{\frac{62.9}{10}} = 2.51 \text{ cm};$$

$$t = \frac{172.4 - 167.0}{2.51} = 2.15 \quad (p = 0.90, \quad n-1 = 9);$$

$$t_p = 1.83.$$

So the hypothesis is rejected.

Fisher criterion

The Fisher criterion is used to check if variances for two normal samples differ significantly.

When two variances are compared, it is convenient to check the relation:

$$F_{\nu_1, \nu_2} = \frac{\sigma_1^2}{\sigma_2^2}, \quad (4.55)$$

and compare this quantity with that in the table for the number of the degrees of freedom ν_1 and ν_2 and the significance level p .

Example. Let there be data from three laboratories (Table 4.4):

$$\bar{X} = \frac{1}{30} \sum_{i=1}^3 \sum_{j=1}^{10} x_{ij}, \quad (4.56)$$

$$\bar{X}_i = \frac{1}{10} \sum_{j=1}^{10} x_{ij}. \quad (4.57)$$

Table 4.4

Measurement data from three laboratories

Meas. number	Laboratory number		
	1	2	3
1	$X_{1,1}$	$X_{2,1}$	$X_{3,1}$
2	$X_{1,2}$	$X_{2,2}$	$X_{3,2}$
4	$X_{1,3}$	$X_{2,3}$	$X_{3,3}$
.....			
10	$X_{1,10}$	$X_{2,10}$	$X_{3,10}$
$\bar{X}_i$	$\frac{1}{10} \sum_{j=1}^{10} x_{1,j}$	$\frac{1}{10} \sum_{j=1}^{10} x_{2,j}$	$\frac{1}{10} \sum_{j=1}^{10} x_{3,j}$

The criterion is

$$F = \frac{\sigma_{\text{between groups}}}{\sigma_{\text{inside groups}}} < F_{p, \nu_{\text{inside}}, \nu_{\text{between}}}, \quad (4.58)$$

where $\nu_{\text{inside}} = \sum_{i=1}^k n_i - k = 27$; $\nu_{\text{between}} = k - 1 = 2$, n_i is the number of measurements in the i laboratory, and k is the number of laboratories.

The formulas to calculate the number of the degrees of freedom and the variances are given in Table 4.5.

Table 4.5

Basic formulas to calculate the numbers of degrees of freedom and variances

Parameter	Total	Inside groups	Between groups
Number of degrees of freedom	$N-1$	$\sum_{i=1}^k n_i - k$	$k-1$
Variance	$\frac{\sum_{i=1}^k \sum_{j=1}^{n_i} (x_{ij} - \bar{X})}{N-1}$	$\frac{\sum_{i=1}^k \sum_{j=1}^{n_i} (x_{ij} - \bar{X}_i)}{\sum_{i=1}^k n_i - k}$	$\frac{\sum_{i=1}^k n_i (\bar{X}_i - \bar{X})^2}{k-1}$

Sampling studies

Sampling studies are used in cases where complete enumeration cannot be done or makes no economic sense. This particularly concerns quality checks of some product or material types requiring destruction (destructive analyses for NM).

The specimen or some of the items taken for the study is called a sample (or a sample set), while the whole set of items sampled is called a universe.

A sampling check is done to decide on the nature of a set based on the set's representative sample.

Observations and measurements will be done only for a sample taken from a universe. The quality of the sampling study results is sure to depend primarily on to what extent the sample composition is representative of the universe or, in other words, on to what extent the sample is representative.

To be representative, a sample needs items and specimens to be randomly selected. Randomness suggests that no factor other than chance determines if the sample should include an item or not.

There are different ways to form samples (sample sets) depending on the characteristics thereof and the characteristics of the universe [6].

Set characteristics

Quantitative characteristics:

- total quantity of nuclear material;
- average level of enrichment in ^{235}U .

Qualitative characteristics:

- proper use of tamper indicating devices;
- the numbers on tested items which should coincide with database.

To have a representative sample, one should be aware of how the characteristic of interest is distributed inside the set:

- uniformly throughout the set;
- uniformly within clusters;
- uniformly inside layers;
- not known.

Each sampling test program includes the following items.

1. Purpose of sampling test.
2. Analysis of the set to be tested and characteristics thereof.
3. Analysis of constraints and statistical concerns.
4. Analysis of constraints and nonstatistical concerns.
5. Calculation of sample size.
6. Selection of sampling strategy.

Let us take a closer look at the above items.

Purpose of sampling test:

- check of earlier measurements;
- determination of the NM quantity as described in the given inventory listing;
- check of database records and the inventory listing for conformity;
- finding out if tamper indication devices are properly applied.

Identification of the set to be tested. When analyzed, the set should have its sample-affecting characteristics identified, so one shall find out:

- if the set is homogeneous in terms of the given characteristic;
- if not, if the set layers are homogeneous;
- how the items of interest are stored;
- if radiation safety concerns exist.

Statistical characteristics. *Qualitative* (discrete) characteristics:

- set size;
- distribution of the given characteristic inside the set;
- required significance level;
- admissible number of defects.

So, for example, a study is required to secure with a 95% probability that not more than 1% of the set elements are defective.

Quantitative (continuous) characteristics:

- what loss, if any, should be regarded significant;
- estimate uncertainty;

- permissible number of type I and II errors (type I error is a false loss detection (the true hypothesis is rejected), type II error is omission of a real loss (a false hypothesis is accepted)).

The foregoing determines to some extent the size of the desired sample.

Nonstatistical constraints:

- a) regulatory requirements;
- b) safety and security requirements;
- c) constraints determined by limited physical resources, finding included;
- d) time constraints.

The **sample size** is determined by the following parameters:

- size of the set to be tested;
- maximum permissible number of defects;
- significance level.

An inspection to check the system of tamper indicating devices (TID) suggests a check for two reliability conditions.

Condition 1. The recording system should show the exact location and identification of at least 99% of the TIDs.

Condition 2. The TIDs should be properly applied in not less than 95% of cases.

For a sampling test, the confidential probability is taken as 95%.

Example. Let us consider a set of 2000 items. We shall try to determine the minimum sample size at which one can check with a probability of 95% (i.e. $\alpha = 0.05$) the second condition: not more than 5% of the elements (i.e. not more than 100) have defects.

The function of distributing the enumeration probability for x defective elements in a sample of n elements from a set consisting of N items and having only D defective items is described by a hypergeometric distribution (4.21):

$$p(x) = \frac{\binom{D}{x} \binom{N-D}{n-x}}{\binom{N}{n}},$$

where, in our case, $x = 0, 1, 2, \dots, \min(D, n)$.

It is obvious that the smallest sample will be for the case where 0 defective items are tolerable, so then:

$$p(x=0) = \frac{\binom{D}{0} \binom{N-D}{n}}{\binom{N}{n}} = \left(1 - \frac{n}{N}\right) \cdot \left(1 - \frac{n}{N-1}\right) \cdot \left(1 - \frac{n}{N-2}\right) \times$$

$$\times \left(1 - \frac{n}{N-D+1}\right) \leq \left(1 - \frac{n}{N}\right)^D = 0.05;$$

$$0.05 \leq (1 - n/N)^D;$$

$$0.05 \leq (1 - n/2000)^{100} \rightarrow 1 - n/2000 \geq \sqrt[100]{0.05} \Rightarrow n = 2000 \cdot (1 - 0.97).$$

We will get $n = 60$.

Similarly, we can determine the sample size to check condition 1:

$$p = 0.05, N = 2000, d < 1\% = 20, x = 0.$$

$$N = 278.2 \text{ or, by rounding to an integer, } n = 279.$$

If the number of elements in a set is rather great, one needs to go on with the study even if one defective item has been found. What should the sample be if we accept that there is one defect? The sample should be such that, provided there are no defects or there is one defect, one can state with a 95% probability that the total number of defects does not exceed 1%, that is

$$p(x \leq 1) = p(x=0) + p(x=1) \leq 0.05;$$

$$p(x=0) = \left(1 - \frac{n}{N}\right)^D;$$

$$p(x=1) = \frac{\binom{D}{1} \binom{N-D}{n-1}}{\binom{N}{n}} =$$

$$= \frac{D \cdot n}{(N-D+1)} \cdot \left(1 - \frac{n}{N}\right) \cdot \left(1 - \frac{n}{N-1}\right) \cdots \left(1 - \frac{n}{N-(D-2)}\right) \leq$$

$$\leq \frac{D \cdot n}{(N-D+1)} \cdot \left(1 - \frac{n}{N}\right)^{D-1} \leq 0.05.$$

The computation gives the results ($N = 2000$) as shown in Tables 4.6 and 4.7.

Table 4.6

Minimum sample size to check conditions 1 and 2

Check of condition 1		Check of condition 2	
Maximum number of defects	Sample	Maximum number of defects	Sample
0	279	0	60
1	432	1	93
2	564	2	122

Table 4.7

Determination of the minimum sample size to check condition 2 depending on the permissible number of defects in sample

Maximum permissible number of defects	Minimum sample size
0	60
1	93
2	122
3	150
4	177
5	203
6	228
7	253
8	277
9	302
10	325

If defects were nevertheless found, corrective measures should be taken and the sample study should be replicated or a 100% inventory taking should be conducted.

As so the sample size, small samples are absolutely evident to be less informative while large samples rather informative and to have higher significance levels, but are however more expensive.

Sampling strategy

There are several sampling options to choose the one to give a maximum of information at a minimum cost:

- simple random sampling;
- systematic random sampling;
- nested (cluster) sampling;
- stratified random sampling;
- probability sampling.

Let us compare these options.

Simple random sampling. All elements in a set are listed and numbered $1, \dots, N$, where N is the set size. Then n numbers are selected from the list in a random manner (e.g. using a generator of random numbers), after which the listed items matching the selected numbers are picked out.

Advantages (+) and drawbacks (-):

- the listed items are not hard to select from (+);
- the estimates of the mean and the variance are not biased (+);
- the elements of the set need to be identified and designated before the sampling test is done (-);
- search for the item to select may take time (-);
- essential, still small subgroups can have an inadequate representation (-).

Systematic random sampling. Each k -th element of the set is selected.

Advantages (+) and drawbacks (-):

- items are not hard to select (+);
- one does not need to know the total number of elements in the set (+);
- the elements of the set may need to be ordered (-).

Cluster sampling. Clusters of nuclear material form pileups depending on how NM is stored. For instance, containers are normally shelved, racked or stored otherwise as specially determined being so naturally grouped. Log entries with respect to a container often provide information on only that cluster to which this belongs, e.g. room and shelf number and so on. So, considering clusters as the elements of the set to be sampled from with the subsequent check of containers in each selected cluster, may turn out to be highly advantageous in terms of time and cost.

There are many cluster sampling types to choose from. Of these, single-stage and two-stage samplings are most common.

Single-stage cluster sampling suggests sampling, as such, done from clusters with a 100% check inside each cluster. Two-stage sampling

suggests sampling both among clusters and inside clusters. In the latter case, fewer items are checked in each cluster but more clusters are tested. A potential drawback is the requirement to have information about each container in each cluster.

Advantages (+) and drawbacks (-):

- a time and cost saving potential, specifically for large sets with a marked nest structure (+);
- essential clusters may fall out of view (-);
- if the cluster elements are homogeneous, parameters will have an underestimated uncertainty (-).

Stratified sampling. Stratum is a uniform material. NM can be stratified by enrichment and content of uranium, by physical or chemical form or by measurement technique. The stratification procedure can be broken down into the following steps:

1) complete information on all items (NM types, rough NM enrichments (by elements or by isotopes), container location data and predicted measurement errors) shall be obtained;

2) items shall be grouped by a certain quantity feature, e.g. enrichment, isotope content, uranium concentration and so on;

3) if the universe contains different NM types (UF_6 , UO_2), the groups obtained in step 2 shall be divided into subgroups by the type of material;

4) if the subgroups from step 3 contain material to which different measurement techniques with different errors will be applied, the subgroups obtained shall be divided into smaller groups by the type of measurements;

5) the stratification is over after step 4 so sampling can be done.

Advantages (+) and drawbacks (-):

- the sample represents at least one element of each layer which ensures the best possible coverage of NM (+);
- one can estimate parameters both for each layer and for the whole of the set (+);
- the elements within a layer should be homogeneous (-);
- a more sizeable sample may be required than if other methods are used (-).

Probability sampling. The set is sampled given the relative relevance measure (with scale attachment) pro rata the significance of the elements tested.

Advantages (+) and drawbacks (-):

- prime attention will be given to the material most attractive for theft (+);

- the sample size depends on the selected relevance measure (–).

Determination of the sample size from variables, mean value and errors

Simple random sampling. The following formula is used to determine the size of a simple random sample from variables:

$$n = \frac{t^2 \cdot \Delta^2 \cdot N}{(N-1)\varepsilon^2 + t^2 \cdot \Delta^2}, \quad (4.59)$$

where $\Delta = \frac{\sigma_x}{\bar{X}}$ is the variance coefficient for the characteristic of interest in the universe (found based on expert data or from earlier measurement results); $\varepsilon = \frac{|\bar{x} - \bar{X}|}{\bar{X}}$ is the allowable difference between the mean (true) value of the characteristic in the universe and the mean sample value; and t_N is the quantity of the standardized deviation for a normal distribution of probabilities (determined by the probability that the relative difference between the sample estimate and the set value does not exceed ε) (Table 4.8).

Table 4.8

Quantity of standardized deviation

t_N	P
1.0	0.683
1.5	0.866
1.96	0.95
2.0	0.954
2.5	0.988
3.0	0.997
3.5	0.999

The mean sample value is found by the following formula:

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n}, \quad (4.60)$$

$$\sigma^2(\bar{x}) = \left(\frac{N-n}{N} \right) \cdot \frac{\hat{\sigma}^2}{n}, \quad \text{where} \quad \hat{\sigma}^2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}. \quad (4.61)$$

For the total values we have:

$$\begin{aligned} X &= N \cdot \bar{x}; \\ \sigma(X) &= N \cdot \sigma(\bar{x}). \end{aligned} \quad (4.62)$$

Here and hereinafter: n is the sample size, N is the universe size, x_i is the measurement result for the i -th sample element, $\bar{x}$ is the mean value of the characteristic of interest for the sample (and for the universe), and X is the total value of the characteristic of interest for the universe.

Cluster sampling. *Single-stage sampling.* The following formula is used to determine the cluster sample size from variables:

$$\begin{aligned} n &= \sum_{i=1}^m N_i, \\ m &= \frac{t^2 \cdot \Delta^2 \cdot M}{(M-1)\varepsilon^2 + t^2 \cdot \Delta^2}, \end{aligned} \quad (4.63)$$

where $\Delta = \frac{\sigma_{\text{clust}}}{\bar{X}_{\text{clust}}}$ is the variance coefficient for the characteristic of interest between clusters (found from expert data or earlier measurement

results); $\sigma_{\text{clust}}^2 = \frac{\sum_{i=1}^M (X_i - \bar{X}_{\text{clust}})^2}{M}$ is the intercluster (estimated) variance; M

is the number of clusters in the universe; $X_i = \sum_{j=1}^{N_i} x_{ij}$ is the total value of the

characteristic in the i -th cluster; x_{ij} is the quantity of the characteristic of interest (variable) for the j -th container in the i -th cluster;

$\bar{X}_{\text{clust}} = \sum_{i=1}^M X_i / M$ is the true mean value of the characteristic of interest for

all clusters; $\varepsilon = \frac{|\bar{x} - \bar{X}|}{\bar{X}}$ is the permissible difference between the mean (true) value of the characteristic in the universe and the mean sample value; and t is the quantity of the standardized deviation for a normal distribution of probabilities (determined by the probability that the relative difference between the sample estimate and the set value does not exceed ε).

The mean sample value is found by the following formulas:

$$\bar{x} = \frac{M \cdot \sum_{i=1}^m X_i}{m \cdot N}, \quad (4.64)$$

$$\sigma^2(\bar{x}) = \left(\frac{M-m}{M-1} \cdot \frac{M}{N\sqrt{m}} \right) \cdot \sigma_{\text{clust}}^2, \quad (4.65)$$

where $\sigma_{\text{clust}}^2 = \frac{\sum_{i=1}^m (X_i - \bar{X}_{\text{clust}})^2}{m-1} \cdot \frac{M-1}{M}$, and $\bar{X}_{\text{clust}} = \frac{\sum_{i=1}^m X_i}{m}$ is the mean total value of the characteristic in the cluster.

For the total values we have:

$$\begin{aligned} X &= N \cdot \bar{x}; \\ \sigma(X) &= N \cdot \sigma(\bar{x}). \end{aligned} \quad (4.66)$$

Here: m is the sample size; M is the number of clusters in the set; X is the estimated total value of the characteristic of interest in the set; x_{ij} is the quantity of the characteristic of interest (variable) for the j -th container in the i -th cluster; N_i is the number of containers in the cluster i ; $N = \sum_{i=1}^M N_i$ is the universe size (total number of containers); x_i is the measurement result for the i -th sample element, $\bar{x}$ is the average value of the characteristic of interest for the sample (and for the universe).

Stratified sampling. The mean sample value is determined as follows:

$$\bar{x} = \sum_{i=1}^L \frac{N_i}{N_{n_i}} \sum_{j=1}^{n_i} x_{ij}, \quad (4.67)$$

$$\sigma^2(\bar{x}) = \sum_{i=1}^L \left(\frac{N_i}{N} \right)^2 \frac{s_i^2}{n_i} \frac{N_i - n_i}{N_i}, \quad (4.68)$$

where

$$s_i^2 = \frac{\sum_{j=1}^{n_i} (x_{ij} - \bar{x}_j)^2}{n_i - 1} \quad (4.69)$$

is the variance inside the stratum, and

$$\bar{x}_i = \frac{\sum_{j=1}^{n_i} x_{ij}}{n_i} \quad (4.70)$$

is the average value of the characteristic of interest in the i -th stratum.

For the total values we have:

$$\begin{aligned} X &= N \cdot \bar{x}; \\ \sigma(X) &= N \cdot \sigma(\bar{x}). \end{aligned} \quad (4.71)$$

Here: n_i is the number of containers selected from the i -th stratum; L is the number of strata in the set; X is the estimated total value of the characteristic of interest in the set; x_{ij} is the quantity of the characteristic of interest (variable) for the j -th container in the i -th stratum; N_i is the number of containers in the stratum i , $N = \sum_{i=1}^M N_i$ is the universe size (total number of containers); $\bar{x}$ is the mean value of the characteristic of interest for the sample (and for the universe).

The cluster sample size determined from variables as required to ensure the specified accuracy level has been estimated from the following formula:

$$\varepsilon^2 = t^2 \sum_{i=1}^L N_i^2 \frac{\sigma_i^2 (N_i - n_i)}{n_i (N_i - 1)}, \quad (4.72)$$

where $\varepsilon = \frac{|\bar{x} - \bar{X}|}{\bar{X}}$ is the permissible difference between the mean (true) value of the characteristic in the universe and the mean value of the sample; t is the quantity of the standardized deviation from a normal distribution of probabilities (determined by the probability that the relative difference

between the sample estimate and the set value does not exceed ε); and

$\sigma_i^2 = \frac{\sum_{j=1}^{N_i} (x_{ij} - \bar{X}_i)^2}{N_i}$ is the variance (variation) of the characteristic of interest inside the i -th stratum.

A note should be made that X and σ_i are not known. Several sets of n_i exist that satisfy the condition (4.72). One may determine n_i from the requirement of minimizing the variance of the mean sampled and the total value of the characteristic in the sample:

$$n = \sum_{i=1}^L n_i, \quad n_i = n \left(\frac{N_i \cdot \sigma_i}{\sum_{i=1}^L N_i \cdot \sigma_i} \right), \quad (4.73)$$

where

$$n = \frac{t^2 \cdot \left[\sum_{i=1}^L \frac{N_i^2 \cdot \sigma_i^2}{N_i - 1} \right] \cdot \left[\sum_{i=1}^L N_i \cdot \sigma_i \right]}{\varepsilon^2(X) + t^2 \cdot \left[\sum_{i=1}^L \frac{N_i^2 \cdot \sigma_i^2}{N_i - 1} \right]}, \quad (4.74)$$

and the respective estimates are substituted for X and σ_i .

4.5. Control and assurance of measurement quality

By quality control we will mean systematic actions one undertakes to ensure adequate operations of a structure, a system or a system component.

The quality of measurements is ensured by two activities: quality control and quality assessment.

1. Quality control includes procedures and actions developed and used to support the needed quality of measurement.

2. Quality assessment includes procedures and actions one undertakes to make sure that the quality control system operates properly.

NM measurement control (MC) is a component of any quality assurance program. MC is a system of procedures to track down and assess sources of errors. MC includes monitoring of instrument operations using standards and estimation of the error instability in particular measurements (this affects the variance of the value obtained and the ID calculation result).

Objectives of measurement quality control:

- acquisition of quantitative data on uncertainties of measurements;
- support of measurement process invariability;
- detection and elimination of unusual occurrences.

Functional elements of NM measurement control systems:

- use of standards;
- qualification of measurement techniques;
- interlaboratory comparisons of measurement data;
- preparation of control charts;
- calibrations;
- other experiments to estimate measurement data uncertainties (auxiliary measurements).

Let us define more accurately some of the concepts.

Effect – a factor which does not represent a measurable quantity and influences measurement results. MC suggests detection and description of effects inherent in the measurement system in use. So an error (the difference between the true and the measured values) is viewed as the result of cumulative effects.

Working standard – a material, a device or an instrument with the value known with respect to state standards or metrology systems.

A standard should be representative with respect to anything that affects measurements. It is normally suggested that the standard and the material to be measured have similar dimensions, shapes and chemical compositions. The hierarchy of standards is shown in Fig. 4.4.

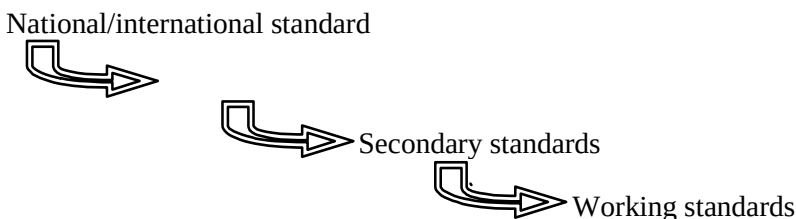


Fig. 4.4. Hierarchy of standards

A low-level standard is qualified by multiple measurements of its value against a higher-level standard. The mean arithmetic value of the measurement result will determine the value of the low-level standard. The uncertainty of the low-level standard value is obtained by summing up the

uncertainty of the high-level standard value and the statistical error of multiple measurement results.

The qualified standard material is a material specimen qualified by a special procedure and provided with a certificate showing the uncertainty of its parameter values. Specimens of qualified standard materials are distributed to operators for MC.

Operator metrology control includes:

- initial qualification of equipment;
- periodic requalification (adjustment) and recalibration;
- regular tests using standards.

Standards are also measured because product batch control is based largely on measurements of the standard. Measurement results are expected to be within the limits of the standard data uncertainty. Control charts (statistical control charts) are used for analysis.

Quality control is also critical to error estimations. The following input sources are used to estimate errors as discussed above:

- manufacturer specifications;
- case study results;
- industry-specific operating criteria;
- calibration data;
- metrology control data;
- interlaboratory comparison data.

The last four of these data sources relate directly to measurement quality control programs.

We shall discuss measurement quality control procedures for some of the techniques.

Weighing

Despite the simplicity of the procedure and quite a minor error involved in a single measurement, weighing, the basic measuring procedure in NM accounting and control systems, needs to be carefully controlled. The minimum required scope of control suggests the following procedures:

- frequent operator checks using standards;
- periodic inspection, maintenance and recalibration of all scales and weights;
- independent reweighing of material in process;
- monitoring of ambient conditions.

Ambient conditions (air temperature, humidity and pressure in the given case) are monitored because weighing process needs the buoyancy acting on the container (depends on the above parameters) to be taken into account.

Sample taking

As mentioned, sample taking procedures can occasionally contribute greatly, if not decisively, to the cumulative error which is due to complicated control of the sample taking process. Normally, sample taking quality control includes the following procedures:

- testing of sample mixing and taking when establishing work procedures for the sampling free of systematic error;
- periodic replication of sample taking using independent procedures to check if sample taking involves a systematic error;
- analysis of independent replicated samples to estimate and analyze the cumulative sample taking error.

Destructive analyses

Destructive analyses, primarily alpha spectrometry and mass spectrometry, are highly complex and time-taking procedures requiring highly skilled personnel to perform. Given that destructive analyses necessarily involve sample taking, the quality of these procedures is equally essential and hard to control. Let us describe a number of regular procedures to control destructive analyses:

- calibration and standardization of all instruments and reagents;
- analysis of standard specimens that simulate specimens in process to estimate systematic bias;
- independent resampling of the material in process and analysis of the sample to estimate the cumulative random sampling and analysis error;
- iterative sample analysis to estimate the random analysis error;
- documentation and description of all measurement techniques;
- training and advanced training of personnel.

Nondestructive assays (NDA)

Nondestructive measurements (NDA) are much easier to perform than destructive ones. However, it is rather hard to control quality of NDA in some cases [7]. In the first place, this stems from the requirement to use standards and standard specimens. Note that a representative NDA standard

is sometimes very hard to make (say, to measure deposition in piping or containers with low-level waste). If the properties of the standard and the material analyzed differ greatly, the standard may be a major source of measurement error.

On the whole, any nondestructive measurement quality control program is very similar to such programs for other measurement procedures and includes:

- calibration;
- periodic measurements of standards;
- timely recalibration of standards;
- qualification of techniques and laboratories;
- documentation and description of techniques;
- personnel training.

Control of internal measurements built in the instrument software is a common way to make it easier for operators to perform procedures and improve measurement quality. This suggests automatic check of each measurement.

Thus, MGA, a plutonium isotopic composition nondestructive measurement code, incorporates the following control procedures;

- control of the detector resolution (if the peak width is in excess of a certain value, the code will not handle the spectrum or will generate the message of a potential error);
- control of the peak positions in the spectrum;
- consideration and introduction of an allowance for the measurement system's dead time;
- consideration of the ^{241}Pu – ^{237}U nonequilibrium condition in plutonium isotope measurements.

Control charts (statistical control charts)

The control chart is an essential statistical quality control tool. The idea of the control chart is believed to be conceived by W. Shewhart, a US statistician. Control charts were originally used to record measurement data for the required (controlled) product properties [9]. A parameter falling out of the tolerance field indicated to the requirement of having the production process adjusted. Charts also helped one be aware of the cause of the defect. In this case, however, a decision to make an adjustment was taken when the defect had already occurred. Therefore, it was critical to find the procedure to accumulate information not just for a retrospective study but, as well, for decision-making applications. The procedure to obtain

cumulative charts and use them in decision-making was proposed by statistician I. Page in 1954.

A control chart normally consists of a center line (CL) representing the given value of the characteristic of interest, two control limits (the upper control limit (UCL) and the lower control limit (LCL)) and the points representing the values of the characteristic under control.

An example of a control chart is given in Fig. 4.5. The points in the diagram indicate the measurement results for the controlled parameter of the process, the mean of the characteristic, the inventory difference value, etc. If any point in the diagram is beyond the control limits, this indicates that the process “is not in control”. Besides, if even all results fall within the control limits but however, trends or other nonrandom data patterns are observed, this indicates that an additional study is required to avoid more serious errors.

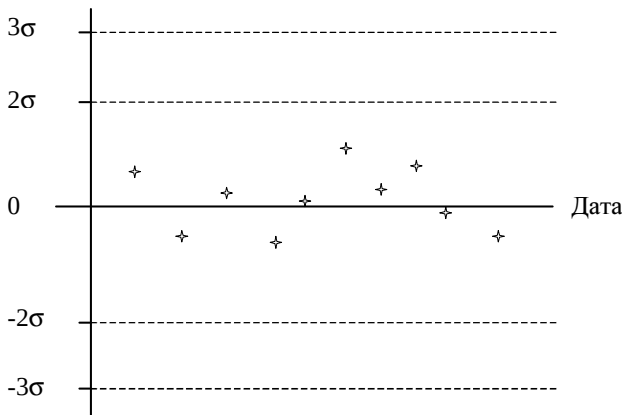


Fig. 4.5. Example of a control chart

That the process “is not in control” may be so signaled by:

- a point falling beyond the control limits;
- a group of consecutive points positioned near rather than beyond one control limit;
- points scattered heavily in the control chart relative to the center (indicates to an accuracy decrease).

We shall discuss just some of the most common types of control charts: the so-called Shewhart charts and cumulative sum charts.

Shewhart charts

The calculation and plotting of a Shewhart chart has the following pattern: let $Y_1, \dots, Y_n$ be a set of values for the random quantity Y ; μ_Y is the mean value for this sample; and σ_Y is the mean's standard deviation, then

$$\begin{aligned} \text{UCL} &= \mu_Y + 3\sigma_Y, \\ \text{CL} &= \mu_Y, \\ \text{LCL} &= \mu_Y - 3\sigma_Y. \end{aligned} \tag{4.75}$$

Fig. 4.6 presents an example of a control chart.

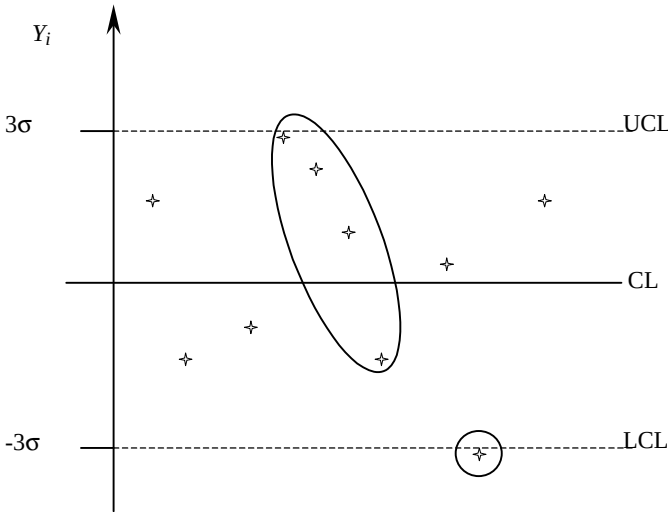


Fig. 4.6. A Shewhart control chart

In a general case, the random quantity Y may have any distribution, from which the control limits should be chosen. So, the mean sample value has normal distribution with the number of defective elements in the sample having a binomial and the event count rate (events per unit of time) a Poisson distribution (Table 4.9).

Table 4.9

Control limits for various statistics

Statistics, Y	Distribution	UCL	CL	LCL
Random mean, $\bar{X}$	Normal	$\mu + 3\sigma / \sqrt{n}$	μ	$\mu - 3\sigma / \sqrt{n}$
Number of defective elements in sample, X	Binomial	$np + 3\sqrt{np(1-p)}$	Np	$np - 3\sqrt{np(1-p)}$
Count rate, C	Poisson's	$\mu + 3\sqrt{\mu}$	μ	$\mu - 3\sqrt{\mu}$

Cumulative sum chart (diagram)

Shewhart charts largely help control retrospectively single and rather great anomalies in a process. A process may however involve minor but permanent biases desired to be controlled on line rather than retrospectively. Cumulative sum diagrams (CUSUM) help detect such deviations rapidly (Fig. 4.7).

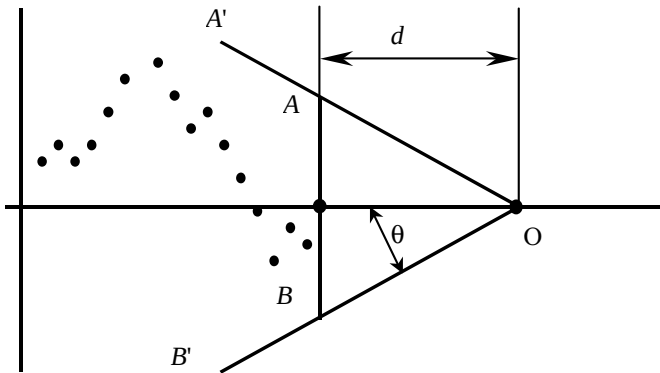


Fig. 4.7. Example of a CUSUM chart

For a CUSUM diagram, the subgroup number is plotted on the abscissa axis and the cumulative sum value for the deviations from the mean value (or a standard quantity) is plotted on the ordinate axis:

$$T_m = \sum_{i=1}^m (Y_i - \mu_0). \quad (4.76)$$

If the process is in control and there are no systematic biases and/or thefts, T_m is expected to vary around zero. If any systematic factors arise in the process (in this case the points in the Shewhart chart are on the one side of the center line), the CUSUM curve will have an upward or a downward trend.

A special note should be made that scale is critically important to the CUSUM diagram plotting. To have points well discernible and make it easier to plot the so-called V-mask, the recommendation is that the distance between points on the abscissa axis should be in a range of $\sigma Y \div 2,5 \sigma Y$. Scale observation is very important since this is what the mask angle depends on. Selecting an acceptable scale helps get the mask angle θ in a range of 30–60°, which, in turn, ensures the best outcome and helps escape errors which are inevitable if the selected angle is too small or too great.

The process control procedure is as follows. The mask (the procedure to plot the V-mask will be discussed hereinafter) is superimposed on the diagram so that the point P falls on the farthest diagram point and the line OP is parallel to the abscissa axis. If none of the diagram point falls beyond the limits of the angle $A'OB'$, the process is assumed to be in control.

To be plotted, the V-mask requires two elements: angle, θ , and distance, d :

$$\operatorname{tg} \theta = \frac{D}{2y} = \frac{\delta \sigma}{2y}, \quad (4.77)$$

where σ is the sample-mean variance; D is the bias quantity (either in one direction or in the other) to be found with the specified probability; δ is the quantity of this bias in units σ ; $y = \frac{\text{scale factor on the axis } Y}{\text{scale factor on the axis } X}$ is the scaling factor that determines the control chart geometry and the mask size;

$$d = OP = E(\alpha) \left(\frac{\sigma}{D} \right)^2 = \frac{E(\alpha)}{\delta^2}, \quad (4.78)$$

where $E(\alpha)$ is the coefficient which is the function α (the probability of a first-order error). The values of this coefficient are given in Table 4.10.

Table 4.10

Factor values $E(\alpha)$ depending on the probability of a first-order error

α	0.0027	0.010	0.020	0.050	0.010
$E(\alpha)$	13.215	10.597	9.210	7.378	5.9911

So, plotting a CUSUM diagram and estimating the process stability involves the following steps:

1) selection of a suitable axis scale, plotting of experimental points on the CUSUM diagram;

2) selection of α and δ , calculation of σ , determination of the V-mask parameters (θ and d), mask plotting;

3) the mask is placed on the control chart as described hereinabove and all points are checked left of the mask's point P , the **upper** mask ray being the **lower** control limit and the **lower** mask ray being the **upper** control limit.

Therefore, control charts are a powerful tool of finding out and analyzing a certain (other than random!) cause of a deviation, a bias or a process instability, say, an organized NM theft.

There are currently rather many computer programs enabling automated data analysis based on control charts.

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CHAPTER 5

MEASUREMENTS OF NUCLEAR MATERIAL FOR ACCOUNTING AND CONTROL THEREOF

This Chapter reviews and looks into the techniques and equipment used to account for and control nuclear material (NM). The nuclear material subject to control is listed, and the properties thereof and the conditions of test measurements are discussed.

The most common destructive and nondestructive test techniques, as well as passive and active analyses are described. Most of the test techniques are based on recording of gamma and neutron radiation. Data on detectors and equipment employed, as well as on calibration procedures and standards is provided. Sources of measurement errors and measures to reduce these are discussed. In conclusion, examples of combined NM measurement methods used in production are given.

5.1. Basic concepts of NM measurements

Prior to the 1990s, onsite NM measurements were conducted in Russia largely for control of processes. Nondestructive assays (except weighing) had minor roles.

In the 1990s, comprehensive measures began to be undertaken in Russia to have nondestructive assay (NDA) techniques more rapidly introduced into the Russian NM accounting and control system, including by way of providing enterprises and organizations with up-to-date devices, developing and qualifying state standard samples for NDA, creating respective regulatory documentation and training personnel through a variety of educational forms. Major emphasis in this has been also placed on international cooperation.

Russian requirements with respect to state accounting and control of nuclear material in production, utilization, processing, storage and transportation are set forth in the General Rules for Accounting and Control of Nuclear Materials, NP-030-05 (OPUK-2005).

As weapon grade nuclear material, uranium and plutonium prevail. Weapon Grade Uranium (WGU) contains 93% or more of ^{235}U .

Weapon Grade Plutonium (WGPu) is a pure plutonium metal that contains not more than 7% of the ^{240}Pu isotope.

Reactor Grade Plutonium (RGPu) accumulates in fuel of power reactors and contains 19% of ^{240}Pu isotope or more. The approximate isotopic

compositions of plutonium in the spent fuel of some reactors are given in Table 5.1.

Table 5.1

Isotopic composition of plutonium in power reactor fuels

Reactor	Fuel burnup, (GW·day/t)	Isotopic composition, %			
		²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu
AGR	18.0	53.7	30.8	9.9	5.0
RBMK	20.0	50.2	33.7	10.2	5.4
BWR	27.5	59.8	23.7	10.6	3.3
PWR	33.0	56.0	24.1	12.8	5.4

The isotopic composition of NM is known to determine the properties thereof. The following depends on isotopic composition:

- critical mass;
- generation of spontaneous-fission neutrons which influence the design and power of explosives. For plutonium, the number of these depends directly on the concentrations of ²⁴⁰Pu and ²⁴²Pu;
- generation of heat (for plutonium, this depends directly on the concentration of ²³⁸Pu);
- radiation.

The NM chemical form is what defines to a great extent the choice of measurement techniques and the measurements results. The mass fraction of nuclear material varies in a sample depending on the oxidation level, this to be taken into account when analyzing the weighing result.

Nuclear material is subject to categorization. The category of nuclear material is a quantitative characteristic thereof in the context of NM accounting and control. The category of the onsite nuclear material defines the requirements to the accuracy of test measurements for the NM balance closing (relative standard percent deviations from the inventories) (see Table 5.2).

Errors of NM test measurement results are of a fundamental importance. For example, no loss or theft of less than 150 g of plutonium can be detected when the mass of a 10-kg plutonium sample is determined with an accuracy of 0.5% in the confidence interval of 68% (or 1.5% in the confidence interval of 99%).

Table 5.2

Requirements to the accuracy of NM measurements

No.	Facility type	Relative standard deviation, %
1	Uranium enrichment	0.2
2	Chemical transformations: uranium conversion and fuel fabrication	0.3
3	Plutonium conversion and fuel fabrication	0.5
4	Chemical treatment of uranium	0.8
5	Chemical treatment of plutonium	1.0
6	Isolated scrap* storage	4.0
7	Isolated waste storage	25

* Scrap – NM reject removed from process for treatment.

The nuclear material balance is the result of comparing the book inventory of nuclear material against its inventory in the material balance area (MBA).

The quantity of nuclear material in each MBA shall be determined by measuring the quantity and composition of nuclear material, controlled through accounting and checkouts of nuclear material and verified by physical inventory takings. The final step in a physical inventory taking is balance closing for each nuclear material over the period between the previous and the given physical inventory taking, and determination of the inventory difference and the error thereof.

Physical inventories for each MBA are taken on a periodic basis with the material balance periods (BP) established depending on the category of the nuclear material in the MBA, as well as on the process and other site-specific features.

An anomaly in accounting and control of nuclear material is as a shortage (a surplus) of nuclear material, errors in accounting records and reports, damage or failures of NM access controls, and breaches in NM fabrication, utilization and transfer procedures.

The measurement program shall be developed for each MBA, this to include the list of measurement techniques, samplers and sampling procedures, measurement frequency data, the required measurement accuracy and the measurement data submission dates and forms.

Measurement procedures are subject to metrological certification as required by effective state or industry standards.

Standard samples (standards) used to calibrate instrumentation and check the measurement data accuracy are subject to metrological certification under requirements of effective state or industry standards and shall have the respective certificate.

Each enterprise shall develop and put into operation a measurement quality control program to be part of the NM measurement system. The objective of the program is to ensure the quality of measurements.

The technique to control NM is chosen given the properties of the material and the measurement conditions: physical state, purity, desired accuracy of determination, time required to perform an analysis, number of analyses (1 per month, 100 per week), volume of the analyzed sample, available equipment and standards, qualification of personnel and the funding allocated.

A note should be made that NM test measurements are not direct: the mass of material or its isotopic composition is found from results of measuring the electrical pulse count rate, current variations, spring deformation and so on. The measured effect (N) and the quantity sought for (F) relate through the coefficient k , which is obtained via calibration by measuring standards (NM samples with the known characteristics F_{st}) on a test measurement bench: $k = F_{st} / N_{st}$, where N_{st} is the measured effect for the standard.

The accuracy of NM mass determination depends on the test measurement error and the uncertainty of the calibration factor k , the second component prevailing in many cases. In turn, the test measurement data normally needs to be corrected to account for a number of influencing factors caused by specific features of the NM sample, information distortions in the electronic measuring channel and so on.

The NM balance equation has the following form: $ID = BI + R - S - EI$, where ID is the inventory difference; BI is the book inventory; R is the NM received for storage over the period between the inventory takings; S is the NM shipped over the same period, and EI is the ending inventory of NM. $EI = k \cdot N$, where N is the number of counts and k is the calibration factor that relates the quantity to be determined to the measurement result.

The judgments on the inventory taking result are made by comparing ID and $3\Delta ID$.

Different stages of a nuclear fuel cycle (Fig. 5.1) deal with different physical and chemical forms of NM and involve loss of NM. Different

physical and chemical forms of NM require various measurement technologies for accounting of material. In addition to control of the NM presence and integrity, NM measurement data serves to control processes, as well as to ensure nuclear and radiation safety standards. Measurement procedures and devices are selected so that to provide a comprehensive solution to all of the tasks listed herein.

Therefore, subject to measurement is nuclear material in different states and forms, combined diversely with other material and having different activity levels. Accordingly, these tasks require different techniques and equipment to be accomplished.

Supervision with respect to accounting for and control of NM involves two measurement types:

- **accounting measurements** – quantitative characterization of NM and products the results whereof are entered on accounting records;
- **verifying measurements** – measurements the results whereof are used to verify the quantitative characteristics or attributes of NM or items.

Test measurements have the purpose of determining the numerical value of the NM quantity. These seek to ensure the best accuracy of the result. There is however a number of control tasks that require only quality data of samples. These include:

- characterization of unlabeled or erroneously labeled samples;
- determination of the NM presence in samples on a “yes or no” basis;
- rapid inventory taking;
- verification of the shipper data by the receiver, etc.

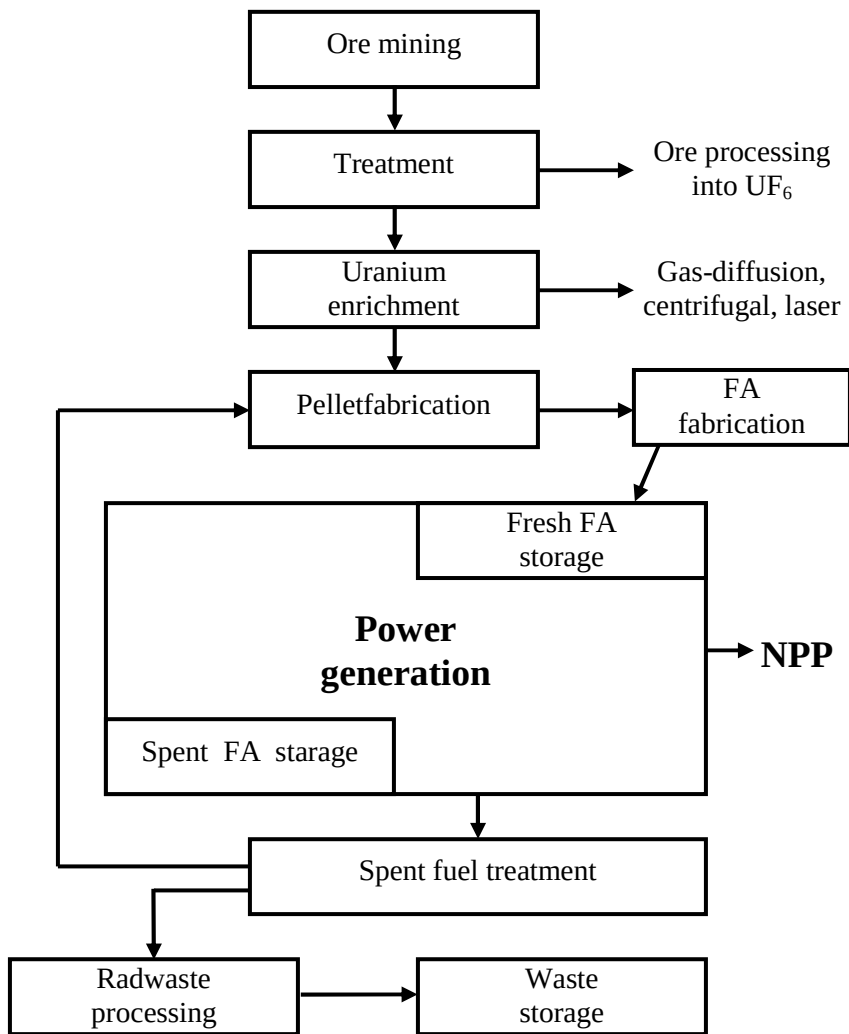


Fig. 5.1. Flowchrt of NM transformations in a fuel cycle

5.2. Nondestructive NM assay techniques.

Calibration and standards

Nuclear material is checked by counting of items, identification of items (barcodes), weighing, measurement of volume, sample taking for chemical analyses and nondestructive assays.

Nondestructive assay (NDA) is determination of the NM type and/or quantity in a sample without changing the characteristics of the sample or penetrating into it.

Nondestructive assay is commonly used in the following cases:

- when there is a need for rapid testing;
- monitoring of processes;
- where no representative sample taking is feasible (e.g. in control of production waste, scrap and so on);
- where no destructive testing is practicable.

Destructive analysis is not appropriate in cases:

- where a great deal of measurements is involved (e.g. during an inventory taking);
- where data is required forthwith (e.g. in an unscheduled inspection);
- where no sampling of the item tested is permitted (e.g. a nuclear explosive);
- where material is not accessible for sampling (e.g. deposits in pipelines);
- where analysis is too expensive.

NDA can be both passive and active.

Active analysis includes irradiation of the items to be tested by an external radiation source (neutrons, X-rays, gamma radiation) to induce secondary irradiation of NM. The radiations emitted (neutrons, X-ray quanta) are interpreted as “signatures” to determine the quantity and composition of the fissile material present.

Passive analysis relies on spontaneous radiation (gamma, X-ray, neutron) measurement for the material which is the “signature” thereof.

There is an extensive choice of currently available instruments and techniques to detect, identify, analyze and test NM in different physical and chemical forms. NDA equipment differs both in dimensions and sophistication, ranging from portable devices used by inspectors to check NM to large-sized factory systems used routinely by operators.

NDA is normally conducted by measuring NM gamma and neutron radiation. NDA equipment is calibrated and assay results are verified by standard destructive methods (radiochemistry, mass spectrometry). The

material involved in processes is analyzed in NDA laboratories using automated instrumentation. Deposits in process equipment are evaluated by portable devices.

The important advantages offered by NDA are as follows:

- assays do not normally take much time;
- assays are not expensive (with no the instrument cost taken into account);
- there is no waste and no reagents are required.

The shortcomings of NDA are as follows:

- relatively greater errors of results (normally 3 to 10% or even more); these are higher than in destructive analysis;
- complexities involved in obtaining standards (large-size NM standards are either costly or do not exist).

The following measurement control procedures ensure the quality of measurements in NDA:

- equipment calibration: required to secure accuracy (avoid biases in results) and estimate standard deviations of calibration results. Calibrations relate the measurement results to the national (international) system of units;
- frequent checks using working standards;
- independent multiple measurements to estimate random assay errors;
- a periodic comparative analysis of samples using proven standard destructive techniques;
- interlaboratory exchange of samples for secured agreement of measurement data with the data from other laboratories.

Calibration of instruments and techniques used for NDA requires standards. Standards are made depending on the measurement method chosen. The quality of any analysis result depends on the quality of calibration, this, in turn, defined by the quality of standards.

Standard-based calibration measurements are used to determine the dependence between the instrument output and the NM mass in the sample. Standards are also used to test, check or normalize instrument and system output.

“True” values of a standard’s parameters are normally found by destructive analysis (DA). Standards are expensive and long to make. Properly understanding the principles on which NDA is based helps minimize the number of standards needed.

Some standards are hard to make and store. Over time, the properties of a standard may change so that it will no longer fall into the same category

as the NM under control. This will also require a new standard to be made to replace the old one.

There are two categories of standards:

- Certified Reference Materials (CRM): these are made of highly pure NM. CRM standards are certified by the most accurate measurement methods and in more than one laboratory. Such standards require certificates;
- Working Reference Materials (WRM) – these have less accurate characteristics than CRMs. WRM standards are normally used to calibrate specific NDA instruments at enterprises where they are required.

CRM standards for specific site uses are not altogether available, so laboratories or factories need to make their own working standards.

Russian regulations respecting calibrations, certifications of procedures and requirements to reference samples are documented in respective state standards: GOST 8.315–97 “Standard Samples of Material Composition and Properties”, and GOST 8.563–96 “Measurement Procedures” and others.

Russian state standard samples (SSS) for the plutonium isotopic composition and mass were released in 2000 (Fig. 5.2). A complete SSS set consists of 10 samples. The isotopic compositions in various sets of ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu are equal to 1.82:60.47:22.20:10.59:4.84 and 0.12:97.20:2.27:0.061:0.10. The relative uncertainty in determination of the plutonium mass fraction in an SSS is $\pm 0.30\%$ with the confidence probability of 95%. The plutonium mass varies between SSSs in a range of 1 g to 2.5 kg.

Mathematical Monte-Carlo modeling makes standards much less required. By determining so the shape of the calibration curve, one can normalize it with the aid of physical standards.

One can also lessen the required number of standards through cross calibration. This principally consists in having one instrument out of a number of similar instruments thoroughly calibrated with a broad range of measurements for the controlled parameter covered (e.g., mass of the NM in samples). The characteristics of this “reference” instrument obtained by the calibration are recorded and used to interpret the results of measurements with other similar instruments. It is assumed in this that the shape of the calibration curve $K = f(m)$ reflects the properties of the whole range of similar instruments.

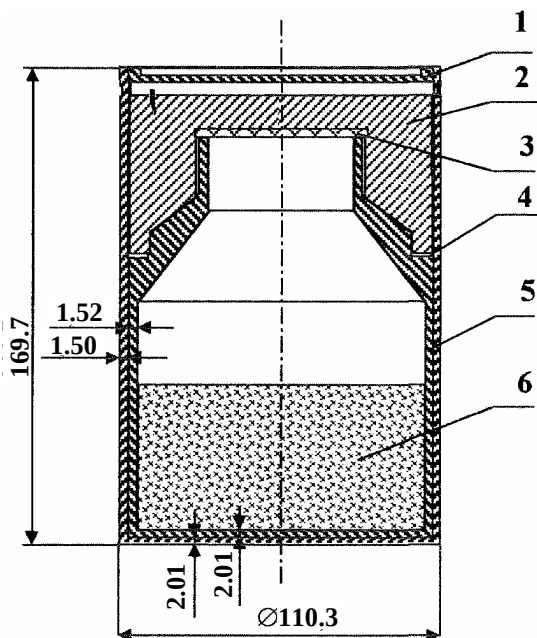


Fig. 5.2. A diagram of a Russian plutonium SSS package with a plutonium mass of 502.26 g: 1 –holder lid; 2 – vial cap; 3 – gasket; 4 – holder body; 5 – vial body; 6 – PuO_2 of the density 3.1 g/cm^3

The IAEA-employed NDA equipment is largely based on measurements of γ -radiations and neutrons emitted by different NM (Table 5.3 and Fig. 5.3).

Gamma ray measurements offer a number of advantages:

- they require small personnel to perform;
- no calibration is needed to interpret assay results in many cases;
- the result is obtained right after the measurement is done;
- errors in results are relatively small.

Gamma ray spectrometry is used to determine the uranium enrichment and the isotopic composition of plutonium, as well as for K-edge densitometry of plutonium nitrate solutions and for checks of the LWR SFA burnup, etc.

Table 5.3

Most intensive NM γ -radiations used for nondestructive assays

Isotop e	Energy, keV	Activity, $\gamma/\text{g}\cdot\text{s}$	Mean free path, mm	
			High Z, ρ	Low Z, ρ
^{234}U	120.9	$9.35\cdot 10^4$	0.23	69
^{235}U	143.8	$8.40\cdot 10^3$	0.36	73
	185.7	$4.32\cdot 10^4$	0.69	80
^{238}U	766.4	$2.57\cdot 10^1$	10.0	139
	1001.1	$7.34\cdot 10^1$	13.3	159
^{238}Pu	152.7	$5.90\cdot 10^6$	0.40	75
	766.4	$1.387\cdot 10^5$	9.5	139
^{239}Pu	129.3	$1.436\cdot 10^5$	0.27	71
	413.7	$3.416\cdot 10^4$	3.7	106
^{240}Pu	45.2	$3.80\cdot 10^6$	0.07	25
	160.3	$3.37\cdot 10^4$	0.45	76
	642.5	$1.044\cdot 10^3$	7.4	127
^{241}Pu	148.6	$7.15\cdot 10^6$	0.37	74
	208.0	$2.041\cdot 10^7$	0.86	83
^{241}Am	59.5	$4.54\cdot 10^{10}$	0.14	38
	125.3	$5.16\cdot 10^6$	0.26	70

Nondestructive γ -analysis has the following stages:

- measurement of the pulse count rate in complete γ -quanta absorption peaks in the detector;
- making the allowance for the electronic path distortions;
- making the allowance for the γ -quanta absorption in the sample and en route to the detector;
- calculation of the corrected count rate.

Where required, calibration may be used to determine the coefficient of proportionality between the measurement results and the NM quantity under determination.

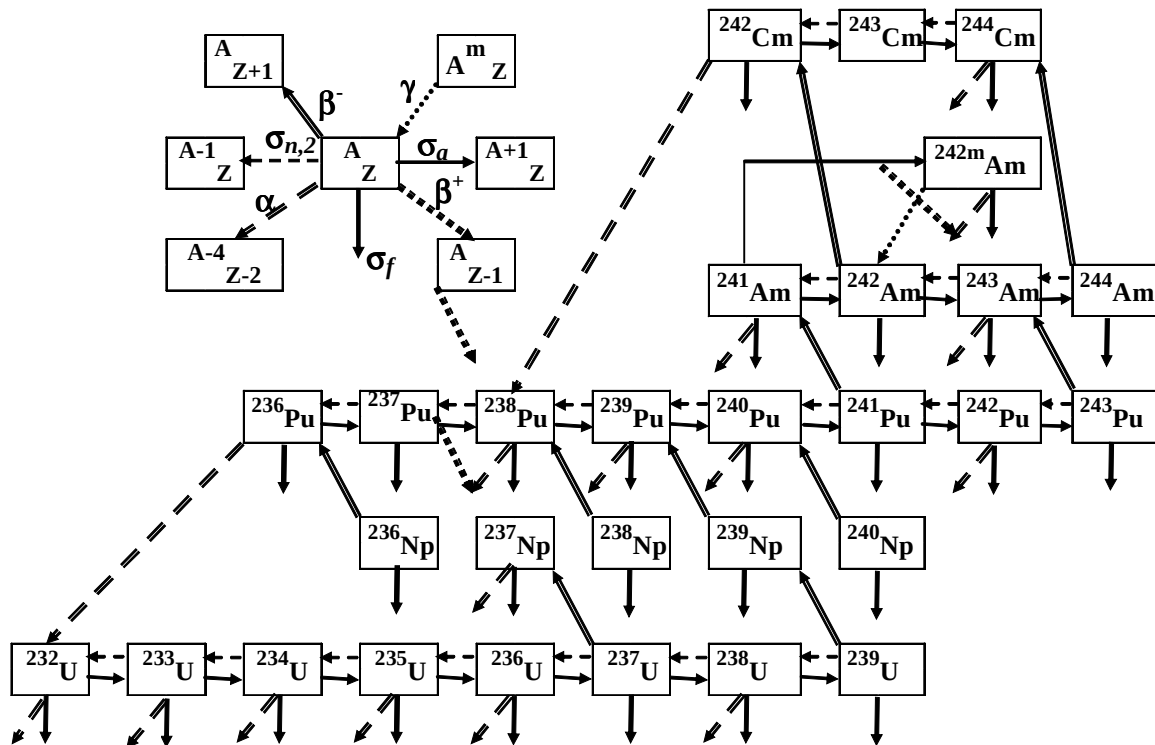


Fig. 5.3. Isotopic transformations in a uranium-plutonium cycle

Determination of NM content by measurements of intrinsic gamma radiations

Factors influencing NDA measurement results

NM solutions are normally homogeneous and one can simply get a standard for measurements using a suitable vessel. The content of NM in the sample is found from the intensity of its emission from the sample. Some of the gamma radiation is however absorbed inside the sample en route to the detector. The correction factor CF(AT) that accounts for the **self-absorption of NM radiation inside the sample** can be found using an external gamma radiation source with an energy close to the NM radiation energy. To do this, the transmission T of the external source gamma ray beam through the sample is measured:

$$T = \frac{N}{N_0} = \exp(-\mu_l \cdot x), \quad (5.1)$$

where N_0 is the number of the source-emitted gamma-quanta getting on the sample; N is the number of the source-emitted gamma-quanta transmitted through the sample; μ_l is the gamma-ray linear attenuation factor; and x is the sample thickness. With a plane geometry, the allowance is calculated from the formula:

$$CF(AT) = \frac{\mu_l \cdot x}{[1 - \exp(-\mu_l \cdot x)]} = \frac{-\ln(T)}{(1-T)}. \quad (5.2)$$

An extra source attached next to the detector is used to correct the **counting losses** caused by the measurement system's dead time. Using a radiation source simplifies the correction circuit and makes it more reliable as compared to instrumented correction based on a pulse generator. Observations of the pulse count rate in the peak produced by this source yield data on the count losses during measurements with samples. Such source is selected such that not to hamper measurements of the NM emission from the samples.

Uranium solutions are tested via passive measurement of gamma rays with the energy of 185.7 keV of ^{235}U , the results being corrected from the measurement results for transmission of the ^{75}Se source radiation with the

energy 136.0 keV and the counting losses corrected using a ^{109}Cd source (the radiation energy of 88 keV).

The range of the concentrations measured covers seven orders of magnitude. The sample dimensions are smaller than in other methods.

Waste control. Segmented gamma ray scanning

This technique is used to test containers and tanks with solid and liquid NM-containing waste. The measurement conditions in this are rather complicated: NM is present in small concentrations and has a nonuniform axial and radial distribution in the container. The volumes of the samples controlled differ greatly ranging from small vials to 200-liter metal drums. The matrix density is relatively low.

Onsite NM-containing waste is containerized in layers, NM in these being more uniform horizontally than vertically. When analyzed, the sample is rotated to mitigate the horizontal nonuniformity effects, as the vertical nonuniformity effects are mitigated by analyzing material by segments. Each segment is measured individually with all the values obtained summed up. The basic assumption is that NM is uniformly distributed inside each segment and one can determine to which extent the gamma radiations inside the segment are mitigated by measurements of the transmission.

Segmented scanning (SS) combines container movements with radiation measurements. SS is probably the most widespread ND measurement technique based on γ -radiation measurements.

Analyzed radiations

Uranium content is controlled by measuring γ -radiation of 185.7 keV.

For ^{239}Pu control, one normally measures γ -radiation of 413.7 keV.

The obtained results distorted by the absorption of γ -rays in the container are corrected with the aid of the correction factors found by measuring the transmission of the ^{75}Se source γ -radiations with the energies of 136.0 keV, 264.6 keV, 279.5 keV and 400.6 keV through the container. The correction for the results of measuring the 185.7-keV radiation of ^{235}U is obtained by interpolation between the transmission values for gamma ray lines with energies of 136.0 keV and 264.6 keV, while the correction for measurements of 413.7-keV ^{239}Pu radiations is found by extrapolation.

Another source, ^{109}Cd , ($E\gamma = 88.0$ keV), serves to correct the pulse count errors.

Measurements and interpretation of results

To have the result to characterize the average NM content in a container, the latter is rotated and moved vertically. The container is lifted gradually as its vertical segments are scanned, this making it possible to average the difference in attenuations of radiations in separate horizontal segments. The facility is shown schematically in Fig. 5.4.

The pulse count rate in the complete n_p absorption peak is found by measurements using the formula:

$$n_p = (n'_p - R_B) \cdot \frac{R_{ref}}{R_{RL}}, \quad (5.3)$$

where n'_p is the measured count rate in the interval that contains the desired peak; (R_{ref} / R_{RL}) is the allowance for the counting loss found by measurements with ^{109}Cd without and with a sample; and R_B is the background count rate below the peak.

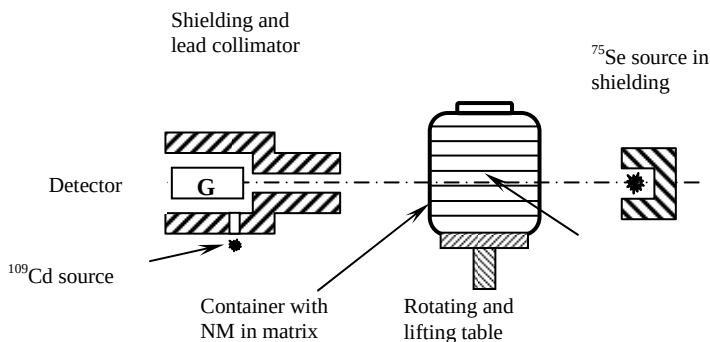


Fig. 5.4. Schematic of a segmented scanning facility

The measured and corrected pulse count rate in the gamma-peak n_p relates to the mass of the isotope determined via the calibration factor which is found with the aid of a standard. The contribution of the calibration factor to the systematic and random measurement error should be relatively small.

The results of measurements using a standard may be influenced by several factors, including homogeneity of the sample material, the

magnitude of transmission (should be over 10%), size of NM particles and others.

Segmented scanning is applicable to many low-density NM-containing materials: paper, sand, plastic, ash and liquids.

Control of deposits

Deposit is NM that remains inside process equipment and cannot be removed by way of conventional flushing. It settles in tanks and accumulates in process piping and ventilation systems. The deposit amount varies from 0.1 to 0.2% of the total facility capacity even after the equipment is cleaned thoroughly. The initial operation phase of a new facility may account for a deposit share of 1 to 10% of the output product.

Most of the uranium and plutonium deposit measurements are based on recording the ^{235}U peak of 185.7 keV and the combination of ^{239}Pu peaks with the energies of 375 keV and 414 keV. Portable scintillation NaI detectors are commonly used to measure these gamma-quanta. For measurements, the detectors have a lead shielding made around them, the latter having a collimator aperture to transmit radiation only from the desired direction.

A deposit mass measurement program has the following stages.

1. Identification of potential deposit points in equipment.
2. Rapid surveying using collimated instrumentation to detect locations with the largest NM deposit quantities.
3. Graduation of the detectors using standard samples. Each detector is graduated for the deposit location as a point, a line or a plane.
4. Selection of the model for deposit in each equipment component. Deposits are characterized as a point, a line or a plane, and are quantitatively measured.
5. Quantitative measurements. Most of the time is given to locations with most of the NM amount.
6. Deposits are measured from different directions and at various distances, using different geometry description models, to estimate the measurement result uncertainty. Corrections for the radiation attenuation thanks to the self-absorption in deposit and the absorption en route to the detector are estimated and introduced.

Graduation procedure

Graduation for a point, a line or a plane can be done using one movable point source of 1 to 5 g of ^{235}U or ^{239}Pu . It should be remembered that self-

absorption of gamma-quanta in uranium or plutonium may be highly intensive.

If a standard point source contains m_0 grams of NM, the mass of the point deposit m (g) is found from the formula:

$$m = m_0 \cdot \frac{C}{C_0} \cdot \frac{r^2}{r_0^2}, \quad (5.4)$$

where C is the count rate in the deposit measurement, and r is the distance from the detector to the deposit.

Where there is a linear deposit distribution, the NM mass per the deposit length unit m_L (g/m) is found from the expression:

$$m_L = \frac{m_0}{L_E} \cdot \frac{C}{C_0} \cdot \frac{r}{r_0}. \quad (5.5)$$

If a planar deposit distribution model is chosen, the NM mass per the deposit area unit m_A (g/m²) is found from the formula:

$$m_A = \frac{m_0}{A_E} \cdot \frac{C}{C_0}. \quad (5.6)$$

Gamma ray spectrometry of uranium enrichment

There are two definitions of the uranium enrichment by ²³⁵U isotope:

- enrichment (mass percent) E_1 =(mass of ²³⁵U/total mass of U) 100%;
- enrichment (atomic percent) E_2 =(number of ²³⁵U atoms/total number of U atoms)·100%.

Commonly used are analyses of uranium enrichment based on the assumption that the intensity of gamma radiation of ²³⁵U from uranium samples of a sufficient thickness is proportional to the enrichment thereof by ²³⁵U. Gamma-quanta with the energy of 185.7 keV in ²³⁵U decays are emitted with a probability of (57.5±0.9)% (the quantum yield of radiation*, the number of quanta of the said radiation reaches 4.6·10⁴ quantum/(s·g)).

* “Branching ratio” is the term often used in foreign literature.

Mean free paths and “infinite” thicknesses for quanta of 185.7 keV in uranium compounds are given in Table 5.4.

Table 5.4

Mean free paths and “infinite” thicknesses for gamma radiation of 185.7 keV in uranium compounds

No.	Compound	Density, g/cm ³	Mean free path, cm	Infinite thickness, cm
1	Metal	18.7	0.04	0.26
2	UF ₆ (solid)	4.7	0.20	1.43
3	UO ₂ (caked)	10.9	0.07	0.49
4	UO ₂ (powder)	2.0	0.39	2.75
5	Uranyl nitrate	2.8	0.43	3.04

Method description

The detector (Fig. 5.5) records the radiation transmitted through the filter and the collimator. The detector-visible surface area is determined with the aid of a collimator. The filter absorbs radiation in the region of the energies below 185.7 keV, which enables the measuring path to be unloaded and the share of 185.7-keV signals in the total flow of signals via the path to be increased. The filters are made of average-weight materials (Cd, Ni and others).

The pulse count rate in the photopeak $n_p = S_{ph}/t$, where S_{ph} is the count of pulses in the photopeak and t is the measurement time, is determined by the following expression:

$$n_p = (\Omega_d / 4\pi) \varepsilon \lambda_{235} (N_A / A_U) \rho_U E I \theta \exp(-\mu_f \rho_f d_f) \times \exp(-\mu_c \rho_c d_c) \int_0^D \exp(-\mu_t x) dx, \quad (5.7)$$

where Ω_d is the solid angle limited by the collimator aperture; ε is the efficiency of the detector at $E\gamma=185.7$ keV; N_A is the Avogadro number; A_U is the atomic mass of uranium in the sample; ρ_U is the density of the uranium in the sample; E is the enrichment; I is the quantum yield (branching ratio) for the irradiation of 185.7 keV; θ is the collimator aperture area; μ_f , ρ_f , d_f are the filter mass attenuation factor, density and

thickness; μ_c , ρ_c , d_c are the container mass attenuation factor, density and thickness; μ_ℓ is the attenuation factor for the gamma radiation in the uranium sample; and λ_{235} is the ^{235}U decay constant.

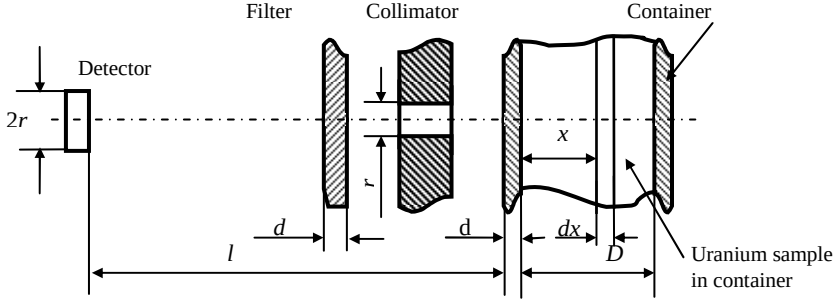


Fig. 5.5. Schematic geometry of uranium enrichment for the sample gamma radiation

Following the calculation of the integral and transformations (and a more detailed representation of the sample composition), the formula (5.7) is reduced to the following form:

$$n_p = K \cdot \frac{E \cdot T_c \cdot T_f \cdot (1 - T_{\text{sam}})}{[1 + (\mu_M / \mu_U) \cdot (\rho_M / \rho_U)]}, \quad (5.8)$$

where $K = [(\Omega_d / 4\pi) \cdot \varepsilon \cdot \lambda_{235} \cdot I \cdot A_U \cdot T_f]$; T_{sam} is the transmission factor for the examined sample; T_c is the transmission factor for the container wall; T_f is the filter transmission factor; μ_U , ρ_U is the uranium mass attenuation factor and density; and μ_M , ρ_M is the matrix mass attenuation factor and density.

The term $[1 + (\mu_M / \mu_U) \cdot (\rho_M / \rho_U)]$ accounts for the uranium dilution in the sample by other materials (oxygen, fluorine, plutonium, etc.). It depends on the composition of the measured material.

K is found with the aid a physical standard and the value thereof turns into the calibration factor. Therefore, the enrichment value sought for is obtained from the formula:

$$E = \frac{n_p \cdot [1 + (\mu_M / \mu_U) \cdot (\rho_M / \rho_U)]}{K \cdot T_C \cdot T_f \cdot (1 - T_{\text{sam}})} \quad (5.9)$$

Now we shall compare the measurements with NaI- and Ge-spectrometers. The portion of the spectrum obtained on a NaI-spectrometer in the region of the ^{235}U peak of 185.7 keV is shown in Fig. 5.6.

The count of pulses in the photopeak $S_{\text{ph}} = p - f \cdot b$ where p is the total count of pulses in the preset range of energies $E_1 - E_2$ that includes the photopeak of 185.7 keV; b is the total count of background pulses in the range above the peak (see Fig. 5.6); and f is the factor of scaling between the measured background in the peak region. The background is estimated via extrapolation by the numbers of counts in the channels above the peak.

In analyses of infinitely thick samples $E = n_p / K = A \cdot p + B \cdot b$, where A and B ($B = -f \cdot A$) are calibration factors found by measurements with a standard.

There is no problem with the background subtraction during measurements on semiconductor Ge-detectors. The peaks are approximately 20 times as narrow as during measurements based on NaI-detectors, so the peak/background relation is accordingly higher.

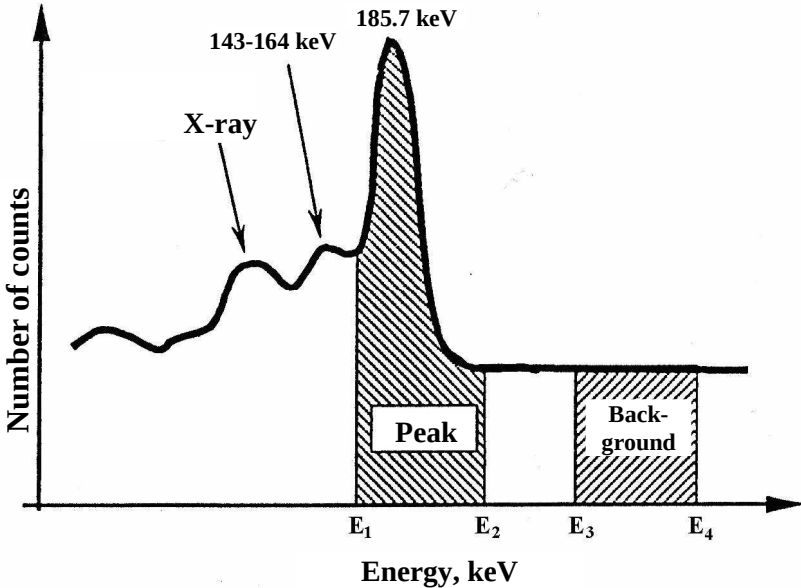


Fig. 5.6. Gamma radiation spectrum measured by NaI-detector

Measurement of the ^{235}U and ^{238}U gamma radiation relative intensity

The major drawback of the uranium enrichment measurement method based on recording of 185.7keV radiation is the requirement to have the measuring system calibrated for each new container with the uranium sample. No such drawback is present in measurements of enrichment from the relative intensity of ^{235}U and ^{238}U gamma radiations.

The gamma radiation spectrum has three energy ranges that can be used for such measurements: 53–68 keV, 84–130 keV and 185–1001 keV.

The region of 84–130 keV includes a series of γ and XK-lines of uranium isotopes. Radiations of ^{235}U and ^{238}U in this region are very close by energy and so are detected with nearly the same efficiency.

The relation between the concentrations of isotopes in the sample is obtained from the formula:

$$N_i/N_k = n_p^i/n_p^k \cdot T_{1/2}^i/T_{1/2}^k \cdot I_\gamma^k/I_\gamma^i \cdot \varepsilon_\gamma^k/\varepsilon_\gamma^i, \quad (5.10)$$

where N_i, N_k are the numbers of the atoms of respectively the i -th and k -th isotopes in the sample; $T_{1/2}^i, T_{1/2}^k$ are the half-lives of respectively the i -th and k -th isotopes; $\varepsilon_\gamma^i, \varepsilon_\gamma^k$ are the efficiencies of radiation detection in the analyzed peaks of respectively the i -th and k -th isotopes, which include, in the given case, the detector efficiency, the geometry of the measurements, self-absorption of radiations in the sample and attenuation of same in the material between the sample and the detector; and I_γ^i, I_γ^k are the quantum yields of the radiations as detected in the analyzed peaks of respectively the i -th and k -th isotopes.

The count rate n_p^i and the concentration of the i -th isotope relate as follows:

$$\frac{n_p^i}{I_\gamma^i} = \left(\frac{N^i \cdot \ln 2}{T_{1/2}^i} \right) \cdot \varepsilon_\gamma^i. \quad (5.11)$$

The term in brackets has the same value for all gamma radiations emitted by one isotope. So the relation (n_p^i/I_γ^i) is proportional to the efficiency ε_γ^i . The relative efficiency measurement procedure includes:

- determination of the count rates n_p^i in a series of peaks that belong to one isotope and calculation of the values n_p^i / I_γ^i that characterize the efficiency ε_γ^i . The quantities I_γ^i are known for each group of quanta forming these peaks S_i ;
- the obtained values ε_γ^i for a series of peaks are used to plot the dependence of ε_γ on E_γ .

The biggest difficulty involved in handling the range of 84–130 keV, that is similarity of the radiations measured by energies, is coped with by using high-resolution Ge-detectors and a special spectrum decomposition program called MGAU (Fig. 5.7).

To determine the relative content of ^{235}U , X-ray peaks of 89.95 keV (Th $\text{XK}_{\alpha 2}$) and 93.35 keV (Th $\text{XK}_{\alpha 1}$) are used. For ^{238}U , a doublet of overlapped gamma peaks of 92.37 keV and 92.79 keV (^{234}Th) is used.

The content of ^{234}U is found from the gamma-ray line of 121 keV. The enrichment determination error makes not more than several percent for uranium samples in a range from depleted to highly enriched uranium (from 0.3% to 93% of ^{235}U).

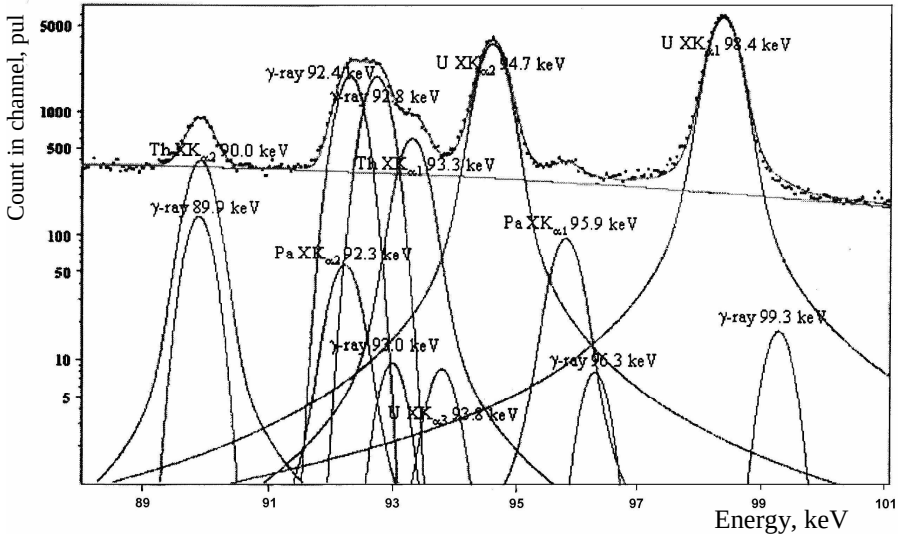


Fig. 5.7. Uranium radiation spectrum in the energy range 88–100 keV and the outcome of its mathematical decomposition into separate components

Constraints: the gamma doublet of 92.37 keV and 92.79 keV used to determine the relative content of ^{238}U belongs to ^{234}Th , which is the product of the α -decay of ^{238}U . Therefore, the daughter ^{234}Th in the sample should be in equilibrium with the parent ^{238}U , which occurs only in approximately 5 months after the chemical isolation of uranium. The container wall thickness influences the accuracy of analysis: a 16-mm wall of a steel container with UF_6 attenuates the radiation of 90–100 keV by a factor of approximately 250.

Nondestructive gamma ray spectrometry measurements of plutonium isotopic composition

Most of the Pu samples contain ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{242}Pu . Besides, these always include ^{241}Am and ^{237}U , which are the products of ^{241}Pu decay. Data on the decays of the above isotopes are presented in Table 5.5.

Table 5.5

Decay data of selected isotopes

Isotope	$T_{1/2}$, years	Activity, decay/s·g
^{238}Pu	87.74 ± 0.04	$6.33\cdot10^{11}$
^{239}Pu	24119 ± 26	$2.2942\cdot10^9$
^{240}Pu	6564 ± 11	$8.3971\cdot10^9$
^{241}Pu	4.348 ± 0.022	$3.8244\cdot10^{12}$
^{242}Pu	376300 ± 900	$1.4522\cdot10^8$
^{241}Am	433.6 ± 1.4	$1.2655\cdot10^{11}$
^{237}U	6.75 days	$9.4080\cdot10^{7*}$

* Given there is equilibrium with ^{241}Pu .

Gamma measurements determine the isotopic relations of f_{238}/f_{239} , f_{240}/f_{239} , f_{241}/f_{239} , f_{242}/f_{239} , with the total of $f_{238}+f_{239}+f_{240}+f_{241}+f_{242}=1$, where f_i is the fraction of the i -th plutonium isotope. Possible compositions of Pu isotopes are presented in Table 5.6.

If to measure the intensities of gamma radiations from the isotopes contained in a sample, self-calibration may help determine the relative efficiencies of the detection thereof. Self-calibration technique is based on using a series of peaks of one isotope contained in the analyzed sample, and on the quantum yield data.

Table 5.6

Possible isotopic compositions of plutonium

Isotope	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Low burnup, %	0.01	94	5.5	0.5	0.03
High burnup, %	2	57	25	11	5

The sample mass may vary from 100 mg* to the limits imposed by nuclear safety and security considerations. The matrix can be any (solid, liquid, powder, heterogeneous). There are no geometry restrictions. The age from the time of the Pu chemical isolation can be also any. Both planar and coaxial Ge-detectors can be used for measurements.

There are different ranges of gamma-ray energies that contain radiations of plutonium isotopes. Within all ranges, helpful data can be found in the peaks of various isotopes which are close by energy. Measurements in high-energy regions enable the Pu contained inside thick-wall containers to be measured without having the sample taken out. This results in a higher safety of the operator and makes it possible to inspect sealed containers used for long-term NM storage.

To measure samples of a large mass, one can use radiations with the energies 642.5 keV for ^{240}Pu , 646.0 keV for ^{239}Pu and 766.4 keV for ^{238}Pu , which are highly penetrable and enter the detector from across the sample thickness.

Measurements of samples in thin-wall containers are done in low-energy regions with the aid of planar Ge-detectors. Coaxial detectors are used both for thin-wall and thick-wall containers.

Planar detectors with an area of 200–500 mm² and a thickness of 10–13 mm are often used. Such dimensions offer a compromise, which is helpful in getting a good resolution and an acceptable efficiency.

Use of planar detectors is confined to the region of ≤ 400 keV. Measurements in higher-energy regions need a coaxial detector with a

* Minimum reported quantity.

resolution of ≤ 1.7 keV for the peak of the ^{60}Co calibration source of the energy 1332 keV.

Test measurements of plutonium samples are conducted based on MGA and FRAM codes.

MGA (multi-group analysis) is a code to determine the isotopic composition of Pu from results of gamma ray spectrometry measurements in the energy range of 99–104 keV. All intensive gamma peaks and X-ray peaks in this region are used. No entry of data (coming from the analog-to-digital converter or ADC) or efficiency calibration is required.

The code has the following drawbacks:

- there is a problem of identifying ^{242}Pu that cannot be measured directly due to a very low intensity of its gamma radiation. A complete analysis of plutonium composition requires either a destructive analysis (mass spectrometry) or estimation of the ^{242}Pu content by isotopic correlation method;
- it is not applicable where there is a strong background of fission fragments and to measurements of samples in thick-wall containers.

Using FRAM code requires the sample gamma radiation spectrum measured on equipment with a high energy resolution and a set of parameters to be used for the analysis. The parameters control the search for peaks and specify the analysis scope and the isotopes to be determined.

FRAM code features:

- ease of adaptation to various measurement conditions with no need for reprogramming;
- a user capability to edit the analysis parameters;
- a capability of analyzing all kinds of samples having the following contents (2–38% of ^{240}Pu , 0.01–50% of ^{241}Am) and samples in thick-wall containers.

Table 5.7 gives data on accuracies in nondestructive measurements of plutonium isotopic compositions.

Table 5.7

Accuracy of nondestructive measurements for plutonium isotopic compositions, %

$E\gamma$ range, keV	T_{meas}	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu
40–60	10–300 min	0.3–5.0	0.05–0.5	0.2–1.0	0.2–1.0
90–105	30–60 min	0.3–5.0	0.05–0.5	0.2–1.0	0.2–0.8
>120	1–4 h	1–10	0.1–0.5	1–5	0.3–0.8

FRAM can be also used to examine uranium samples, specifically to test enrichments of uranium articles inside a container. The thing is that commonly used MGAU-based analyses rely on soft radiation measurements and are not suitable for testing shielded samples. Using FRAM enables use of harder radiations for analyses by measuring the spectrum thereof with the aid of a coaxial HPGe-detector. Fig. 5.8 presents the radiation spectra for differently enriched uranium samples obtained with the aid of a coaxial HPGe-detector.

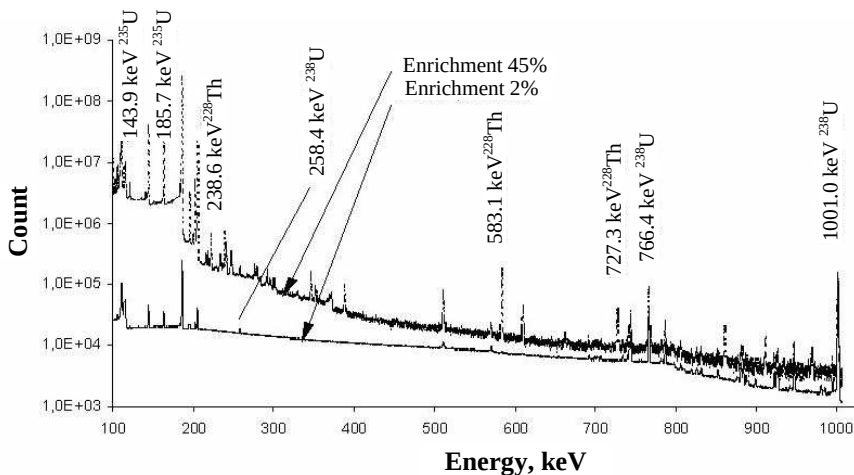


Fig. 5.8. Spectra of uranium sample radiation

Standards have quite different roles in gamma ray spectrometry measurements of Pu (and U) isotopic compositions as compared to other nondestructive test techniques. The values sought for in gamma ray spectrometry are obtained using certain physical constants and self-calibration results. Standards are used just to control measurement results.

Analyses of NM solutions. Densitometry

K-edge or L-edge densitometry (KED or LED) is based on measuring the transmission of a highly collimated photon or gamma-quanta beam from an external source through an NM solution sample. The technique is practically insensitive to the radiation emitted by the sample itself (for example, high content of fission products in the solution is allowable). The

collimator confines observation to only a small sample portion. For this reason, the sample should be strictly homogeneous throughout the thickness. K-edge or L-edge densitometer is the instrument for nondestructive assays of NM concentrations in solutions (Fig. 5.9).

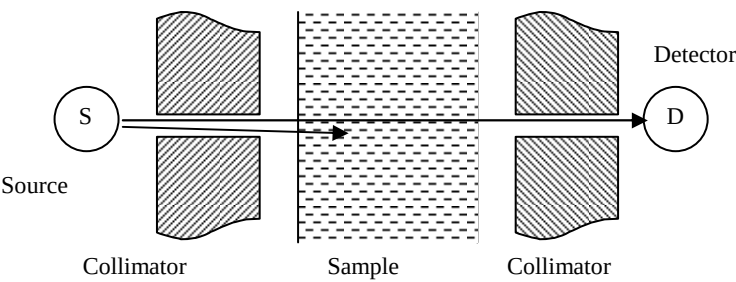


Fig. 5.9. Diagram of densitometry measurements

The absorption factor for each element is measured in steps with the energies being equal to the energies of the electron coupling on the K- and L-shells of atoms (Table 5.8).

Measuring the transmission of one-energy radiation through a sample may give information on the content of one material or one component of a mixture. Using a radiation of two different energies makes it possible to control the composition of a two-component mixture.

Table 5.8

Energy of electron coupling on K- and L-shells in various NM, keV

Element	Th	U	Np	Pu	Am
K-edge	109.56	115.61	118.68	121.82	125.03
L-edge	16.3	17.2	17.6	18.0	18.5

A measurement of epy transmission with two energies E_1 and E_2 yields a system of equations for two unknown concentrations:

$$\left. \begin{aligned} (-\ln T_1) / x &= M_1 = \mu_1^1 \cdot \rho_1 + \mu_2^1 \cdot \rho_2 \\ (-\ln T_2) / x &= M_2 = \mu_1^2 \cdot \rho_1 + \mu_2^2 \cdot \rho_2 \end{aligned} \right\} \quad (5.12)$$

The solution to the equations looks as follows:

$$\left. \begin{aligned} \rho_1 &= (M_1 \cdot \mu_2^2 - M_2 \cdot \mu_1^2) / D \\ \rho_2 &= (M_2 \cdot \mu_1^1 - M_1 \cdot \mu_1^2) / D \end{aligned} \right\}, \quad (5.13)$$

where $D = \mu_1^1 \cdot \mu_2^2 - \mu_2^1 \cdot \mu_1^2$.

The more accurate is the solution, the more nonzero is the quantity D . This condition is fulfilled if two radiations near and on both sides of the heavy mixture component absorption K -edge (or L -edge) are used. With even the absorption factors of a light components differing slightly at these energies, the difference of D will be rather great.

We shall consider in detail the changes of $\mu(E)$ near the K -electron absorption edge (Fig. 5.10).

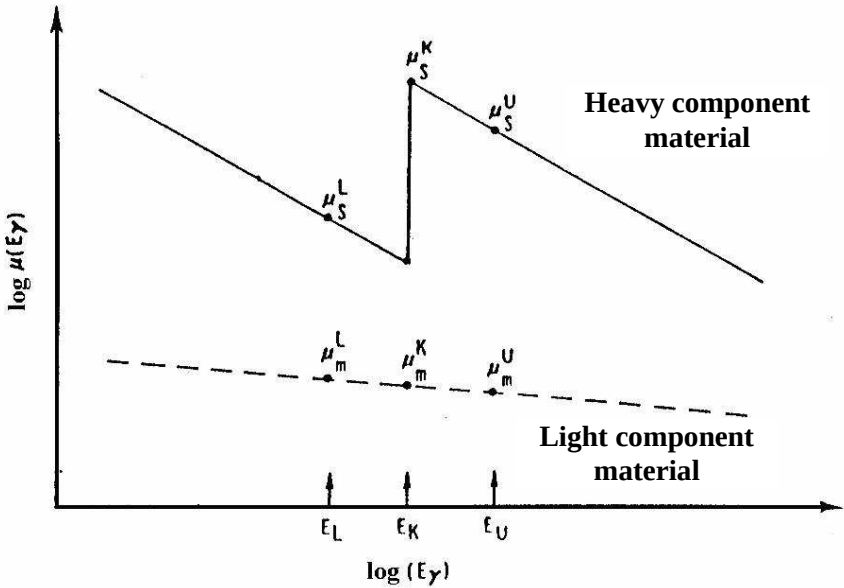


Fig. 5.10. Changes in the absorption factors of a heavy and a light NM component near the K -edge

By measuring the transmission of γ -radiations with the energies of E_L and E_U , we find the concentration of NM in the solution ρ_s sought for:

$$\rho_s = \frac{1}{\Delta\mu_s \cdot x} \ln\left(\frac{T_L}{T_U}\right) + \rho_m \left(\frac{\Delta\mu_m}{\Delta\mu_s}\right), \quad (5.14)$$

where $\Delta\mu_s = \mu_s^U - \mu_s^L > 0$, $\Delta\mu_m = \mu_m^U - \mu_m^L < 0$.

If E_L and E_U are very close to E_K , then $\Delta\mu_m$ is tending towards zero, and the measurement result is insensitive to the absorption in the matrix.

Extra measurements (calibrations) are done with reference solutions placed in standard containers.

If NM concentrations are small (dozens of g/l), L-edge densitometry is used; where higher NM concentrations are involved (hundreds of g/l), K-edge densitometry is employed.

Two types of radiation sources are used: the first one is X-ray generators that produce photons with a continuous broad spectrum. These are used both in K-edge and L-edge measurements. Examples of spectra are given in Fig. 5.11. The relation of the sample spectrum to the comparison spectrum gives the transmission.

The second type of employed sources is represented by radioactive γ -sources of monoenergy radiations. For example, plutonium solutions ($E_K=121.82$ keV) are measured using two sources: ^{75}Se ($T_{1/2}=120$ days, $E_\gamma=121.1$ keV) and ^{57}Co ($T_{1/2}=270$ days, $E_\gamma=122$ keV). The result of the absorption in a light-weight matrix during measurements with these sources is influenced negligibly, still different decay rates thereof should be taken into account.

Measurements of uranium solutions ($E_K = 115.61$ keV) use the ytterbium-196 (^{169}Yb) γ -source with a half-life of $T_{1/2} = 32$ days. In this case, no allowance for decay is required to be made because one source emits both quanta groups. However, a major difference in the energies thereof ($E_L = 109.8$ keV, $E_U = 130.5$ keV) causes a great sensitivity to the absorption in the matrix (high $\Delta\mu_m$).

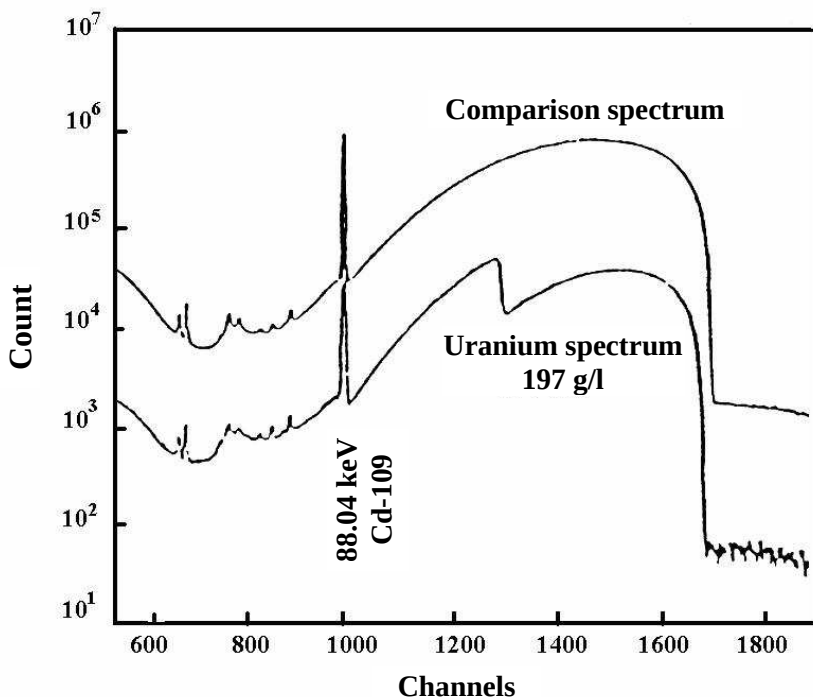


Fig. 5.11. Spectrum of solutions obtained with the aid of an X-ray generator: the upper curve is the comparison spectrum measured by a K-edge densitometry detector in an NM-free solution (3-mol solution of HNO_3); the lower curve is the spectrum of an uranium solution sample with a concentration of 197 g/l; the ^{109}Cd source is used to correct the counting losses caused by dead-time

L-edge analyses are used for samples of a smaller thickness, this being dictated by a smaller penetrating power of the radiations measured. L-edge densitometry (LED) is normally used to control solutions with smaller concentrations of NM, and K-edge densitometry (KED) is used for higher concentrations (Table 5.9). With lower NM concentrations in solutions, an X-ray fluorescence analysis is used.

Table 5.9

Representative NM concentrations in solutions for densitometry analyses

Representative concentrations, g/l	Uranium	Plutonium
ρ_s (KED)	270	294
ρ_s (LED)	18	19

Analyses of NM solutions. X-ray fluorescence analysis (XFA)

All atoms have ordered systems of electron shells that are characterized by particular values of binding energy. Where a vacancy emerges on an electron shell, it is filled with another electron passing from a higher shell (Fig. 5.12). The difference of potential energies is liberated as an X-ray quantum with the energy equal to the difference of binding energies on the lower and the upper shells. The characteristic radiation spectra are fairly simple, this making it easier to analyze these.

To release the electron from the shell, one needs to give it the energy in excess of E_{binding} . To do this, outer excitation sources are used.

The probability of exciting an X-ray source of a K (or L) series depends on the difference between the excitation source quanta energy E_0 and the K-(or L)-shell electron binding energy E_{binding} . The excitation probability reaches the maximum when the gamma-quantum energy exceeds the electron binding energy just slightly.

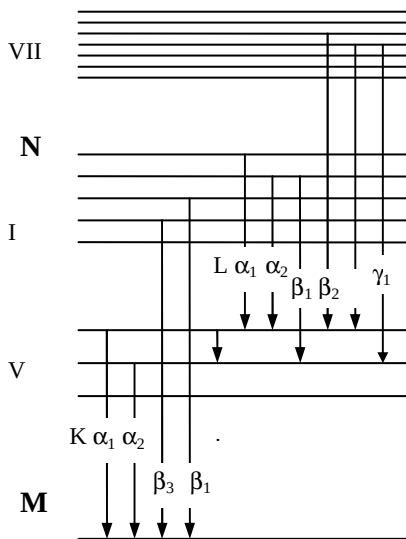


Fig. 5.12. Diagram of the electron transitions in an atom

Radioactive sources or X-ray tubes are used to excite characteristic radiation. The advantages of radioactive sources are a simple design and stability of the exciting radiation energy. The exciting radiation spectrum

should be as simple as possible. In the event of a complex spectrum, there are “inactive” high-energy lines that create the background in the region of measured X-rays or even interfere with these.

Table 5.10 gives the values of the Pu and U X-ray energy and yields.

Table 5.10

Values of the Pu and U transition energies and X-ray yields

Line	Transition	Uranium, %	Plutonium, %
K _{α1}	K-L ₃	98.44 (100)	103.76 (100)
K _{α2}	K-L ₂	94.66 (61.9)	99.55 (62.5)
K _{β1}	K-M ₃	111.31 (22.0)	117.26 (22.2)
K _{β3}	K-M ₂	110.43(11.6)	116.27 (11.7)
L _{α1}	L ₃ -M ₅	13.62 (100)	14.28 (100)
L _{α2}	L ₃ -M ₄	13.44 (10)	14.08 (10)
L _{β2}	L ₃ -N ₅	16.43 (20)	17.26 (20)
L _{β1}	L ₂ -M ₄	17.22 (50)	18.29 (50)

To observe representative peaks, one needs to choose the proper measurement geometry. Observations may be hampered by the background created by the quanta resulting from the source’s Compton radiation scattering.

The i -th element X-ray quanta detection rate $n_{\Phi i}$ relates to the content of this element N_i in the sample and the quantum yield of its radiation I_i^X through the following:

$$n_{\Phi i} = N_i \cdot I_i^X \cdot W_i^X \cdot \epsilon_i^X , \quad (5.15)$$

where W_i^X is the X-ray excitation function which is the product of the photoeffect cross-section $\sigma_F^i(E)$ and the source quanta flux onto the sample $\Phi_\gamma(E)$; and ϵ_i^X is the efficiency of X-ray detection:

$$W_i^X = \int_{E_i}^{\infty} \sigma_F^i(E) \cdot \Phi_\gamma(E) \cdot dE = (Z_i)^5 \cdot \int_{E_i}^{\infty} [\Phi_\gamma(E)/(E - E_i)^3] \cdot dE , \quad (5.16)$$

where E_i is the threshold energy of photoeffect on the respective electron shell (K or L) of the i -th element, and Z_i is the atomic number of the i -th element.

Obviously, excitation function depends strongly on the Z element and the more, the closer is the energy of the excitation source to the photoeffect threshold energy (the electron binding energy on the shell).

Radioactive gamma sources have small dimensions. They are also simple to handle and fit for many XFAs. The major deficiency involved in these is disintegration thereof over time and the requirement to have them periodically replaced. There is also a transportation problem. As the power of such sources is over 1 mCi, handling them requires shielding of both personnel and the detector. An XFA facility layout is shown schematically in Fig. 5.13.

As with passive gamma measurements, the XFA data accuracy may be limited by the absorption inside the sample. This effect is to be taken into account both for the characteristic radiation measured and for the exciting radiation of the external source. The absorption in large-size and solid samples is so great that XFA is not appropriate for analyzing such samples. So it is used to control liquid homogeneous samples.

The source radiation absorption is more intensive as the radiation energy exceeds the absorption threshold for the NM analyzed. Attenuation depends also on the material and the thickness of the container walls. An XFA to study L-radiation requires using plastic rather than metallic containers.

The XFA measuring system is calibrated using a set of reference solutions with different NM concentrations in containers, these being of the same type as used for the solutions under examination.

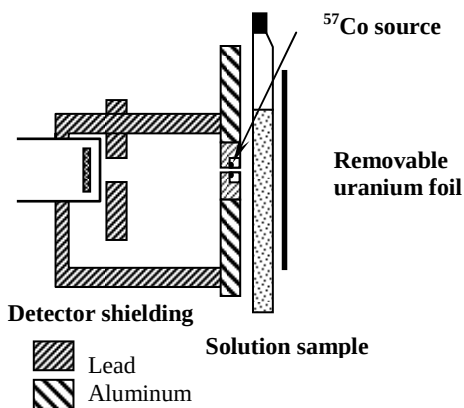


Fig. 5.13. Schematic of an XFA facility

X-ray generator has more power than radioactive sources. It generates 10^{12} photons/s and more. The major complications involved in using generators are the requirement to keep high stability of the parameters thereof and relatively large dimensions that make it difficult to move them.

X-ray fluorescence measurements help determine the relation of NM concentrations in a solution. Fig. 5.14 gives the spectrum of a solution with a content of uranium and plutonium.

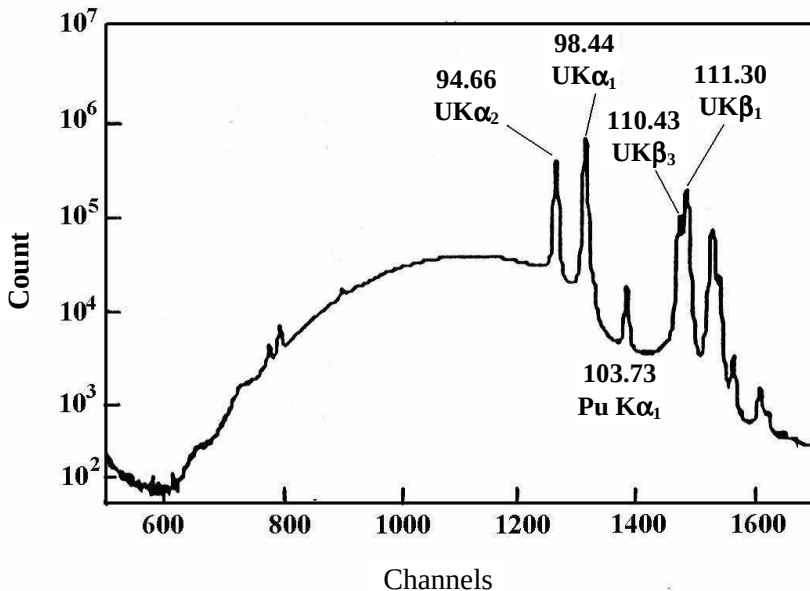


Fig. 5.14. Fluorescence spectra of uranium and plutonium solutions

The U/Pu weight relation can be found from the areas of the $XK_{\alpha 1}$ peak for uranium (S_U) and the $XK_{\alpha 1}$ peak for plutonium (S_{Pu}):

$$U / Pu = \frac{A_U}{A_{Pu}} \cdot \frac{S_U}{S_{Pu}} \cdot \frac{\varepsilon_{Pu}}{\varepsilon_U} \cdot \frac{1}{R_U / R_{Pu}}, \quad (5.17)$$

where A_U and A_{Pu} are the atomic masses of uranium and plutonium, $(\varepsilon_{Pu}/\varepsilon_U)$ is the relative efficiency of uranium and plutonium detection; and (R_U/R_{Pu}) is the factor allowing for the difference in the probabilities of uranium and plutonium radiations being excited using the given source.

Neutron measurements of NM

There are three processes causing neutron irradiation of NM samples:

- spontaneous NM fission;
- induced NM fission;
- (α, n) – a reaction induced by NM α -radiation.

Neutrons are highly penetrating particles. They go out from all over the sample and pass easily through the walls of the container with the sample.

Spontaneous fission is most likely for isotopes with an even mass number (^{238}Pu , ^{240}Pu , ^{242}Pu and others). The relative probability of ^{240}Pu fission with emission of a different number of neutrons is shown in Fig. 5.15. The average number of neutron/fission is about 2. Altogether, there are 473 spontaneous fissions per second occurring in 1 g of ^{240}Pu .

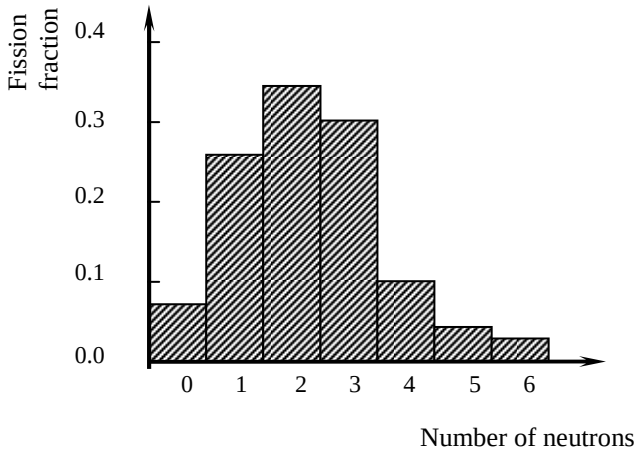


Fig. 5.15. Relative probability of fissions with emission of different neutron numbers

The number of neutrons generated by one fission is called multiplicity. In total, 1 g of ^{240}Pu has 473 spontaneous fissions per second taking place therein.

The technique based on detection of spontaneously emitted neutrons is called passive.

Handling of passive neutron measurement results often includes the notion of “effective” ^{240}Pu which is believed to account for all neutron radiation of a plutonium sample:

$$^{240}\text{Pu}_{\text{eff}} = 2.52 \cdot f_{238} + f_{240} + 1.68 \cdot f_{242}, \quad (5.18)$$

where f_i is the fraction of the i -th plutonium isotope in the sample.

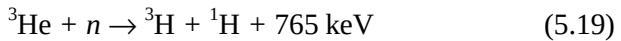
Induced fission is most likely for fissile isotopes (^{235}U , ^{239}Pu , ^{241}Pu). Induced fission generates 0–8 neutrons per fission. In the event of ^{239}Pu , the average number of these is about 3. The neutron measurement method using an external source is called active.

More neutrons may be generated in spontaneous or induced fission as the result of the multiplication thereof in the sample. The (α, n) -reaction is an extra source of neutrons that hampers neutron measurements of NM. Radioactive decays of uranium and plutonium isotopes are commonly accompanied by emission of α -particles. The energies of the emitted α -particles are from 4 to 6 MeV. A major source of α -particles is also ^{241}Am .

Alfa-particles emitted by uranium and plutonium react with 11 elements with a small atomic number Z , including oxygen, fluorine, carbon and aluminum.

One neutron is generated as the result of the (α, n) -reaction. Cases of single $((\alpha, n)$ -reactions) and multiple (spontaneous and induced fission) neutron generations may be divided by detecting time coincidences of neutrons.

Helium counters are commonly employed to detect neutron in NM test measurements. The reaction taking place in such counters is the (n, p) -reaction:



The $^3\text{He}(n, p)$ reaction cross-section for thermal neutrons reaches 5330 barns and varies in a broad energy range (10^{-2} to 10^5 eV) according to the law $1/\sqrt{E}$.

For higher efficiency of fast neutron counting, the counter has a moderator made around it. The ^3He -counter is normally placed in a 10-cm thick polyethylene block.

^3He -counters are fit for neutron measurements in strong γ -fields. They are highly reliable, stable and durable.

Active analyses for the contents of fissile isotopes (^{235}U , ^{239}Pu , ^{241}Pu) in samples require a source of neutrons with the energy below the fission thresholds of even-even isotopes (^{238}U , ^{240}Pu). Such neutrons are emitted by $^{241}\text{AmLi}$ -sources. Fig. 5.16 shows the neutron spectrum of a $^{241}\text{AmLi}$ -source. The power of $^{241}\text{AmLi}$ -sources used for nondestructive assays is 10^4 – 10^5 n/s.

Real cases generally give an excessive number of the sample-emitted background neutrons from (α, n) -reactions, this making it impossible to find the NM content by counting single neutrons. Active analyses have the same intensive background created by neutrons from the (α, n) -reactions inside the source.

As noted, one can separate the neutrons generated by the fission of isotopes in the NM sample from the neutrons of (α, n) -reactions by detection of time-coinciding pulses.

If the number of neutrons emitted in a fission equals n , the probability of detecting k neutrons is given by the equation:

$$P(n, k) = \frac{n!}{(n - k)!k!} \cdot \varepsilon^k \cdot (1 - \varepsilon)^{n-k} . \quad (5.20)$$

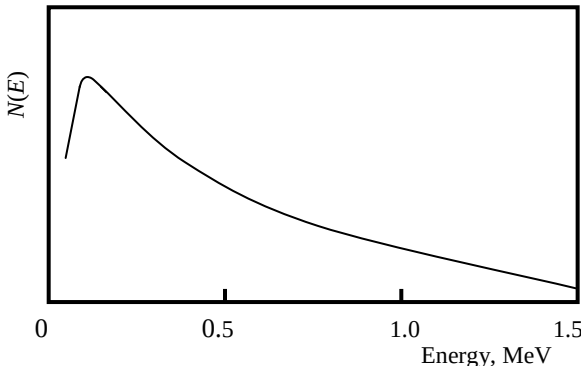


Fig. 5.16. Neutron spectrum for a $^{241}\text{AmLi}$ -source

If two neutrons have been emitted, the probability $P(2,0)$ of no neutrons to be detected is equal to 0.64; the probability $P(2,1)$ of detecting one neutron is 0.32; and the probability $P(2,2)$ of having two neutrons detected

is 0.04. Therefore, the probability of detecting an actual coincidence of two neutrons from one fission is relatively small. A great deal of coincidences observed in a sequence of pulses will be random and caused by coincidences between the neutrons of (α, n) -reactions, the neutrons of (α, n) -reactions and fission neutrons or neutrons from different fissions.

To identify and determine the number of real and random coincidences, Rossi-alpha distribution is used. This distribution is obtained when the timer is started at the instant the pulse arrives. The timer counts the time and each subsequent pulse is memorized in the cell that matches its arrival time. When the preset time of counts is over, the timer stops and is switched on again as the new pulse launches the counting. Fig. 5.17 presents a Rossi-alpha distribution. The probability of the coincidence count after the fission event is decreased exponentially over time. Where neutrons of (α, n) -reactions or background neutrons coincide, the probability of such random coincidences in any time interval is the same.

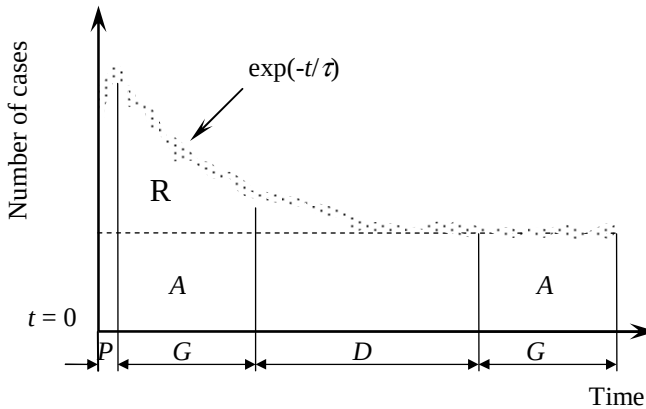


Fig. 5.17. Rossi-alpha distribution represents the number of neutron detection cases as the function of the time that has elapsed after the first fission neutron was detected

The number of true double coincidences is found by the formula:

$$R = \frac{[(R + A)_{\text{count}} - A_{\text{count}}] \cdot \exp(G \cdot T)}{\exp(-P / \tau) \cdot [1 - \exp(-G / \tau)] \cdot [1 - \exp(-(D + G) / \tau)]}, \quad (5.21)$$

where R is the number of true coincidences; A is the number of random coincidences; P is the time of the pulse count delay, G is the coincidence count time; D is the long delay; τ is the time of the neutron life in the detector, and $D \gg \tau$, T is the total neutron count rate.

A neutron coincidence counting circuit is shown in Fig. 5.18.

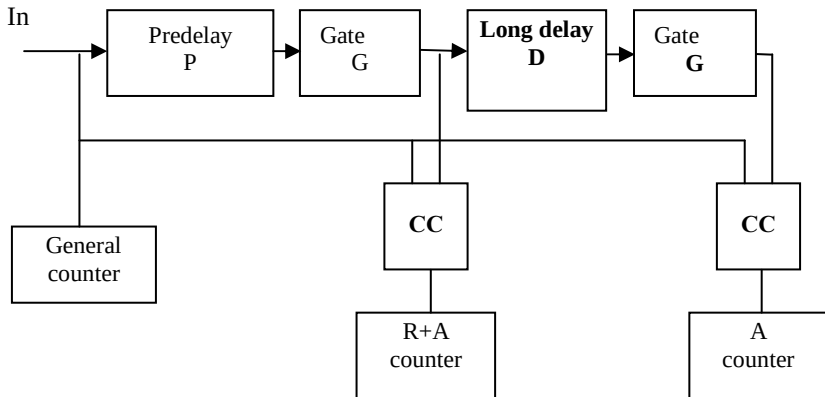


Fig. 5.18. Separation of fission neutron coincidences

Practical uses of such circuits are confined to count rates of below 20–30 kHz as large corrections are required to take into account dead time of electronics. Further evolutions of measuring technology were based on using a shift register.

A shift register comprises a set of timer-controlled triggers. The sequence of pulses coming in for the time G is memorized. Each subsequent pulse opens its own gate so there is no need to wait for one gate to close to have another gate opened. It makes it possible to operate count rates of hundreds of kHz and more. Coincidences start to be detected not straight away but just in a short interval after the pulse P arrives (preliminary delay). During this time (3–6 μ s), the coincidence source rate is distorted due to overlapping pulses and the electronics dead time. Following the preliminary delay, the shift register opens the $R+A$ gate, the width of which is normally 32–64 μ s. True and random coincidences are detected during this time. Then, after the long delay D , the gate A opens. As the quantity D is normally equal to 1000 μ s, which exceeds considerably the neutron lifetime in the detector (30–100 μ s), the scaler A detects only random coincidences.

A simplified shift register circuit is given in Fig. 5.19.

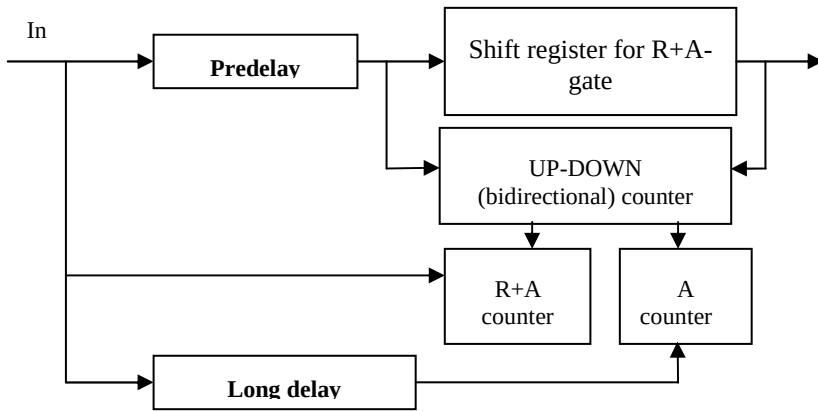


Fig. 5.19. A shift register circuit

Measurements using the above shift register can produce only two quantities: random and true double coincidences. Some contaminated or heterogeneous samples require one more quantity, triple coincidence (triplet) count rate, to be measured.

Measurements of single neutrons, doublets and triples may help determine the quantity of the ^{240}Pu effective mass, the neutron multiplication factor in the sample and the yields of (α, n) -neutrons without the need to calibrate the measuring system.

Instrumentation for NM neutron measurements

There is a variety of measuring systems for a range of applications fit to analyze different types of samples, including containers with PuO_2 powder, pellets and rods filled with mixed uranium-plutonium fuel, metal slugs, intact fuel assemblies, and drums with scrap and waste. Unlike chemical analyses where the sample is adapted to the instrument, nondestructive assays have equipment adapted to the sample.

Neutron analysis is used to control highly dense NM with results thereof having the potential of depending greatly on the matrix material.

Coincidence count results are used to determine the NM quantity in samples in passive and active neutron measurements.

Passive neutron methods are employed extensively to test plutonium samples which emit their own neutrons as the result of spontaneous fission and during (α , n)-reactions (Table 5.11) in different forms: in fuel slugs, rods, powders, granules, scrap, waste and $\text{PuO}_2 + \text{UO}_2$ mixtures. To interpret such measurement results, one needs to know the plutonium isotopic composition (spontaneous fission occurs largely in even isotopes such as Pu: ^{238}Pu , ^{240}Pu and ^{242}Pu).

Active neutron methods serve to control uranium samples for the content of ^{235}U as the uranium isotope spontaneous fission rates are low. Use of an AmLi-source in the sample causes induced fission with the number of fissions found by counting neutron coincidences. High penetrating power of neutrons enables determination of the total ^{235}U content in the entire volume.

Table 5.11

Yield of NM-emitted neutrons

Isotope	Spontaneous fission period, years	Yield of spontaneous fission neutrons, n/s·g	α -decay period, years	Yield of α -particles, α /s·g	α, n yield in oxide, n/s·g
^{238}U	$8.2 \cdot 10^{15}$	$1.36 \cdot 10^{-2}$	$4.47 \cdot 10^9$	$1.2 \cdot 10^4$	$8.3 \cdot 10^{-5}$
^{238}Pu	$4.77 \cdot 10^{10}$	$2.59 \cdot 10^3$	87.74	$6.33 \cdot 10^{11}$	$1.34 \cdot 10^4$
^{239}Pu	$5.48 \cdot 10^{15}$	$2.18 \cdot 10^{-2}$	$2.41 \cdot 10^4$	$2.3 \cdot 10^9$	$3.81 \cdot 10^1$
^{240}Pu	$1.16 \cdot 10^{11}$	$1.02 \cdot 10^3$	$6.56 \cdot 10^3$	$8.4 \cdot 10^9$	$1.41 \cdot 10^2$
^{242}Pu	$6.84 \cdot 10^{10}$	$1.72 \cdot 10^3$	$3.76 \cdot 10^5$	$1.4 \cdot 10^8$	2.0

Passive coincidence count is based largely on the following principles:

- the NM sample is placed in a cavity surrounded by neutron counters;
- coincidences of pulses generated by spontaneous-fission neutrons are detected;
- the coincidence count rate is directly proportional to the mass of the fissile material:

$$R = {}^{240}\text{Pu}_{\text{eff}} (473 \text{ fis/s} \cdot g) \varepsilon^2 \exp(-P/\tau) \times \\ \times [1 - \exp(-G/\tau)] \sum_{\nu} P(\nu) \frac{\nu(\nu-1)}{2}, \quad (5.22)$$

where P is the pulse count predelay time, G is the coincidence count time; τ is the neutron lifetime in the detector, ε is the neutron detection efficiency, ν is the number of neutron emitted by fission, and $P(\nu)$ is the probability of ν neutrons to be emitted by fission.

A schematic of a passive neutron coincidence counter for measurements of small-size samples is shown in Fig. 5.20.

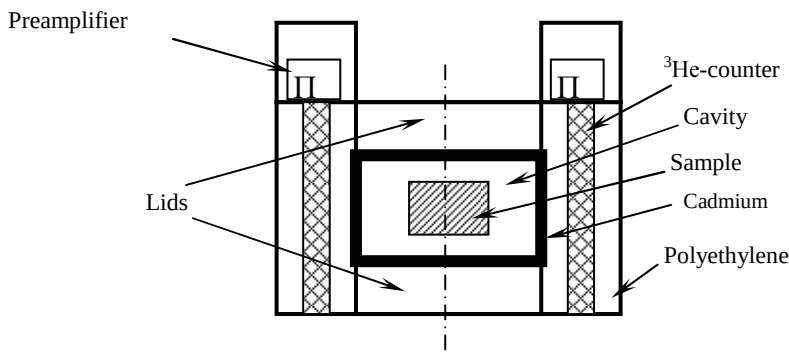


Fig. 5.20. Schematic of a passive neutron coincidence counter for measurements of small-size samples

The neutrons emitted by the sample are slowed down in the polyethylene and detected by ${}^3\text{He}$ -counters. The cavity for the samples is cadmium-shielded against slow neutrons, coming back from the polyethylene, to reduce the sample self-screening.

The counter operates in two modes: for thermal and fast neutrons. For fast neutron count, the sample cavity walls are coated with cadmium. Measurements in the fast-neutron mode fit better large-mass samples and thermal-neutron measurements are fit for small-mass samples. Thermal-neutron measurements entail a smaller statistical error of small-size sample control. For large-size samples, a great cross-section value leads to the inner space being screened and the result distorted.

The counter is calibrated to interpret the analysis results. Calibration curves for the fast- and thermal-neutron modes differ greatly. The calibration curve for the fast-neutron mode comprises two different segments: a segment with the influence of self-screening present (samples of the mass up to 500 g of ^{235}U), and a further segment with multiplication where the ^{235}U mass is rather large to compensate for the self-screening effect thanks to auxiliary fissions. Calibrating the interval of 150–900 g of ^{235}U requires more than one standard. Each material type needs a special curve (Fig. 5.21).

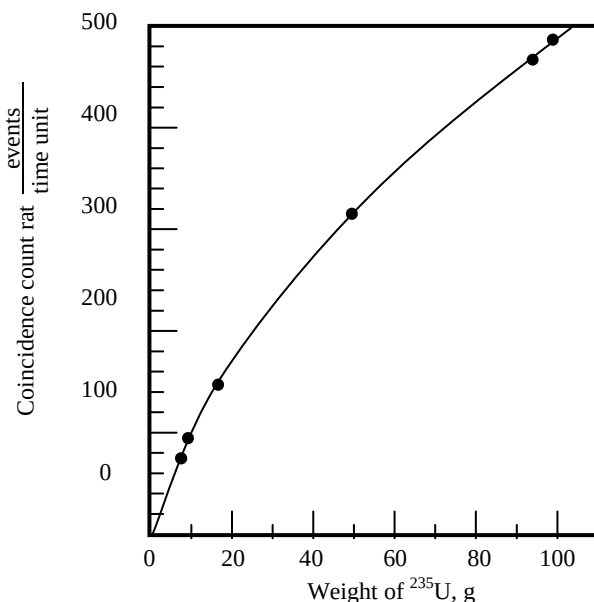


Fig. 5.21. Coincidence count rate depending on the ^{235}U mass for low-enriched U_3O_8 samples in the thermal neutron detection mode

Table 5.12 gives characteristics of an active well coincidence counter (AWCC).

There is a great variety of instruments based on neutron coincidence count, still all of them have standard electronic components.

Both neutron and gamma ray measurements involve a problem of measuring lengthy NM samples. Passive measurements of lengthy samples require ensuring similar probability conditions for detection of neutrons

emitted by all sample surface elements, while active measurements additionally require the same irradiation of all these elements by source neutrons. So every effort is made in designing neutron measuring systems to ensure a uniform sensitivity and a uniform field of external source neutrons in the cavity for the samples.

Table 5.12

Data of active well coincidence counter (AWCC)

Characteristics	Thermal mode	Fast mode
Mass of measured samples	up to 100 g of ²³⁵ U	100–20000 g of ²³⁵ U
Coincidence count rate for low-enriched U ₃ O ₈ sample	11 count/(s·g of ²³⁵ U)	0.18 count/(s·g of ²³⁵ U)
Absolute measurement error for large-size samples for 1000 s	0.3 g ²³⁵ U	18 g ²³⁵ U

Calorimetry

Calorimetry is a passive nondestructive technique of NM (plutonium and tritium) control based on accurate temperature measurements. Generally, this is a more accurate technique, still it requires good temperature stability and control thereof, and is less fast and handy as compared to other NM nondestructive measurement methods.

Calorimeter is an instrument to measure the heat quantity emitted by an object.

Calorimetry offers an advantage that measurement results do not depend on the sample geometry, the matrix material or the NM distribution inside the sample. No standards identical to samples are required for calibrations. Calorimetric analyses have the accuracy comparable to that of chemical analyses*.

Method description

All energy of α -decays transforms into heat. Each α -decay is accompanied by the energy yield of $Q = \left(M_{^{240}\text{Pu}} - M_{^{236}\text{Pu}} - M_{\alpha}\right)c^2 =$

* Measurements of homogeneous burnt-up Pu samples give the accuracy of 0.1% as in chemical analyses and weighing. Measurements of waste containing Pu of a uniform isotopic composition gives a 1% accuracy.

5.25578 MeV. β -decay of ^{241}Pu yields $Q_\beta = 20.81$ keV, and β -decay yields ^3H $Q_\beta = 18.59$ keV.

Radioactive decays of ^{240}Pu liberate $P = \lambda \cdot N \cdot Q$ of power, where N is the number of ^{240}Pu atoms, and λ is the ^{240}Pu decay constant. α -decay of ^{240}Pu liberates 0.00707 ± 0.00002 W/g of power. The total power generated by all plutonium isotopes is $P_{\text{eff}}(\text{W/g}) = \sum f_i P_i$, where f_i is the mass fraction of a single isotope.

Table 5.13 gives an example of the contribution made by some isotopes to P_{eff} . P_{eff} increases with the Pu burn-up increase. Burn-up fraction is characterized by the content of ^{240}Pu .

Table 5.13

Contribution of selected isotopes to P_{eff} for one of the samples

Isotope	Content, mass fraction	Contribution to heat generation, %
^{238}Pu	0.0006	11.0
^{239}Pu	0.8567	53.3
^{240}Pu	0.1211	27.7
^{241}Pu	0.0194	2.1
^{242}Pu	0.0022	0.0
^{241}Am	0.0016	5.9

By measuring the heat generated by a plutonium sample and knowing its isotopic composition, one can find the content of Pu.

The sample-generated heat is recorded by a heat sensor out of a sensitive wire laid in circles around the sample cavity. A double calorimetric bridge with two identical thermostats is shown in Fig. 5.22.

Measurements are done using a potentiometer or a digital voltmeter incorporated in an electric circuit called Wheatstone bridge (Fig. 5.23). The measured voltage is proportional to the difference between the temperature in the sample space and the temperature of the comparison probe, the latter being in an air or water “bath” with a constant temperature (maintained within ± 0.001 °C).

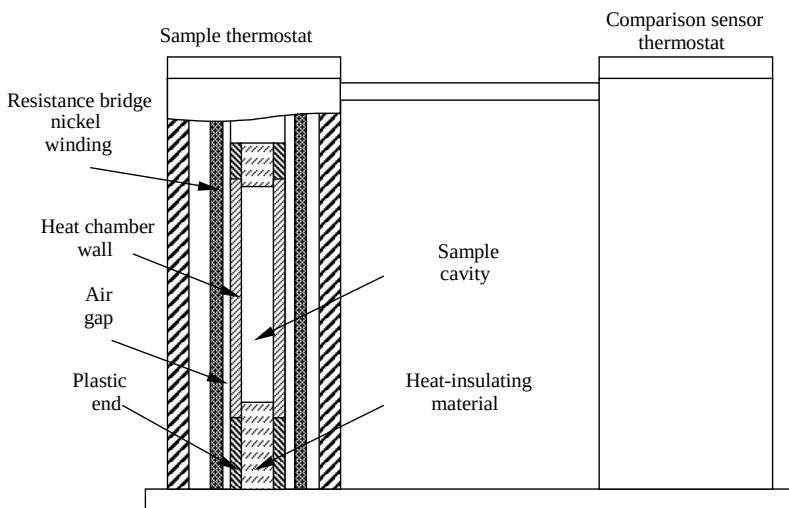


Fig. 5.22. Schematic of a double calorimetric bridge with two identical thermostats

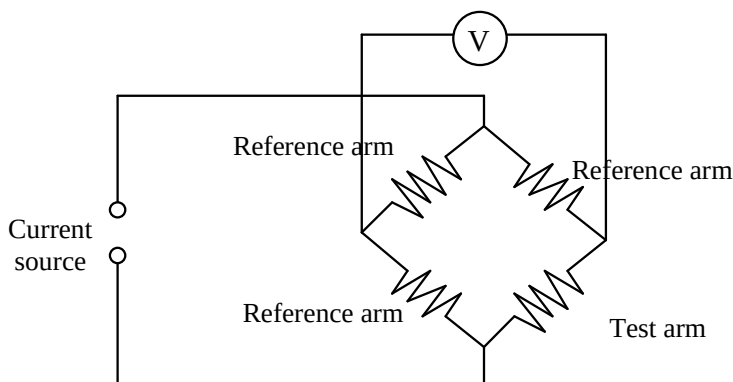


Fig. 5.23. Wheatstone bridge for heat flux measurements

If the temperature in both thermostats is identical, that is there is no sample, the Wheatstone bridge is balanced. When the sample is placed in the thermostat, the temperature changes and the bridge turns unbalanced.

The voltmeter indication is taken some time after the sample is placed in the thermostat. The time needed to have equilibrium reached depends on the sample dimensions and amounts to hours (Fig. 5.24). Preheating of the

thermostat chamber for the sample helps reach the equilibrium in several times as fast.

To determine the power generated by the sample in the thermostat from the measured potential difference, a sensitivity diagram is normally used.

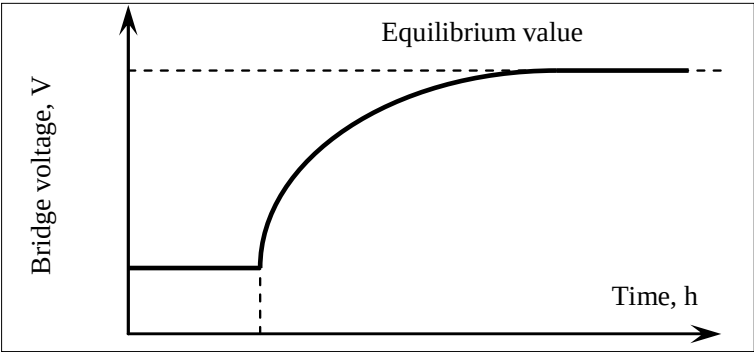


Fig. 5.24. Time-dependent voltmeter indications

To this end, a curve for the thermostat sensitivity to the sample-generated power is plotted. Fig. 5.25 shows a calorimeter sensitivity diagram option.

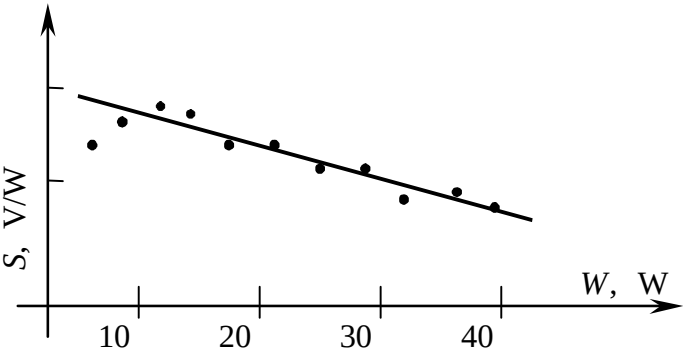


Fig. 5.25. Calorimeter sensitivity diagram

For calibration, the calorimeter is switched on and the potential difference at the bridge ends (BP_0) is measured without a sample or any other heat source. Then a plutonium standard is placed in the sample

chamber, the equilibrium value for the potential difference BP_s is measured and the calorimeter sensitivity is calculated by the formula:

$$S = (BP_s - BP_0)/W_s, \quad (5.23)$$

where W_s is the standard-emitted power (not known).

Normally, the quantity S depends slightly on the heat source power. For example, a 1.6% sensitivity decrease was recorded in measurements of samples with the power of 0.1 to 10 W.

As the diagram in Fig. 5.25 shows, sensitivity in the given case is not constant and depends on the sample-generated power.

By and large, the best of the calorimetric analyses have the following errors: power measurement error $<0.1\%$, effective specific energy release determination error $<0.2\%$.

Typical calorimeter parameters: diameter – 120 mm, height – 275 mm, range – 0–6 W.

Referenced standards or electrical standards (probes) are used to calibrate calorimeters:

1) heat generation standards – ^{238}Pu samples. These feature:

- small dimensions (enable determination of errors depending on the heat distribution over the chamber);
- qualification accuracy – 0.02%;
- decay may be accurately taken into account;

2) electrical heat generation standards. These feature:

- absence of radioactive radiation;
- no need for decay to be taken into account;
- electronics may not depend on the calorimetric system;
- electronics requires calibration.

The following is taken into account in calorimeter design.

- Sample size (specifies the sample chamber size). A close sample-calorimeter contact makes it possible to minimize the analysis time. The chamber diameter in existing calorimeters varies from 1 to 30 cm.
- Sample heat power. High-power samples need low-sensitivity calorimeters with a low heat resistance, and small-power samples require high-sensitivity and highly heat-resistant calorimeters.
- Graduation techniques. The calorimeter design depends on what heat source is used for graduation (a radioisotope or an electrical one).
- Capacity. Selection of the calorimeter type depends on the analysis time required.

- Accuracy. When the calorimeter type and its operating mode are selected, the analysis accuracy is planned given the time to be spent and other conditions.
- Application environment. Selection of the calorimeter design depends on the environment and the available workroom area to install it.

5.3. Destructive analyses

Normally, a destructive analysis (DA) includes sample taking, sample chemical treatment and measurement stages. Test material may be a single item or a bulk material. Destructive analysis normally offers a higher accuracy of results than nondestructive measurements. However, DA takes more time to perform and is more costly than nondestructive tests.

Destructive analyses are used to:

- check nondestructive measurement data;
- perform critical test measurements;
- qualify standards.

Sample taking

Destructive analyses have a small portion of controlled material examined and require a representative sample to be taken for analysis. The sample composition should be strictly representative of the average material composition with the sample mass (volume) accurately determined.

If the sample is soluble, it needs to be, generally, dissolved. Sometimes, uranium or plutonium requires separation from interfering elements.

Sample should be taken given a potential heterogeneity of NM, which can be of three types:

- heterogeneity of material within the container;
- differences among containers;
- differences among groups of containers.

Some dispersed and powdered materials, such as ash and roasted scrap, are hard to mix. A number of factors exist that require homogenization of dry powders and dispersed compositions. These are, for example:

- variations of the composition depending on the particle size and density;
- differences in the particle forms;
- cohesion and conglomeration of particles.

Nuclear industry often deals with insufficiently homogeneous materials, this limiting sample taking capabilities by ladling material to compare from each container batch. Random sampling is so employed, which requires more samples in each case to account for potential differences.

The sample taking method and equipment are chosen given the identity of controlled material, the requirements to the accuracy of results, the material accessibility for sampling and safety of sample taking operations.

Within the nuclear fuel cycle, sample taking and treatment methods differ between sites. There are two categories of sampling-related errors. One should differentiate sample taking error from analytical error:

$$\sigma_s = (\sigma_t^2 - \sigma_a^2)^{1/2}, \quad (5.24)$$

where σ_s is the random sampling error; σ_t is the total random deviation of the results for all analyses of all samples; and σ_a is the random deviation estimated from replicated analyses of each sample.

No replicated analyses with each sample are however performed at some enterprises and no random sampling error is differentiated from the random analytical error. In this case, the sample taking error may be estimated from the spread of the standard analysis results, which is approximately equal to the random analytical error:

$$\sigma_s = (\sigma_1^2 - \sigma_{st}^2)^{1/2}, \quad (5.25)$$

where σ_s is the estimated random sampling error; σ_1 is the random spread based on single analyses of all samples; and σ_{st} is the random spread based on replicated analyses of the standard.

Interpreting the obtained results leads to two conclusions: the solutions in enrichment and conversion processes are fairly homogeneous so representative samples thereof can be obtained through comparatively simple sample taking operations. NM scrap and waste are heterogeneous so large sample taking errors should be expected. This requires prior homogenization with a random sample taking technique to be employed to get a representative result.

Dissolution of NM samples

One should always try to make so that the inspected material is fully dissolved. Even minor amounts of deposit may cause major losses of the target element. Pure uranium preparations are fairly simple to dissolve.

In the event of plutonium and compounds thereof (thorium as well) there is a potential problem of extremely chemically stable dioxide being formed and disintegrated, having, above other things, an extremely high melting temperature.

Mixed uranium and plutonium dioxides are highly resistant to chemical effects, still they have higher dissolution rates than pure plutonium preparations.

NM extraction from solutions

Uranium can be fairly selectively separated from a solution by extraction thereof into an organic solution other than mixable with the original aqueous solution.

Extraction is an auxiliary analytical chemistry purification process used specifically to identify uranium. Though some elements, including plutonium and thorium, are also extractable, selecting proper conditions for separation helps avoid obstacles caused by these elements at subsequent identification stages. So, by changing the plutonium oxidation level, one can make plutonium extraction quite easily controllable.

The so-called purex-process is the most common spent nuclear fuel treatment technology. This is an extraction process using tributylphosphate ($(\text{H-C}_4\text{H}_9\text{O})_3\text{PO}$ (TBP) solutions in saturated hydrocarbons (hydrogenated kerosene).

Uranium purification of fission products (FP) after three cycles has a factor of around 10^7 , and uranium purification of plutonium has a factor of $3 \cdot 10^5$.

Ion-exchange separation

Ion-exchange separation is used for selective extraction of the analyzed element from a multi-component mixture. In fact, the whole of the uranium ion-exchange extraction and separation process is run, to the highest extent possible, with plutonium solutions in a hexavalent form. In aqueous solutions, uranium, plutonium and a great deal of other elements may occur as components of cationic and/or anionic complexes.

Ion-exchange properties are inherent in insoluble substances composed of acidic (cationite) or principal groups (anionite) that are firmly bound thereto. One example of cationite is Dowex-50 (Russian analog, KU-2), a styrenedivinylbenzoic polymer with grafted-SO₃H groups. An example of highly basic anionite is Dowex-1 (Russian analog, AV-17), a styrenedivinylbenzoic polymer with grafted charged-CH₂N⁺(CH₃)₃ groups.

Uranium ions can be absorbed by way of cationic exchange from relatively dissolved sulfuric-acid solutions (<0.5 n). This also involves removal of unabsorbed impurities. Most of the uranium separation and purification processes are however based on desorption by flushing the column with a reagent solution that forms an anionic complex with uranium. Uranium sorption (VI) from a solution based on a cationite out of acidic solutions is intensified in the following series of acids: H₃PO₄<H₂SO₄<HCl<HNO₃<HClO₄. Analytical procedures normally use cationites to remove phosphate-type anions, arsenats and whatever else hindering analyses.

Use of anionites helps sorb uranium's anion complexes with such anions as nitrate, chloride, fluoride, acetate, sulfate or carbonate.

Gravimetry

Gravimetry is the oldest and a highly accurate analytical chemistry technique. Essentially, gravimetric analysis consists in measuring (weighing) the mass of the analyzed substance. This method has a weighed portion of material, being roasted in the air, converted into black-and-green U₃O₈ with the resultant pure product subsequently weighed. The measured weight of U₃O₈ is adjustable given the presence of nonvolatile impurities identified otherwise, say, spectrometrically.

U₃O₈ is used as a weight form, e.g. as a stable compound with a constant uranium-oxygen relation. To arrive at an accurate result, one needs to control stoichiometry of the sample following the roasting (constancy of uranium-oxygen relation). This depends on initial chemical composition, surface/volume relation in the analyzed sample, temperature and combustion time. It has been found that obtaining homogeneous U₃O₈ from the whole of the sample requires slow combustion in a controlled environment.

The uranium concentration in the analyzed sample is calculated from the formula:

$$U_A = \frac{W \cdot (F - C) \cdot G}{S}, \quad (5.26)$$

where U_A is the uranium concentration in the sample, g(U)/g(sample); W is the roasted oxide weight (uranium oxide and impurity weight), g; F is the nonstoichiometry factor (the relation of stoichiometric uranium oxide that contains impurity oxides to nonstoichiometric impurity-containing uranium oxide obtained by roasting), g/g; C is the quantity of impurity oxides, in grams, as contained in a gram of the roasted oxide, g/g; G is the gravimetric (stoichiometric) factor (U/U_3O_8) subject to adjustment given the uranium isotopic composition, g(U)/g(U_3O_8); and S is the charge of the sample taken for the analysis, g.

Gravimetry is employed also to analyze plutonium samples, more rarely though than for uranium. The weight form in the event of plutonium is PuO_2 . For a high accuracy attainable by gravimetry, one needs to know precisely and take into account the content of oxygen and impurities in the sample.

Titration by Davis-Grey method for quantitative analysis of uranium content

Redox potentiometry is a titration method in which a titrating solution of the known concentration is added from a burette to a certain amount of the inspected solution the concentration of which is not known. Titration involves emf measurements with the titration curve $E=f(V_T)$, where V_T is the titrant volume, plotted. The measuring system is made of two electrodes plunged into the analyzed solution and an emf recorder (Fig. 5.26). One of the electrodes in the circuit, the so-called comparison electrode, has a constant potential value, and the potential of the other, the indicator electrode, varies in the titration process, with an abrupt jump taking place at the equivalence point.

For a potentiometric curve, the added titrating solution volume V_T is plotted on the abscissa axis and the emf value is plotted on the ordinate axis. To determine accurately the equivalence point, the differential titration curve $\frac{\Delta E}{\Delta V_T} = f(V_T)$ is plotted. Equivalence point is the instant during a titration process when the number of gram-equivalents of the titrating substance is equal to the number of gram-equivalents of the titrated component.

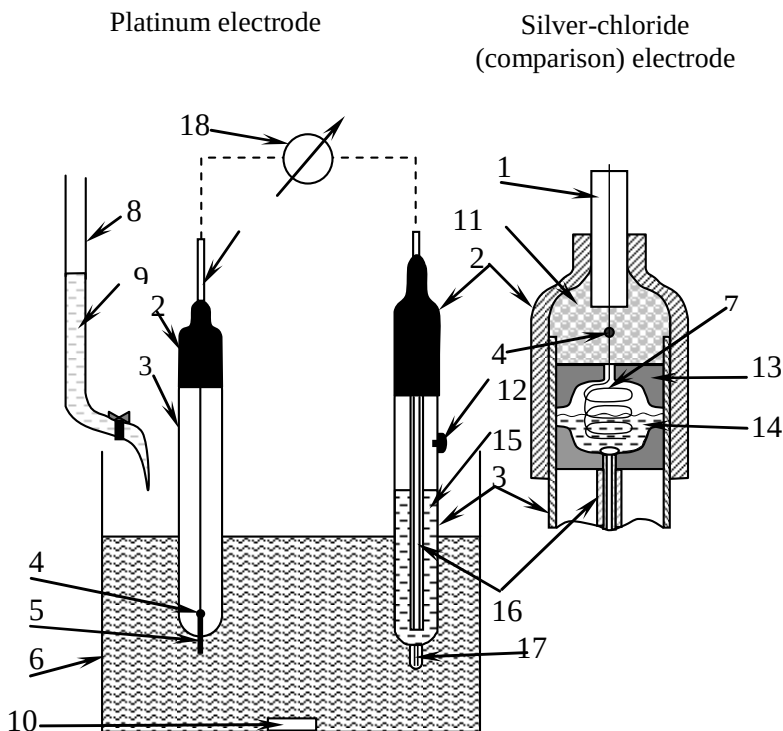


Fig. 5.26. Electrode system for potentiometry

1 – connecting wire; 2 – plastic cap; 3 – glass housing; 4 – solder; 5 – platinum; 6 – beaker with analyzed solution (pH_x); 7 – AgCl-coated silver wire; 8 – burette; 9 – Cr(VI); 10 – magnetic stir bar; 11 – hermetic; 12 – hole with a rubber plug; 13 – rubber gaskets; 14 – KCl and AgCl mixture; 15 – saturated KCl solution; 16 – tube with asbestos; 17 – asbestos thread; 18 – pH meter (millivoltmeter)

Here is the list of analysis steps and applicable chemical reactions involved in the potentiometric variant of Davis-Grey method.

1. Sample taking.
2. Sample dissolution.
3. Pretreatment (purification, etc.).
4. Conversion of hexavalent uranium to a tetravalent condition. It is required to have all uranium turned tetravalent to be titrated.

At the equivalence point, all of the uranium in the solution turns hexavalent with its quantity characterized by the volume of the oxidizer used:

$$U = \frac{(NV + 6W/M \cdot A/100) \cdot [\text{atomic weight of uranium}/2]}{\text{sample weight, g}}, \tag{5.27}$$

where U is the uranium concentration in the analyzed sample; N is the normality* of the titrant (potassium bichromate); V is the volume of the titrant used (in liters); W is the weight of the added solid potassium bichromate (in high-accuracy measurements or when a large quantity of U(IV) is titrated); A is the purity of potassium bichromate shown in the certificate (in %/100); and M is the molecular weight of potassium bichromate (294.19 g/mol).

Davis-Grey method (NBS) is applicable to analyses of different uranium solutions: nitro-, sulfate- and perchlorate. The solutions to be analyzed are obtained by dissolving samples of uranium oxide, uranium metal, salts and alloys, as well as nuclear fuel fragments in aluminum, steel or zirconium cladding.

The accuracy data of titrimetric analysis by Davis-Grey method is given in Table 5.14.

Table 5.14

Errors in data of uranium content measurements by Davis-Grey method

No.	Material	Accidental error, %	Systematic error, %
1	Uranium metal	0.06	0.018
2	Metal particles – TRIGA reactor fuel	0.06	0.017
3	UAl alloy	0.074	0.018
4	UO ₂ powder	0.11	0.035
5	Uranium solutions	0.10	0.060

* Normality is the number of gram-equivalents of the dissolved material in 1 liter of a solution. For example, 2N-solution of N₂SO₄, each liter whereof contains 98 g of acid.

Mass spectrometry

The mechanical charged particle trajectories in magnetic fields depend on the masses and velocities thereof. The equation that describes ion movements has the following form:

$$m \frac{d\vec{v}}{dt} = q_e \vec{E} + q_e [\vec{v} \cdot \vec{B}], \quad (5.28)$$

where m is the ion mass, q_e is the electric charge, $\vec{v}$ is the ion velocity, $\vec{E}$ is the electric field intensity, and $\vec{B}$ is the magnetic field induction vector.

If to direct a beam of identically charged monoenergy ions into a transverse magnetic field, the trajectories thereof will be circular orbits with the radius proportional to the ion masses. So ions with a different mass have different trajectories, this making it possible to separate and identify them.

Not all ion sources generate strictly monoenergy ions. In a static magnetic field, ions are separated both by mass and energy, which makes it more difficult to analyze them. By choosing the appropriate combination of an electric and a magnetic field (including variable ones), one may compensate ion separation by energy. So acting instruments are called double-focusing spectrometers.

A mass spectrometer consists of an ion source (this generates and accelerates ions, as well as forms the ion beam or packets), a mass analyzer (separates ions by masses) and a detection system. The measurement gives an ion distribution by masses (mass spectrum).

The intensity of the mass spectrum lines relates to the content of individual components in the analyzed sample:

$$H_i = k_i \cdot P_{i0}, \quad (5.29)$$

where H_i is the peak height (or area) in the mass spectrum, P_{i0} is the weight or relative quantity of the i -th component in the sample, and k_i is the proportionality factor.

The quantity k_i depends on whether a portion of the analyzed sample component has got into the detector and has been detected. The factor k_i is the instrument sensitivity characteristic and has its own value for each atom type. k_i is required to be invariable throughout the measurement. For

quantitative measurements, the instrument is calibrated to determine the quantity k_i .

Evaporation is used to produce ions out of atoms of a solid volatile substance. For a heatproof substance, spark discharge, laser irradiation or ion (electron) bombardment is used.

The quantity of material in the sample is limited since:

- normally, the experimental facility is served manually so its radioactive contamination should not exceed personnel safety standards;
- the result of the experiment may be distorted due to the substances that have got into the sample, including those left from earlier analyses.

Less material in the sample gives less contamination of the instrument, this making it possible to keep it highly sensitive*.

A thin source has the sample atoms therein transformed into ions, these being directed to the analyzer via the electric field. Strip heat-emission sources are used extensively to analyze samples of heavy elements. In such a source, the substance to be analyzed is applied to the evaporator strip and ionization takes place near the ionizer strip.

Box-type sources are in common use nowadays. These have several samples placed therein to be analyzed in a series, thus saving time spent otherwise for sample replacement and evacuation.

The initial analysis phase when the sample is heated has the element composition in the vapor differing from that in the sample thanks to the predominant evaporation of light isotopes (the so-called discrimination by mass with a stronger effect for small-size samples). It is only after a while that true isotopic ratios are attained in the vapor. Due to the sample burning, the ion current decreases over time. These factors may bring systematic errors in the analysis data.

To control the discrimination by mass, the analyzed material has an indicator added thereto, the latter containing two isotopes that differ in mass and are absent in the sample: $^{233}\text{U} + ^{236}\text{U}$ to analyze a uranium sample $^{242}\text{Pu} + ^{244}\text{Pu}$ to analyze a plutonium sample. By measuring the mass spectrum of the mixture, one may estimate the discrimination effect and correct the analysis result from the relative intensity of the lines of said isotopes.

Ions from the source get into the analyzer where the mass spectrum can be scanned by magnetic field. Depending on the field variations, ions have

* Isotopic sensitivity is the relation of the background ion current in the mass spectrum interval of $M \pm 1$ to the current of ions with a mass of M .

their mechanical trajectories changed, so that ions of a different mass get into the fixed detector. High-rate scanning, using variations of the electric field that accelerates the ions in the source, may be used instead of low-rate magnetic-field scanning. Electric-field scanning is employed more commonly when the range of the ion mass differences is small, while magnetic-field scanning is used when this is broad.

A variety of detectors and measurement modes are used to detect ions, including current-type ones to analyze large-size samples and pulse-type ones to analyze small-size samples. Often, electronic multipliers (VEU) with a signal amplification factor of $\sim 10^6$ and Faraday cylinders are used for detectors.

Nowadays, multicollector detection systems are in common use. Each detector in these systems is tuned to a particular ion mass and the system measures simultaneously the content of several isotopes (up to 9) in the sample. For example, analyses of Pu give, at a time, the content of isotopes with the masses of 238 to 244. No scanning is involved in analysis. A multicollector system makes measurements several times as fast.

Mass spectrometry analysis of uranium isotopic composition

A pure uranium fraction is applied to the strip. Strips are placed inside the mass spectrometer's ion source with air pumped out of the source. The sample evaporates as the strip is heated while the singly charged ions produced by thermal ionization are accelerated and focused with the aid of electrostatic ion lenses in the mass analyzer. By presetting respective variations of the magnetic field or fields and/or the accelerating potential, the beams of ions of a different mass are sequentially focused onto the detector.

Using automated scanning, one sample insertion lock, a high-rate evacuation system and digital data processing, two operators are capable of analyzing 12 to 16 samples per day, still it is more realistic to have 7 to 9 daily analyzed samples.

Measurement quality control requires at least one analysis of a reference standard with the enrichment close to that of the measured material to be done throughout the series of analyses.

Mass spectrometry is the preferred and broadly employed technique to control uranium isotopic composition. Depending on the instrument sensitivity, an analysis requires 10^{-8} to 10^{-5} g of U.

Surface ionization mass spectrometry is also commonly used for destructive analyses of Pu isotopic composition. A plutonium analysis

requires 10^{-9} to 10^{-6} g of Pu. Random errors of the Pu sample isotopic composition analysis are given in Table 5.15.

Table 5.15

Random errors in a Pu sample isotopic composition analysis by mass spectrometry method

Relative concentration, %	Relative error, %
0.01 ²³⁸ Pu	20
93.8 ²³⁹ Pu	0.10
5.8 ²⁴⁰ Pu	0.26
0.3 ²⁴¹ Pu	0.81
0.03 ²⁴² Pu	7.1

Isotope dilution method

Isotope dilution is a method used to find the quantity m_x of the element Z in a sample of the analyzed material. One must know the isotopic composition of this element (x_i) (measured in advance).

The technique is based on using a hanging indicator of the same element with however an isotopic composition differing from that of the element in the analyzed sample. The sample solution of the analyzed material has a certain amount of the indicator m_0 with the isotopic composition x_i^0 added thereto. After the mixing, a sample is taken. The isotopic composition of the element in the sample taken ($\bar{x}_i$) differs from that in the original sample (x_i) and in the indicator (x_i^0):

$$\sum_i x_i = \sum_i x_i^0 = 1; \tag{5.30}$$

$$\bar{x}_i = \frac{1}{A_i} \cdot [m_x x_i + m_0 x_i^0] \Big/ \sum_i \frac{1}{A_i} \cdot [m_x x_i + m_0 x_i^0], \tag{5.31}$$

where A_i is the atomic weight of the i -th isotope of the element Z.

The relation of the contents of the isotopes i and j in the mixture is equal to:

$$\bar{x}_i / \bar{x}_j = \frac{1}{A_i} \cdot [m_x x_i + m_0 x_i^0] \Big/ \frac{1}{A_j} \cdot [m_x x_j + m_0 x_j^0], \quad (5.32)$$

wherefrom the formula to determine m_x is derived:

$$m_x = m_0 x_i^0 \left(1 - \frac{\bar{x}_i x_j^0 A_i}{\bar{x}_j x_i^0 A_j} \right) \Big/ x_i \left(\frac{\bar{x}_i x_j A_i}{\bar{x}_j x_i A_j} - 1 \right). \quad (5.33)$$

The sample and the indicator are mixed so that U (Pu) from the sample and from the indicator would acquire similar properties and behave in the same way in further transformations. This is done using multiple redox cycles.

Isotope dilution mass spectrometry (IDMS) is a commonly used technique to determine U and Pu (and isotopic composition thereof) in fuel processing.

Resin bead technique

This is a dedicated technique to determine U and Pu in high-level solutions of spent reactor fuel. It is used for cases where the sample is to be moved to a long distance between laboratories. This does not require shielding against sample radiation. The analytical procedure is as shown in Fig. 5.27.

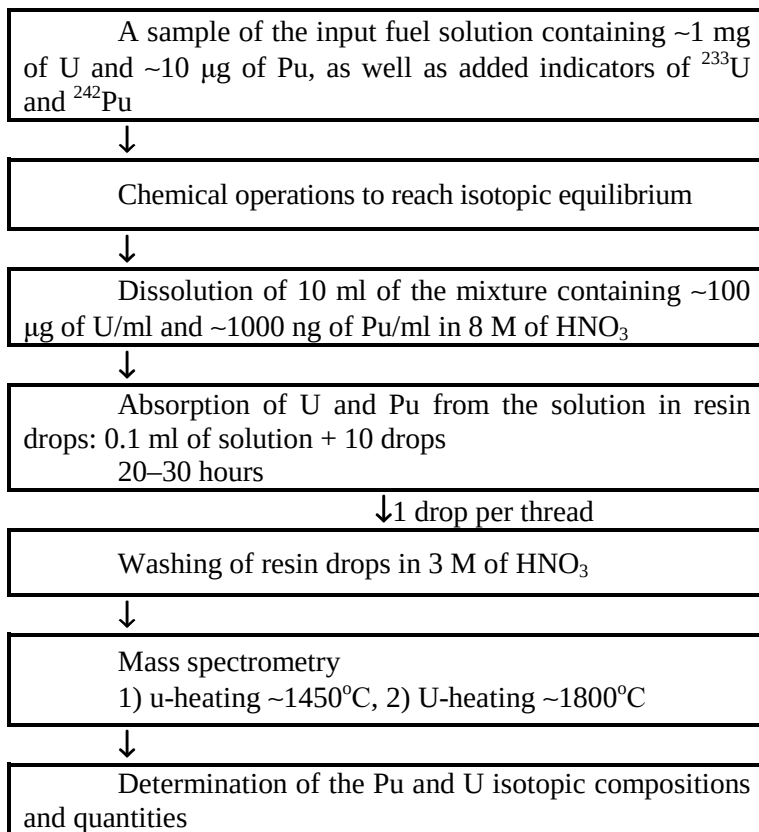


Fig. 5.27. Flowchart of a resin bead analysis. The potential accuracy of results is 0.6% for U and 0.9% for Pu

5.4. Combined use of NM measurement techniques

The most common NM measurement techniques have been discussed. Each technique has a limited application. Each task can be solved by a variety of different techniques.

Conventionally, all techniques can be interchangeable or complementary. So one may use Davis-Grey titration, isotope dilution mass spectrometry, densitometry and XFA to determine uranium content in a sample.

Gamma ray spectrometry and neutron coincidence count are complementary techniques a combination of which enables determination of plutonium content in NM. Another example is when standards are made by titrimetry to calibrate nondestructive measurement systems by densitometry and XFA.

Simultaneous use of more than one technique to measure any NM parameter makes it possible to improve the confidence of the overall result thanks to mutual compensation of potential methodological errors (see Fig. 5.28 for the flowchart of a coupled plutonium analysis at a Sellafield facility).

Simultaneous use of more than one technique leads to the integration of their respective equipment in one facility and the creation of measuring systems in the form of stations.

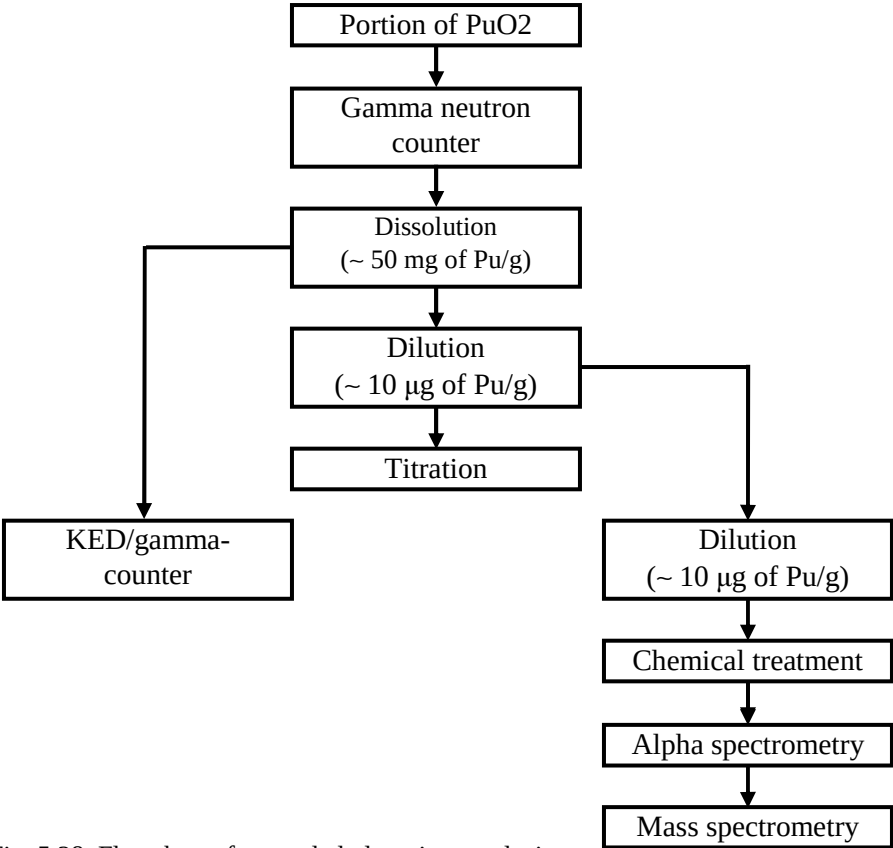


Fig. 5.28. Flowchart of a coupled plutonium analysis

Table 5.16

Basic NM analysis technique used at analytical laboratories

Analysis technique	Analyzed element or isotope	Material type	Error, %	
			random	systematic
Element analysis				
Titration by Davis-Grey method	U	U, U–Pu, U–Th	0.05	0.05
Titration by McDonald-Savage method	Pu	Pu material	0.1	0.1
Coulometry	Pu	Pure Pu material	0.05	0.05
Gravimetry with combustion	U, Pu	U oxides, Pu oxides	0.05	0.05
K-edge densitometry	U, Th, Pu	U, Pu, U–Pu, U–Th	0.2	0.2
XFA	Pu	Pu material	0.2	0.2
XFA with photon wavelength separation	Pu, U	Pure U and Pu oxides, MOX-fuel	0.3	0.3
Isotopic analysis				
Isotope dilution mass spectrometry	U, Pu	Spent fuel solutions, Pu and U–Pu material	0.1	0.1
Thermal ionization mass spectrometry	U and Pu isotopes	All Pu and U material, spent fuel solutions	0.05	0.05
Gamma ray spectrometry with high-resolution detectors (Ge-detectors)	Am, Np, Pu isotopes	Pure U and Pu material	0.5–2.0	0.5–2.0
Gamma ray spectrometry (NaI-detectors)	²³⁵ U	Low-enriched U material	0.2–0.5	0.2–0.5
Alpha spectrometry	²³⁸ Pu	Pu material	0.2	0.3
Laser fluorometry	<u>Np</u>	Pu material	2.0	2.0
Pu spectrophotometry	Pu	Pu, U–Pu	0.2	0.2

CHAPTER 6

MAIN ACCOUNTANCY PROCEDURES

6.1. NM transfer procedures

Shipper/receiver difference

A classic problem exists: let there be a 28-kg bar of butter. It is required to divide this butter into 280 pieces of 100 g each using scales measuring 100-g weights with an accuracy of plus or minus 5 g. The question is: can it be done? That is, can 28 kg of butter be cut into 280 pieces of 100 g each with the aid of such scales.

Many higher schools of commerce in the world use this problem to demonstrate the existing difference in the shipper's and the receiver's data.

Solutions to the problem were searched for experimentally involving both skilled salespersons and beginners. The answer to the question is that, provided both of them use the scales with a division of 5 g, the beginner normally cuts the butter into 274-278 pieces, which is slightly less than it ought to be. Contrary to this, the one with professional skills cuts a bit more than required, that is, from 282 to 286 pieces.

The explanation to this discrepancy is that the people involved are inclined to behave differently when addressing the problem. A skilled salesperson knows that weighing is sure to involve errors, systematic errors included, because measuring equipment tends to have their characteristics changed over time. Scales are prone to aging, rusting (e.g. through oxidation) and so on. Understanding this leads to skilled persons getting 280 pieces of butter exactly by putting into each piece a bit less than 100 g, which is, still, within the acceptable tolerance of 5 g.

A beginner tries to get pieces of exactly one hundred grams each by making them initially a bit heavier because making them weighing less than 100 g is subject to penalty. So this results in the above statistics.

The experiments of the kind serve to confirm that an uncertainty in data (say, a scale division of 5 g), if any, makes the measurement result dependent on secondary factors, including the mentality of the person doing measurements. The mentality of a skilled salesperson is not to sell at a loss.

This problem (with respective experiments) is exactly the one concerned with the concept of the shipper/receiver difference. An accurate shipper normally ships more than an accurate receiver receives. They have different mentality.

In the given context, things stand like this. No bookkeeping system takes account of the existing shipper/receiver difference. Yet, this difference is taken into account by any measured material balance system. The material concerned is not, quite naturally, stolen or has anything done with it en route. This simply shows to what extent our knowledge about what is really going on is uncertain. We should remember that our knowledge is far from being absolute, the difference being a random quantity and depending on how perfect the shipper's and the receiver's measurement systems are. It should be also noted that multiple transfers of large NM quantities may lead to the uncertainty of data on the total material accumulating and reaching significant values.

Tolerable shipper/receiver differences

So what shipper/receiver difference is allowed in Russia?

The shipper/receiver difference in the mass of the nuclear material being transferred is determined as the difference between the values of the masses shown by the shipper (certificate data) and those obtained in verifying measurements.

Let S and R be respectively the shipped and the received NM quantities. S and R are random quantities as measured by the shipper and the receiver and have respective errors of σ_S and σ_R .

For the shipper/receiver difference ($S-R$), the mean-square deviation from its mathematical expectation is

$$\sigma_{S-R} = (\sigma_S^2 + \sigma_R^2)^{1/2},$$

if the measurements of S and R are assumed to be independent.

It should be remembered that the confidence interval is the one that covers the parameter of interest (random quantity) with a given probability. The following confidence intervals are used in accounting for and control of NM:

- 0.95 – insignificant statistical straggling interval;
- 0.99 – permissible statistical straggling interval.

If $S-R$ is a normally distributed random quantity and $M(S-R)$ is its mathematical expectation, then the interval $M(S-R) \pm 2.58 \cdot \sigma_{S-R}$ makes a 99% confidence interval.

The General Rules specify that where the difference ($S-R$) is other than zero within its 99% confidence interval, this may be believed to be the sequence of the shipper and receiver NM measurement errors. The NM

concerned is booked by the receiver subject to the shipper data. This is normally explained by the shipper data having been obtained by accounting NM measurements and the receiver data by verifying NM measurements.

Where the difference ($S-R$) is beyond the 99% confidence interval, respective measures should be taken either to have this data agreed or, if the shipper/receiver discrepancy has been confirmed to be great, to identify the causes for the NM loss or surplus. In this case, the receiver shall send special reports to the state atomic energy management authorities and the nuclear safety regulator.

How nuclear material is transferred

NM transfers involve the following as the General Rules define.

1. A transfer of NM shall be authorized only if the shipper and the receiver have been licensed to handle NM and have contracted with Rosatom for transfers of NM for use (for federally owned NM).

2. The shipper shall give the receiver a prior notification of NM to be shipped (this is the binding requirement because any NM dispositions entail nuclear and radiation safety/security issues).

3. The shipper shall condition and measure the material and prepare respective account and cover documents. Cover documents give NM container data (seal types and identifiers, gross weights of containers, etc.). These attributes are used for the initial acceptance of cargo. Data on NM characteristics (certificate data) shall be dispatched by special mail or together with cargo.

4. NM shall be transferred in the presence of the shipper and receiver representatives. The receiver representative shall check the attributes of NM, including:

- external examination and quantity check of the NM containers;
- integrity check of the tamper indicating devices applied to the vehicle and the NM containers;
- conformity of the container identifiers and the tamper indicating devices to respective invoices.
- verifying measurements of the NM container gross weight.

5. Where required, the receiver shall implement verifying measurements for other NM parameters.

The receiver shall define the necessity, form and volume of verifying measurements given that, after these are done, NM should be booked within the NM A&C system of the receiving organization which shall take over, from that time onwards, the entirety of the legal responsibility for the

safety of NM in such quantity as shown in the shipper's cover documentation. Verifying measurements shall take into account the form of transfer (between MBAs within one site, between sites, export/import), the category of the NM transferred, the type of the containers and tamper indicating devices, and the shipper's measurement quality.

6. If no verifying measurements have been done in full, the NM is subject to initial acceptance and booking.

The NM shall be finally accepted and booked no later than 10 days after it is received, which is the deadline for all required verifying NM measurements to be completed with the measurement results compared against the shipper data and the significance of the ($S-R$) difference estimated.

7. Where major discrepancies are detected, the NM received from the shipper shall be accepted for the time being based on the receiver documentation with a statement to be made out as to the nonconformity of the data. The NM received shall not go into process until the discrepancy with the shipper data is settled.

Example of the allowable shipper/receiver measurement difference calculation

A transfer of containerized NM is considered. The shipper and the receiver measure the gross weight of the NM container using scales with normally distributed measurement errors.

The shipper's cover documents show the container gross weight to be 25.05 kg. The receiver's incoming test measurement gives the container gross weight of 24.96 kg, which is recorded.

The relative errors of both the shipper's and the receiver's scales are indicated in the scales specifications and constitute $\delta = 0.4\%$ for the scales concerned, these having being reduced to a 95% confidence interval.

a) May the receiver book this NM in its corporate records?

b) May the receiver accept this NM if the shipper has failed to show the measurement error data in its documents?

6.2. Physical inventory taking and balance of NM

The knowledge about nuclear material suggests that we have data on the NM inventories in an MBA and on the incoming and outgoing NM flows over a special period called the material balance period (MBP). NM transfers and physical inventory takings are the main accountancy procedures that give such knowledge about NM. These procedures suggest

that all incoming and outgoing NM flows are measured with all NM inventories measured at the end of the material balance period.

NM transfer procedures have been discussed hereinabove in this chapter. Hereinafter, NM physical inventory taking (PIT) procedures and the structuring of the NM balances in MBAs will be considered [1].

Many in the expert community believe a physical inventory taking to be a large-scale physical experiment, so a detailed examination of PIT procedures is to be complemented with practical training to model individual PIT stages. PIT modeling needs not necessarily involve use of nuclear material (thus, river sand can be weighed instead of NM). Here, we shall try to describe this procedure as the whole.

Grouping of physically inventoried items

1) Type of nuclear material means nuclear material having its isotopic composition within the given interval. NM types are defined by regulatory documents (uranium, uranium-235, uranium-233, plutonium and so on). NM balance is closed for each NM type.

2) For convenience of PIT data adjustment, any material that was received in or shipped from the MBA, or was generated or being available at the beginning or left at the end of the material balance period, is classified as active or passive material.

Active NM includes products that were subjected to accounting measurements over the most recent material balance period or during the physical inventory taking. Specifically, active NM includes products processed in the given material balance period, fabricated products, waste generated in the given material balance period, products which came to require accounting measurements to generate a new certificate, etc. Where active NM was undergoing accounting measurements prior to the current PIT, these are subject to verifying measurements during the inventory taking.

Passive NM includes products that have not changed by the inventory taking time, since the previous inventory taking, products for which no accounting measurements have been done, and products being under access controls or having such coatings as may be viewed, as such, as access controls with the absence of access confirmed by means of access controls. Passive material also includes the material received in the MBA in the material balance period, booked based on the shipper data and having been, as of the inventory taking time, under access controls since the receipt time.

Passive material is subject to verifying measurements during the inventory taking.

3) Stratification is grouping of items with similar characteristics. Stratum is a group of batches or separate items having similar physical and chemical characteristics and isotopic compositions. Grouping by strata makes it easier to analyze large quantities of identical items (sampling measurements).

Objectives of physical inventory takings

The new accounting (measured material balance) system requires mandatory physical inventories to be periodically taken in each MBA.

Physical inventory taking is determination of the NM physical inventories in MBAs by measurements. So the object of physical inventory takings is formulated in the definition thereof. Additionally, physical inventory takings:

- Determine if the physical parameters of the item conform to the existing accounting data. The conformity confirms the integrity of NM and the confidence of NM data;
- Detect, as the result of the total check, drawbacks and infringements in accounting and control of NM (that is, efficiency of the NM A&C system is evaluated).

Types of NM physical inventory takings

Physical inventories may be taken both on a scheduled (at regular intervals) and an unscheduled basis. A scheduled PIT determines the inventory of all NM types in the MBA (including the NM received for use on an interim basis).

An unscheduled PIT may determine the physical inventory of some NM types or determine the physical inventory of NM in a portion of the MBA (for all or any NM types). Unscheduled physical inventories are taken in the MBA:

- when the custodian is substituted;
- when, in the event of a team custodian, the team head (leader) is substituted, more than 50% of the team members retire or at least one team member so requests;
- by a decision of the enterprise administration;
- if anomalies are detected in accounting and control of NM;

- in the event of an off-normal occurrence (lack of an item, unauthorized access to the MBA, an accident and other emergencies);
- when the enterprise is reorganized involving change of custodians.

Frequency of inventory takings

The approach to determining the PIT frequency is based on the concept of NM attractiveness and overall quantities, that is, the category of NM.

Thus, the frequency of physical inventory takings will be different for different nuclear material, say, plutonium metal in significant quantities and low-enriched dioxide uranium quantities (or nuclear material in irradiated fuel). In particular, as recommended by the US Department of Energy, physical inventories for top-graded nuclear material in respective process departments should be taken not less than once in two months. That is, 100% control of the NM physical inventories should be carried out every two months.

As applied to the material balance area as may be determined in spent fuel stores of nuclear power plants, the requirements are naturally less stringent. The reason is that spent fuel as such is intrinsically safe due to being rather highly active.

The following frequency of inventory takings is accepted in Russia, depending on the category of nuclear material in the MBA (NP-030-05):

- 1 calendar month for MBAs with material of category 1;
- 3 calendar months for MBAs with material of category 2 and/or 3;
- 6 calendar months for MBAs with material of category 3 to 6;
- 12 calendar months for MBAs with material of category 4 to 12;
- 12 calendar months for all onsite nuclear material.

The frequency of physical inventory takings for MBAs with nuclear material inventorying which involves major personnel exposures may be reduced as agreed with Rostekhnadzor and Rosatom of Russia subject to the justification provided. This normally involves extra technical arrangements to control access to nuclear material (for example, BFS–1,2 at State Research Center “Institute of Physics and Power Engineering”).

Organization of onsite physical inventory takings

As a large-scale physical experiment, a PIT procedure requires the whole series of prior measures to be successfully implemented. We shall consider these in brief.

Prior to each PIT, the order for this to be held is issued by the chief executive officer. The order specifies the basic organizational arrangements required for the site physical inventory to be taken. Among other things, the following is determined:

- the MBAs in which the PIT will be implemented;
- the names of the PIT commission members;
- the dates for preparing accounting data, equipment and instrumentation required for the inventory taking;
- the dates for preparing the items to be inventoried for checking;
- the inventory taking dates and the submission date of the PIT reports.

To prepare, hold and analyze the results of the NM physical inventory taking, the following PIT commissions are formed at the enterprise: a central inventory-taking commission (CITC) and, within the site divisions, working inventory-taking commissions (WITC).

The WITCs plan the PIT, prepare the MBAs and implement the PIT within the specified dates. During the inventory taking the WITC members:

- detect and record the shortcomings in accounting, storage and utilization of NM, and make proposals on eliminating these;
- bring to the notice of executive staff the detected shortcomings in accounting and storage of NM.

The CITC shall provide procedural guidance for the inventory taking to be organized and implemented within the enterprise's material balance areas (coordination of works and counseling). Essential to the PIT implementation are safety and radiation safety precautions. These should be therefore defined in the respective inventory-taking instruction and approved by the organization's nuclear and radiation safety services.

A division's WITC shall be made up of skilled personnel having access to operations with NM, as well as to accounting and technical records. Normally, a WITC comprises:

- the chairman (head of division);
- representatives of the nuclear safety and radiation monitoring services;
- representatives of the A&C system computerized accounting service;
- physical measurement and statistical experts;
- a representative of the CITC;
- representatives of the security service and other members.

The custodian shall take part in preparing the MBA for the PIT and shall be present during the commission's work. However, he/she shall not be a member of the PIT commission.

PIT planning

Onsite physical inventory taking is an extremely responsible procedure which requires stringent work planning. “Failing to plan is planning to fail” is the best adage to describe the significance of the PIT planning.

The PIT commission shall estimate the volume of the PIT work and develop the PIT plan. The PIT plan shall describe in full the sequence of all operations with NM to be done, the facilities to be employed and the respective deliverables. The PIT plan shall include the following important parts:

- breakdown of NM by types;
- selection of NM for accounting and verifying measurements;
- grouping of passive NM by strata and calculation of the random sampling volume for each stratum;
- sequence of measurements and required instrumentation;
- operation of working materials to record measurement results and preparation of reports;
- a complete time profile of the work performance;
- persons in charge of work stages.

The PIT plan constitutes a voluminous package of documents. Early experiments in the field made by the Kurchatov Institute proved PIT planning to be a responsible and time-taking procedure. Thus, the documents that described all procedures of the initial physical inventory taking for one bulk (HEU) handling facility formed a volume of several hundreds pages. Each facility unfortunately requires generation of its own procedural documentation based on generic regulations. One important note in this connection is that a model document has been issued by Rostekhandzor of Russia to provide a general guidance for the PIT preparation and implementation (Methodical Recommendations on Implementing Nuclear Material PIT at Nuclear Facilities and Nuclear Material Storage Points (RB-026-04, Moscow, 2004)). This general guide serves as the basis for each facility to generate procedural documentation of its own.

Enterprise preparation for physical inventory taking

After the order to implement the physical inventory taking in the MBA is received (before the PIT starts), the required arrangements shall be undertaken. These shall include preparation of documentation, nuclear material, process components and instrumentation for the PIT.

All NM in operation is given the form to be convenient for the inventory taking. For example, packages with NM shall be positioned so that the inspection of seal prints, the reading of seals' factory numbers and batch numbers and so on would not be hampered.

NM that requires accounting measurements of the quantities and compositions thereof shall be placed separately from the other. Labels shall be prepared to designate the material that has been inventoried.

The equipments and service lines shall be cleaned.

Preparation of documentation shall include the making of the inventory listing (IL) as of the PIT time and checkout of same against the rest of documentation. When this is checked out, the custodian shall compare the data on the items shown in the IL against the physical inventory listing (PIL) data from the previous PIT, the inventory change report (ICR) and the initial information on the items (certificates, invoices, measurement records, etc.).

Metrologists shall check the availability of all the instruments to be used for measurements during the physical inventory taking.

Sequence of physical inventory takings

Site PIT techniques and procedures depend on the type of the process and the quantity and the type of NM in the MBA and are specified in the PIT plan. However, there are a number of general conditions to be noted. These are namely as follows:

- For the period of the PIT, the MBA to be inspected shall have NM shipment, receipt and write-off operations and formation of new items suspended.
- Measurements should be done during the inventory taking based on the developed time profile and subject to the specified sequence of measurements.
- The nuclear material inventory taking work in the MBA shall be carried out by not less than two persons simultaneously.
- The inventory taking shall involve the custodian's control of nuclear material.

The physical inventory work requires the reconciled IL for NM within the MBA to start. Using this listing, the WITC shall check the conformity of the physical inventory to accounting data:

a) Checkout of the attributes of the items within the MBA (presence of the IL items and the integrity thereof):

- items with NM in the MBA are checked for being actually present;

- location;
- items are examined for external defects and TIDs are inspected for the absence of breaks;
- IDs of the TIDs and the items are reconciled (using a scanner if there are barcode labels);

Measurements of the attributes are assumed to confirm the declared data if:

- the items with NM are at such locations as indicated in accounting records;
- the items do not have external defects;
- the TIDs are not broken;
- the barcode information matches that in the accounting records.

Measurements of NM attributes are normally done for all items in the MBA.

b) Verifying and accounting measurements. Measurements shall be performed at key measurement points using instruments intended for verifying and accounting measurements.

c) The quantity and accuracy of discard, if any, shall be estimated.

Verifying measurements (audits) shall be performed to check the availability and conformity to accounting data within the item material measurement error limits. Verifying measurements shall be performed for passive nuclear material, as well as for active NM that was subjected to accounting measurements prior to the current inventory taking and have been under access controls since. Verifying measurements shall seek to identify defective items. Defective items are understood as items with characteristics other than conforming to accounting data.

Verifying measurements shall include checks of the following NM parameters:

- net weight;
- product volume;
- element and isotope concentrations;
- NM mass in the product.

The parameters for the last two positions are normally checked by nondestructive assays.

Where checks find the difference of the measured value and the accounted quantity being other than falling beyond the 99% confidence interval, the accounted value of the said characteristic is assumed to be confirmed. Otherwise, the item that contains this NM shall be considered defective. In this case, the anomalous discrepancy obtained shall be

analyzed and investigated and accounting measurements of the NM shall be performed.

Where access controls have been applied to NM, verifying measurements of the material shall be performed on a sampling basis using sample size statistical calculation techniques. The volume and type of verifying measurements shall be specified in the PIT program.

Accounting measurements. The inventory taking includes accounting measurements for the characteristics of active NM that have not been performed prior to the inventory taking.

Based on the work results, the WITC shall prepare the nuclear material physical inventory listing (NM PIL), the material balance report (MBR) and the inventory taking statement. The WITC shall report all discrepancies (deficiencies, surplus, wrong writes-off or registrations of material used in processes, etc.), as detected in the course of the work, to the enterprise administration.

The inventory taking shall be finished with the material balance closing, and the inventory difference (ID) and ID determination error estimations for each NM type. If no anomaly in the nuclear material accounting and control is established by the PIT, the documented inventory of nuclear material in the MBA shall be taken as the inventory of nuclear material in the MBA as of the beginning of the next material balance period.

Finalization of physical inventory taking results

NM PILs, inventory taking statements with the WIC findings and recommendations, as well as material balance reports (MBR) shall be prepared as the result of the PITs.

1) The items measurement results shall be entered on the PIL. This lists data for each item in the MBA as obtained by accounting measurements (given errors). Similarly to the IL-list, the PIL-list shall have the items entered thereon grouped by types, strata and batches.

2) Preparation of the material balance report (MBR). Each NM in the MBA shall have a separate MBR prepared for it, this to represent the NM balance with a breakdown by facilities. The MBR shall be prepared based on the PIL from the previous and the current inventory takings and the ICR over the current MBP. Separate columns in the MBR shall show the booked NM inventory, the NM quantity increase and decrease for the MBP reported on and the final physical inventory of NM.

The data in the MBR shall be given for each item (stratum) in such sequence as would match the PIL and the ICR. The NM quantities in each item (stratum) and errors shall be entered by lines so that the MBR columns had the material balance components aligned in the MBR columns.

The ID value shall be determined as the algebraic sum of all items in the MBR. The MBR shall give the calculated error σ_{ID} . The MBR shall be signed by the chairman and the members of the WITC.

3) The inventory taking statement shall contain the conclusion with respect to the conformity or nonconformity of the NM physical inventory to the IL data. The ID quantity and the estimated range of its permissible values shall be presented. Entries on the detected anomalies (if any have been found by the inventory taking) shall be made, the inventory taking commission to formulate recommendations for these to be removed. The anomaly established by the WITC shall be described in details in the memorandum enclosed with the PIT document package. The statement shall be signed by the chairman and all the commission members who took part in the inventory taking. The statement shall be made available to the custodian for examination.

PIT cost. Initial PIT problem

Physical inventory takings are an extremely costly process. For example, the US Department of Energy that has in control six national laboratories and some three dozens more nuclear industry facilities, including assembly and disassembly plants at Pantex, a commercial nuclear production facility in Hanford and others, spends millions of US dollars annually on physical inventory takings. This takes place in the conditions when US nuclear industry has large quantities of material held currently in containers which are sealed and inspected periodically or continuously. This spending is allocated when not all material is subject to measurement and the initial inventory takings date back to a long time ago.

Russian spending on PITs, with the initial physical inventory takings being required and NM inventories being no less immense than in the USA, can hardly be overestimated.

An initial PIT requires all nuclear material to be measured. There are many organizations in Russia that need initial physical inventories to be taken. The experiments made by the Kurchatov Institute [2] have proved that initial inventory takings for only two of its facilities are expected to take nearly one year of work. This brings to life a great deal of problems with the total labor expenditures the initial physical inventory taking at

Kurchatov's may entail estimated at a level of 60 to 70 man-years. The initial physical inventory to be taken at Kurchatov's is expected to last for several years.

It needs to be said that the labor consumption in physical inventory takings can be decisively curtailed to a great extent by means of access controls (containment and surveillance), provided these are employed as extensively as they can be. Estimates show that access controls, if applied to the nuclear material of the Kurchatov's facilities, are expected to make the volume of routine physical inventory takings (not of initial ones) several times smaller. Thus, a five times reduction in this value means that all this work can be done by a team of 6 or 7 persons in approximately 2 years.

Manning problem

Manning problems are faced by many operators within the Russian nuclear fuel cycle. It needs to be acknowledged so that lack of sufficient personnel to have NM physical inventories taken in Russia in near future is rather a concern. Later on, however, things with this can be somewhat settled thanks to a reduction in the overall labor expenditures after the initial PITs are completed given access controls are employed.

Early physical inventories takings led to the understanding that even expert staff who were or are involved in building the existing economical and safe nuclear facilities have proved to be unable to elaborate and use the physical inventory taking procedures without being given a prior special training. The explanation is that a physical inventory taking is actually a sort of a global physical experiment, so the absolute must for Russia now is a well-established framework for training and retraining personnel to operate the NM accounting, control and physical protection system.

Nuclear material balances

We shall assume that the site under consideration has periodic NM physical inventories taken thereat (Fig. 6.1). The period of time T between the two successive physical inventory takings is called the material balance period.

Let we know the physical inventory PI of the material in the given material balance area as of the time t_0 of the previous physical inventory taking and that IN of material was received in the given MBA over the material balance period T . This is exactly the quantity of the material the receipt whereof has been booked in records.

Similarly, DE is the quantity of the material shipped from the given balance material area over the period (t_0 , t_1) between the physical inventory takings.

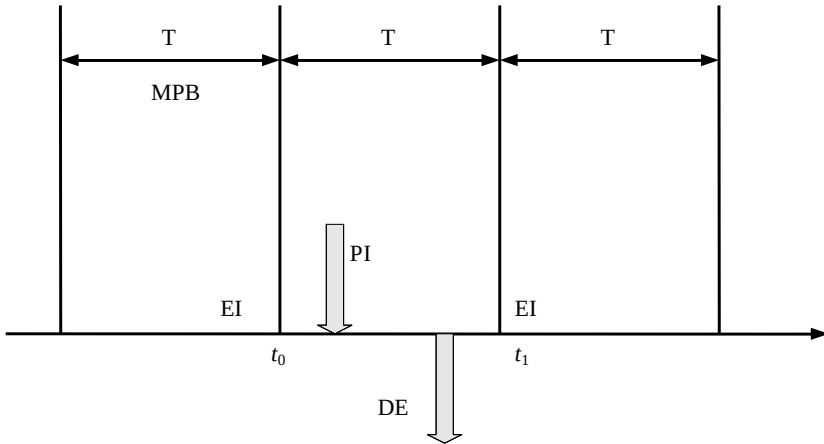


Fig. 6.1. NM balance closing cycle in an MBA

The book inventory of the nuclear material is the quantity of the nuclear material to be present in the MBA as shown in the documents as of a particular date. The final book inventory BI of the material in the given material balance area as of the current physical inventory taking time is evidently:

$$BI = PI + IN - DE \quad (6.1)$$

The physical inventory EI of the nuclear material is the quantity of the material as determined in the course of the current physical inventory taking by measurements and computations.

The difference between the book inventory BI of the material as of the current PIT time and the physical inventory EI is called the inventory difference (ID). The objective of the nuclear material balance closing is to find the ID.

The following equation gives a formal determination of the inventory difference ID:

$$ID = BI - EI = (BI + IN) - (EI + DE) \quad (6.2)$$

The equation (6.2) is the basic balance relation. This equation should be solved on a periodic basis for each material balance area. It is solved for separate types of the NM held within the MBA concerned. Let us remind that the NM type is the nuclear material the isotopic composition whereof is in the given interval limits (e.g., uranium, uranium-235, plutonium, etc.).

Statistical interpretation of the nuclear material balance

The inventory difference cannot be avoided because of unavoidable measurement system errors. It may both positive and negative.

In a general case, the values I, EI, IN and DE in equation (6.2) are found experimentally and contain systematic and random measurement errors. The measured values I, EI, IN and DE are not negative random values having certain probability density distributions. The total value ID is also a random quantity, either negative or equal to zero, having a certain probability density distribution as generated by the superposition of the probability density distributions of the quantities I, EI, IN and DE.

Equation (6.2) has three important sequences.

- 1) The quantity ID is the superposition of multiple random quantities and so, according to the central limit theorem, its distribution is close to normal (Gaussian distribution). In this case, the bounds of the 95% and 99% confidence intervals are determined easily depending on σ_{ID} .
- 2) The inventory difference (ID) is linear relative to the components thereof. This circumstance will be further used to plot calculation models for σ_{ID} .
- 3) If the terms of equation (6.2) are independent variables, then the statistical straggling of the ID is described by the quantity

$$\text{Var (ID)} = \sigma_{PI}^2 + \sigma_{EI}^2 + \sigma_{IN}^2 + \sigma_{DE}^2 \quad (6.3)$$

To determine the quantity of the ID's mean-square error, the "measurement error carry" technique shall be preferably employed. This consists in that the inventory difference errors are computed from the measurement errors for the quantities in the NM balance equation. Also taken into account are random and systematic components of errors and potential correlations of the NM characteristic measurement errors.

It should be noted that where a great deal of measurements is involved in the components of equation (6.3), Var (ID) may amount to an intolerably great quantity. The approach with the division of measurements into accounting and verifying ones, as taken in the measured material balance

system, enables the problem of great ID variances to be removed to a certain extent. To this end, the material balance equation (6.2) is considered by components. The NM available for the MBP under consideration may be classified as follows.

Passive NM is the material that has not been changed in any way (and has been under access controls) over the MBP preceding the given PIT. It is subject to verifying measurements during the PIT.

Active NM is the NM that has had its state changed and have undergone or is subject to accounting measurements (processing, change of accounting data, etc.).

Examples of passive and active NM determination

1) A storage facility for unirradiated NM. All material is under TIDs. Over the MBP, material was received at and shipped from the storage facility. How shall the material left as of the time of the next PIT be classified?

2) A process department for uranium dioxide production out of uranium hexafluoride is considered. There was no nuclear material in the MBA as of the previous PIT time. Over the MBP, cylinders with UF_6 were received from which UO_2 was produced, containerized and shipped to another department. As of the time of the current PIT, the MBA had cylinders with UF_6 remainder and containerized UO_2 left therein. Shall all NM be classified as active?

Anomalies in accounting of NM are revealed in the course of physical inventory takings and material balance closing. For the above NM classes, the following criteria for detection of anomalies in accounting and control of NM are considered.

Passive NM balance closing

The anomaly for passive NM is the discrepancy in accounting and verifying data to above the permissible limits. In this case, a new accounting measurement of NM is performed. Where the accounting data is verified, this NM changes neither ID nor the ID uncertainty. Therefore, with anomalies absent in the verifying measurements:

$$\text{ID} = \text{ID}_{\text{ACT}}; \quad \text{Var}(\text{ID}) = \text{Var}(\text{ID}_{\text{ACT}}).$$

Active nuclear material balance closing and inventory difference determination

For active NM, in a general case, the conclusion on the balance arrived at, based on the coincidence of the IL and the PIL for each item, cannot be

made due to active NM being subject to change during the MBP. So in the event of active NM, an integral criterion for the conformity of the accounted for and physical NM remainder in the MBA as of the current PIT time is considered. The inventory difference quantity acts as this criterion.

The active NM balance closing suggests that the IL and PIL conformity should be established both in the number of products and in attributes. Apart from this, the inventory difference and its limiting values should be determined for active nuclear material. A correct evaluation of the inventory quantity requires waste, loss, discard and NM deposition in process equipment to be taken into account.

For active NM, the anomaly is the IL/PIL discrepancies in the number of items or attributes thereof. The integral criterion of the anomaly detection is the modulus in excess of the inventory difference or its threefold mean-square error, or the values of any of the following quantities, the confidence probability being 0.95:

- 2% of the total book inventory of the given nuclear material and all quantity increases thereof over the MBP for commercial nuclear facilities;
- 3% of the same quantity for nuclear research facilities;
- 3 kg of plutonium or uranium-233 in the MBAs that contain category 1 and 2 nuclear material;
- 8 kg of uranium-235 in the MBAs that contain category 1, 2 and 3 nuclear material;
- 70 kg of uranium-235 for uranium enriched to below 20%.

Limits of allowable ID deviations based on accounting of NM measurement errors

Let us assume that the ID is characterized by normal distribution. We shall designate

$$S = \sigma_{ID} = (\text{Var}(\text{ID}))^{1/2} = (\sigma_I^2 + \sigma_{EI}^2 + \sigma_{IN}^2 + \sigma_{DE}^2)^{1/2}. \quad (6.3)$$

Two intervals are considered to analyze the allowable ID values. The interval $(-2\sigma_{ID}, +2\sigma_{ID})$ is a 95% confidence interval. The interval $(-3\sigma_{ID}, +3\sigma_{ID})$ is a 99% confidence interval:

a) 95% confidence interval. The probability of this interval being exceeded is small (0.05). It defines the bounds (warning limit) of the statistically insignificant ID straggling range.

b) 99% confidence interval. The bounds of this interval define the permissible ID values. The frequency of false signals for such interval is

1%. These bounds exceeded (alarm limit) is viewed as the anomaly and indicates that it is necessary to analyze the causes in detail. The bounds of this interval are normally used as the threshold level for the alarm to be generated.

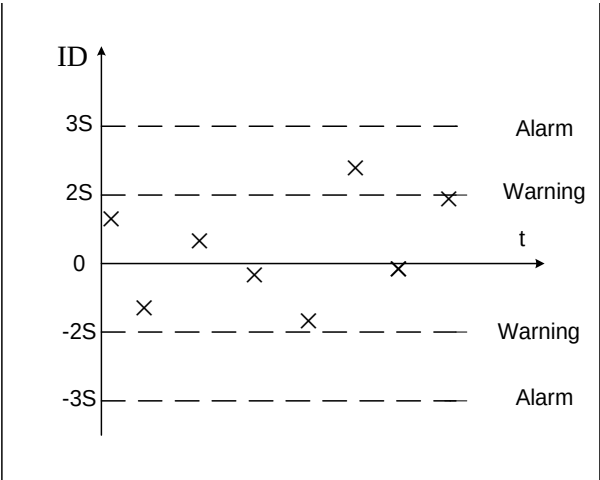


Fig. 6.2. A chart of NM balance control in an MBA (S – one ID sigma)

Determination models of allowable ID deviations based on accounting NM measurement errors

Determination of the resultant error in the NM balance or, in other words, the ID error, requires a model matching the conditions of the given physical inventory taking in the MBA concerned (the model is expected to “sense” the existing uncertainties).

Fig. 6.3 gives examples of the limits calculation models that are not adequate to the existing statistical ID straggling.

Fig. 6.3a shows an overestimation of the tolerable ID statistical uncertainty when there are excessively great limits for the alarm. Meanwhile, a real NM theft or loss may not trigger the alarm. This makes all efforts spent useless.

Fig. 6.3b shows a case of the tolerable ID statistical uncertainty underestimated. Underestimated tolerable limits lead to a high intensity of false alarms, though there is no NM shortage or surplus. Each of the false alarms has to be responded to, which is highly time-taking and costly. Frequent false alarms may cause a real NM theft or loss to be missed.

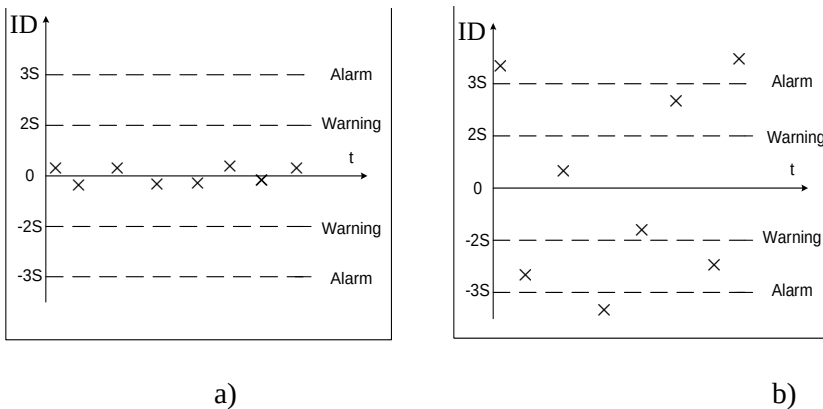


Fig. 6.3. Examples of inadequate calculation models for ID straggling limits:
a – model with the ID uncertainty overestimated;
b – model with the ID uncertainty underestimated

Therefore, the model of plotting tolerable limits for the ID statistical straggling should be reconciled.

Determination of tolerable ID deviations based on historical data

For production facilities with sustained operations, it is also permitted to use earlier inventory difference values. The established limits are determined by the recorded straggling of the ID values from the earlier physical inventory takings in the given MBA. This suggests that no anomalies with NM were detected in the previous PITs. Such approach has some positive points to it: the values of the limits are easily obtained with no computer models involved. This does not require detailed data on measurement errors. All NM accounting and measurement errors may affect the tolerable deviation limits.

General rules both in Russia and in the USA permit use of an approach with determination of the tolerable ID deviation limits based on historical data. This case however requires the applicability of such approach to the ID prediction to be proved. This takes place where no ID error formation structure changes over time.

Use of historical data is also helpful in reconciling computer models when these are used to calculate the allowable ID limits. Historical data provides a quality criterion for checking the estimated ID error. Namely,

the observed statistical ID straggling that is expected to match the interval of statistically insignificant ID values: $(-2s_{ID}, +2s_{ID})$.

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CHAPTER 7

COMPUTERIZED NM ACCOUNTING AND CONTROL SYSTEMS

The prime objective of nuclear material (NM) accounting is early detection of shortage/surplus, loss, theft or unauthorized use of NM, as well as identification of causes for these to emerge and sources of origin thereof. Along with control and physical protection, accounting is what helps with achieving this goal. Accounting systems are also responsible for furnishing state authorities and other respectively authorized official bodies with data they may require for discharge of their functions.

These goals cannot be achieved in full with no respective data collection and handling processes automated.

The requirements imposed by the Federal Information System (FIS) upon reports by operators in nuclear industry, both with respect to the volume of information and the data submission time, cannot be complied with unless modern data processing technologies in place.

Along with the centralized computerized data acquisition and processing system, computerized (automated) NM accounting and control systems established at NM material handling and storage sites shall form the Federal Information System (FIS). Complete FIS requirements to reports, data detailing and data submission frequency place operators under severe constraints with respect to functionality and software support of their computerized NM A&C systems.

7.1. Industry-standard requirements to NM A&C systems

The functions of and requirements to material accounting systems are set forth in OST 95 10537-97, an industry standard of the Russian Federation Ministry for Atomic Energy [1]. We will refer to this standard when discussing the components of accounting and control systems, and review its requirements to the sections studied. This is the earliest industry standard that governs functions, properties, development procedures and requirements to computerized NM A&C systems. Much experience has been gathered in establishment and handling of such systems since the standard adoption time, so a new release of the industry standard is the order of the day.

As defined by the standard, accounting and control (A&C) systems are intended to:

- provide data for accounting and control of nuclear material held at sites, coming in or going out of same or liquidated subject to operator's legal responsibility;
- account for any movement of material between material balance areas and any change in the material type or form;
- give out timely and credible data to support accounting and control.

To realize these functions for each MBA and the site as the whole, the A&C system shall:

- keep data records of NM quantities and characteristics for all measurements at key points;
- keep track of any changes in the NM type, form or location, including offsite transactions (shipment/receipt);
- determine the material quantity in each MBA and at the enterprise as the whole;
- keep accounting records and reports;
- oversee the timeliness and correctness of transactions with NM;
- control and account for personnel and personnel access to data;
- support inspections and inventory takings;
- search for product locations on a timely basis;
- communicate with the enterprise's physical protection system;
- protect information circulating within the system;
- communicate with A&C systems of other enterprises and the Federal Information System.

Two A&C system functionality areas are identified by the standard: administration and management of databases. There are three functions of administration:

- servicing of customer and administration data queries for the status of the enterprise operations;
- monitoring and control with respect to authorization of access to the NM A&C system data;
- information support for investigations of contingencies.

The functions of database control are to:

- receive and process data on all NM movements within or out of or into the site;
- form site databases;
- generate reports in formats and on carriers as required;
- check information for mutual consistency;
- search for and put out data on a timely basis;

- keep files and create backup copies.

The standard requires information on NM to be objective, consistent, timely, complete, coherent and successive. The following shall be understood by this. **Objective** information requires all database entries to have a documented confirmation with all documentation to form a unified system and not to contain contradictions. **Timely** data suggests that changes in the status of items to be updated on a timely basis (in near real time) and to be **complete** (not to contain unlogged changes). **Coherent** requires that once entered data not to be changed or erased with any correction to accounts to be only subject to a specified procedure and recorded. **Successive** means the consistency of a newly established computerized system with the site's NM A&C system that already exists.

The information subsystem of the A&C system shall contain complete information on NM, accounting and control documentation, data on the activities arranged for, personnel access authorization data, technical data of the facility required to carry out accounting and control, and instrumentation data.

The standard includes a very important requirement that the information subsystem should be a normal operation system, i.e. an emergency failure or trip thereof should not be harmful to NM accounting.

By its section pertaining to information support requirements, the standard requires incorporation of all types of reports as required by operator, federal and, where international obligations apply, IAEA standards. The system shall generate paper reports in required formats. These requirements of the standard are further detailed by the FIS requirements.

Special requirements are imposed on security of information, these taking into account both security aspects: safety of information when the system fails or breaks down, and security of information against unauthorized access. It is so required that:

- backup database copies should be created and updated on a regular basis;
- the track record of each item that has changed hands should be kept to trace the sequence of actions;
- NM for peaceful and military uses should be accounted for separately;
- secure communication channels, local networks, and paper and magnetic carriers should be used.

We shall take a closer look at information security issues of computerized A&C systems, components thereof and requirements to the development of such systems in Chapter 8.

7.2. Architecture of computerized NM accounting systems

The history of systems for accounting of nuclear material goes back to the very dawn of the nuclear era in the 1940s. Since then, NM accounting systems have gone through a number of evolution phases.

Initially, in the 1940s and the 1950s, nuclear material handling used manual data processing systems. No computers existed at the time and material volumes in use allowed data to be inventoried manually with the respective entry made for each item. Operating these systems involved complications making it hard to systemize information on particular items and search for required data. Time of arrival was the only criterion to which information could be arranged in logs. More complex operations and more items to be handled meant much more time to be spent to process and search for data. Still, such systems may exist nowadays as well, say in educational laboratories with just few items in storage. Also, industry standards may bind operators to keeping hard copies of computerized accounting records.

The advent of computers in the 1960s gave birth to systems based on processing of computerized packages. To operate such a system, one had to create packages on punch cards or other data media and update databases by passing these packages. No database theory was practically developed at this IT evolution stage. Data was stored as so-called flat files. Distinctive of these systems were primitive databases and extremely slow information updates. All this made systems slowly operating and troublesome. Information was practically always backed up manually.

A major breakthrough in the employment of ITs to evolve control and accounting systems was brought about by creation of the first mainframes linked to user stations. By the time (the 1970s), the first database management systems (DBMS) came into being. Coupling rather high-power computers with advantages offered by interactive data input led to high-performance systems having some commercial application to date. Functionality of such systems is however limited because of the need to network large volumes of information and because of the necessity to process all data from all users on the mainframe computer. The requirements to the mainframe and network components are therefore rather rigorous leading so to the whole of the system getting more expensive.

The advent of personal computers has changed all human technologies. These can have varied applications in accounting systems. A PC can be used as:

- a terminal station networked to the mainframe computer;
- a computer to handle data coming in from the mainframe in file server systems;
- a database client or server in a client/server system.

Depending on the system architecture, use of PCs may be both advantageous and limiting. Practically all current systems have PC as the basis so we shall give this a closer look.

We shall first define what “client/server” architecture is [2]. An important function of this architecture is to achieve highly efficient use of computers in a computer system by partitioning tasks into smaller levels and allocating operations at these levels to computers. A number of tasks that form a level require auxiliary operations to be done at another level. So we say that the applicant program is a “client” while the auxiliary task serves it, that is, acts as a “server”. A client/server application can be defined as composed of essential parts of other applications executed on different computers. A well formed client/server application suggests that processes are run exactly where the process-specific work is done most efficiently.

Applications in existing computerized accounting systems incorporate several application levels, which can be assembled into three global logical levels in three functionality areas:

- user data presentation logic. This is largely enclosed in the user interface supporting software;
- business rules support logic. In our case, this should to realize NM accounting standards and regulations and the system functionality;
- database access logic. This normally includes mechanisms that support a particular DBMS, deal with storing and update of and access to data and support the integrity thereof.

Depending on how operational logic support applications are allocated, one can build various types of client/server systems.

Having all system levels realized on one computer, we will nevertheless deal with a client/server model because processes are divided internally into client and server ones. Such integration is representative of most mainframe-based systems. Listed below are the major features of a so arranged computation process:

- terminal stations have only application data coming in, the rest of the levels being handled on the base computer;

- where graphic data is involved, all of it is networked. So, depending on how data is processed, the network traffic can be both small and overcrowded;
- a substantial weakness of such systems is lack of convenient interface and graphics, and limited report creation capabilities;
- high-power mainframes are expensive.

A recent trend has been towards cheaper mainframes, while, for the other part, the capacity of workstations has enhanced lately drastically. In parallel, the evolution of client/server architectures has led to systems with a very “thin” client. Such systems have most of the data handling processes run on the mainframe. Obviously, the architecture of these systems is nearly conventional.

File server systems are based on architectures realizing another extremity. This suggests use of the server as simply a databank with all application logic realized on the workstation. The greatest advantage of such a system is simplicity. Drawbacks are more numerous though. The biggest one is that all data to handle needs to be networked from the server to the workstation. Such systems are normally realized on a PC basis and offer a user-friendly interface with advanced graphics (graphic data is front-end created and processed).

To realize a client-server architecture, one needs to break down the level of the client and server tasks so that to optimize use of the local network’s computational power and network traffic. This breakdown is typical of systems known as database servers. Such structuring balances use of client and server capabilities in computer systems. Its greatest advantage is a decrease in data communication load as it is only data needed by a particular application that is conveyed over the network.

Client/server systems are also cost-effective. Mainframe-based systems are highly expensive and dear to maintain. Client/server systems are cheap and employ affordable hardware and commercial software. They are also cheap to serve and upgrade.

The major advantages of client/server architectures are as follows:

- work load is intrinsically distributed among more than computer;
- users easily share data;
- data is secured on a centralized basis;
- better cost efficiency.

Still, such architecture has drawbacks:

- high load on the application creator;
- complicated network topology;

- server software changes apply to all clients.

The client/server computation model forms the underlying paradigm of information technologies (IT). It began to evolve in the 1980s when computer industry started to move from centralized systems to systems of multiple-PC networks.

The simplest client/server architecture that was realized in the earliest applications of the kind is shown in Fig. 7.1. This is a dual-linked architecture which links two computers: a server computer and a client computer [3]. As such, it is realizable in two versions. The first one places most operational burden on the client. So, in this case, they say about a "thick" client and a "thin" server. The server includes the DBMS which realizes data access logic. Each of the client computers incorporates applications that realize business and presentation logics.

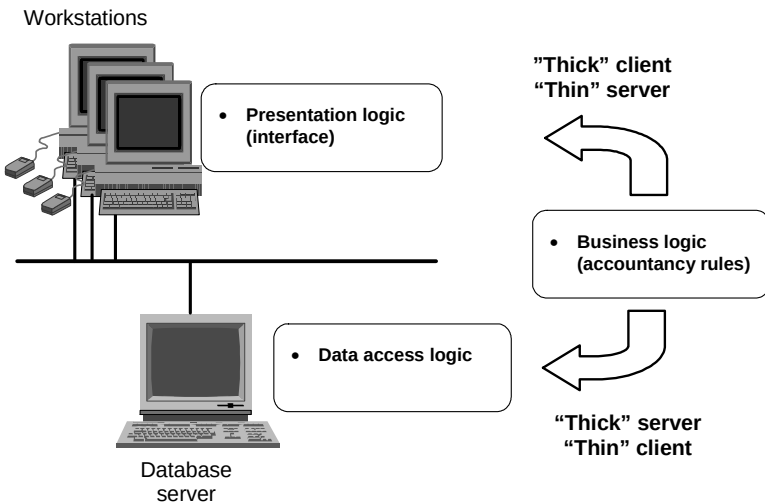


Fig. 7.1. A two-linked client/server model

This approach is simple. Such architecture is still limiting:

- it requires rather a high-power computer for use as the workstation and the sufficient disk space;
- in the event of a large data series to be handled by the client that is produced in response to a request, the network may be burdened severely;
- each workstation-server connection requires rather a high-capacity server RAM; thus, MS SQL Server 6.5 (not in the least the costliest DBMS

in this respect) requires 37K of memory per connection, which may be a potential problem with large networks;

- any change to the business logic leads to the necessity of changing software for all workstations.

Being simple, this model is highly convenient in environments with a limited number of workstations. An optimum exists beyond which problems start to arise as described above.

An alternative dual-linked circuit is a model with a “thin” client and a “thick” server. Unlike the previous model, this has business logic moved to the server. This is a diversely realizable model using different software. In particular, MS SQL Server enables the writing of so-called stored procedures in a query language. These procedures realize business logic. Some DBMSs have auxiliary capabilities, including change, rule incorporation or data value limiting admissibility checks, with no excessive data communicated over the network. Such systems however require the server RAM for each connection so new constraints additionally emerge. First, this requires rather a high-power DBMS. For example, unlike the first model realizable in MS Access, the second model requires MS SQL Server to realize. Furthermore, different firmware has somewhat different query language syntax. This makes the approach in question somewhat limiting to the system evolution capabilities and requires use of a more powerful DBMS, e.g. Oracle.

The client/server model is evolving further towards a decentralized computation process, and multilink client/server systems are realized so. Fig. 7.2 shows a schematic of a triple-linked client/server model.

Such architecture offers an extra link between the “thin” client and the “thin” server and has components of it linked via standard network protocols, say, TCP/IP. This auxiliary feature contains core business logic. The distinction of these systems is that they do not need RAM on the database server to support each connection to the client.

Where triple-linked systems are set up, all three application levels (presentation logic, business logic and data access logic) are partitioned throughout. This gives the system more flexibility and makes it easier to upgrade any level. Such system has extra services, e.g. Internet, e-mail and phone or fax communications, easily connected thereto.

Database and application servers for small networks and slack applications can be physically combined in one computer. This, however, will still make a triple-linked system because it has a functionally separated logic.

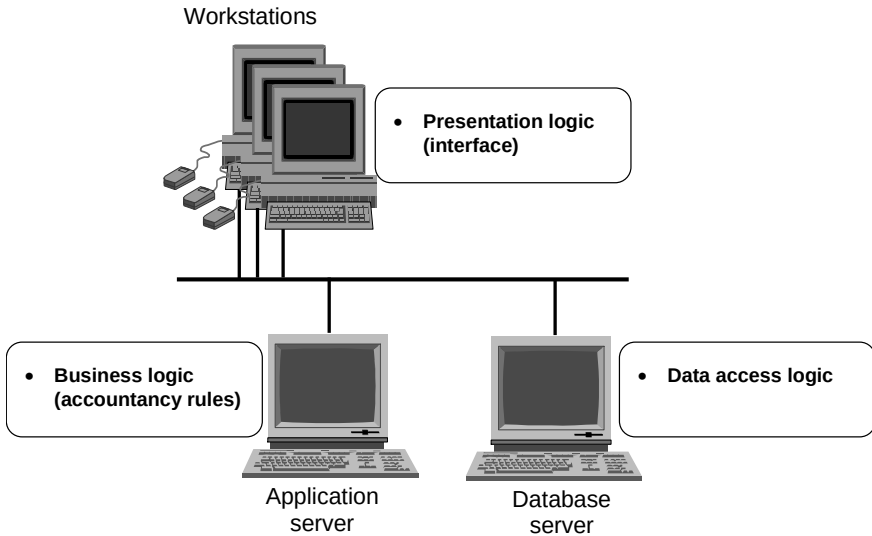


Fig. 7.2. A triple-linked client/server model

The multilink model tends to evolve towards so-called n -linked client/server systems. These systems retain all the benefits offered by the triple-linked model and have business logic distributed among a number of servers, this making it possible for the client to choose the one it needs at the time. Connection to different database servers is also in place. Such a system displays excellent flexibility, ease of modification and a capability for new applications to be inserted. The system components can be spatially separated. Global Internet is a global example. Any user can exploit business logic of many search servers and select data from the source required.

The most recent technology of multilink model realization is Web-service. This technology makes it possible to get required data in standard formats without dedicated software or hardware.

Microsoft experts give the following definition of Web-service: Web-service based on XML is used for exchange of data between applications and enables other applications to be called irrespective of how these are organized, what platform is used for operation and what tools are employed to make them accessible.

Requests come to Web-services via various standard network protocols from applications realized based on different software and hardware platforms with the result going back in standard XML coding. Large

applications are broken down into independent parts which exist on the application servers as Web-services.

7.3. Base software

The industry standard [1] identifies the following three types of base software:

- operating systems;
- database management systems;
- development tools.

Base software used in computerized NM A&C systems must be certified to the respective information access security class. The requirements to information security are set forth in the Guidelines of the Russian Federation's Gostekhkomiissiya (State Technical Commission) which govern the classification of NM A&C systems [4]. Details of the base software classification and information security requirements, depending on the specified class, will be discussed in Chapter 8. There are no special requirements to development tools.

Hereinafter, we shall consider in more details each base software type. Requirements imposed on these by the industry standard will be discussed, modern software will be reviewed in brief and advanced software considered.

7.3.1. Operating systems

Operating system (OS) is essential software needed to form the NM A&C system's working environment. OS is what primarily secures the information system against unauthorized access and defines reliability thereof.

The requirements to operating systems are set forth in the industry standard and in data access security requirements of Gostekhkomiissiya. The industry standard requires that an operating system should contain and ensure:

- networking features;
- data access security features;
- log-in access control;
- memory protection;
- discrete and accounted for access to resources;
- error handling facilities;
- operability support facilities;

- advanced database access providers;
- support of distributed network protocols;
- hardware fault tolerance;
- system operation statistics.

An OS may support:

- client/server technology;
- multitasking with a prioritization system;
- workstation networking capabilities;
- uninterruptible power supply. The standard's requirements are rather general and do not establish particular criteria. More specified requirements imposed on operating systems by the classification of NM A&C systems introduced are set forth in Gostekhkomiissiya's Guidelines [4]. The document specifies requirements to various data security subsystems, as well as certification and qualification requirements depending on the class of the system.

A major technical problem developers of computerized NM A&C systems are faced with is lack of operating systems certified to classes higher than 3. A number of Microsoft Windows NT 4.0 modifications have been currently certified by Gostekhkomiissiya for use in computerized NM A&C systems. The system itself is certified to data access security class 3, the certificate thereof having been renewed more than once.

An OS certified to access security class 3 do not permit operating data of different sensitivity levels, this making it impossible to use it at most nuclear material handling sites. More than that, Windows NT 4.0 is a legacy system. Microsoft said they would stop to support this OS in 2004. So a top-priority task the Federal Information System is faced with now is to certify a new OS for use in class 3 systems and choose a system to build class 2 NM A&C systems.

There are two ways to address the problem. The first one is to use Microsoft software. Prerequisites exist for Windows 2000 to be accepted as an advanced operating system. This operating system has been internationally certified to class 4 [5–7], so certifying it to class 3 under Gostekhkomiissiya's requirements to NM A&C systems is not expected to be technically complicated. The system is an evolution of NT-based operating systems, so it will not be a problem to adapt existing applied software to the new system. Responding to the criticism of its software openness policies, Microsoft after all announced its GSP (Government Security Program). The GSP is Microsoft's answer to states' demand for secure information systems. The partnership in the GSP has entitled

Russian organizations to getting access to Windows source code. The GSP will also connect developers in Russia to joint work with Microsoft to verify security functions and to other research activities planned as part of the program. Apart from the source code access, the GSP members will be provided with the Windows platform technical details to enable design and creation of still more secure computation systems. Experts in the industry believe the GSP may help bring Microsoft products, Windows 2000 in particular, to the level of security class 2 [8]. Another approach relies on plain-code base software meaning use of a Linux-based operating system. This approach is based on a license agreement enabling the system to be readily modified with a capability to build a Linux distributive to be certified to security class 2. The reasoning behind the latter approach is that open-code software is relatively cheap.

As of the time this handbook was being redacted, things with getting operating systems certified stood like this. Because of organizational problems, which were partly due to the restructuring of the industry's executive bodies, the Windows 2000 codes were made available only in late 2006. This operating system had been obsolete by the time. So the requirement now is to have Windows XP and Windows 2003 Server, Microsoft's next-generation operating systems, certified. Accordingly, no work is under way to bring the Windows NT family operating systems to the level of the access security class 2 requirements for NM A&C systems.

In parallel, Yanux 2.0 [9], a secure Linux-based operating system, was built by NPO "Luch" in Podolsk. Subject to [10], this system was certified in 2005 to access security class 2 under requirements for NM A&C systems [4].

Further listed are the major features a secure operating system is expected to possess and the implementation thereof will be looked at using Windows NT operating systems as an example.

A secure OS is expected to feature [11]:

- identification and authentication capabilities;
- management and control of access to all system resources;
- auditing of events;
- resiliency and resilience tools;
- control of covert data leakage channels.

Most secure operating systems operate on a microkernel basis. The microkernel resides in memory and controls data flows among components of the system. Any application refers to the microkernel for the permit to execute commands. Using special server processes, the microkernel checks

if execution of the command has been authorized and either permits or prohibits execution. Such approach realizes a client/server architecture. If the request made has been authorized, the microkernel calls the respective server process to realize it.

The security system of Windows NT is based on an objective protection model. Object is understood as any OS resource (file, devices, program, memory area).

Each Windows NT user should log in to the system. He/she has a login and a password entered in the database.

When logging in, the user undergoes identification and authentication procedures (Fig. 7.3). Identification means confirmation that the user who is logging in has an account in the database of registered users. This procedure checks the user name (login). Authentication confirms the identity of the user logging in. This procedure checks if the password entered is valid. The user enters his/her login and password. The security account manager checks if the user with such credentials exists and permits or denies access to the system. A so-called access token is generated that contains user data needed to have access to resources (objects), any process to be further initiated by the user to receive a copy of this token. This process is called the user account subject and has the same rights of access to objects as the user himself/herself.

Identification and authentication are rather formal in many current operating systems so it is quite easy for a subject to pass himself/herself off as another subject and use his/her rights of access to data. No authentication altogether is required for network interaction in Internet where global compatibility requirements are binding.

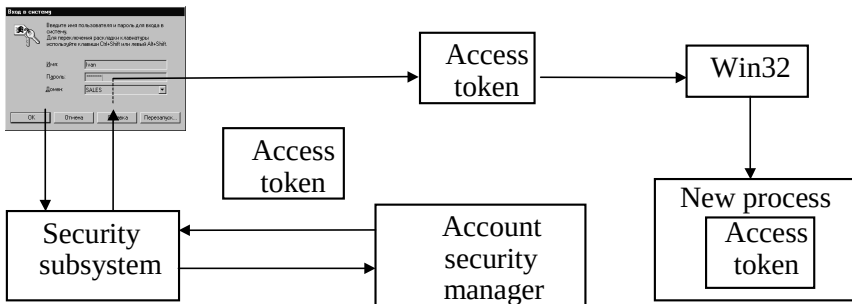


Fig. 7.3. Login access token creation procedure

Control of access to resources includes check of the user's rights to use the given object when an OS resource is requested for. There are a number of models realizing this function. We shall look into how two models, a discretionary model and a mandatory model, are organized [11]. The discretionary access control model is realized in Windows NT [12] and realization of mandatory access control is the necessary condition for an OS to be certified to access security class 2.

The discretionary model requires that each OS object should possess the so-called security descriptor that contains the object owner data and the system access control list to check the right of access to the object. By default, the creator of the object becomes the owner thereof, the right of ownership being transferable. The owner has the right to create and change the rights of access to the object. The access control list consists of access control records that specify the permits for the user to address the object. Access control records contain an access mask that defines what can be done with the object. For example, the access mask for a file contains “no access”, “full access”, “read”, “write”, “change” and “execute” operations. When an object is addressed to, the security monitor checks the object's access control list and grants or limits, as the access mask defines, or denies access (Fig. 7.4).

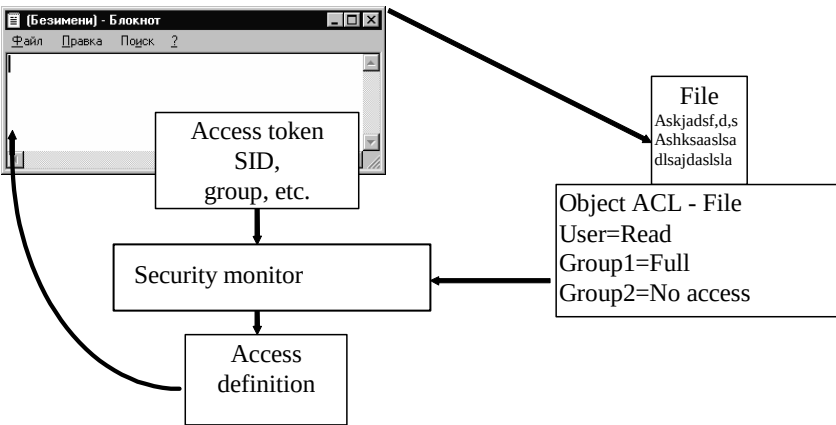


Fig. 7.4. User's resource access procedure

The mandatory access control model is based on classified document management rules. All objects and users are given a special label called security level with dominance relations established among levels, e.g. the

Top Secret level is superior to the Secret level. Control of access to data is established based on two simple rules:

1. A user is entitled to getting only data of the security level not higher than that of his/her.

2. A user has the right to enter data only in objects of the security level not lower than that of his/her.

The first of the rules ensures data protection from being accessible to lower-level users. The second (and more important) rule prevents data leakage on the part of high-level users.

Mandatory access control does not differentiate between entities and is normally used, along with a discretionary model, for better flexibility.

Apart from access control, secure operating systems are expected to allow event auditing. This is normally realized in the form of security event logs by reviewing which the IT administrator traces down the user actions with respect to information security.

As computerized NM A&C systems are basically systems designed to operate in corporate local area networks, operating systems used to support functionality of these need to have built-in tools to support computer network operations. Thus, Windows NT operating systems have support of distributed network protocols and help organize PCs into logic groups or domains. Inside domains, users have to log in on the primary domain controller only. Whatever workstation is used for logging in, the rights of access are checked on a centralized basis. This makes the same security policy to be easily organized and pursued on all computers within the domain.

NT-based operating systems include a component termed Internet Information Services. When installed, it allows creation of a Web-server on the computer, thus enabling use of Internet global network technologies to be used in local corporate NM A&C system networks.

7.3.2. Database management systems

Database forms the core of any computerized accounting and control system. A computer database is an array of specifically arranged information. Database management systems (DBMS) are employed to operate databases and give a computerized support to storing and handling of data. To a great extent, DBMS selection defines the future user characteristics of the NM A&C system under construction, including speed of response, the amount of information to be stored and security attributes

to protect information against both unauthorized access and objective factors.

The industry standard imposes the following requirements on DBMSs. A DBMS should offer convenience of backup copy creation and data recovery. Where required, a DBMS may include a convenient user interface and DB automatic replication features.

A DBMS shall support:

- networking operations;
- high speed of response and capacity.

Where required it also supports:

- the driver ODMC;
- security of data and data access control;
- an SQL query language.

Two of these requirements are clearly defined: a DBMS should support data backup and networking capabilities. The rest are either general (high capacity) or not binding (“as required”). DBMSs are also subject to data access security certification. As of the time this chapter was being written, three DBMSs, including Microsoft SQL Server 6.5 and two Oracle versions, had been certified to access security class 3. These are systems that support client/server architectures and operate relational databases. In fact, these two requirements are presently the accepted industry standards. The client/server architecture was discussed above. In general, things with certifying modern DBMS systems stand in the same way as with operating systems.

As to open-code base software, PostgreSQL 7.4.6 DBMS was certified by NPO “Luch” in parallel with their Yanux 2.0 operating system. Therefore, in the context of open-code software applications, there is now a complete set of certified software required to develop and operate computerized NM A&C systems.

Relational databases

There are a number of requirements to satisfy to which a relational DB is expected to:

- submit information as tables;
- support the logical data structure irrespective of the physical presentation form;
- use a high-level language to execute requests and change data in databases;
- support basic relational and set operations;

- support virtual tables for alternative data viewing;
- discriminate unknown values, zero values and gaps in data;
- support data integrity, authorization, transaction and recovery mechanisms.

Tables consist of columns (fields) and rows (entries), each entry describing the entity the data whereof is contained in the table. Entry fields contain properties (attributes) of this entity. For unambiguous identification of an entity (an entry), the table contains a special field called the primary key. The value of this key must be unique in the given table. More than one field (composite key) may be used for the primary key. In the NM A&C system practices, a special ID field is introduced to be used as the primary key. For relation to other tables, the table also has fields called foreign keys. The foreign key is the primary key for another table. Foreign keys relate a table entry to a particular object (entry) of another table (Fig. 7.5).

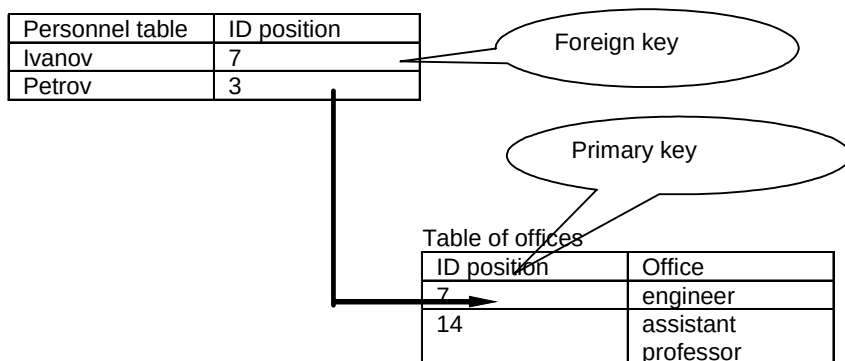


Fig. 7.5. Relationship between tables via key fields

A key aspect in a database design is identification of entities and organization of relationships among them. This should be done keeping in mind how stored data will be further handled.

The selection of entities should be followed by normalization of data to give the database the status as would prevent corruption of data and facilitate data manipulation. There is a set of rules which help, if adhered to, with achieving different levels of data “normality” (normal forms). A database is considered to be operational if the third normal form is achieved. Each subsequent normal form includes the requirements of the

previous one. The purpose of normalization is primarily to speed up access to data and give data more integrity. These objectives may be mutually contradictory. A well normalized database is the necessary compromise between these trends. The first three normal forms are as follows.

First Normal Form (1NF) is expected to satisfy to the only requirement of atomicity: each data field should contain a single data element and no element should be duplicated.

Second Normal Form (2NF) should additionally satisfy to two more rules:

- each table contains data of only one object;
- each table contains a unique field or set of fields (termed the primary key) for unique identification of the entry.

Finally goes Third Normal Form (3NF) which requires all table fields, other than key-defined, to be mutually independent.

Occasionally, a designer may intentionally break the 3NF rules to improve performance of an application. This process is referred to as denormalization and is expected to conform to particular rules:

- Validity of denormalization. The only purpose for which denormalization is practicable is to improve performance of an application.
- Debugging and testing of the program code created to avoid problems from potential data corruption. For example, introducing a computed field requires a code to be written to accomplish this.
- Complete documentation of the actions performed.

A relational database differentiates the following types of relations among tables:

- One-to-one relation. In this relation each entry in the table relates to one entry in another table. Normally, if such relation exists, it makes sense to consolidate the tables. However, cases occur when this relation is realized.
- One-to-many relation is used to relate an entry in one table to more than one entry in another table. This is the most commonly encountered relation type.
- Many-to-many relation. Each entry in one table is related to more than one entry in another table and vice versa. Relational database rules require this relation to be presented in a dedicated table. As foreign keys, the additional table contains the primary keys of both tables. It has a one-to-many relation to the base tables, which realizes the many-to-many relation of the original table.

Integrity of data is a separate aspect to be ensured in the context of information security. Data integrity shall be understood as a correct and noncontradictory status of a database. This means that information in separate tables should make a whole and should not have contradictions. Relational database management systems help maintaining the integrity of data automatically without the need for a program code to be written to check the input. There are a number of procedures to keep data integral.

Thus, sharing an entity among tables and linking tables via primary and secondary keys helps avoid duplication of identical information and errors this may entail. DBMSs allow data types to be specified in particular table fields to hold down an attempted input of knowingly incorrect data with field values to be limited where possible.

Transaction support

Any change to the database in computerized NM A&C systems shall be made through transactions. Transaction is a set of database transformations which results in the database changing over from one noncontradictory state to another noncontradictory state. Transactions should meet four requirements known collectively as “ACID”: Atomicity, Consistency, Isolation and Durability.

- Atomicity means that a transaction can be performed only in full and not in part.
- Consistency is the condition when no traces are left by a transaction. Aborted transactions should reset the system. This operation is called rollback.
- Isolation is the notion meaning that transactions should not interact. If transactions try to handle the same data in the database, this data should be blocked for all other transactions before completion.
- Durability of a transaction means that if the transaction has been completed and its goal achieved, it becomes completed even if something happens with the system.

DBMSs with transaction support should contain additional tables. Tables of independent values describe one object but at different time. These tables are used before the transaction is completed with data stored that may be required if there is a rollback.

Special transaction logs are needed to log all transactions in the database. Where in place, these logs, along with backup data copies, allow the transaction to be considered a data recovery unit. When data is

recovered, the DBMS reviews the transaction log data and consistently performs all transactions performed since the time of the latest data backup.

Structured query language (SQL)

Structured query language (SQL) is a high-level language for manipulation of data and objects in relational databases. Such language is the necessary condition for a database to be considered relational. Relational model was developed by IBM in the 1970s. In parallel, the original version of a structured query language appeared. The latest SQL standard was adopted in 2003.

DBMS manufacturers tend to extend the language standard by giving it extra capabilities. Normally, if successful, these changes are made part of the next language standard. Still, practically all SQL versions support base requests and functions of the standard. Following the standard helps create applications other than depending on a particular DBMS with standard requests employed to manipulate data. Dedicated mechanisms (ODBC or OLE DB) are exploited to communicate with databases, thus enabling conversion of requests to respective DBMS formats.

Use of SQL makes it unnecessary for programmers to write a great deal of routine sampling and data merger operations. This will also cut the load on the client computer as the operations done using SQL queries in the client/server architecture will be accomplished on the server.

Given below are the formats of the basic language queries enabling manipulation of data. Uses of SQL structures will be illustrated by examples.

The basic SQL command is **SELECT** which is a data sampling command. It has a rather complex syntax and makes it possible to compile queries for a great deal of operations to furnish the user with information from the database. Here are some examples to illustrate the language capabilities:

```
SELECT title, price FROM titles  
WHERE price >= 5 AND price <=10
```

In this example, values in the *titles* and *price* fields are selected from the *titles* table for all entries in which the *price* field values lie in the interval of 5 to 10. The key words **SELECT** and **FROM** are necessary in the query because they specify the table sampled and those fields the values whereof

are to be supplied to the user. The key word WHERE defines the sampling condition. Where this word is absent, all table entries will be sampled from.

With the predicate in the WHERE sentence assuming the meaning of “truth”/“lie”, Boolean algebra operators can be used to form it. In a Boolean expression, the only predicate may use any number of conditions which makes it possible to form exclusively powerful predicates. SQL may use the following comparison operators: equal to, greater than, less than, greater than or equal to, less than or equal to, not equal to. The last one looks as <>.

Apart from comparison operators, SQL distinguishes basic Boolean algebra operators which interlink a number of Boolean expressions, a Boolean expression being obtained again as the result. SQL distinguishes the following Boolean operators:

- AND – logical AND. The operator takes two Boolean expressions (A AND B) and gives out “true” if both of them are true or “untrue” if otherwise;
- OR – logical OR. The operator takes two Boolean expressions (A OR B) and gives out “true” if at least one of these has the meaning “truth”;
- NOT – logical negation. One expression (NOT A) is used as an argument. This operator inverts the value.

Using predicates with Boolean operators, one can give them a much greater selective power.

As stated in the discussion of the database relational model features, table fields should be independent. However, data is often needed, which can be obtained based on these fields with the aid of certain procedures: summation, averaging, etc. SQL performs these operations using aggregation functions.

- COUNT – determines the quantity of rows or fields selected by query and being other than NULL values.
- SUM – computes the arithmetic sum of all selected values in the given field.
- AVG – computes the average value of all selected values in the given field.
- MAX – computes the greatest of all selected values in the given field.
- MIN – computes the least of all selected values in this field.

Here is one example to illustrate how the aggregation function can be employed:

```
SELECT AVG(price) FROM titles
```

In this example, a user gets a single number that is equal to the average value of the quantities contained in the *price* column of the *titles* table.

The sampling command SELECT is capable of sampling more than one table by linking data with the aid of primary and secondary keys. Data grouping commands and some other capabilities exist. Consideration of these is however beyond the scope hereof. The literature on the query language is abundant so anyone with an interest in this will have no problems with finding the information he or she needs.

INSERT is the command used to insert data into a database. Here is one example of how values can be inserted into the F_name, L_name, U_login and U_password columns in the Users table:

```
INSERT INTO Users (F_name, L_name, U_login, U_password)
VALUES ('Сергей', 'Иванов', 'Sergey', 'HM235YPAH')
```

The key words used here are INSERT INTO followed by the table name and a bracketed list of the fields inserted. The further key word is VALUES, which is followed by the bracketed values of the data to be inserted.

UPDATE is the command used to change data in the existing rows. To illustrate this, we shall write the command to change the input name of the user with ID 1034:

```
UPDATE Users
SET U_login='master'
WHERE user_id=1034
```

Here, the name of the table in which changes are made follows the key word UPDATE. Then, the change as such is indicated after the key word SET. Finally, the predicate that follows the key word WHERE specifies the entry for which the change in question is made.

The delete command has rather a simple syntax. One example is:

```
DELETE FROM Users
WHERE user_id=1002
```

This case displays how the entry with the data of the user with ID 1002 is deleted from the USERS table.

There must be an understanding that the examples given include the simplest queries to illustrate the use of SQL for manipulation of data. The language capabilities are remarkably greater and make it possible to generate complex queries to cover practically all user demands. Literature is abundant to give anyone a profound knowledge of SQL.

Many DBMSs include objects which are precompiled and optimized SQL queries. An example of these is stored MS SQL Server procedures. Such queries are highly fast to execute. A user-data interaction can be also organized such that to provide the user with access to only stored procedures and not to the data these operate. This sets up an additional data access security barrier.

Use of DBMS in computerized NM A&C systems

As of the time this chapter was being compiled, developers had a limited choice of two SQL servers certified to access security class 3. These are Microsoft's SQL Server, version 6.5, and two Oracle DBMS versions. Being highly expensive, Oracle products have a confined application. MS SQL Server is available at a more affordable price and offers a power adequate for corporate applications at different levels. The most recent Oracle DBMS applications include the Federal Information System and a number of major operators in the industry. Most other products operate MS SQL Server 6.5 [13]. Likewise operating systems, new software products are subject to certification. Plans exist to have MS SQL Server [14] and Oracle 10 certified to access security class 3. Apart from DBMSs designed to operate in Windows OS environments, another DBMS, PostgreSQL, has been certified along with a secure Linux distributive.

7.3.3. Development tools

Development tools form the third component of base software for computerized NM A&C systems. These have two important roles in design and operation of systems. First, developers use them to create a graphic user interface (GUI). Nowadays, one cannot imagine a marketable software product without a developed and convenient interface. The second role of applied software is to ensure the integrity and security of information by program features. Depending on the type of the DBMS based on which an A&C system is built, this role may turn out to be central. Thus, MS Access, a popular DBMS, has most data integrity control functions vested in forms, that is, in applied software. In contrast, MS SQL Server realizes these

functions on the server. No binding certification requirements to development tools exist.

There are some requirements imposed on such tools by the industry standard. These require that tools should provide the developer with:

- convenience of program development;
- visual programming capabilities;
- good debugging features;
- a developed error handler;
- support of multiwindow environments;
- convenience of communication with databases.

Some of the requirements are general, though two well-defined requirements exist that limit the number of tools that satisfy to the standard. These require that visual programming and database communications should be in place.

Visual programming is to be understood as a capability to generate a user interface with the aid of readymade graphic control objects. The programmer simply gets them on the work form and defines further the functionality thereof. Systems of the kind make it much easier for anyone to form an interface and give the ability to create professionally looking program in the Windows environment even to developers with limited programming skills.

There are different ways to organize communications with databases in a software environment, still professional systems exist that incorporate dedicated objects and features enabling the user to get access to data in various formats.

Current software development systems offering such capabilities are rather many. The most sought-after systems are Microsoft's Visual Basic and Visual C++, and Borland's Delphi and C++ Builder.

According to a survey, in 2001 about one third of corporate developers in Russian nuclear industry employed Visual Basic and some 15% used Delphi. The existing demand for VB in domestic community of computerized NM A&C system developers is attributed chiefly to the experience of LANL experts who created CoreMAS, a product which, though not adopted to date in the industry, has been used as the model to build many Russian-developed systems. VB is also rather a simple and convenient software system various versions whereof offer ample data access capabilities.

There is one more point to application development systems to mention. While not being formally adopted in the industry standard, this has long established itself as a standard for all professional application development

systems by expecting each development tool to support object-oriented programming (OOP). We shall discuss the principles thereof in brief [15].

Object-oriented programming

The difference of OOP from traditional procedure-oriented programming consists chiefly in the following. In object-oriented programming, program is a set of specific objects with specific properties that act and respond to user actions. Program, in fact, turns into a process of user interaction with the program objects. When responding to any user manipulations, the program, or more precisely, the objects therein will operate in this or that way. This approach offers more flexible programming and allows one to escape a great deal of complexities involved in debugging, which comes down to testing methods and properties of the object rather than of the entire bulky program.

This leads to a question of what an object in OOP is. To answer it, let us take a brief look at the sequence of program units. An identifier defines any one value, say, color. Further, all current programming languages use the notion of record as a set of identifiers. One can create a record that contains a rectangle screen location (four numbers), a color (one number), a caption (character string) and a position - if the button is pressed or not pressed (Boolean variable). Such record gives a complete identification of the menu button in the form. Object-oriented programming goes even further. The object incorporates the procedure that realizes some action to be performed by pressing the button. This is called method and this procedure is accessible only from the object. The object so includes not only data but also a program code. Where many buttons are created, the method of each of these will relate to the parameters, that is, the properties of this very button.

Let us formulate the basic OOP-related concepts.

Object – a program unit that contains a complete description of the entity programmed, including data and the program code which enables some object-inherent actions to be realized.

Object properties – define the essence of the object, e.g. appearance for visual objects or data source for database-related objects.

Event – an object-related action or situation. For a graphic object, e.g., button pressing is the event that relates to the mouse click on the button. An event may result not from a user action but from an action of the program or the operating system (when time comes or the iteration process converges).

Method – a program module (procedure, subprogram, function), which processes object-related events.

Class – an object template. An object with filled in property values is an instance of the class.

The following concepts characterize OOP:

encapsulation – integration of data and the program code while concealing their realization methods from the user. The user access to the object is provided only via respective methods and events;

inheritance – one can create classes based on the existing classes with methods and properties being inherited;

polymorphism – derived objects know exactly to what method an event should be passed to be handled. Thus, a child may have a method which has the same name as the parent's one but is different in properties. For example, the cool looking button and 3D-button objects have "pressing" one name as their event handling method but use different pressing display graphics. Then, if the 3D-button is the child, its method will be called.

Current program development environments that take the object-oriented approach are rather many. Most of these systems use C++ as the programming language. Object Pascal is utilized by Delphi. Microsoft Visual Studio.NET includes Visual Basic 7, which has eventually been given all the properties an object-oriented programming language is expected to possess.

The choice of the software development environment shall be primarily defined by corporate or industry standards. An enterprise normally has a staff of qualified programmers who have a good command of customary development tools. A shift to new development tools is dictated by the requirement to adopt novel technologies calling for special programming patterns; employ a DBMS including development tools and change over to a new operating system.

Certification of base software on an open code basis has led to the possibility of using program development tools compatible to this environment. Java-based J2EE (Java2 Platform Enterprise Edition) can be used as the platform for such tools. We shall further dwell on the concept of program development platform and the advantages it offers to the database application developer.

Program development platforms

There are now two rival program development platforms: Sun Microsystems' J2EE (Java2 Platform Enterprise Edition) [16] and

Microsoft's .NET [17] (read as "dot net"). Both platforms enable creation of user applications of different architectures. To start with, these are classic client/server applications. Most current computerized NM A&C systems use exactly this architecture. Another capability provided is creation of Web-applications. This requires only a browser program, which is part of many operating systems, to install into the workstation. Web-server is where the application operates, communication with data is organized and Web-pages to be supplied to the user are formed. Finally, both platforms offer a new application development method which creates and uses Web-services. Web-services hinge on their ability to transmit data from the supplier to the consumer via a standard HTTP protocol. XML is used as the data format. The available standard data formatting and transmission facilities help create applications that do not rely on hardware platforms. The user application makes a query which is sent to a Web-service via HTTP. The query result is transformed into an XML format and delivered to the user. XML is a dedicated data markup language used to communicate data and is readily transformed into browser-viewable formats. Web-services can be referred to both from the Web-application and from a standard workstation-based application.

The two platforms are of nearly the same functionality. They differ mostly in cross-platform application transportability and capabilities to support various programming languages. J2TT is now the only program development environment with multi-platform support features. Microsoft customarily makes use of its own proprietary operating systems.

On the other hand, J2EE uses one development language, Java, while Visual Studio.NET. includes four: Visual Basic, C++, C# and Java. For an enterprise using Microsoft products for its base software, .NET offers a minimum-cost option of changing over to new technologies. Those using Visual Basic to design database applications will find it easy to switch to VB.NET-based programming of Web-services in their customary program development environments.

Changing over to open-code operating systems will yet require use of other development tools and so then J2EE becomes a natural choice.

Support of application/data communications

To be able to satisfy to a major industry standard requirement in the context of future computerized NM A&C systems, development tools should possess dedicated database access features. Microsoft has developed a spectrum of object class collections that model the database structure and

allow one both to handle database data directly and get SQL queries running. These object collections are continuously updated with new ones coming out. One of the earliest collections of the kind was DAO (Data Access Objects) [17]. This gave applications the capability to manipulate data which could be communicated with via the SQL query language. Fig. 7.6 presents a DAO-realized object hierarchy.

This collection can be engaged by an application created with the employment of Microsoft Visual Studio for communication with data in formats of popular DBMSs and spreadsheets, e.g. Access or Excel. This also permits the user to get connected to the database with the connection kept by the application that remains open throughout the session. Data from tables or with the aid of SQL queries are copied into datasets (Recordset object). Recordset objects include the sufficient number of methods to allow navigating the dataset and carrying out search functions, that is, doing everything needed to operate data.

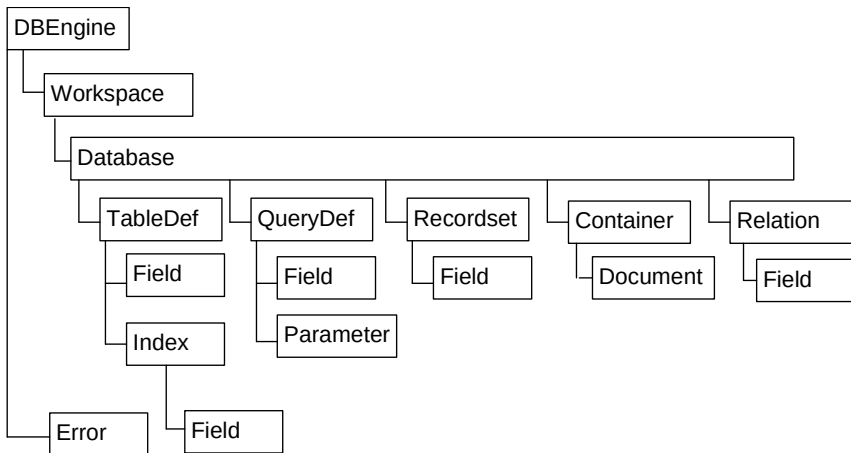


Fig. 7.6. Hierarchy of objects in the DAO collection of data access object classes

A great deal of data sources, say, those certified for use in MS SQL Server and Oracle NM A&C systems, cannot be however operated directly from DAO. Data in these formats are accessible via a more universal data access technique. ODBC (Open Database Connectivity) is utilized by Microsoft to handle data in various formats.

ODBC is a set of drivers and interfaces enabling connectivity to various platforms and use of a standard query language for different data management types. To implement access to data storable in different formats, the required drivers are installed into the operating system and a particular database in the format selected is given the logical name of the ODBC set. Thereafter, the application program developer can afford not to think about a particular data presentation because it is enough for him just to employ standard SQL queries to create DAO Recordsets from the databases of any formats. The application can subsequently handle data with the aid of a high-level language and, as required, update data in the database or add new data thereto using standard SQL queries.

DAO was used to create a great deal of database applications. Thus, in particular, it is used for handling data in the LANL-developed computerized NM A&C system (LANMAS) and in COREMAS, its localized version for applications in Russia and other CIS member-countries.

There is another collection of classes to mention in the context of database access objects. This is RDO (Remote Database Objects), which has been optimized to operate in client-server applications. Similarly to DAO, RDO uses ODBC for connections to remote data sources. This collection of object classes was employed by the Kurchatov's developers to build КИМАКС, a computer-based NM A&C system.

The evolution in ITs has brought about changes to information systems. To begin with, Web-accessible program applications appeared. This required new objects of access to data to be used for Web-applications. Further on, the development of business support electronics brought to life the demand for access to such nonrelational data as electronic documents and letters and others. For support of these capabilities, OLE DB (Object Linking and Embedding), a new technology for accessing all kinds of data, and ADO (ActiveX Data Objects), a new collection of object classes [17], were developed. Unlike ODBC, OLE DB can connect applications to data in any formats. In particular, it can also use ODBC drivers for connections to relational databases. To make use of OLE DB, one needs the services of an OLE DB provider which is to be installed for each type of data sources. OLE DB providers are supplied in the operating system and DBMS delivery packages. Therefore, using ADO with an OLE DB provider for ODBC, one can get the same functionality as with DAO and RDO. Along with this, ADO objects do not form such a stiff hierarchical structure as DAO and will offer more flexibility in handling data in different formats. Fig. 7.7 presents a schematic of the ADO collection of classes.

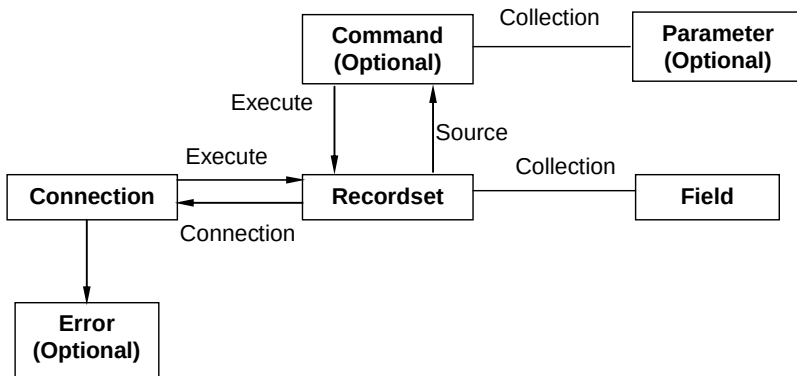


Fig. 7.7. ADO collection of data access object classes

Until recently, ADO was the central component of access to data in Windows-based applications. These components were supported by a number of software products from outside developers, e.g. Borland Delphi. They have an important role in creation of database applications, so we shall discuss them in more detail.

All ADO objects, excluding Error and Field, can be opened independently. The Command, Error and Parameter objects are not mandatory. Connection is the object that encapsulates communication with the data source within. It possesses the Execute method which returns, as the result of the query accomplished, the Recordset object containing a data sample. The Recordset object is the core of ADO. It can be also created independently of other objects and enables navigation through record sets, addition, deletion and editing of records, as well as retrieval and filtration of information. A number of examples follow to illustrate the principal object methods.

Let there be an ODBC-configured data source the name whereof is stored in the string variable myDSN. Then the following sequence of commands on VB will establish connection with the said data set. Further, the SQL query creates the Recordset object that contains Titles table data:

```

Dim myADOConnection As New ADODB.Connection
Dim myRecordset As ADODB.Recordset
MyADOConnection.Open myDSN
Set myRecordset = MyADOConnection.Execute(«Select * from titles»)

```

Further on, one can operate the data selected using Recordset’s methods and properties. Table 7.1 presents Recordset methods and Table 7.2 presents Recordset basic properties.

Table 7.1

Recordset methods

Method	Description
AddNew	Creates a new record for the Recordset
Close	Closes the open Recordset
Delete	Deletes the current record
GetRows	Returns the number of rows
Move	Moves the position of the current record
MoveFirst	Moves to the first record
MoveLast	Moves to the last record
MoveNext	Moves to the next record
MovePrevious	Moves to the previous record
NextRecordset	Returns the next Recordset if the query result is multiple sets
Update	Saves changes to the current record

Table 7.2

Recordset properties

Property	Description
BOF	Returns True if the current position in a Recordset object is before the first record
Bookmark	Sets or returns the record value as a bookmark
CursorType	Sets or returns the cursor type: 3 – static cursor, changes made by other users are visible; 2 – dynamic cursor, changes made by other users are invisible; 1 – keyset cursor, changes and deletions made by other users are visible, additions are invisible
EOF	Returns True if the current position in a recordset object is after the last record
Filter	Specifies the filter value
RecordCount	Returns the number of records in a Recordset object

A further evolution of ADO technology was Microsoft.NET, a development platform in the form of ADO.NET [18]. This data access

model was developed with emphasis placed on its applicability in Web-applications, though, further on, it will operate equally successfully also in traditional Windows applications. There are two basic features in which ADO.NET is different from its predecessor. First, it has the ability to handle data separately from the source of data, and, second, it uses the XML language for data exchange.

The first of these properties is of an extreme significance when operating data in Internet. Each connection to the server consumes its resources. When a certain number of user references to the server are made, it may have its efficiency decreased abruptly. This should be taken into account by those web-applications where the potential number of users is great. Therefore, ADO.NET connects the application to the database for a short time which is just enough to obtain a sample of information or update the database. Communication is interrupted after the data set is delivered or the command is executed, and the data obtained is further processed on the client with no communication with the server.

Use of XML as the data transmission format gives more flexibility to the applications created with the use of ADO.NET, because XML is a technical standard for transmission of data. Where an application operates in Internet/Intranet networks, it becomes no longer dependent on the client platform. Figure 7.8 gives an example of a data access model in ADO.NET.

To realize the concept of data handling separately from the data source, ADO.NET, unlike ADO, forms DataSet rather than Recordset. RecordSet represented a sample of one or more database tables as obtained using an SQL query. DataSet is a partial database copy and may consist of several tables with set relations.

To conclude the overview of data access tools, we shall look at how data objects should be selected to update current and create new applications. It is quite natural that up-to-date data access objects are employed to design new applications based on novel information technologies. However, no object model of access to data should be changed for upgrading the existing applications unless extremely necessary. This model forms the framework of the application/data communication logic so changing this will lead to the requirement of the whole application code to be rewritten.

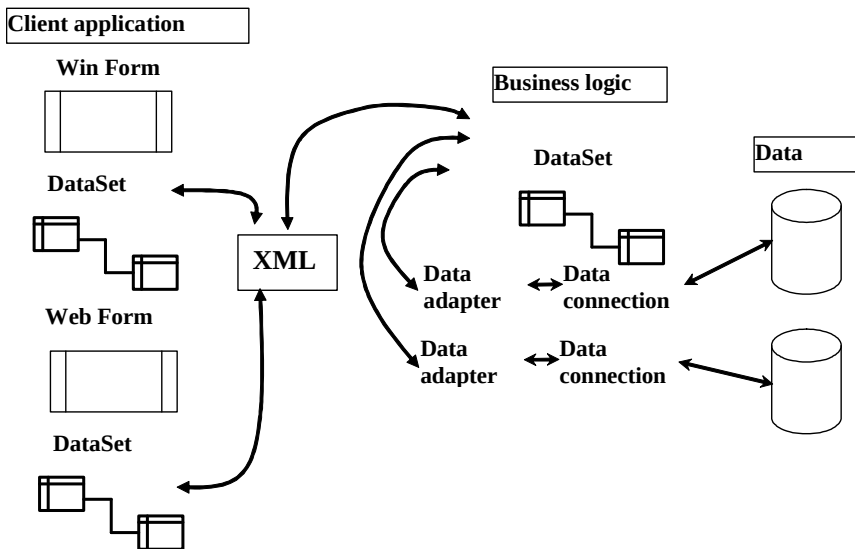


Fig. 7.8. ADO.NET data access model

7.4. Applied software

We shall further look at the state of the art in design of computerized NM A&C systems for nuclear material managing enterprises. Russia embarked upon modernizing its NM accounting, control and physical protection system in 1996 with the US funding and organizational support under an intergovernmental agreement. Russian parties to this collaborative effort were Russia's fuel cycle enterprises (Siberian Chemical Combine, Mining and Chemical Combine, "Mayak" and others) and top nuclear research institutes (the Institute of Physics and Power Engineering (IPPE) and the Kurchatov Institute). The specialist training capability for the project was provided by Moscow Engineering Physics Institute (MEPhI). The US participants were leading national laboratories, including LANL, SN, BNL, PNNL and ORNL.

Los Alamos National Laboratory (LANL) was the partner in the development and implementation of computerized A&C systems. Two software products, CoreMAS and E&ZMAS, were developed and adapted to uses in the CIS member-countries by LANL. As part of the effort, the

Windows NT 4.0 operating system and the MS SQL Server 6.5 and Oracle 7 DBMSs were certified in Russia. Built initially under US standards, many of Russian designs for computerized NM A&C systems had the same software and a similar architecture as the basis. The USA also contributed financially to the establishment of the network infrastructure within the industry, supplied computer technology, trained personnel and funded the creation of new applied software.

Over the decade since then, teams of software engineers have been established within the industry to develop software for its NM A&C systems. The evolution of computerized NM A&C systems for the industry was discussed at the 7th international workshop “Development of the Federal Automated Nuclear Material Accounting and Control System in Russia” held in September 2006, where facts about what had been accomplished were made public [19].

At federal level, the regulatory NM accounting and control framework was established and got started, the pattern for submission of reports on NM was defined by Rosatom, the FIS information analysis center was formed and acquisition of information from operators was organized. Separate information systems that, among other things, had tasks in accounting for and control of NM were established at the agency level. The level of organizations, as evidenced by a data survey, had shown, in the previous years, a marked trend towards more vigorous activities in creation and implementation of NM A&C systems.

For all MBAs, computerized NM A&C systems had been installed at 17% of the nuclear industry enterprises, while 27% had established these just for part of their respective MBAs. Another 12% planned the creation and deployment of NM A&C systems as their short term perspective. The rest 44% did not however have plans to establish such systems.

Some enterprises had problems with commissioning computerized NM A&C systems due to lack of sufficient funding and because of getting a late start on the work. There were also certification problems coming from the requirements to systems not having been well defined early in the FIS evolution process, which tended to change occasionally in the process of the system development. By the time, systems had begun to be established at nuclear power plants with computerized accounting and control of NM implemented nearly across the industry.

All certified systems had an individual architecture and had been designed using a variety of development tools. This was by and large the industry’s first generation of computerized NM A&C systems and these continued to evolve. This early generation of systems use base software

certified to access security class 3, which makes it not possible to use the computer network infrastructure in any other roles within the enterprise, making so the whole of the system more expensive to operate.

The Kurchatov Institute's КИМАКС [20] was the only system certified to access security class IB (under Gostekhkomiissiya's 1992 requirements: Chapter 8, Part II), which gave it access to handling data of different secrecy levels. This capability was achieved thanks to its own security system that operated independently of the Windows NT 4.0 security system.

No object-oriented programming and development quality control technologies are practically used to design systems. No use of Web-applications is made as well, except for some systems. The FIS is required to expand further both in scope, so that to encompass, in a longer term, all the enterprises managing nuclear material, and in depth. The latter suggests creation of computerized A&C systems to be certified to access security class II. This, first of all, calls for a shift to new base software.

To be built, the systems of a new generation will require, as a complement to the novel base software, industry software development standards to secure excellence, upgradeability and cost-effectiveness of systems. This, in turn, brings about the need for advanced IT solutions to the development of database applications. And this is what the industry just embarks upon. In a longer term, a team of software engineers is expected to emerge to create and support, on a pay basis, all corporate NM A&C systems within the industry.

This brings to life the demand for a range of software to meet corporate needs for computerized NM A&C systems. There is an occasional debate about the creation of a product to be shared by all enterprises. The first attempt of having such software introduced was the supply of CoreMAS, a US NM A&C system. This was not successful because of the product having failed to win recognition and find application in Russia.

A versatile product seems to be unfeasible because of the NM handling technologies and the material, as such, varying greatly between enterprises. For most of these, such product will be excessively capable and, accordingly, unreasonably expensive and hard to adopt. Further, we shall review the enterprise demand for computerized NM A&C systems depending on the volumes of the NM held and the way it is handled.

Requirements to computerized NM A&C systems depending on the enterprise type

Experts at LANL have reviewed the enterprise types that deal with NM. A classification of these has been suggested and proposals made on matching the enterprise type to that of the A&C system. The complexity of an A&C system is defined by the complexity and the number of operations done on NM. Enterprises were reviewed in a spectrum from a small-size storage facility to a high-tech processor. Five enterprise types have been identified.

Type 1. A small storage facility with the number of items below 50. No complex operations. The material is static and items have been in storage for a long time (up to 10 movements per month). One MBA of about 100 m².

Type 2. A medium-sized enterprise with the number of items below 500. No complex operations or processes. Key function: storage and moderate activity (up to 100 movements per month). One or two MBAs.

Type 3. A large-sized storage facility with the number of items from 500 to 10000. Several MBAs. A great deal of measurement and inspection. Movements are largely internal (up to 1000 per month). No processing and mechanisms of loss.

Type 4. A medium-sized production facility with many items and a great deal of activity (from 10000 to 20000 items and up to 10000 movements per month). Has several buildings and multiple MBAs. Complex operations on material and more than one mechanism of loss.

Type 5. A large-sized enterprise with a great inventory of items (from 20000 to 100000). The material is very dynamic (up to 50000 movements per month). Mechanisms of losses are very many.

Type 1 enterprises do not have material processing. Items are very few. A simplest paper-and-pen accounting system will do for an enterprise of the kind. One custodian will be enough to make logbook entries.

Type 2 enterprises have material kept in storage most of the time, still may need material to be moved for nondestructive assays. Operations are simple and require a simple accounting system. A paper-and-pen database will do, still an elementary computerized database capable of generating reports with a breakdown by grades is the preferred option. It is enough to have one custodian per MBA.

Type 3 enterprises have more items than a manually operated system can be expected to handle. These, importantly, involve a material change function. A computerized system with one to three workstations will do for

the case. The database shall be installed in one mainframe networked to other workplace computers.

Type 4 enterprises are major research establishments with noncommercial operations on material. These should have a custodian for each MBA with an access to the workstation. A client/server system is the suggested option. A well-designed database and a control system to support complex functions are required. The accounting system is required to serve bulk handling operations. The activity is up to 800 movements per day. Reporting functions are diverse. Several persons are needed to operate and maintain the system.

Type 5 enterprises have several custodians, each MBA being specific, but a central database is required. The volume of operations is greater than for Type 4, still functions are the same. This complexity requires a synchronized backup server.

The survey led to the understanding that the industry needed no less than three or four types of computerized NM A&C systems. Material processing and mechanisms of natural process losses this entails are the key factors that influence the complexity of systems.

Two computerized A&C systems were designed by LANL with this approach taken. One is E/Z MAS, a simplified NM A&C system for enterprises of types 1 and 2, as well as for some of type 3 enterprises. The system has been functionally extended, which makes it potentially fit, subject to a bit of an update, for more complex installations. The CoreMAS, a more complex and versatile system, can be used for enterprises of types 4 and 5.

Implementing the whole range of technologies and offering nearly the complete spectrum of operations one can expect of them, the two systems will be looked at hereinafter as examples of computerized NM A&C systems.

CoreMAS, a client/server-based NM A&C system

CoreMAS is a computerized NM accounting and control system built by Los-Alamos National Laboratory (LANL), the USA, based on a classic client-server architecture [21]. The reasons for which this system has been chosen for the study are as follows:

- this is a fairly recent system built on a client/server ideology and based on advanced software;

- being, by ideology, sufficiently expandable and adaptable to each new site, the system is delivered fully documented and complete with training aids and all program source codes;
- Russia does not have now a so documented and industry-generic A&C system, while CoreMAS was installed at some sites in Russia and has influenced greatly the choice of software for and the ideology of Russian-built NM A&C systems;
- finally, it was CoreMAS that was delivered free of charge by the US partner to MEPhI to form the framework for training a specialist staff in the field.

The system is considered hereinafter to demonstrate the capabilities of the earlier discussed software and review, with a real system taken as an example, the database design for site applications in treatment and storage of nuclear material.

Key concept of CoreMAS

CoreMAS (Core Material Accountability System) is a daughter product built based on the LANMAS (Local Area NETWORK Material Accountability System) system. As the name says, the latter system is designed for use in respective corporate LAN systems. Both systems are LANL-developed. LANMAS is a computerized A&C system for applications within the USA, while CoreMAS has been adapted to uses in nuclear fuel cycles of the CIS member-countries.

CoreMAS is a fully documented system, which is in keeping with the US standard requirement that creation, maintenance and support of any software product must be accompanied throughout by a specific set of documents, including:

- SRS (Software Requirements Specification). This document describes the basic concepts, functions and relations between parts of the software. This is the key document fundamental to interface design.
- SDD (Software Design Description): created based on the SRS.
- STP (Software Test Plan): formed based on the SRS.
- User manual.
- Courseware.

When installed, the system has practically all of these documents delivered along with it on a CD. The user is also given all stored procedure and source codes in Visual Basic.

Conceptually, central to CoreMAS, as an A&C system, is its functional core which is expandable for each site installing the system, with the needs thereof and local standards taken into account.

The system’s core is expected to satisfy to national and lower-level regulatory requirements. This is a ready-to-go core. When the system is installed, users get all source codes to facilitate creation of their own tools.

Three system levels can be identified by analyzing the CoreMAS design features (Fig. 7.9). The top one is the interface level. This core level contains data input/output template forms enabling the user to create his/her own forms to be used in place or along with the CoreMAS forms. Functions can be also added to validate input data before there is a connection to the core’s functional programs. The interface is VB-realized, this making it easy to realize it in the computer screen.

User level	CoreMAS Sample forms	Site-specific forms
Functional level	Transactions Administration Maintenance	Site-specific code
Database level	Core level	Site-specific tables

Fig. 7.9. High-level design of the CoreMAS NM A&C system

The core’s functional level contains program codes that support required operations (transactions):

- transactions on material and items;
- system user and database administration;
- support of NM storage administration.

In addition to codes and subcodes implementing the core’s functions, there are site-specific codes which realize the functions specific to the given site or in a specific manner, and codes realizing basic functions.

The database level contains the database formed of tables required for the accounting system to operate to its utmost.

Overview of the CoreMAS design

CoreMAS uses a client/server architecture. The client computers are used to provide interfaces and pretest data. The server controls access to the database. Fig. 7.10 shows a standard CoreMAS working environment. In its center the system has a server computer which is accessible from the client workstations. There are two communication options: via the EtherNET local network and, via modems, over the telephone line. There is the following software to support operations of the system:

- Windows NT 4.0 operating system;
- MS SQL Server 6.5 DBCS;
- Visual Basic 5.0 visual programming system.

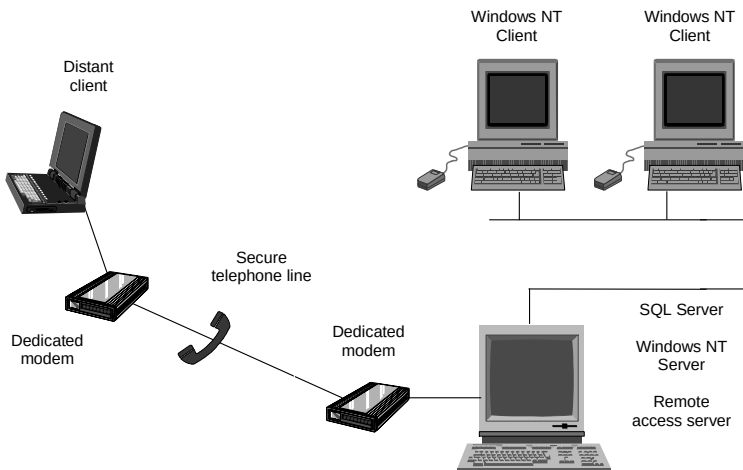


Fig. 7.10. Standard CoreMAS work environment

The Software Requirements Specification (SRS) specifies the following characteristics of the CoreMAS system:

- A capability to generate and print out the inventory records for all material in less than 3 hours. This is one of the key parameter requirements to A&C systems as imposed by the DOE standards.

- Exact status and location determination for items in not less than 99% of cases, given there is adequate data input by operator (the system does not identify item locations physically).
- At least 150000 transactions per month.
- Up to 30 users simultaneously served with a time delay of not more than 3 s.
- Support of at least 500000 inventory items.
- Support of at least 10 000 000 transactions.

These characteristics of the system make it potentially the right choice for large-sized and complex enterprises with a great deal of active material (dynamic material, multiple MBAs and material loss mechanisms). Still, such parameters also make the system hard to utilize by small research establishments, this having led to E/Z MAS, a later, simplified, A&C system.

In the context of accounting, CoreMAS features a range of properties that characterize its functionality. These, as identified by the system creators, include:

- a complete set of accounting functions;
- support of special reports;
- cost effectiveness (against systems using other architectures);
- supportability and scalability (installable at different sites with diversely scaled networks and requirements);
- reliance on commercial software only;
- high security level;
- no requirement for spatially confined rooms, and entrance and door control functions.

The reliance on commercial software, the system developers believe, makes the system, by and large, more informationally secure. Russian software engineers think quite differently. The point is that the base software the COREMAS is based on was originally designed for systems handling national security information. The products were developed, rather, for small- and medium-sized business applications. So giving the COREMAS the status of a highly secure system, as LANL experts do, is, to put it mildly, not quite fair.

A test was devised to verify the system performance. This was designed for 10000 items with a supposed history of 100 earlier entries for each. The system was expected to give out, in a span of 1 to 2 minutes, a list of inventory items for the randomly chosen storage location. The real database, for which the test was performed, contained 16000 items with

160 historical entries each. It took the system 3 seconds to produce the inventory listing for the required location.

Now, we are going to discuss the key structural features of the system. First comes an overview of the database design.

CoreMAS database design

Much in computerized accounting systems relies on how the database is designed. The quality of database design is what all other system parts depend on. The quality of the ready-made product is to a great extent defined by the approaches taken in designing the database. The CoreMAS database employs chiefly Third Normal Form with certain variations reasonably involved for efficiency reasons.

Technologically, the CoreMAS basis is the client/server concept. In this, the database core is server-based, while the user interface is based on the client computer and networked to the server via a “trusted connection”. An SQL Server and Windows NT security framework is used for the data security purposes. An ODBC mechanism is employed for client-database communications.

We shall further dwell on the key database objects used to describe information about these objects.

Nuclear material is the central object in any NM A&C system. The database was designed so that to span all of the required material attributes. Each existing material can be characterized by any number of elements. Each element can be characterized by any number of isotopes. Knowing everything about the chemical identity of a material, the system’s database allows multiple user demands to be satisfied.

Essential database notions are locations and counts of material. Each site is required to have, at least, one MBA. Many departments have each “accounting location” in the A&C system matched by a physical location, still some may have an MBA shared by more than one physical location, while there may be a physical location that contains more than one MBA. The CoreMAS system takes the material count (whether the material belongs to the MBA) and the material location as separate concepts. Most departments refer to locations by naming the one they need. For example, a location’s name may be the building, room or cabinet number. Locations are viewed as physical locations and not as structures to account for. Each material is matched by a unique material count, which is required to be such for data in the CoreMAS core database to be easier to manage. To this end exactly, the location name demands that the CoreMAS should

designate the location for this to be identified. So each location is given a unique identifier. The location name does not need to be unique, still this may be accepted as a rule if approved within a department.

The CoreMAS database core accepts the concept of item. Item is what determines the material accounted for when this is split down to the smallest parts that have one type of material relating to an “item” or more than one in addition to the elements or isotopes unaccounted for. The item identifier should be unique, while the item name needs not be such.

Containerization proceeds from the logic concept of items being often batched together. A so formed batch may be in a physical container or in an assembly or combined otherwise. A physical container may contain an assembly, another container, one or more package types, or one or more items. This leads to the following generalization: a container may contain a container or containers, a package or material. Therefore, a physical container or an assembly may be dealt with using the logic containerization concept. An item in a container ceases to be capable of moving singly, without the container. For example, if a physical container contains items A, B and C, it makes no sense to account for whether item B is capable of moving without items A and C moved simultaneously. The container description identifier is used to expressly identify the container. The CoreMAS requires a unique container identifier to be given to each container. No container names or types need to be unique, still this may be made a rule if approved within a department. If process requires so, the CoreMAS database may limit the number of containers that can be placed one in another.

The CoreMAS database supports the concept of bulk material. This is generated where items are mixed so that no individual pieces can be distinguished. The examples are solutions, spills, etc. Bulk material normally has the form of a solution in a tank or a process line. When moved across accounting or physical boundaries, these are measured to determine the material quantity to be accounted for as of the given time. A bulk material description identifier is used to expressly identify bulk material.

CoreMAS user characteristics

Expected to delimit access to data depending on the user status, an NM A&C system requires its database to contain the concept of user. Depending on the functions performed, the following CoreMAS user groups are identified:

- accounting of NM: persons who enter data on the operations done on material to be used by personnel who have no access to the material accounting system. They enter data on operations for offsite shipments and receipts of material;
- handling of NM: all persons immediately involved in material handling. These include those dealing with in-process or stored material and with the material prepared for shipment;
- guarding of MBAs: persons responsible for the material held in the MBA they are in charge of;
- measuring operations: persons who measure material;
- inventory taking: persons who compare the physical inventory data against the book inventory;
- management of material: persons who prepare regular and special reports and respond to inquiries for internal and external use;
- system administration: persons in charge of the CoreMAS configuration and servicing.

Users are given the rights and permits of access to information as defined by their respective status.

CoreMAS database tables

The database core includes all the tables essential to the accounting system operation. We shall look at essential groups of database tables and into how these interconnect. Each table in the relational database describes one entity, be it a subject or an object. The communication between entities is via primary and foreign keys (PK and FK). Some CoreMAS tables may have no connections to other tables whatever; these are archive tables, tables of constants and some others. For example, the Container ID table stores the ConID value that contains the next container number to be given to the next databased container.

The CoreMAS contains a total of about one hundred tables. The complete ERD is very complicated and cannot be described herein. Organizationally, all tables are grouped by functionality. Given below are the functionality descriptions and the listing of basic tables for each of such groups. These groups are:

- authorization;
- computation;
- measurement;
- containerization;

- transaction;
- material;
- reporting.

Authorization. This group of tables controls the process of operations on the CoreMAS menu options being authorized. It defines which accounting and control functions are accessible to the given user. Names of tables in this group: Users, Usergroup, Groups, GroupAuth, Authorization, Operation, UserOpNameAcct.

Correction. This is a group of correction tables that deal with the algorithmic steps to be taken to compute or determine the quantity of material by measurements. Example: there is a tank containing a liquid and it is required to compute the volume from the liquid level, for which purpose a cylinder volume formula is used. The tables in this group are: MatlTransformNumber, MtMatlOutput, MtIsoAmountOutput, MtInput, MtElementToOutput, MtMeasurement, and Decay. The Decay tables keep track of the decay rates for isotopes and their derivative isotopes. The MT tables are temporary tables which contain intermediate splits, combinations and changes of material as of the transaction result approval time, following which information is saved into the Material (NETWt), Element (ElementWt) and Isotope (IsoWt) tables.

Measurement. The Measurement group of tables stores measurement results and measurement units. The tables in this group are: MTMeasurement, MeasMatl, MeasElem, MeasIso, MeasType, UnitConversion, Unit, MeasNumber, Instrument and InstrumentNumber. The MTMeasurement table links measurement results to the transaction during which the material's quantitative characteristics were updated by calculation.

The **Containerization** group's tables are arranged so that to ensure the unlimited:

- 1) number of containers that can be put into one another;
- 2) packaging relating to containers;
- 3) number of tamper indicating devices (seals) applied to container, material or location.

This group includes Container, ContainerNumber, ConType, ConTypeNumber, Packaging, PackageType, PackageTypeNumber, TID, TIDType, TIDNumber and TempConMovement tables.

Transaction. The Transaction group of tables describes transactions in the CoreMAS. The Transfer and TransferNumber tables describe links to the report generation function. The Terminal table contains information on

the client computer from which the transaction was put in. The StatusType, StatusOpType and OpType tables contain types of transactions that can be done to material in different states (e.g., anticipated, unmeasured, written off). This group includes Transaction, Terminal, AcctPeriod, TransactionNumber, AcctPeriodNumber, StatusType, StatusOpType, OpType and TIC tables.

The **Material** group includes all other tables to the exclusion of the reporting tables (STPError and TableVer). These tables contain descriptions of material, elements and isotopes; the accounting logic (to which, logically, material balance areas (MBA), physical location, material forms, detailed or general types of material the given material belongs); physical elements and isotopes; descriptions of forms and processes relating to elements and material; material classification for the report generation function (COEI tables). Some of the tables in this group are: Material, Element, IsoAmount, ElemType, IsoType, ElemForm, MatlForm, COEIProfile, COEICode, Project, DetlMatlType, SumMatlType.

The **Reporting** group includes tables which are representative of the state report system (clearly, the USA's). These tables have been included in the COREMAS with a premise that each country to where COREMAS will be delivered will form its own state standard. Some of the tables in this group are: TransactionEvent741, TransferNumber, Transfer, TransactionDetail741, ShipRecMatlDiff, ShipRecElemDiff, ShipRecIsoDiff, Comment, TransportPackaging, TmpProject, TmpCOEIDetail, TmpMBRSubtotal, TmpCOEI, TmpIntAdjust, TmpCOEISumIso.

When operating the database by adding and deleting rows, one needs to see that the foreign keys of tables always indicate at the existing primary keys. This rule is called *consistency of links* and should be at all times observed. Most up-to-date relational databases do checks automatically whenever table fields are declared to be primary or foreign keys. This property is ensured in SQL Server 6.5, but, because the CoreMAS was originally developed for version 21 which did not ensure the consistency of links to be tracked down, the CoreMAS includes other software tools to support this consistency.

Stored procedures of the CoreMAS database

Stored procedures are the following database objects to consider as components essential to the A&C system operations. It is only via stored procedures that a CoreMAS user is granted access to the database. This

gives the database a much greater capability, efficiency and flexibility and accelerates drastically the speed of response for SQL queries.

Stored procedures are translated and optimized in the Transaction SQL language queries that are stored and processed directly on the server. Only the name and formal parameters of the procedure are networked and the query result is sent back. This accelerates processing and cuts network traffic.

One more point to this approach is that it enables highly differentiated control of access. Though SQL Server 6.5 allows user authorizations at the column level, stored procedures enable this to be done without using SQL Server access accounting mechanisms.

The CoreMAS uses a total of over 300 stored procedures which support most diverse NM A&C system functions.

General requirements to transactions

Essential functional operations of any A&C system are organized via transactions. Transaction is a set of data handling operations performed integrally in the database. Where not all of them can be performed, the transaction “rolls back”, which means that the database is reset to the status it had before the transaction. Any CoreMAS transaction is done in five consecutive steps:

- input: what the user should submit for the transaction to be successfully launched,
- normal handling: what is to be done by the CoreMAS core application,
- exception handling: handling of exception cases,
- user authorization: determination of which transaction may be entered by the given user for the material in the given record,
- output – the anticipated result of the successful transaction.

To enter a transaction, one needs to have a unique identifier to enable identification of the data record concerned. It may be identifiers for the descriptions of material, containers or material location, or identifiers of instruments. The moment the identifier is authenticated, data elements are needed to specify the type of the transactions required.

Any time the material is changed as the transaction is normally handled, the respective transaction will be recorded and so the changes in question will be identified. No transaction record is subject to erasure or update. In the event of an error found after the transaction is recorded, input data is to be created to rectify the error and a separate corrective transaction should be done. No description data is permitted to be physically updated or erased

for the table containing item, container and location data. Any change to each material record is to be saved to enable this to be revised in different cases.

Where a transaction happens to involve a case of an identifier having been entered erroneously, this case is dealt with as an exception and the procedure should respond with a code indicating the error handled.

In the event of an attempted access to an unauthorized account, the core application should give out the exception code, deny access and log the attempt of unauthorized access.

Functionality of CoreMAS

The diversity of stored procedures can be employed by the user to realize the A&C functions. The CoreMAS core application includes the following functions and standard programs:

- movements of material, including relocations within the MBA, movements between MBAs, as well as receipts and shipments with the report identification external tag;
- transformation of material – split, combination, decay, adjustment and change of project numbers;
- containerization of material;
- example of the state report system;
- physical inventory support features;
- supply of data to prepare standard and special reports, as well as to respond to queries. Outside programs will handle special reports and queries;
- a complete history of transactions for each item;
- support for striking the balance in the accounting period;
- TID tracking;
- saving of instrument readings;
- management of the system and administrative functions;
- example of built-in user help functions.

Now we shall look in more details at some of the A&C system functions.

Movement of material. There can be internal or onsite and offsite material movements. Material can be shipped to and received from anyone. To be moved, the item concerned is put into an in-transit condition and, after having been moved, out of the in-transit condition with its new position recorded. For offsite shipments/receipts, the CoreMAS supports

the logging and identification mechanisms, and generation of respective documents (reports).

Transformation of material. This function describes transformations of respective material. Transformation is understood as split of material, adjustment of records and combination of material. It is not applicable to containers. When this transaction is performed, one needs to determine:

- the identifier of the material transformed;
- the identifier of the new material;
- the type of the transaction performed.

Containerization. There are two transactions through which this function is implemented: placement of a material, a package or a container inside a container and removal of these from the container. The items require the following source data to be identified: a material, a package or a container to be placed inside a container or withdrawn from the container, and the receiving or giving container.

Seal tracking. Seals are subject to record-keeping with reports generated for seal locations and seals linked to containers.

Radioactive decay. This function accounts for changes in the quantity of a nuclear material over time. So that this material to be accounted for accurately, masses thereof are required to be updated given radioactive decay of the material. The CoreMAS computes decay on a monthly basis for all nuclear material for which quantities subject to accounting can be changed by decay. These computations and corrections are applicable to all material items of types 44 (americium 241), 47 (berkelium), 48 (californium), 83 (plutonium 238) and 87 (tritium).

Control of measurements. The CoreMAS supports control of instrumentation. Each measurement is added to the measurement control history which contains all measurement information. If indication values of an instrument fall beyond the set limits as defined by independent calculations, the instrument can be rendered “inoperative”. Such instrument cannot be used for accounting measurements. Only authorized personnel have the right to bring it back to operation. This function is set by two transactions: instrument disactivation and activation.

Any A&C system should operate as a reference system. Therefore, the CoreMAS core should support responds to queries. The data wanted should be put out in response to queries. Each installing department is expected to devise its own techniques for setting out results in response to queries. The system core supports responds to the following queries:

- location queries;

- count queries;
 - container content listing;
 - material condition listing;
 - in-movement material listing;
- transaction details.

Crystal Report is the software used for the CoreMAS report generation function.

Security requirements

The US DOE's requirements to A&C systems are set forth hereinafter. These include only the requirements to which the CoreMAS core satisfies. The satisfaction to specific requirements is with the developers adapting the system to national uses.

- The purchased CoreMAS software should be examined prior to being used to make sure it does not contain anything to be potentially compromising to security.
- All commercial software should be respectively licensed before it can be inserted into the CoreMAS core development environment.
- Each user is subject to authentication by the respective user identifier.
- A password should be used along with the user identifier.
- The CoreMAS core should permit access only to those users having an approved user identifier and a password.
- Access should be denied after a maximum of five failed attempts to log into the system using the same user identifier.
- The password should have a maximum of 12 month validity and be invalid thereafter.
- Stored passwords should be protected by means of access control, coding or both.
- Access control provisions should be made to protect the database against unauthorized modification or cracking.
- Measures should be taken to avoid display of the password.
- The computer's operating system should store the password change record. This record is storable for at least 6 months.
- The computer's operating system should store records of each system login and logout. This record is storable for at least 6 months.
- The computer's operating system should store records of each action leading to file creation, opening, closing or destruction. This record is storable for at least 6 months.

- The computer's operating system should store records of each action leading to access to the files system. This record is storable for at least 6 months.
- The computer's operating system should supply file access control listings. A file access control listing should allow the file owner to permit access to the file (separately to each file).
- The computer system should be fitted with a dialog session disable mechanism after the user idle time. The idle time after which the disable function is initiated is specified by the installing department.

Components of the CoreMAS computerized A&C system

Excluding the data transformation and transport component, the CoreMAS NM accounting and control system comprises two basic components: Admin and CoreMAS.

Admin has been developed to give administrative support to the A&C system and authorize the initial system installation by the system administrator. The Admin capabilities include:

- configuration of user groups;
- authorization thereof;
- configuration of the site specifics. Where the developers have created site-specific tables or wish to create a new form to model one of the forms of this component, they are expected to authorize operation of these tables.

The CoreMAS component is properly an automated NM accounting system based on a client/server architecture and an advanced relational database management system. The CoreMAS tracks the site activities that influence the NM status. The system design offers broad accounting and reporting capabilities. The CoreMAS design is based on an readily expandable system compatible to site-specific modifications and functionality.

To launch the program, the name "CoreMAS" shall be specified as the source of the ODBC data on the client machine. The connection to the database is by calling the OpenData data access subprogram. The ODBC connection is via the ODBC data name "CoreMAS". Unlike the User Data source, this is to be set as the System Data Source so that all those connecting to the system have access to it.

Fig. 7.11 shows the system's interface master form with the unfolded system menu.

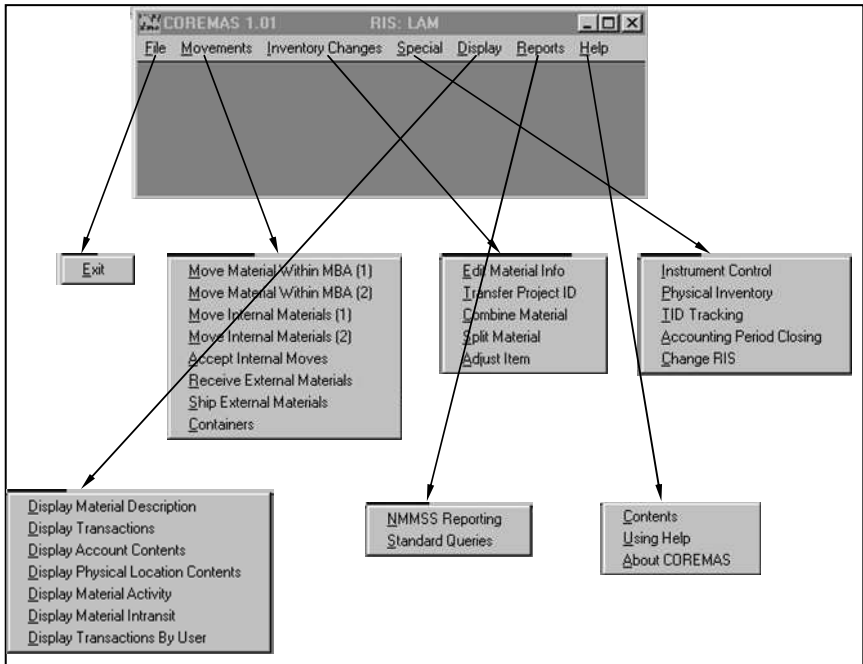


Fig. 7.11. Main menu of the CoreMAS component

E/Z MAS as an example of Web-based systems

The E/Z MAS, a simplified A&C system, may be viewed as one of client/server systems which have been defined hereinabove as three-linked [21]. Fig. 7.12 shows a schematic of the system's architecture components.

In this terminology, there are three system components standing out: presentation logic, business logic and database access logic. Here, as in the CoreMAS system, the database access logic is concentrated on the database server. The difference is that Access can be used as the DBMS, so no capabilities of stored procedures are employed to transport part of the business logic to the database server. Most of the business logic is concentrated on the Web-server in the form of *.asp files. Finally, the presentation logic is distributed between the Web-server in the form of www pages and the workstation as the browser program. Such program is readily expandable to multilinked connections.

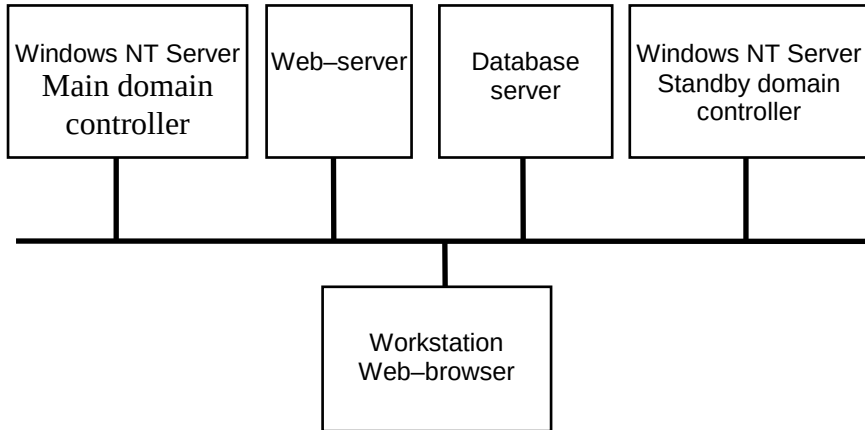


Fig. 7.12. Components of the E/Z MAS NM A&C system

Noteworthy is that the above functional units have to be distributed on physically separated computers. Thus, small networks may have the domain controller, the database server and the Web-server combined.

This system is capable of operating under control of any Windows-family operating system. Specifically, it operates in the certified Windows NT 4.9 OS environment, while its operability has been tested under Windows 2000 control.

The system operations require activation of the server component in the OS. For the said operating systems, this is Internet Information Server of 4 version onwards.

The database interface in the system purports the possibility of any DBMS that supports the relational model to be used. All references to data are via SQL queries, and the data source is connected to the system via ODBC. The system intrinsically interacts either with MS Access or with MS SQL modules. These two DBMSs have a somewhat different query language syntax, so two query versions are generated in the modules' text depending on the system settings.

The type of the operating system on the workstation is not decisive. All security functions are performed on the server side, and the Windows 95/98 and Windows NT operating systems enjoy absolutely equal rights. Basically, Web-based systems do not depend on the platform on which the workstation is based, since the ASP-technology generates HTML-

documents “on the fly”, in such form as acceptable for the given system and the browser. There is however one thing limiting to this. Some of the functions in the scenario are written in the VBScript language and are to be executed on the client computer, while the VBScript language is nowadays supportable only by the MS Internet Explorer browser. So when other platforms or another browser program is used in Windows systems, faults may occur.

Application and performance of the system

As mentioned earlier, the E/Z MAS has been designed for enterprises with a moderate NM accounting and control demand. The requirements specification for the E/Z MAS software is a much less voluminous document than its CoreMAS counterpart. It specifies the criteria to be looked at for the potential application at a enterprise as follows:

- enterprise type – the system is intended for item handling enterprises rather than for bulk handling ones;
- number of transactions per month – the E/Z MAS is intended for enterprises with a minimum of 50–100 and a maximum of 1500–2000 transactions per month;
- item type – the E/Z MAS is intended for enterprises with both static and dynamic type of items;
- inventory dimensions – this parameter should be considered along with the type and the number of transactions per month. For example, an enterprise with 100000 static items and 100 transactions per month is the right candidate for the E/Z MAS installation. And an enterprise with the same number of items and 100000 transactions per month is the wrong one.

Here are some of the E/Z MAS features to mention:

- the E/Z MAS can operate as a closed system or as an open system in a closed environment.
- the E/Z MAS can operate both on a isolated computer and in a network with a dedicated database server.
- the A&C system controls system logins by name and password, both of these not relating to the user parameters in the domain (unlike the CoreMAS) and verified by the system as such.
- data can be databased using barcode devices and scales.
- the E/Z MAS is available for operation immediately after the installation. At the same time, with all files being presentable to user, the system can be readily updated by adding functions.

E/Z MAS A&CS database design

The database tables can be grouped into a number of domains:

- Users and right of access: Users, UserOp, Operation.
- Enterprise: Enterprise, PhysLoc, MBA.
- Material batch: Batch, BatchMat, MatType, PhysForm, ChemForm, Packaging, Quality.
- Containers: ConInfo, ConType.
- Transactions: ShipTrans, TransType, Trans, ConTrans, StatusType.
- TIDs (seals): TIDTrans, TIDInfo, TIDTransType, TIDType.
- Barcodes: BarcodeError, InvVerify, InvTrans, InvInfo.
- Federal-level reports: UnitConversion, Classification.
- A separate Log table not connected to any table is used to control logins by memorizing the URL from which the system was logged in.

The E/Z MAS system includes base tables from which data cannot be removed so that no data integrity be disturbed, e.g. physical location. These tables are filled in when the system begins operations and information can be only added thereto.

We shall discuss the key concepts and entities the E/Z MAS database contains.

The description of any material used in the database is based on the concept of material batch. The material type, weight, physical/chemical form and package are identified for each batch. Batches of material can arrive from beyond the site or result from processing of material.

The material of any batch is subject to distribution among containers. The system watches that the overall material weight be the same as that of the batch. The containerization concept is close to what was employed in the CoreMAS A&C system: no limited number of containers that could be placed one in another, application of seals and conformity of these to containers. The only difference of the containerization concept is that no material can exist in the E/Z MAS beyond the container. If it does (ingot metal, for example), the system creates a virtual container which expressly conforms to this part of material. The container may be empty.

Each container, unless it is in-transit (the same status exists in the CoreMAS), is matched by a location. If a container is contained or placed in another container, the location thereof has the NULL value and is identified via the location of the external container.

The location is identified in the database by a number of notions. The most general notion is enterprise. Enterprise for this database is only one and it may receive only external shipments so these exist as names

(addresses). There is at least one MBA matching the enterprise. The number of material balance areas for enterprises is not limited. It is inside the MBA that the location is specified. There can be not less than one location while the maximum number of locations is not limited. The location may contain containers or be empty.

Finally, an important component of the database is users. Each user has a login and a password. Rules of access to MBAs and containers and rights to perform any function in or out of the MBA are specified for each user.

The E/Z MAS developers believe that such database arrangement is adapted the best to accounting of item material, though bulk material can also be accounted for.

Functionality of E/Z MAS

The E/Z MAS possesses all the functionality an NM A&C system is expected to have. The system keeps track of nuclear material using the inventory listing. The information on material in this listing is changed synchronously with the actual changes in the so-called near real time. This, naturally, suggests that the user enters the transaction data on a timely basis when the real action takes place.

Still, the system is not designed to control material physically; it does not control racks, doors or locks, and does not track down TIDs.

Five categories of the E/Z MAS functions can be identified:

1. Movement of containers.
2. Transfer of containers into or out of the enterprise.
3. Inventory-affecting operations.
4. Generation of reports.
5. Operation of statistical database tables.

More details on the system's functionality are given in descriptions of the following operations.

- Movements within MBAs – this function allows an authorized user to move containers and the content thereof between different physical locations within one MBA. For this operation, the user identifies the MBA, selects the containers, defines the new location and orders the process to be started. Where the process runs routinely, the following transactions are implemented and logged: the one showing that the container has been moved and that indicating the container's new location.
- Movements between MBAs – this function exists in two forms: 1) containers are moved between different MBAs in one operation, and 2) material is moved between different MBAs in two steps in an in-transit

condition. The container shipment function can be performed by one user and the container receipt function by another user.

In both cases the user selects the original MBA, the container, the destination MBA and the physical location therein. In the second option, the user ships the container without giving the destination, the container being later put out of the in-transit condition at the destination point.

- External transfers: shipments/receipts – this function enables material receipts and shipments from and to beyond the site to be recorded.

When material is received, the authorized user can add a new container and the new material it contains to the system in such form as it has been received from another enterprise. It is exactly where the material's physical appearance, chemical composition and form are identified and the material is linked to the container. In all other operations we deal with containers and not with material. It is also where the MBA to which the material is shipped, the number and composition of containers and the outside enterprise from which the material was received are identified.

When material is shipped, the user records the enterprise to which the material is shipped and the container or containers to be shipped.

- Inventory change – this may involve a number of operations:
 - correction of material parameters. This function enables the user to modify the material weight and the elements and isotopes thereof. The user selects the MBA, the material type and the type of the correction to follow. One may change the material weight and update information on an element and an isotope in the material;

- combination of materials into a new material;

- split of a material batch into two batches;

- bulk separation – makes it possible for the user to record isotope separation operations.

- Containerization – may involve the following operations:
 - formation of a container not linked to material – empty container;
 - placement of containers in another container;
 - withdrawal of containers from a container;
 - movement of material between containers.
- Physical inventory taking. This function helps the user to enter the physical inventory taking results with recorded observations. The checked container is labeled and the check results are entered in process.
- Accounting of tamper indication devices (seals). The system enables the user to generate seals, update seals and be provided with reports on

seals. All this is virtual, i.e. the connection to real seals is the responsibility of the operator.

- Generation of reports. In general terms, the system enables new reports to be easily added and you will do it as part of your lab practice. The base reports are reports for the following groups:

- containers (transactions with containers and the content of containers);

- content of physical locations;

- MBAs (transactions in the MBA selected and the MBA content);

- transactions (output of transactions as arranged by dates and users).

Besides, the system supports generation of special reports for the Federal NM Accounting System. As no form for such reports has been specified by the system establishment time, the system contains an arbitrary report.

There should be also an understanding that “report”, as seen by the E/Z MAS developers, is an ordered table, formed according to specific rules, that has been chosen from the database with the aid of an SQL query. Russian requirements to A&C systems demand that an electronic system should be backed up by collection and keeping of hard information copies. This does not imply anything that cannot be done, still one should understand that, in addition to the electronic version, a potential Russian user of the E/Z MAS is expected to make so that to be able to get printouts of reports in any form. It can be easily done in the MS Access environment.

- Configuration of data. As mentioned hereinabove, the system includes rarely updatable tables (locations, MBAs, enterprises, users). These tables can be updated only for special authorized users with the administrator status.

- DB interoperation with peripherals. The most recent E/Z MAS version offers a capability to database information directly from peripherals. Functions of communication with two types of devices (barcode equipment and scales) have been built in. The communication is via a com-port from a dedicatedly equipped workstation. Programmatically, Active-X that communicates with this port is used in the asp-file. This function entails a problem still requiring solution. When peripherals are off the computer, there are no these functions in the system interfaces. When a workstation gets connected to peripherals, the functions are on in all interfaces because of having been uploaded from one file on the Web-server. It is not a big problem and one solution to this is to switch on this function for users with special logins who have measurement and inspection authorizations.

- System access security also has a key role in operations. Each user has his/her name linked to a set of functions he/she is authorized to perform. The E/Z MAS supports three user types:
 - users with the right of viewing only authorized information;
 - users with the right of modifying authorized information;
 - database administrators – users with the right of authorizing the rights of other users.

Examples of E/Z MAS interfaces

To conclude with, we shall consider examples of the system's interfaces, that is, how the above-described functionality is realized in asp-pages. Here are some of the typical examples to illustrate how a script technique and a system form design can be used.

Fig. 7.13 shows the E/Z MAS home page opening in the browser as the system is logged in. The user is offered to enter the login and the password. There is a version of the E/Z MAS A&C system that requires two independent user identifiers to be entered. This version is realized for enterprises where the so-called two-person rule is practiced (two persons only may have access to an activity with NM or information thereon).

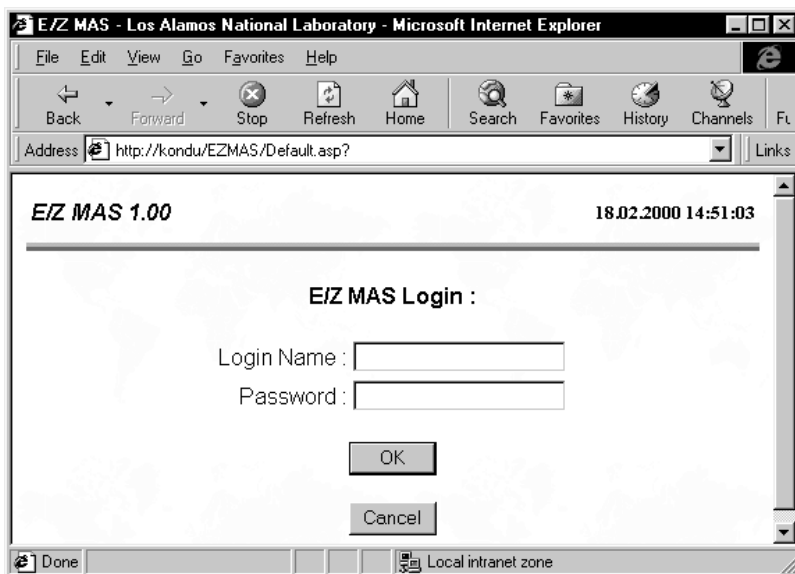


Fig. 7.13. The E/Z MAS initial page

After the user identifier and password are entered and the user is authenticated, the system's home page opens (Fig. 7.14). The system's home page has its top and bottom window fragments respectively containing the system version name and the main menu. The successful login message is in between.

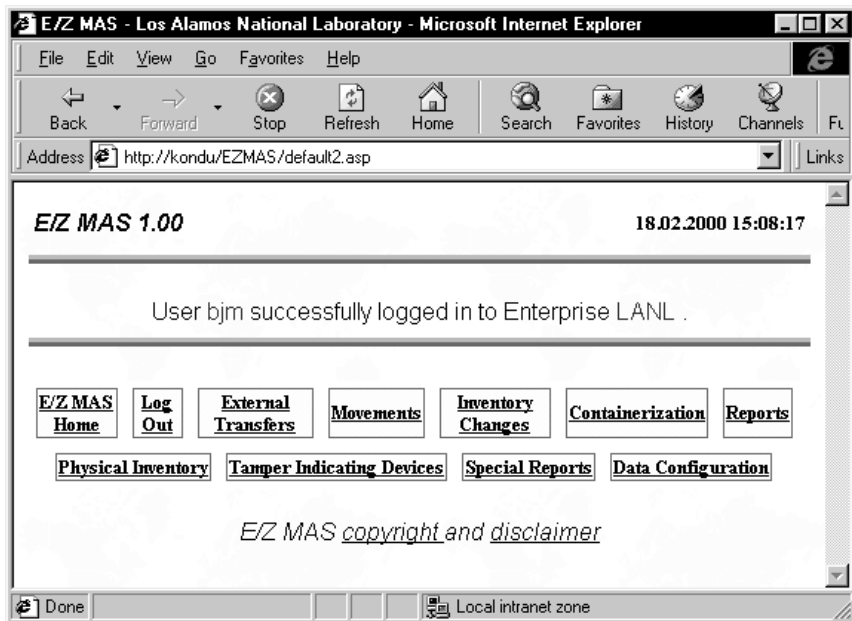


Fig. 7.14. The E/Z MAS initial page. User menu

Use of the E/Z MAS at MEPhI

The E/Z MAS is the only US-designed NM A&C system operated in Russia. It was supplied to MEPhI in 1999 and certified following an upgrade to meet the FIS requirements [22]. The upgrade was given largely to those database tables and functions dealing with the FIS' NM accounting and control requirements. The codifier and notation tables were added and functions built in to generate reports in electronic form in FIS-required formats.

The system has one uncertified component, the MS Access DBMS, which limits, mostly, its applicability. To be recertified, the system is being given a profound upgrade based on open-code base software.

To finalize this chapter on computerized NM A&C systems, we shall discuss how such systems are developed and commissioned and the whole process is regulated.

7.5. Development of computerized NM A&C systems

A study of computerized NM A&C systems has one important point to consider. This is about how a software product is being built throughout the series of phases, from the inception to the commercial implementation. In this respect, it is not only the system creation procedures that matter but also the documentation that becomes required.

Russian standards are fairly regulatory in this regard. The USA, with a much greater experience in establishing large software projects than Russia, has however in effect diverse procedures and techniques to plan, design, test and commission software. Software development concepts and methods demand a separate consideration, so these will be overviewed in brief further in this Chapter with some guidance provided.

Industry standard's requirements to development, commissioning and operation procedures

The respective industry standard [1] identifies a number of phases involved in creation of A&C systems. The initial one is the predesign stage opened with a site survey. This needs a feasibility study and an analytical (data security) justification to be prepared for the A&C system development. A design specification is developed with well-defined information protection requirements included.

Next comes the design. The final step in this is the detail design, including organizational and technological concepts, software development, and data protection provisions and practices. All concepts accepted are to satisfy to the regulations and requirements of standards and the design specification requirements.

The hardware and software designed need to go through a series of tests. Hardware:

- tests for functionality in the installing site's environment;
- tests for conformity to data security requirements.

The base and applied software undergoes a laboratory test series. Data security features shall be certified for conformity to respective data security regulations.

The system is commissioned at the subsequent phase.

To commission an A&C system, it is required to:

- develop the listing of operating documentation;
- submit a general description of the system, including performance, application and required hardware data;
- develop a package of regulatory working documentation;
- submit a description of a package of organizational and technical measures, the institutional structure and the manning schedule of the enterprise to the extent concerned with the A&C system;
- develop a systems programmer guide to include information on the system installation, setup, testing and crash recovery (reference to GOST State Standards follows);
- develop a user guide with the information to support the user and A&C system software/hardware dialog;
- submit the software acceptance certificate;
- submit the A&C system commissioning schedule.

The commissioning shall involve the A&C system software certification for the conformity to information security requirements.

There can be pilot and commercial operation. Pilot operation of the system requires its prior certification by a special commission. The commission formed to bring the system into pilot operation shall be composed of the developer, customer and operator representatives. Where the A&C system is connected to the central information system, the commission shall also include a representative of the inspecting agency. A technical acceptance certificate shall be made out.

No further steps are regulated by the standard. Other standards exist on automated systems and information technologies. This is where maintenance, support and decommissioning issues are regulated. There is also an abundance of engineering documentation that accompanies the project.

Software lifecycle

The US standard introduces the concept of software lifecycle. This represents all processes relating to a particular software product, from conceptualization to decommissioning and substitution for a newer product.

No software lifecycle stages are expressly identified, still the most important steps are as follows:

- concept;
- review of requirements to software;
- development;
- implementation;
- tests;
- deployment and testing;
- operation and servicing.

Depending on the purpose and scope, the effort and cost relation for various steps may vary between projects. Planning/design (covers the three initial steps) and testing/deployment are the two most costly stages.

One should also remember something some US developers call a 1:10:100 rule, which is understood like this. The cost involved in correcting an error (inaccuracy) at the planning/design stage is assumed to be 1. The error correction cost at the programming stage will then be equal to 10. The error correction during the final test stage will ultimately require a 100 times greater effort to spend. This estimate gives an idea about how important predesign is.

The USA has up to 175 thousand program projects undertaken yearly in various fields, the total spending for these reaching 250 billion dollars. Only 16% of these are implemented on time and at the cost planned. 31% of the projects simply fail and are not brought to fruition. This has given US developers rather a broad experience, both positive and negative, and has led to the underlying requirements having been shaped on all system development stages that are decisive to the success of the project.

Planning of accounting and control systems

The system planning opens with a requirements review. This review has the purpose of formulating, analyzing and documenting functional, information, operating, interface, characteristic and design constraints for the software product. This is the stage for the designer to detail WHAT the system must do and, by no means, HOW this must be done. This is also the reason for software developers not to be preferably involved in this project stage. Anyone with an experience in building systems inevitably thinks about how to realize requirements, and so, when doing this, may turn to ready-made solutions to satisfy the customer requirements.

The following is involved in the requirements review:

- determination of the initial project scope;

- analysis of the task membership region;
- determination of the region's key functions;
- determination of alternative project decision patterns;
- selection of the unique decision;
- generation of the output document (Software Requirements Specification or SRS);
- determination of the deployment program.

A work unit is formed to implement these stages. This unit is expected to include the following roles:

- a business leader. This is an expert in the subject matter (business) for which the project is established. He/she is in charge of business decisions;
- a coordinator – chairs meetings (a project management and performance expert). The physical project leader;
- an administrator – a representative of the developer in charge of the overall guidance, budget and project implementation;
- a sponsor – the person responsible for funding;
- a technical leader – a representative of the developer in charge of technical guidance;
- a user representative – acts on behalf of end users;
- a program project unit – a work unit.

Work starts. So now we shall talk in brief about the project planning and design key stages.

Determination of the initial project scope. This stage requires the developer to expressly:

- define what shall be or shall not be included in the project, i.e. identify a subtask in the overall task region that can be solved for the money and time allocated;
- conceive the problem in general;
- select the requirements review procedures and tools;
- secure the customer's and the sponsor's documented approval for the project scope.

A project unit is formed at this stage to prepare activities and equipment and to outline the general concept.

Workshops and interviews are used to acquire data at the planning stage. The most important thing to focus on is to have all information recorded and do not permit leaders to suppress the opinions of other people involved. Often it is required to keep division or enterprise leaders away from these workshops. The discussion should be as free as it can be. The main thing at this stage is to have immediate users involved. As the experience of

successful US projects shows, the user involvement is decisive to the success of any project.

The next stage deals with design as such. This will analyze the functions and processes the designs will involve.

Functions are what is performed or is to be supported by the system. Process is a specific realization of a function – a process starts, continues and ends. Specified processes and functional requirements are documented and presented graphically. Development needs to include decomposition of functions. This means that global functions, say, a material movement function, are considered first. Then the function is subdivided into lower-level functions: movement of material inside MBA, offsite receipt of material or shipment of material. All this continues until one obtains elementary functions or functions one cannot subdivide into further lower-level functions.

Dependencies are established between functions. The following dependencies are identified:

- direct dependency – a process starts after another process ends;
- mutually exclusive dependency – conditions are used;
- recursive dependency – the process is rerun;
- parallel dependency – the result leads to more than one process run.

Objects of activities and attributes thereof should be further identified. Object is a person, a place, a thing, an event or an idea, information on which needs to be obtained for the activity to be performed successfully. Objects have attributes; which are properties of an information object. Later into the database design stage, objects will be realized in tables, while attributes will become table fields (columns). This is a very important stage that requires immediate user involvement. If an object fails to be specified at this stage or no attributes thereof are identified but come out as late as at the programming or deployment stage, the whole of the database structure will need a change.

After objects are specified, relations between them are established. This process is close to the process of linking database tables.

Technical requirements are established at the next stage. This stage requires the following technical constraints to be established and documented for the future system:

- capacity;
- design;
- information security;
- accessibility;

- interface;
- DBMS in use.

Requirements need to have a particular measurable form. Let us take an example. The time of access to a table is 2 s. The number of users, clients and transactions is per day. The requirements of standards and reports should be taken into account. We were considering examples of such requirements when reviewing specific software products and the CoreMAS and E/Z MAS A&C systems.

Following the above procedures, the developers need to screen the potential decisions for the unique or the best decision. One screening technique is expert appraisal. An expert unit evaluates different key requirements giving them rankings and evaluating alternatives in these rankings. The parameters are tabulated. The ranking is multiplied by the appraisal value and summed up. The result specifies the options preferred. Then potential risks of the project failure are evaluated.

We proceed finally to the closing design planning stage when the software requirements specification (SRS) is prepared. This stage will result in a document that describes the key software requirements. Further on, this will be what will guide the design of essential software components. The extent to which the SRS is formal depends on the design dimensions and relevance. The specification shall contain:

- functional requirements;
- data requirements;
- technical requirements;
- decisions;
- problems;
- recommended decisions.

Software design

After the SRS is prepared, the developer starts software design. The deliverable at this stage is the database created, including fully structured tables with links and facilities to support information integrity (triggers, limits, saved procedures) and the Software Design Description (SDD), a detailed document about the data structure and functions. Following this preliminary review, the next postdesign step (coding proper) turns into merely a technical operation.

Let us now look at the software design process and some of the techniques this involves. The deliverables for the design stage are:

- the architecture design which mutually relates the system's major structural components;
- the procedural design which supports the conversion of major structural components to a procedural software description leading to a program source code generation;
- the data system design which converts the information model to the data structure (database and program data).

The first of these three stages is, normally, development of data. The most important thing in the development of data is selection of logic object representations identified when the SRS was being written. The following data development strategy has been proposed:

- systems analysis, which is used to analyze functions and processes, is applicable to data as well;
- all data structures and operations on these should be identified;
- a data glossary should be generated and used during the program creation;
- consistent detailing of data – low-level data is left for the next design stage,
- data structures should be known only to the models that use them directly;
- libraries of data structures and associated functions should be created;
- the programming language should support abstract data types.

The program architecture development is aimed primarily at getting a developed modular structure and showing the relations among different modules. The program architecture development combines program structure development with development of data via the interface among the modules.

Procedures are developed after the program structure (architecture) and the data structure are established. The development of procedures involves largely two techniques: use of flow charts and a reference programming language (pseudocode).

Software testing

After the software is designed, the coding stage begins. It makes no difficulty with all the work done before. The coding stage accounts for just a small portion of all efforts spent. As evidenced by the US experience, the cost of code writing is negligibly low as compared to the program design and functional check costs. After codes are written, we set on a new step, which is a software test stage.

There are three processes involved in checking the performance quality of different project stages: tests, debugging and testing. Tests and checks take place at all project stages to identify errors as early into the development process as possible. Defects may occur at any project stages, e.g. some of the required functions may be neglected at the requirements review stage or mutually incompatible requirements may be introduced.

Reviews and inspections are used to localize defects at the development stage. These are performed by teams of experts other than involved directly in the given development work. There is no fixed standard so respective reports may have any form.

Testing and debugging take place during and immediately after the coding stage. Debugging is different from testing in that the programmer who does debugging corrects the error, if any, while testing just records inaccuracies. Testing begins during planning, the earliest design development stage. As the development goes on, the software testing program is generated or updated for each stage. Unit testing takes place at the coding stage. After the product is completed, system testing is performed, this including detection and correction of inaccuracies. Finally, the software system undergoes user acceptance testing when installed for the customer. Final testing is subject to documentation. Practical evidence exists that testing, however careful, can never completely eliminate all the defects within real designs. Testing, on the average, identifies about half of the existing errors. The rest are identified and, where possible, removed as late as at the software maintenance stage. There are special firms in the USA providing services in independent testing of software.

Commissioning of A&C systems

Deployment is a frequently used alternative term for this, as viewed by US experts, important software lifecycle stage. The following principles are identified which make it possible for the process to run smoothly.

Realization of how important the early and careful deployment process planning is. This is of special importance to the client/server environment. Keeping in mind the future deployment when at the design and testing stages will help avoiding a great deal of painful problems when a designed and carefully tested system fails to perform as efficiently as required in a real environment. The cause for this is that the system was debugged on other equipment, on more powerful computers or on a more productive network.

- There should be an understanding that deployment is a scheduled process and must not violate normal cause of business.
- There should be one person responsible for the deployment.

There is an example to illustrate the complexities involved in deployment of software. It took Mitsubishi, California, two years to deploy a software product instead of one year planned initially. This raised the cost of deploying the Oracle system to nearly 3 times as high as that of the software development effort.

So what are the problems involved in software deployment? The major of these are:

- Cost of network equipment, DBMS and so on.
- No computer hardware and software standards on the client's side.
- Personnel training in new user interface standards.
- Incorporation of software that changes standard work procedures.
- Unfriendly user.

This leads to recommendations on how some of the said concerns to be removed. The simplest and one of the most efficient ways is to have particular users involved in the system creation process since its earliest phases. User training needs to be started well in advance with equipment and software standards to be phased in as the system development process goes on (management of configuration). The user must be a partner.

Deployment stages:

- Analytical phase. Starts in parallel with the development of requirements and runs continuously until the deployment begins. The following should be defined at this stage:
 - the user qualification level and presence of hardware/software;
 - requirements to parameters of existing computers;
 - operating environment, access and security control requirements;
 - the need for conversion of the existing data;
 - roles, duties and costs for the maintenance phase;
 - if new hardware and software should be acquired and license rights granted.
- Construction phase. Hardware and software is acquired in this step. Data conversion systems are tested. User, operation and other manuals are compiled.
- Training is a very important activity given special emphasis in the USA. Timely training is essential. Skills may be lost if acquired too early, while the user may not accept innovations if the training was late. Rather a great spending is required (course preparation, training logistics).

- Deployment phase. All documents are released, training is given, data is converted and the system begins to operate.
- Closing phase. The powers of servicing the system are delegated.

Servicing, maintenance and decommissioning

Servicing is the personnel activities on ensuring normal operations in the stage of production. Servicing includes support of performance, support of data accessibility, support of information security and fallback recovery.

Servicing of a system requires a particular staff of personnel. These include systems administrators, database administrators, security experts, network administrators and operators.

Maintenance means the developer's activities on correction of errors, as well as on the system upgrading and evolution after delivery to consumer. This is a very important activity. As analytical survey data shows, software maintenance in the USA accounts for 70% of the corporate spending on software. Only 30% is spent to purchase new software. The following maintenance types are identified:

- corrective (emergency and routine);
- adaptive (new hardware and software as conditions change);
- perfection;
- preventive.

It should be remembered that an intervention with the software operations bears the risk of an error. This stage normally involves the minimum volume of testing with no minor changes documented. No earlier standards are observed. Hence the best strategy is to minimize maintenance. Maintenance should be largely reduced to emergency maintenance. User demands for the system updates should be accumulated and lead to a new release of the system. Updates should be dealt with as new designs with the maximum volume of testing and documentation for all updates.

Where the system maintenance cost goes in excess of the gain from the system's operations, the time is ripe for having this decommissioned. Normally, the existing system is replaced by a similar but a more advanced system.

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CHAPTER 8

INFORMATION SECURITY OF COMPUTERIZED NM A&C SYSTEMS

8.1. Secure information processing systems

Integrity of information and information access security are two of the critical aspects involved in design and operation of automated nuclear material accounting and control systems. Information security is given top priority in NM A&C systems which are established to handle national security information. Any intentional or unpremeditated loss, distortion or theft of information in these systems may have harmful effects, so the industry standard that regulates hardware support for NM A&C systems [1] requires any NM A&C system to have an information protection system as its integral part. All NM A&C system's operation stages need to involve information protection ensured through a combination of measures taken to avoid leakage of information or exclude influences thereon to be exerted over technical channels, as well as to prevent premeditated software and hardware impacts to violate the integrity of information in process, transmission or storage, or break down hardware.

Confidential information is handled based on regulatory documents that govern protection of national security information. A shift from processing of paper documents to computerized handling of information demand that these requirements to be fulfilled on a continuous basis. A computerized system intended to process classified data is expected to be organized as these documents require. Thus, one requirement is to have user access to information in computerized systems to be arranged in such manner as defined by the document's secrecy class or the officer's access level.

Electronic handling of confidential data involves extra factors which are potentially compromising to an information system. These factors are called security threats. Some security threats are inherited by computerized systems from conventional data processing systems, e.g. theft or disclosure of information. At the same time, however, computerization brings about new threats. These come from the fact that automation of data processing keeps humans away from direct operations with data carriers. Powers are delegated to computer programs which may disturb confidential data handling as the result of premeditated actions or program code errors. To be usable for automated confidential data handling, a computer system needs to counter security threats successfully.

Russia, lastly, has a well-established system of information security standards. A system used to handle nuclear material data is expected to satisfy to the criteria required by these standards. This conformity is subject to verification by qualification tests. There are also industry standards and guides in effect at the enterprise level. These contain requirements to be also taken into account.

Therefore, a secure information processing system [2], specifically a computerized NM A&C system, should satisfy to the following three requirements and, subject to these, is expected to:

- automate confidential data handling processes, including all aspects thereof involved in ensuring security of the data processed;
- counter security threats that act in a particular environment;
- meet the requirements and criteria of security information standards.

Secure information processing systems should ensure information security. Information security, as viewed by the expert community, is security of the information environment that supports its formation and evolution in the interests of an organization or the state. Prevention of information security threats and response to these is achieved through a combination of organizational, legal, technical and technological measures known, collectively, as information protection features.

8.2. Information protection in accounting and control of nuclear material

In recent years, security of information technologies has been the cause of an increasingly growing concern, while analytical surveys show a yearly increasing damage from security violations. Here are some figures to illustrate the level of damage from computer viruses for the several past years. The virus-caused damage was about 13 billion US dollars in 2001 and 20 to 30 billion in 2002 reaching, a year later, 55 billion. Nearly the same was the damage, as some estimates show, from the Mydom virus in January 2004. Therefore, there is every reason to speak about a crisis in the field of IT security.

The security crisis has its roots in the rapidly evolving information technologies and the security provisions lagging behind the technological advances both in theoretical and practical terms. The huge computational capabilities of modern computer systems are combined with the handiness of these. The formation of the global information environment makes information resources accessible to a great number of differently skilled users. Most users are not competent enough to keep security of their

computer systems at required levels. Most computer-virus plagues could be realized because of users failing to check their computers on a routine basis, update antivirus databases and install timely operating system upgrades which eliminate software errors revealed.

The advancement in computer technologies brings about an explosive development of software. Newly built and distributed software products often fail to conform to security requirements. One example is the software built by Microsoft, the world's most powerful IT corporation. Microsoft's operating systems (OS) and database management systems (DBMS) have somewhat limited information security features and feature a great deal of "undocumented capabilities". These make it possible for intruders to infiltrate information systems via global networks, crack user passwords, give themselves arbitrary access levels and, ultimately, easily manipulate confidential information.

With the theoretical basis of information security lagging behind the technological advances and new security threats coming out continuously, most security systems have their protection systems simply "patched" for the loopholes found therein.

The status of computer security is greatly influenced by the existing national information security standards also lagging behind the requirements imposed on security of modern information technologies. The globalization of the information space has led to the necessity of international security standards to be developed to standardize security requirements, the information security features made feasible and protection features properly realized.

A noteworthy fact is that state authorities and computer/software engineers are well aware of the existing concerns. Recent years have seen efforts to ensure protection of information placed in the forefront also in promotion of novel software. International computer security criteria was established and approved by the International Standardization Organization (ISO) in 1999 [2, 3]. This standard has been in effect in Russia since 1 January 2004. Software developers seek to have their products certified under these criteria, which is expected to improve, in general, the information security level. Thus, in 2002, the Windows 2000 operating system was certified to these criteria, followed by distributives of the Linux operating system certified in 2003.

Russia, by and large, sees its information security technologies evolving in the stream of global trends. Still, some specific points exist. This country shows a slower IT dissemination pace than economically developed countries. One explanation for this is that Russia was somewhat later in

building its capability to evolve commonly available information systems than more developed countries; the other one is that most Russian people cannot afford using information technologies for economic reasons. This, in turn, leads to a worse dynamics in the development of regulatory documentation for the field of information security. Thus, the first data access security guidance documents of Gostekhhkomissiya under the President of the Russian Federation [4 – 8] were adopted in 1992. The ideology of these documents was modeled after that of the US Department of Defense's criteria, known as Orange Book, passed in 1983. Close to these is also a guide adopted in 1997 to regulate security of information in automated NM accounting and control systems [9]. It was only in 2004 that international criteria were adopted as standards in Russia.

There are no practically dedicated classified data handling systems, such as operating systems and DBMSs, offered in Russia's home market. Those systems used as the base software are beneath criticism in security terms. Often these are commercial systems for small business and office applications that cannot be used, in principle, for the confidential data handling purposes. The existing software security products can be used for some, e.g. cryptographic, tasks, still cannot offer a solution to the problem as the whole.

A point to security of information in accounting and control of nuclear material is that use of foreign-made commercial base software to process national security information can hardly be thought normal. So governments in many countries tend to give up imported software for domestically developed software systems. One recent example is a number of countries having given up use of Microsoft products for national and regional management and control purposes. Here, two solutions are possible. The first one is to build domestic software based on a home-developed platform. The second solution is to update the existing software through creation of domestic information security systems (ISS) and incorporation of these in the current systems subject to license agreements. The first approach is very costly to take, so the second concept has been adopted by the Ministry for Atomic Energy to implement. As is known [3], in 2003, Microsoft made source codes of its operating systems available to authorized organizations in a number of countries as part of its GSP (Government Security Program). In Russia, such agreement with Microsoft was signed by the Federal Agency for Government Communications and Information. Microsoft was also announced to provide in due manner for appraisal the required design documentation and enable program modules

to be developed where no functional capabilities sought for had been realized in Microsoft products.

8.3. Threats to information security and countermeasures

Threats to information securities are understood as factors seeking to violate normal operations of a system. Threats may be purposeful (subjective) and random (objective). Russian standards focus chiefly on purposeful threats, that is, on information access security. Objective factors pose no smaller threats to normal operation of information systems. Thus, a loss of information integrity from an inadequately designed database may nullify the value of existing data. Information may be also lost throughout as the result of a hardware breakdown unless special measures are taken to archive and copy this.

The following three broad classes of threat types are identified:

- threats to confidentiality;
- threats to integrity;
- threats of denial of service.

Countermeasures to objective threats relate to the system reliability. Countermeasures to subjective threats are a key information security task.

Information security experts consider different influences of threats on a computerized information system. Information, software, physical, and organizational and legal influences are identified.

Information influences mean all kinds of unauthorized manipulations of database data. These include illegal access to data, theft and unauthorized duplication of information, concealment and premeditated corruption of information, as well as compromise of the handling technology and timeliness.

Software influences mean influences on the protected system through insertion of malicious programs or hardware. These programs or devices are capable of realizing undocumented functions leading to thefts or corruption of data. Foreign-made hardware and software products are used chiefly to build automated NM A&C systems, so insertion of special “bugs” therein is very likely. Moreover, real cases of such insertions are known. A form of software influences from information security threats are currently common virus influences on computers.

Physical influences are implemented through physical impacts of various factors on computers, network components, data carriers and, ultimately, on the personnel operating confidential information and security systems. Physical threats, as evidenced by estimates from the US

Information Protection Association, account for 39% of computer system faults. A physical influence can be staged with the aid of high-tech electronic devices that are capable of intercepting hardware signals and stealing so information. It is possible to disable signals and compromise hardware systems by insertion of data intercepting devices in workrooms. A database can be destroyed by elementary influences, such as fire or flooding of hardware. This case does not necessarily require any influence on the room or the hardware which stores data. It will be enough, say, to set fire to a neighboring room more accessible to outsiders.

Less obvious are organizational and legal influences of threats. These influences include personnel's or executive staff's failures to abide by regulatory requirements or delays with adoption of regulations and rules. A failure to fulfill or absence of regulatory requirements leads frequently to other influences of threats coming into being. Threats may also come from purchases of outdate equipment, unauthorized restriction of access to data and so on.

Prevention, suppression or neutralization of threats to information security is implemented through information security features based on developed and introduced countermeasures to various information security threats. Information security features include organizational, technical, cryptographic and software means designed to protect limitedly accessible data, as well as the software and hardware in which this is realized. Besides, these also include information protection efficiency controls.

Efficient and all-round protection of information against potential threats requires a variety of countermeasures to said threats and techniques to be used to prevent these from being enabled. Threats can be prevented, suppressed or neutralized by organizational, legal, physical protection and software/hardware methods.

Organizational and legal methods primarily suggest development of a set of regulatory legal acts and bylaws to govern information relations of guides and procedural regulations for information security support purposes. These regulations form the basis on which an information security licensing system is established, and information security techniques and facilities are standardized. In turn, organizations need to form and provide operations of the sensitive and confidential data security systems. These systems are subject to certification and qualification based on information security guide requirements. A major procedure involved in the development of automated NM A&C systems is generation of personnel job descriptions and regulations governing personnel behaviors

in various situations. Operations require these instructions to be strictly observed.

Physical protection of rooms, communication lines, data transmission channels and information carriers must be organized to prevent information from being physically infiltrated, stolen or intercepted. Physical protection is highly instrumental to information security. We shall see when looking into the classification of computerized NM A&C systems that it is exactly physical protection that enables base software certified to information security class 3 to be used for NM accounting purposes.

Finally, design and creation of computer networks immediately requires employment of software- and hardware-based countermeasures to information security threats. These countermeasures have increased roles in overt data transmission channels. In a brief account, the following measures are used:

- avoidance of unauthorized access to data;
- prevention of special influences leading to destruction, elimination and corruption of information or malfunctions of equipment using information technologies;
- detection of inserted software and hardware bugs;
- use of data security features, including cryptographic ones, for transmission of information over communication channels.

Planning of countermeasures to purposeful information security threats need to take into account that, despite an increased publicity given by media to outside attacks on computer systems, much greater security damage may come from internal security violations. The data provided by a computer crime research center [10] says 70% of security violations in 2002 took place within organizations, having been often caused by discontented staff members. So crucial in this respect is a bona fide manning policy and correct distribution of personnel responsibilities to avoid cases of security depending on one person.

8.4. Standards on information security in automated NM A&C systems

There is rather an extensive list of Rosatom's documents pertaining to information security in automated systems of the ministry's enterprises and organizations. These are listed in the industry standard on equipment of NM accounting and control systems [1]. As such, the industry standard contains provisions that deal with security of information both in terms of data access security and reliability of data storage. This section will consider Russian standards in the field of information access security

expected to guide developers of NM A&C systems in designing data security features. The prime document that establishes the classification of NM A&C systems and governs requirements to information access security in these is a guide of Russia's State Technical Commission (Gostekhkomiissiya) and Ministry for Atomic Energy (Minatom) entitled "Requirements to Information Access Security in Automated Nuclear Material Accounting and Control Systems", approved in January 1997 [9]. This document also contains requirements to certification of information security features for such systems and qualification requirements to NM A&C systems.

The document was developed based on the 1992 information security guides of Russia's Gostekhkomiissiya [4–8]. Precedents exist when computerized NM A&C systems were qualified based on these criteria rather than on the 1997 requirements. Finally, it was on 1 January 2004 that a new standard, ISO/MEC 15408–99 [11–13], developed based on the international Common Criteria, was put into operation in Russia. This was an important step in the development of an information security regulation framework because it introduced up-to-date approaches and requirements to security of information systems in Russia. Prospectively, steps towards harmonizing domestic and international requirements in the field will make it possible for Russian software developers to enter foreign software market. Still, the introduction of new standards does not make the requirements of Gostekhkomiissiya's guides null and void.

In near term, the state of art in the field of regulatory computer security requirements is thought to be greatly influenced by the Federal Technical Regulation Law that took effect on 1 July 2003. Hereinafter, we shall discuss in brief the concerns and tasks arising out of the newly adopted law.

8.4.1. Requirements to information access security in automated NM A&C systems

This document has been developed by the Russian Federal Nuclear Center – All-Russian Research Institute for Experimental Physics (RFNC-VNIIEF) and the Pacific Northwest National Laboratory (PNNL), the USA, as part of an agreement to upgrade physical protection, accounting and control of nuclear material in Russian Federation. The document's prime objective is to form a regulatory framework for certification, subject to information security requirements, of automated NM A&C system software developed based on Microsoft's commercial software products. The

document introduces a classification of automated NM A&C systems, defines requirements to information access security features depending on the class of the NM A&C system and, finally, specifies certification and qualification requirements to information security features.

Classification of NM A&C systems

Classification of NM A&C systems is introduced for the purpose of developing and employing valid measures to achieve the required level of information security. The security class is determined by the NM A&C system user and developer with involvement of information security experts. The following system features are used as criteria in establishing the class of security:

- presence in the NM A&C system of information of different secrecy levels;
- level of the user authority for access to classified information;
- procedures and conditions for the deployment and operation, and the physical security status the NM A&C system computers.

Based on the estimates for these factors, the requirements establish three security classes for automated NM A&C systems. The highest of these is Class 1.

Class 3 includes NM A&C systems which are characterized by:

- the presence of information of strictly one secrecy level;
- all access subjects (except the administrator) having equal rights (powers) of access to the NM A&C system information;
- all NM A&C computes installed within a controlled area and having no external physical information communications (leading to beyond the controlled area).

Class 2 includes NM A&C systems which are characterized by:

- the presence of information of several secrecy levels;
- subjects of access having different rights of access to the NM A&C system information;
- all NM A&C system computers installed within one or more controlled areas and having no open external physical information communications.

Class 1 includes NM A&C systems which are characterized by:

- the presence of information of several secrecy levels;
- subjects of access having different rights of access to the NM A&C system information;

- the NM A&C system computers installed within a controlled area and having external physical information communications with computers other than in NM A&C system.

All currently certified base software falls only into Class 1. Table 8.1 presents software products certified for use in computerized NM A&C systems.

Table 8.1

Base software certified for use in computerized NM A&C systems

Software type	Description
Operating systems	MS Windows NT 4.0 Workstation (Russian) with the SP 3 or SP 5 update package
	MS Windows NT 4.0 Server with the SP 3 and SP 5 update package
	MS Windows NT 4.0 Server Enterprise Edition with the SP 5 update package
Database management systems (DBMS)	Microsoft SQL Server, version 6.5., with the SP 4 or SP 5a update package
	Oracle7 Server and Workgroup Server, version 7.3.4.0.0
	Oracle8i Enterprise Edition, version 8.1.7.0.0

The major problem that hampers the evolution of computerized accountancy at this state of the Federal Information System development is the absence of base software certified higher than to Class 3. An NM A&C system falling into Class 3 is expected to contain information of only one secrecy level. Still, the industry's enterprises often use materials of different secrecy levels. In this case, the fulfillment of Gostekhkomiissiya's requirements is expected to lead to either the creation of not less than two segregated local area networks to account for materials of different secrecy levels or to all materials having their secrecy level raised to the maximum. The former case entails a dramatic increase in the network creation cost, while the latter makes it much more difficult for personnel to handle material of originally low secrecy level. Finally, the last, but not the least, requirement demands that the whole of the enterprise to be based within one site. This requirement is not applicable to large-sized fuel cycle enterprises. The only solution in this case is to build computerized system

components at separate sites and establish communication between these by dispatching information on carriers by special hand delivery.

Therefore, the task at hand is to have base software certified to information access security class 2. Class 1 NM A&C systems will be needed in the event where it is necessary to transmit information over open information channels. This requirement is now part of the Federal Information System (FIS) development program for the period up to the year 2010.

Requirements to information access security systems depending on the NM A&C system classes

The requirements of Gostekhkomiissiya identify four subsystems of the Information Access Security System (IASS). These are:

- an information access control subsystem;
- a logging and accounting subsystem;
- a cryptographic subsystem;
- an integrity support subsystem.

Certification and qualification requirements are specified for each subsystem depending on the NM A&C system class. Table 8.2 lists the requirements with respect to classes for various components of these four subsystems. “+” means the existence of respective requirements to the given class, and “-“ means the absence of such requirements.

Table 8.2

Subsystems and requirements	A&C system classes		
	III	II	I
1. Access control subsystem			
1.1. Identification, authentication checks and control of access subjects:			
• when logging into the operating system	+	+	+
• when getting access to the DBMS	+	+	+
• when getting access to the OS objects (workstations, servers, networks, domains, communication channels, ports, storage areas, peripherals and network components, processes, disks, volumes, catalogs, files, etc.) and to the DBMS subjects (files, tables, indices, records, entry fields, diagrams, procedures, etc.)	+	+	+
1.2. Control of transmitted (received) data in the network	+	+	+
1.3. Limitation of processes to access data	–	+	+
1.4. Control of information flows	–	+	+
2. Logging and accounting subsystem			
2.1. Logging and accounting of:			
• login/logout of access subjects into/of the system (workstation, server)	+	+	+
• output of printed (graphic) documents	+	+	+
• launch (closure) of all programs (processes, assignments)	+	+	+
• access of software (processes, programs, tasks, assignments) to secured files and catalogs	+	+	+
• access of software (processes) to network fragments and components (domains, servers, workstations), ports (lines, communication channels), peripherals and network devices, and processes	–	+	+
• access to the DBMS objects (files, tables, indices, records, entry fields, diagrams, procedures, etc.)	+	+	+
• changes in access subject powers and access object status	–	–	+
• created secured access objects	–	+	+
• all network data exchange breakdowns	–	+	+
• the establishment of communication between remote processes	–	–	+

Table 8.2 (continued)

Subsystems and requirements	A&C system classes		
	III	II	I
2.2. Accounting of information carriers	+	+	+
2.3. Cleaning (zeroing, initialization, depersonalization) of vacated computer and outside accumulator storage areas	–	+	+
2.4. Alarms of attempted compromises	–	–	+
3.2. Use of certified encryption-based safeguards	–	–	+
4. Integrity assurance subsystem			
4.1. Software and processed data integrity assurance	+	+	+
4.2. Connection integrity assurance	–	–	+
4.3. Data transmission and delivery proofing	–	–	+
4.4. Physical protection of rooms, computers and information carriers	+	+	+
4.5. Presence of the information security administrator (service) in the A&C system	–	+	+
4.6. Periodic testing of the IASS	+	+	+
4.7. Presence of the IASS recovery facilities	+	+	+
4.8. Use of secure communication lines	–	+	+
4.9. Use of certified fire walls	–	–	+
4.10. Use of certified security features	+	+	+

Requirements to certification of the IASS depending on the NM A&C system classes

Certification of information security features (ISF) is understood as the establishment of the ISF conformity to a set of requirements that ensure protection of data of the respective secrecy level. The procedures for carrying out mandatory ISF certification and the organizations authorized to carry out certification are described in detail in the section “Development and Commissioning of Computerized NM A&C Systems”. This section presents certification requirements to different subsystems of an A&C system depending on the class thereof. The requirements for a higher class automatically include the requirements for a lower class.

Below, we set forth requirements for **class 3 A&C systems**. The requirements to components of an **access control subsystem** demand the following:

- identification and authentication of the users logging into the operating system;
- identification and authentication of the users during the access to the database management control system (DBMS);
- identification of servers, workstations, peripherals and network components by physical addresses;
- identification of subjects and objects by names;
- identification of the database objects by names.

We shall explain some of the concepts. The identification process consists in that the system identifies the user. To this end, the user logging in to the system enters his/her identifier (login). Authentication verifies the trustworthiness of the user, that is, the fact that the identifier has been entered by the user himself/herself. To this end, a password (a secret word) known only to the user is entered. The requirements of Russia's Gostekhkomissiya establish that a password should comprise not less than 8 characters. Besides this requirement, recommendations exist based on long-term practices. Specifically, it is recommended that passwords should use not only letters but other symbols as well. Characters should be entered with different cases selected. A password must by no means be a meaningful word or contain personal information. All this is expected to make it more difficult to crack the password electronically. The password length of 8 characters was chosen in view that it takes about half a year to guess a combination of 8 characters by a simple search method using an up-to-date computer. The password validity normally expires over this time. At present time, because of increasing computer capabilities, the recommended password length is not less than 10 characters. User passwords should be accessible only to specially authorized personnel (administrators). The password expiry date is to be fixed with passwords to be changed from time to time.

A subject of a system is any system process initialized by the user and run in the user interests. An object of an operating system and a database object is any resource in the OS or the DBMS. This is discussed in more details in the "Base Software" section.

The following requirements are imposed on components of the **logging and accounting subsystem**. The following events are subjected to logging:

- user login/logout into/out of the operating system, as well as logging of the operating system loading and programmed shutdown;
- launch/closure of all programs;
- attempted access of software to secured files and catalogs;

- access to database objects.

Logging facilities should be accessible only to the administrator and include for him/her respective facilities for viewing and reviewing stored events by the above parameters and archiving these.

The following should be indicated during logging:

- time and date of the user login/logout into/out of the system and of the system loading/shutdown;
- the identifier of the user initializing the process;
- the result of the action (successful or unsuccessful – unauthorized).

When files or database objects are accessed, specification of the access object and the code of the operation requested for are also logged.

The **integrity assurance subsystem** should ensure:

- integrity of the IASS software and database.
- integrity of the IASS database in the DBMS through isolation of this from users and online recovery on the part of the administrator.

No class 3 A&C systems have a cryptosystem.

Hereinafter, requirements to **class 3 A&C systems** are set forth. An access control subsystem should:

- identify communication channels by physical addresses;
- control the access of subjects to secured OS resources in accordance with the access matrix based on a discrete principle;
- control the access of subjects to the DBMS objects in accordance with the access matrix by sampling, modification, insert, deletion and other operations;
- limit user access to secured objects using only strictly specified processes;
- realize a mandate principle of access control;
- control information flows using the subject and object secrecy attribute;
- transmit data over the network together with secrecy attributes which should be secured.

Unauthorized operations on networked data and unauthorized duplication of data should be safely identified as an error and logged respectively.

We shall clarify the requirement of the access control mandate principle. Theoretically, there are two basic principles (or models) to control access to resources. These are a discrete model and a mandate model. When the discrete principle of access to objects is realized, each object contains an access control listing, i.e. a list of users with a permit of access. An access matrix is specified for each user, that is, what action exactly the given user

is permitted to undertake with respect to the given object. For files, for example, the access matrix realizes the following rights: read, write, add, create, delete, rename and execute (for executable files).

When a mandate principle of access control is realized, each object and subject is assigned a double attribute. The first part of the attribute should reflect one of five secrecy levels: “unclassified”, “restricted” and so on. The second attribute part should reflect one of topical categories. In this, the following rules should be observed:

- a subject is granted the right to read information only in the event that the subject secrecy level is higher than or equal to the secrecy level of the object and the category of the object either coincides with or is a subset of the subject category;
- a subject may get the right to write with respect to an object in the event that the object secrecy level is higher than or equal to the secrecy level of the subject, and the subject category either coincides with or is a complete subset of the category (group) of the object.

More details on access to information based on the discrete principle are given in the “Operating Systems” section.

For data networking, the requirements of Gostekhkmissiya establish that this should involve facilities that prevent transmission of data to an object of a secrecy level lower than that of the data transmitted.

The **logging and accounting subsystem** should:

- log output of classified printed documents as hard copies;
- log attempts of software access to the following secured access objects: networks components and fragments, ports, peripherals and processes;
- log all errors of network data exchange revealed;
- automatically account for created secured objects by giving them additional labels used in the access control subsystem;
- clear (zero, initialize, depersonalize) vacated storage areas in computers and segregated external carriers. Clearing is done by a double random entry into any vacated storage area used to store secured information.

Printout of classified documents requires automatic labeling of sheets by numbers and accounting requisites. Simultaneously, an account card should be made out for the document with specified logging parameters.

Requirements to the integrity and cryptography support subsystems coincide in full with requirements to similar subsystems of Class 3 A&C systems.

Requirements to **class 1 A&S systems** include all requirements to class 2 and 3 A&C systems.

Requirements to **access control subsystems** include authentication of users during remote access to the server and the workstation using such techniques as are resistant to interception of communications and active influences on networked data. The subject, which is the source of data, should be also authenticated, that is, features should be used that verify the trustworthiness of the data block source by such techniques as are resistant to interception of communications and active influences on networked data.

The **logging and accounting subsystem** should log changes in the powers of access subjects and in the status of access objects. Subject to logging are also the connections between distant processes and attempted compromise alarms sent to the workstation display and the attacker.

The **cryptographic subsystem** should encode all classified information written on data carriers shared by various access subjects, in network communication channels, as well as on portable data media. The access of subjects to encoding operations and to respective cryptographic keys should be additionally controlled by the access control subsystem.

The **integrity support subsystem** should ensure:

- the integrity of the connection to protect data transmitted over the user network against unauthorized modification, substitution or retrieval of any data using such techniques as are resistant to interception of communications and influences on networked data;
- proofing of the data source to prevent any sender attempt to deny thereafter the transmission of data;
- proofing of the data delivery to prevent any receiver attempt to deny thereafter the receipt of data.

Requirements to qualification of the IASS depending on the NM A&C system classes

The whole of the computerized NM A&C system is subject to qualification. Qualification is understood as documented verification of the conformity of the set of organizational and technical arrangements used in operation to requirements of standards and other information security regulations. It involves in-service qualification tests of the secure AS to determine if the measures employed and the ISS meet the required level of information security. Information is further arranged in the same manner as the qualification requirements.

Requirements to **class 3 A&C systems** are presented hereinafter. Components of any **access control system** have the following qualification requirement imposed thereon. Personnel access to the information in the

A&C system is expected to be effected in accordance with the valid system of user permits of access to classified documents and data.

A **logging and accounting subsystem** shall:

- account for all protected data carriers with the aid of any labeling system;
- log and account for printouts manually as per the requirements to recordkeeping of the respective secrecy level. Documents should be printed out only in accordance with the specified list of output documents indicating their secrecy level.

An **integrity support subsystem** shall ensure the following functions.

- The software environment should remain invariable with the integrity of the software environment ensured by the absence of program development and debugging tools in the A&C system.
- The functions of the IASS should be tested on a periodic basis, with the aid of tests simulating attempts of unauthorized access, any time the software environment or the A&C system personnel change.
- The IASS recovery tools should be available, which implies operation of two IASS software copies with periodic updates and serviceability checks thereof, as well as online recovery of the IASS functions when equipment fails.
- Rooms with the A&C system hardware, which includes carriers of classified information, should be fitted with safeguards to ensure the security level meeting the secrecy level of the information stored.
- Information access security features certified for this A&C system class should be used.

Qualification **requirements to class 2 A&C systems** differ from those to class 3 A&C systems only as far as the **integrity support subsystem** is concerned. There should be an information security administrator to be responsible for maintenance, normal operation and online control of the IASS. The administrator should have a workstation of his/her own and the required A&C system online controls and security influence means. Additionally, secure communication lines extending to beyond the areas under control should be used.

Qualification requirements to class 1 A&C systems differ from requirements to class 2 A&C systems in that they include a **cryptographic subsystem**. Cryptographic facilities certified for class 1 A&C systems should be used. Besides, the **integrity support subsystem** should use fire walls certified for class 1 A&S systems.

8.4.2. Guides of Gostekhkomiissiya

Five information access security guides were published by Gostekhkomiissiya of Russia (the State Technical Commission of the Russian Federation) in 1992 [4–8]. These documents formed the basis for the requirements to NM A&C systems we have described above. So, now, we shall discuss in brief the most important of these.

Ideologically, these documents are based on the “Concept of Information Access Security (IAS)” [4] that contains the system of Gostekhkomiissiya’s views on the problem of information security and guidelines for computer system security. As developers of these documents see it, the key role of security is to make information secured against unauthorized access. No consideration is practically given to support of serviceability of information handling systems. The explanation for this bias towards maintaining secrecy is that these documents were originally developed with a view of using them within information systems of the Russian Federation Defense Ministry and security services, as well as an insufficient maturity of information technologies in the early 1990s against current analogs.

Gostekhkomiissiya’s guides offer two sets of security criteria: criteria of computer protection against unauthorized access and protection criteria for automated data handling systems. The former makes it possible to evaluate the security of computer system components delivered to the consumer, while the latter is intended for fully functional data handling systems. We shall look at what is provided in the document entitled “Automated Systems. Information Access Security. Classification of Automated Systems and Information Security Requirements”. This document establishes the classification of automated systems in terms of information access security. It makes sense to compare this classification against the classification of automated NM A&C systems.

For automated systems, five classes of information access security are specified in Gostekhkomiissiya’s guides. Each of the classes is characterized by a specific combination of requirements to security means. In turn, classes are subdivided into three groups with a specific information handling concept each. Automated systems are grouped based on the following features:

- presence of information of different confidentiality levels in the AS;
- levels of the AS user authority with respect to the access to confidential information;
- data processing mode used in the AS (collective or individual).

A hierarchy of the AS security classes is established within each group. The class matching the highest security level for the given group is indexed A, the next one being indexed B and so on.

The third group includes automated systems operated by one user with a permit to handle all AS data contained on media of one confidentiality level. The group has two classes: 3B and 3A.

The second group includes automated systems in which users have equal rights of access to all information processed and/or stored in the AS on media of different confidentiality levels. The group has two classes: 2B and 2A.

The first group includes multi-user automated systems which simultaneously process and/or store information of different confidentiality levels. Not all users have equal rights of access. This group has five classes: 1Д, 1Г, 1Б, 1В and 1А.

A review of the requirements in question shows that the second class of information access security in computerized NM A&C systems corresponds, by and large, to class 1B for automated systems. A precedent exists when an automated NM A&C system qualified to information access security class 1B is used to account for and control NM in environments matching class 2 for NM A&C systems.

The development of the said documents in the early 1990s filled up the gap in the legislative support for information security standards. Being, in fact, the first ever attempt of standardization in so a delicate field, these do have a number of shortcomings. Besides, the time since the adoption of these criteria has seen advances in both the theory of information security and approaches to formulation of information security standards. The approaches taken in the documents are mostly limiting in that the requirements for security classes are ranked only by way of identifying the presence of a set of security tools, which makes these requirements much less flexible and feasible. These documents treat the notion of security policy as the keeping of the regime of secrecy and the absence of unauthorized access. Because of this approach, security tools tend exclusively to counter external threats with no requirements practically imposed on operations of the system and its structure. A note should be made that requirements to computerized NM A&C systems adopted in 1997 are based on the documents listed and involve the same deficiencies.

8.4.3. Common Criteria for Technology Security Evaluation

The Common Criteria (the Common Criteria for Information Technology Security Evaluation) was the result of the consistent efforts undertaken to develop IT security evaluation criteria that was subsequently accepted internationally.

The Trusted Computer Systems Evaluation Criteria (TCSEC) was developed in the USA in the early 1980s. In the decade that followed, different countries initiated the development of evaluation criteria that was based on its concepts but offered more flexibility and adaptability in the context of IT evolution.

Thus, in 1991, the European Commission published the Information Technology Security Evaluation Criteria (ITSEC) developed collaboratively by France, Germany, the Netherlands and Great Britain. The Canadian Trusted Computer Product Evaluation Criteria was developed in Canada in early 1993. It was also then that a draft standard, the Federal Criteria for Information Technology Security, was published in the USA.

In 1990, the International Standardization Organization (ISO) began to develop an international standard of generic evaluation criteria. The new criteria were intended to meet the demand for the mutual acceptance of the standardized security evaluation results in the international market of information technologies. In June 1993, the consolidated efforts of the national criteria developers led to the initiation of a joint program on harmonization of varied criteria and establishment of a unified collection of security criteria.

The early version of the Common Criteria was finalized in January 1996 and approved in April 1996 for circulation as the committee's draft criteria. A number of experimental evaluations followed with steps undertaken to have the document broadly discussed in public. Later on, the document was revised extensively, as part of the Common Criteria project, based on the experience of its experimental application. The later version was released in May 1998. Version 2.1 of this standard was approved in 1999 by the ISO as an international information security standard (ISO/IEC 15408). Some countries nowadays require their information systems, critical in terms of national security, to be certified to the CC.

On 27 March 2003, the State Technical Commission under the President of Russia unveiled a program to introduce the international information security standard. Russia began introducing the standard practically unaltered, having divided this into three State Standards (GOST) indexed

collectively as ISO/IEC 15408–2002. The new GOST series was put into operation in Russia on 1 January 2004.

Let us familiarize in brief with the new standard. The standard as such is complex and bulky. It consists of three parts with the overall volume of about 600 pages.

Part 1 of the standard contains the IT security evaluation methodology and defines the types of security requirements (both functional and confidence ones) and the basic formats (protection profile, security job) to present security requirements in the interests of three user categories: consumers, developers and appraisers of IT products and systems. The evaluation object (EO) security requirements under the Common Criteria methodology are defined depending on security objectives, which, in turn, are based on analyzing secured information resources, and the EO function and application environment (threats, statements, security policy).

Part 2 of the standard contains a versatile specifically arranged catalog of functional security requirements and enables regulated detailing and expansion thereof.

Part 3 of the standard contains a systemized catalog of confidence requirements that define the measures to be taken at all lifecycle stages of an IT product or system to make sure that these satisfy to the functional security requirements imposed thereon. This part also contains evaluation levels of confidence representing standardized collections of requirements that enable an increasingly complete and stringent evaluation of design, testing and operating documentation, and correctness of the security complex operation, as well as assessment of the IT product or system vulnerability and the stability of security features.

As its content suggests, the Common Criteria is a methodological document that contains a well arranged and structured collection of requirements, their presentation forms and the definition methodology. Using these criteria, security for different IT products is evaluated not as stringently and uniformly as Gostekhkomiissiya's effective documents require, but given the functions, types and application environments of IT products and systems with a flexible approach to generation of respective security requirements in protection profiles enabled. The CC-based security profiles may additionally include any other valid requirements needed to ensure security of a particular IT product type.

As evidenced by information security expert estimates, the Common Criteria excels other current standards in the systematization, completeness and detailing level of requirements, as well as in versatility and flexibility of applications.

It should be noted that the International Agreement applies only to the acceptance of evaluation results for IT products and systems intended to process confidential information (up to the confidence level of EAL 4 inclusively) and does not deal with issues of evaluating products and systems designed to handle national security information in the member countries of the International Agreement. Still, the methodology of the Common Criteria can be used by and for the sake of the parties concerned.

Since January 2001 the USA has been evaluating IT security exclusively based on the Common Criteria, while the leading European countries (Germany, Finland and others) have some 40% of their recently developed IT products evaluated also under the Common Criteria with only CC-based evaluations applied to newly emerging products.

A directive, No. 140-23, was issued in May 2000 by the US National Security Agency, which made it mandatory for the US Department of Defense and its public and private contractors to use only CC-certified IT products and systems for handling classified information.

The directive also applies to privately owned nuclear power plants in the USA where special roles are assigned to the Common Criteria in evaluating security of information technologies employed in critical systems.

All this gives evidence of the emphasis placed internationally on information security issues and of the CC approaches and methods becoming increasingly attractive as a tool to resolve these.

In the run-up to the introduction of the new standard in Russia, the Comments on the Russian Standards were developed by “Atomzashchitainform” Center, TsNIIatominform and the Information Security Center (ISC). These had the purpose of giving Russian experts a more in-depth understanding of the objective, basic concepts, methodology and terminology of the Common Criteria as well as clarifying discrepancies between the standard’s terminology and the terminology accepted in Russia and the effective regulatory documents.

The underlying associated document issued to support the Common Criteria, which is mandatory for use in the framework of the above International Agreement, is the General Methodology for Evaluating Security of Information Technologies currently being revised by an expert team of a number of the member-countries to the International Agreement. At present time, based on an authentic translation of the relevant General Methodology version by an expert team of the ISC, “Atomzashchitainform” and TsNIIatominform, involving the CC international work unit, the methodology for evaluation of IT products and systems is developed.

The standard introduction program also stipulates:

- development of the concept to ensure security of information technologies (the draft was prepared by the ISC and submitted to Gostekhkomiissiya of Russia);
- development of the guide to develop protection profiles and security jobs (the draft was prepared by the ISC and submitted to Gostekhkomiissiya of Russia);
- development of the guide to register protection profiles based on the ISO/IEC 15292 international standard (the draft was prepared by the ISC and submitted to Gostekhkomiissiya of Russia);
- creation of a system of tools for automated development of protection profiles and security jobs (presently developed by the ISC);
- development of protection profiles for the basic types of IT products and systems: operating systems, database management systems, fire walls, virtual private networks and others (some organizations, including the ISC, TsNIIAtominform and MEPhI, develop security profiles for IT products and systems for various applications; one example is a protection profile of security class II developed by TsNIIatominform for automated NM A&C systems);
- development of model techniques for certification tests of IT products and systems based on the General Methodology of Evaluation;
- certification tests of some IT products and systems, including operating systems (specifically, the Windows family).

The said activities have the purpose of not only introducing the GOST State Standard R ISO/IEC 15408–2002 “Information Technologies Security Evaluation Criteria”, but also taking Russia closer to joining the International Agreement as a country with a CC-based certification system.

As mentioned hereinabove, Rosatom of Russia is also considering evaluation and certification of software products used in NM A&C systems based on the Common Criteria requirements. This obviously requires development of a protection profile for systems of security class III and the security jobs to which the software products chosen for these functions to be certified. The solution of these issues will determine the perfection of effective and development of new NM A&C systems, as well as the operation of the Federal Nuclear Material Accounting and Control Information System.

It is a belief with Russian experts involved in implementing the Common Criteria methodology that, if put into operation, the Russian standard, the General Methodology of Evaluation and other regulatory and

methodological documents to support these, as well as practical use of the Common Criteria methodology will make it possible to:

- reach the state of the art in the criteria and procedural framework for evaluation of information technologies;
- create a new generation of interagency and departmental regulatory and procedural documents to evaluate IT security on a uniform basis;
- provide users and developers of IT products with a highly efficient tool for formulating requirements to IT security and building information protection systems;
- enable users to assess objectively the capability of information security IT products;
- give users and developers of computerized systems of various levels and functions the capability to provide, accordingly, more valid formulation and implementation of information security requirements for these systems;
- take Russia closer to joining the International Agreement, which will, in turn, enable:
 - users and developers of IT systems to cut product certification costs;
 - consumers to expand the market of certified products;
 - testing laboratories to attract extra inflows of orders for certification from abroad;
 - Russian makers of high-tech products to obtain international certificates in Russia, which will give them a share in the earlier inaccessible foreign markets.

For all that, Russia (as well as other parties to the mutual certificate acceptance agreement) retains the right to make allowances for its national requirements in certification of IT products and systems, primarily, those for protection of national security information.

This, however, entails a great deal of efforts to take for the Common Criteria and the General Evaluation Methodology to be put into practice of requirement formulation and IT security evaluation, as well as for Russian IT security terminology and standards to be harmonized with international standards, specifically the ISO/IEC 15408–99 standard, with a view to the entry of Russian testing laboratories (centers) and certification authorities, as well as of Russian products certified to the Common Criteria methodology, to the international market of products and services.

This requires the solution of the whole range of technical, organizational and financial issues relating:

- for developers of IT products, to the strict adherence to the specified procedures of preparing and providing evidence for evaluation, and the support of the product lifecycle;
- for users and developers of automated systems, to the development or sound choice of protection profiles, security jobs and, accordingly, IT products meeting real demand for security of automated systems;
- for testing centers and certification authorities, to the preparation for and harmonization of their IT security evaluation work with international standards, as well to the accreditation of these within the International Agreement framework.

Still, this is the way for us to go. It will help use the extensive experience gained to date internationally not only in the field of standardization but also in the development of ITs in general, and enable Russian experts to take an active part in creating new and improving current international standards, and influence so the IT and IT security evolution.

8.5. Effects of the Federal Technical Regulation Law on IT security

The Federal Technical Regulation Law took effect on 1 July 2003. Prospectively, this was expected to give impetus to major changes in the information security policies. This law governs relations arising in the development, adoption, use and fulfillment of mandatory requirements to products and fabrication, operation, storage, transportation, sale and disposal processes; as well as in the development, adoption, use and voluntary fulfillment of requirements to products and fabrication, operation, storage, transportation, sale and disposal processes, and to performance of work and services. Falling within the regulation scope of this law is also creation of products and information security services [14, 15].

The new law seeks to simplify the product marketing formalities, create prerequisites for harmonizing Russian and international standardization systems and provide legislative support to the powers of inspecting and supervising authorities. The law declares the accessibility of standards to users and enables makers and consumers to get involved in elaboration of regulations and standards. It also envisages the development of technical regulations which will guarantee security of goods and services and will be binding upon makers. Standards, as such, will cease to be mandatory. It is the consumer that will be expected to evaluate the quality of products and

choose the one of a better quality (particularly that certified for compliance with some standards).

Still, there are some concerns brought to life by such sweeping changes in the field of standardization. These include absence of the requirement for producers to comply with standards, a potential decrease in the quality of products and lack of responsibility for this. All this was discussed at the conference “IT-SECURITY: New Requirements to Participants in the Information Security Market” held in Moscow on the new law adoption day.

While noting the positives the adoption of the new law entails, the participants in the conference formulated proposals for state authorities to realize towards avoiding potential negative effects of legislative changes in the field of information security. The most important of these are as follows:

- the current procedures of employing technical requirements to information security should be preserved for the transitional period;
- the Law should be amended so that to enable development and introduction of information security technical regulations;
- a state authority should be appointed to be responsible for development of information security technical regulations;
- licensing exemptions should be introduced for any information security facilities;
- testing laboratories and certification centers of different agencies should be joined for providing services on a one-stop-shop basis;
- differentiation should be provided between where information security rights shall be guaranteed by the state and where the customer and the contractor shall be entitled to be guided by any tools, in a range from corporate standards to expert appraisals, to determine the quality of services and products;
- a number of laws, including the laws “On Electronic Digital Signature”, “On Official Secrets”, “On Information Security” and “On Standards in Information Technologies and Information Security Facilities”, should be adopted.

If realized, as seen by the participants in the conference, these will lead the new law to improve the state of the art in the field of information security. Anyhow, all regulations will have effect over the period of transition (7 years).

8.6. Reliability of computerized NM A&C systems and backup of information

Along with access security, reliability and fault tolerance of information systems are what is also decisive to information security. As evidenced by the foregoing, Russian information security criteria lay emphasis on countering subjective security threats. However, reliability of systems is not less important to the design and operation of NM A&C systems.

The following data has been made available by GERLIG, a German insurance company [16]. It is loss of information that accounts for 74% of cases of closures of businesses in Germany. Statistical evidence exists that, in the event of a breakdown, an information system has a critical recovery time. If no recovery of information takes place over this time, the organization will cease to exist with a 100% probability. The critical recovery time is 5 days and a half for an insurance company, 5 days for a production facility, 2 days for a bank and some 24 hours for a facility with a continuous production cycle.

Such estimates should take into account that serviceability of many critical applications shall be guaranteed at 100%, since operations of these are what the whole of the current social infrastructure (law enforcement bodies, government authorities, energy generating and shipping companies, etc.) relies on. Examples of such critical systems are enterprises circulating nuclear material. Full loss of nuclear material at these must be avoided with a 100-percent guarantee. The industry standard [1] establishes some requirements and regulations pertaining to ensuring reliability of NM A&C systems.

Excluding complete loss of information in conditions of normal operation and in design-basis accidents requires a data storage and recovery system in place. This system includes the following:

- backup of the server or use of backup on hard magnetic disks (RAID-technology);
- in-house storage of distributive copies of both base and applied software;
- storage of backup database copies. Not less than two sets of alternately used external media of backup copies should be in place, these to be stored, as agreed respectively, in a separate file depository or/and at another computer center.

The above components relate to the choice of the function and information backup strategy. We shall comment in brief on these. Normally, local networks designed to handle critical information are

required to include a backup server (a standby domain controller for networks controlled by Windows NT). The data in the main and backup servers is synchronized periodically during operations. If the main server fails, information handling is automatically taken over by the backup server. Modern solutions offer diverse cluster systems with distributed loading when the server failure does not lead to the failure of the whole system.

Instead of one magnetic carrier, RAID-technology (Redundancy Array of Independent Disks) uses an array of many comparatively cheap high-reliability and high-speed disks. This disk array is organized using a controller such that the resulting system had a higher reliability than the disks it is composed of. Different modes are used to write data on disks, making it possible to mirror information or recover same after faults. Such high-reliability disk arrays are often combined with cluster systems for operations. There should be however an understanding that a catastrophic failure of RAID-arrays will lead to complete halt of such systems.

Choosing a backup strategy needs serviceability support requirements to the system to be evaluated. It should be remembered that backup of functions makes the whole of the system costlier. The desire to have the functions of a system backed up multiply and safely runs counter to a couple of important engineering principles: first, the reliability of a system is inversely proportional to the number of components therein, and, second, a system cannot be more reliable than the least reliable component thereof. In parallel, it needs to be determined if a system is of the class $24 \times 7 \times 365$, that is, is expected to operate 24 hours a day, seven days a week and 365 days per year. In fact, no NM A&C system requires to be so rigidly regulated. The industry standard requires the serviceability of an NM A&C system to be recovered in not more than 10 hours. It is emphasized that this standard is established for each particular subsystem at the stage of developing a computerized NM A&C system.

Where all information is lost, emergency recovery of the system requires the base and applied software and the content of databases to be restored. This is achieved via storing software distributives and backup database copies. The standard identifies two requirements to storing backup data copies: there should be more than one copy in place and the backup copies should be stored separately from the original copies, preferably in a territorially remote location. The fundamentals of data storing principles are set forth in [17]:

- each backup data copy shall not be the only one but shall be multiply duplicated based on a “grandfather–father–son” pattern;
- reliable data media is chosen for making backup copies;
- full-value backup copies are made;
- for reliable storage, backup copies shall be kept in a separate room which is distant from the primary data media;
- the quality and the restorability of the backup copies shall be checked on a regular basis.

The recovery of data based on these principles is somewhat time-taking. Still, they need to be strictly observed. So, where backup copies are kept in the server room, they are of a practically zero value for the recovery of information. In the event of a fire, they will be lost together with the original information.

A span of 250 hours is established by the standard as the maximum value of the average operating time to fault. It is specified that computers should fall into class 5 and meet the reliability requirements under GOST 27201–87. Rooms that accommodate components of the NM A&C system should satisfy to fire and general industrial requirements under GOST 12.4.009–89.

Human factor should not be disregarded as well. Poor personnel skills and negligence of duties often lead to the absence of a data backup and recovery strategy or to this being merely formal and failing to conform to respective regulations and rules. As evidenced by expert estimates for Western companies, up to 75% of all backup copies are not fit for recovery.

For the human factor to be taken into account, the standard has organizational support provisions set forth in a separate paragraph. The standard requires each enterprise to develop a set of documents to specify the organizational structure, and the rights and the obligations of the NM A&C system operating personnel. The documents should also specify:

- the personnel’s functions, rights and obligations for supporting the operations of the NM A&C system, including as far as preventive maintenance is concerned;
- the personnel actions during hardware and software faults and failures;
- the personnel actions in specific cases;
- the personnel actions for the system recovery;
- the responsibility of officials, personnel and users.

It is suggested that each enterprise should develop requirements to the training level, qualification and number of the specialist personnel needed

for servicing the NM A&C system. Development of a personnel training and retraining program is also essential.

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CHAPTER 9

AUTOMATION OF NM ACCOUNTING

Components of automated NM accounting are automated NM identification and measurement processes and automated data handling in computerized NM A&C systems (taking over and making commonly available data on the inventories and movements of nuclear material from the custodian through centralized databases, balance closings and so on). These serve to achieving a particular level of continuity and credibility to existing knowledge about nuclear material.

Most of the automated systems that have been until recently involved in nuclear material handling were manufacturer process systems, largely those used at bulk material handling plants, including nuclear material conversion, enrichment and fuel assembly fabrication facilities. Operations of these automated systems are quite likely to be adapted to uses in accounting and control of NM.

By now, however, it has become clear that large quantities of material fail to be encompassed by these process operations. Acquisition and processing of data on material accounting and control outside manufacturing sites has proved to be rather complex and time-taking. So then they need to be automated.

9.1. Use of barcode technology for identification of NM

Once converted to a computer-readable form, NM data will be perceived rapidly, accurately and, ultimately, cheaply. This can be ensured, say, through the use of a US information interchange code (ASCII). Bar coding is a binary presentation form for automated processing and communication of data. Barcode (a term composed of the words *bar* and *code*) is a machine-readable symbol made by a combination of bars and intervals between these.

Basically, the new accounting and control system is distinctive in that it uses barcode technology to identify items, containers, seals, locations, vehicles, etc. [12]. Barcode technology is based on making optically recognizable line widths and spacing between lines. Both these parameters are used to encode data. Barcode technology saves time and efforts one needs to spend on NM physical inventory taking and random testing (i.e. where a great deal of label checking is involved). Barcode data input entails fewer errors, as compared to keypad data entries, by many orders of magnitude. It has been shown statistically that the probability of an error

when using barcode technology is not more than $10^{-7} \div 10^{-6}$. Credibility of barcode operations is achieved through avoidance of human factor, invariability of coding symbols and algorithms, and presence of check characters in symbols.

Barcode symbologies

Barcode represents a meaningful message ciphered according to certain rules. A message is composed of words as a combination of characters. There are continuous and discrete characters. A discrete character begins with and ends in a bar with a space between characters. Continuous symbology has characters beginning with a bar and ending in a space with no intercharacter spacing.

Each barcode symbology is characterized by its own set of symbols, including using:

- only digits (0–9);
- letters and digits (A–Я, A–Z, 0–9);
- full set of ASCII codes.

The bar and spacing width is a multiple of the width quantum X referred to as “mil”, this being equal to $0.001 \text{ in} = 0.025 \text{ mm}$. Symbologies may use:

- two widths of elements: these can be narrow (X) and wide (multiples of X , often $2X$);
- several widths – X , $2X$, $3X$, $4X$, etc.

The message length may be fixed or varying. One and the same set of symbols, if expressed in different symbologies, has different lengths. The message length expressed in characters per inch (CPI) depends on the print density. The word begins with a start marker and ends in a stop marker. There are quite zones before and after the word. Quite zones have the size $5\div 10$ times as large as the width of the widest element. This makes barcodes easy to read since these are readable whatever the scanning direction is.

All barcodes incorporate a self-testing function. A code is tested at character, word and message levels (the message level not necessarily). Peculiarities of barcode testing at character and word levels depend on the symbology used. Integrally, character-level self-testing suggests control with respect to:

- total number of bars and spaces in a character;
- number of bars in a character;
- number of spaces in a character;

- total number of wide bars and spaces in a character;
- number of wide bars;
- number of wide intervals;
- ratio of the widest element width to the width of the narrowest element.

Word-level self-testing is conducted for:

- presence of quiet zones;
- presence of the word start and stop markers;
- presence and meaningfulness of check characters.

A check character is calculated depending on symbol data and encoded when words are printed. The algorithm of check character production depends on symbology. We shall consider an elementary example of a word-represented message - 73594. The digits in this word total 28. We leave the remainder from dividing this number by 10 as the check symbol. Then the message with the check symbol will be 735948. When the message is read, the check symbol is decoded and compared to the value calculated from the word characters read that have been read. The message is not given out if there is a nonconformity. Thus, barcodes represent a credible means of computer-aided data acquisition.

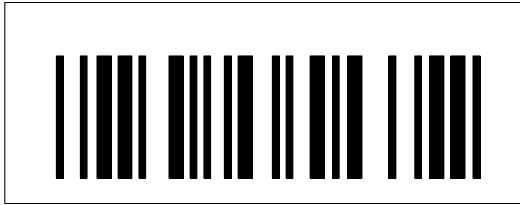
Selected barcode symbologies

To date, there are over one hundred known barcode symbol systems. Some of these are used extensively thanks to their positive qualities.

Code 39 symbology (current version – Mod. 43) has 43 characters (originally, there were 39 characters) and is one of the simplest symbologies. This barcode standard has rather multiple industrial, military and medical uses in Russia. This is a discrete alphanumerical code with start and stop markers. Mod. 43 makes it possible to add check characters to words. Figures 9.1 and 9.2 give an example of a barcode mark for standard 39 and a symbol encoding pattern. It can be seen that letters, digits and other symbols are encoded using as few as 9 elements: 5 bars and 4 spaces, of which each may be wide and narrow. The word start and stop marker is asterisk.

The encoding simplicity ensures high probability of marker resolution where complexities occur (the marker image is not clear). When used, this symbology gives, on the average, less than one error observed per 3 million readings even if there is no check character. Mod. 43 features high credibility of symbology thanks to a check character added to words.

Code 39¹



Code 39¹

- A Code 39 character comprises, in the aggregate, 9⁹ elements, including 5 bars and 4 spaces;
- Out of 9 elements, 3 are wide elements, including 2^e wide bars and 1 wide spaces.



Fig. 9.1. An example of the code 39 standard

SYMBOL	Bar and space sequence	Binary sequence	SYMBOL	Bar and space sequence	Binary sequence
1		100100001	M		101000010
2		001100001	N		000010011
3		101100000	O		100010010
4		000110001	P		001010010
5		100110101	Q		000000111
6		001110000	R		100000110
7		000100101	S		001000110
8		100100100	T		000010110
9		001100100	U		110000001
0		000110100	V		011000001
A		100001001	W		111000000
B		001001001	X		010010001
C		101001000	Y		110010000
D		000011001	Z		011010000
E		100011000	hyphen		010000101
F		001011000	point		110000100
G		000001101	space		011000100
H		100001100	asterisk		010010100
I		001001100	dollar sign		010101000
J		000011100	slash		010100010
K		100000011	plus		010001010
L		001000011	percent sign		000101010

Fig. 9.2. Code 39 symbols

UPC/EAN Code (UPC – Uniform Product Code, EAN – European Article Code). Has a highly common use in all retail and worldwide trade applications. This code has several versions. In its basic versions, this is a digital, continuous code with a fixed number of characters (basic version has 12 characters, inclusive of the check character). The highest possible record density is 5.5 characters per cm.

The code symbol has two halves. The left-hand half contains the manufacturer number as specified in the Unified Commercial Code (UCC), and the right-hand one contains the manufacturer-assigned product number. The code includes self-testing based on the checking character and by parity. The symbol's left-hand half is tested for oddity and the right-hand half is checked for parity. Figure 9.3 shows the structure of characters in UPC-A code's right-hand half. A symbol's right-hand half has characters beginning with a bar and ending in spacing, the symbol's left-hand half having, contrarily, each character beginning with spacing and ending in a bar.

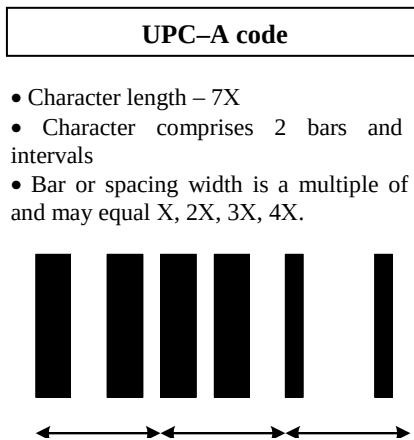


Fig. 9.3. Structure of the UPC–A code's right-hand characters.

PDF417 Code is a barcode with a high data density in excess of the standard density by about a factor of 100. Code PDF417 is a commonly accessible barcode standard with a capability to record comparatively large arrays of data. It includes the complete set of ASCII–codes and is used as a compact data file with product documentation, medical data and so on. Symbols are placed on labels and tags. The highest possible record density

is 360 characters per cm. The message is capable of comprising up to 1850 characters.

Printing and reading of barcode symbols

Barcode symbols may be applied to the whole range of materials, including paper, plastic, metal, glass, wood and others. Symbol application requires printers with respective software. Symbols may be applied both to articles and to special tags and labels that are attached to articles. Thus, Figure 9.4 shows the design of a standard sticker. This represents a multilayer sandwich of at least 3 layers.

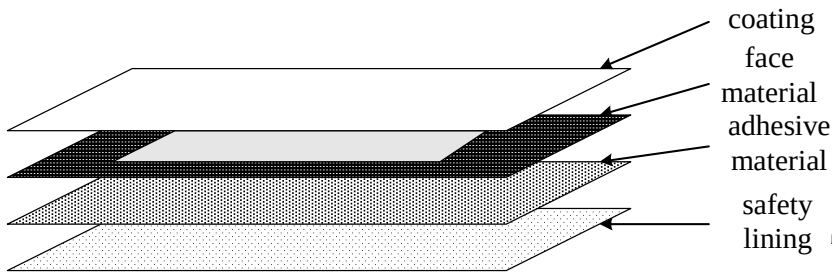


Fig. 9.4. Composite layers of a barcode sticker

Various technologies are used to print barcode symbols: conventional (offset lithography), matrix, thermal and other print technologies. Offset lithography is the best process to produce large numbers of one symbol, this requiring a print matrix to be made with the image transposed then from the matrix onto the drum. All labels obtained are identical but cheap to make.

Thermal printing uses a matrix of heating elements. The elements are switched on and off selectively for image generation. Zebra S-500, a thermal printer by Zebra Technologies Corporation, is convenient to use to make self-adhesive labels with a high print quality. It supports printing of barcodes using 15 symbologies, including PDF-417. The printing speed is 5÷15 cm per second and the resolution is about 8 dots per mm. Labels are relatively cheap to print if batches thereof are not large. A special basis is however required for printing.

Barcode symbols applied directly to articles are more durable and harder to falsify as compared to labels and tags. Still, this marking application

technique may involve process complexities. Choosing a technology to apply barcodes to articles requires further operational environments for these to be accounted for. Inter alia, this includes a potentiality of the coating to which the barcode is applied to be damaged or wear out, the requirement of decontamination, restrictions with respect to adding harmful substances and so on. So, practically, barcodes are applied to pretreated metal surfaces using:

- laser-beam surface treatment;
- jet printers;
- extrusion;
- etching, etc.

Ink-jet technology, which is contactless, may be used to apply marking to different surfaces, including abrasive, fragile and rough ones. One example is Willet 3940, an ink-jet printer that applies images by an electronically controlled ink jet directed onto the surface. The complexity of the jet control system confines uses of Willet 3040 to applications not accessible to other printers.

Therefore, there is a range of technologies and respective devices to apply barcode symbols to articles. Quality requirements and potential operation environments are what selection of techniques to apply symbols to articles relies on. Developed printing software provides automation of respective processes.

Readers are used to read barcodes with data transmitted further to a computer via an interface. Readers receive a standard electric signal that matches in time the symbol's spatial image and convert this signal to ASCII-coded words. Readers have two component devices:

- a scanner that emits a controlled luminous flux, receives and measures the reflected light, and generates the electric signal;
- a decoder that analyzes the electric signal from the scanner and converts the signal to an ASCII-code form.

Nowadays, there are many barcode readers in a range from elementary scanners to multi-channel, high-speed data capture and handling terminal devices.

Scanners differ in light sources (LED, laser), beam movements (scanning and fixed-beam), type of contact with the barcode symbol (contact or contactless) and type of installation (portable or fixed).

Decoder functions are:

- recognition of the scanned item as a barcode;
- determination of the wide bar/narrow bar width ratios;

- monitoring of quiet zones on both sides of the barcode symbol;
- identification of the symbol type by analyzing some of the initial and closing bars;
- comparison of the signal with memorized samples and conversion of same to ASCII codes;
- performance of check calculations;
- transmission of data to the computer.

Data is exchanged between the reader (or the data capture terminal device) and the PC through an interface which supports electric and logic reader-PC mating.

Data exchange between the barcode hardware and the PC is done via:

- COM ports (RS 232C);
- LPT ports (Centronics);
- Net ports (Ethernet).

RS 232C (RS 422/485) is the standard recommended for serial transmission of data and communication facilities. This is the most popular, relatively simple and system-independent interface supported by all hardware makers. However, RS 232C has a low noise resistance and requires extra components (modems) for long-range communications.

Centronics Parallel is a parallel data transmission standard. Data is transmitted by bytes.

Ethernet is a network data transmission standard.

Brief descriptions of some barcode readers:

Trakker Reader 9445 (INTERMEC), a portable self-contained programmable barcode reader with data initial handling and interim storing features. Includes a LED emitter, an LCD, a standard RS 232 interface and a 64Kb program and data memory.

Trakker ANTARES 2420 (INTERMEC), a self-contained portable barcode reader. Includes a laser scanner, an LCD, a standard RS 232 interface and a 2Mb program and data memory.

JANUS J2020 (INTERMEC), a portable self-contained barcode reader. Includes a 386-processor DOS minicomputer. Features a multi-disk memory, one of the disks (1 Mb) allocated for applications and data. The instrument is fitted with a laser scanner, an LCD, a near-eye display and a standard RS 232 interface.

Three programmable barcode readers deserve a special note here.

PictoRL (Pictorial Reader Language), a generator of barcode reading applications. So PictoRL's software package includes a pictorial language for readers. The software package enables applications to be made by

barcode hardware users with no special skills. The PictoRL package includes an ICW application that supports reader-PC data exchange. PictoRL's software package is intended for use with Intermec readers, including Trakker Reader 9445, Trakker ANTARES 2420 and JANUS J2020.

EZBuilder, a simple and graphic instrument to create applications for Intermec readers. Intended for particular reader types, including Trakker ANTARES and JANUS. The reader can be used to create menus, displays, data fields, tags and so on. Features built-in PC-reader data exchange and does not require operators with SI programming skills. Includes a high-power HELP-file for rapid user self-training. A user simply needs to select some of the options and preset the system of parameters for EZBuilder to create the application for the above reader types. There is also a built-in simulator enabling tests of applications for operability without being downloaded into the reader.

LabelView, an application package enabling users to design labels and tags. LabelView-designed labels may include texts, barcode symbols, graphic images, fields and more.

Efficiency of barcode technology in NM physical inventory takings

Barcode technology enables automation of marking check processes to cut so drastically the labor expenditures in periodic nuclear material inventory taking and control.

Experiments were conducted by the Kurchatov Institute to identify different nuclear material in containers or in fuel assemblies as individual samples and individual fuel elements. The identification procedure was to check their respective names against what was given in certificate data. This is a standard procedure used in physical inventory takings.

Statistically, visual comparisons turned out to entail the following personnel errors: trained, skilled, competent and motivated personnel had one error per one thousand of marking check operations on the average. The process was certain to involve rather a great scatter of uncertainties in a range of a factor of 10 both upwardly and downwardly. This means there was someone who made one error per 100 regulated actions and another one making one error per 10000 actions. On the average, however, there was one error per one thousand regulated actions. That is, if a person has a task to check one thousand markers, there is at least one case when he or she says they are definitely identical though actually these differ. After one

thousand markers, there is one case (on the average) when markers are different and he/she says they are absolutely identical.

It should be noted now that if inventoried items are one thousand named articles to be checked visually in a physical inventory taking (particular articles are checked against respective certificate data), one can imagine how many errors this will entail.

Barcode application effect. Checking is a relatively time-taking procedure. It takes about 30 seconds to check markers of ten symbols (certificate data and the item). This stems from the preparation of the item and its respective positioning to make markers readable by two or three readings since markers are long and cannot be forthwith memorized by humans. This means these should be compared in a by-symbol manner.

It was ultimately found that use of barcode markers, with a respective computer support in place, involved a marker misreading probability, this, as experimentally shown by the Kurchatov, found to be at a level of about 10^{-6} . There can be approximately one such error per one million markers. Still, the most important thing is that comparison here takes 1.5 to 2 s instead of 30 seconds needed by humans (the probability of an error being rather certain).

Conclusion. Barcode technologies offer a radical solution to problems involved in checks of articles with documented data for physical inventory taking.

9.2. Automation of NM measurements

Automated measurements of nuclear material form an essential component of automated NM accounting. Fortunately, the equipment used nowadays to measure and control nuclear material is either computerized or require communication to computer-based data handling systems.

Examples of NDA equipment

Until recently, up to the advent of electronic scales into nuclear industry, analytical laboratory scales were used to measure nuclear material. These are exclusively accurate lever-type scales capable of weighing nuclear material of up to 5 kg with an accuracy of 0.001 g. The scales normally have a seismic-proof base. Just imagine the length of a weighing session on such a scale. It takes much time, occasionally hours, because multiple measurements are required. Electronic scales, in turn, enable weighing to an accuracy of ~ 0.1 g done virtually in seconds.

Electronic scales are also fitted with an RS-232 interface for connection to a PC.

Gamma spectrometry suggests application of not only detectors and digital-to-analog transducers but also of a computer built in the system to process experimental data. This leads to a statistical data capture in 5 to 10 minutes and a computer processing time of 1.5 to 2 min. Depending on respective accuracy requirements and use of nuclear material samples, a measurement session may take from several minutes to an hour or several hours. The situation is nearly the same with neutron measurements based, say, on neutron wells. A switch to instrumentation with built-in statistical handling of measurement data has led to significantly less labor-consuming processing of measurement data and a much shorter time needed to get the final result.

The order of the day now is therefore the mating of accounting and control systems with measuring equipment that generates statistically handled data ready to be put in computerized NM A&C systems.

Program (hardware-based) interfaces have been developed and are used by the Kurchatov Institute for measurements in the КИ-МАКС system. Similar interfaces have been designed and employed by the Institute of Physics and Power Engineering (FEI) in Obninsk, the All-Russian Research Institute of Experimental Physics (VNIIEF) in Sarov and other organizations. These interfaces have made it possible to automate data transmission in NM A&C systems and decrease (by approximately three orders of magnitude) the probability of instrument data to be read erroneously. This leads to a current measurement automation system built in an accounting and control systems enabling instrument operators to make decisions competently and in a statistically sound manner and not to rewrite instrument readings (estimate to what extent the measurements performed fit or do not fit).

9.3. Systems approach to construction of enterprise NM A&C systems

Accounting and control of nuclear material is a complex man-machine system in which machines (devices, instruments, standards, computer networks) represent tamper indication, identification, measurement, data input and handling functions, while humans represent analyzing, decision-making and implementation functions. Normally, such systems incorporate a great deal of hardware support arrangements and features. Accounting and control of nuclear material is being technologically upgraded primarily to convert to computerized accounting and automated identification, control

and measurement of NM. So evolution of NM A&C nowadays largely needs these to be combined efficiently in a coupled system of arrangements and features. This is achieved through a systems approach to building an NM A&C system model (Fig. 9.5).

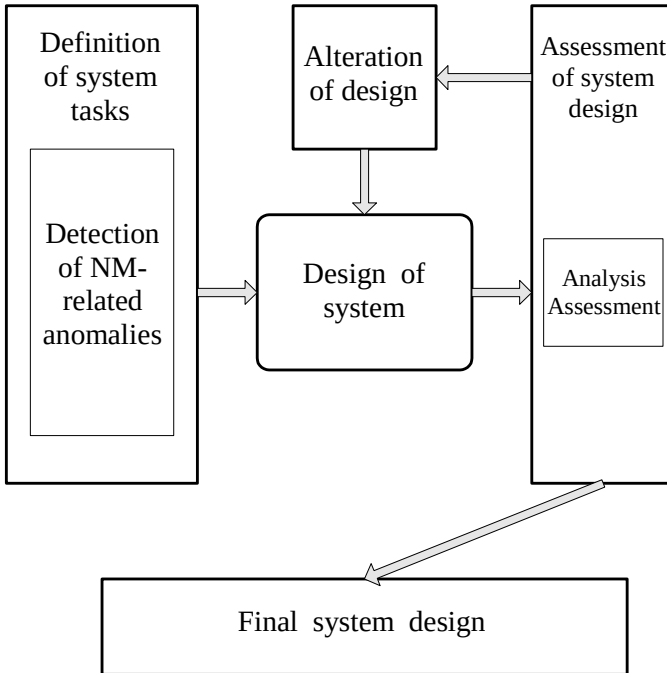


Fig. 9.5. Construction and assessment of an NM accounting and control system model

The systems approach primarily suggests definition of the system-solved tasks. For NM A&C, this means determination of NM inventories and flows, as well as timely detection of unauthorized NM handling or potential NM identification and measurement errors. The latter gives significance to the listing of potential NM onsite handling or storing anomalies as a part of the system task definition.

The next step is to build a model of the system. This is the system model version evolution phase. The construction of an NM A&C system model needs to structure the site so as dictated by the NM disposition and flows, lay out hardware within this structure, define the sequence of major

accounting and control procedures, arrange for maintenance and control of the system operations and so on. Said NM A&C system components are expected to be present in the model such that to make the system meeting the defined tasks to the highest extent possible.

It is at the closing work phase that it is decided on to what extent the developed NM A&C system version meets the tasks it is assigned to. The purpose of this design stage is to estimate the efficiency of the system operations to the selected criterion. It is a general knowledge that efficiency is the property of a system showing to what extent it fits the tasks at hand. Different approaches are under consideration for use to estimate NM A&C system efficiency. Thus, confidence of data on NM attributes is considered to be the efficiency index.

It should be however noted that NM A&C system efficiency is not easy to estimate universally. It is normally estimated on computer models with estimates relating to the quality of NM balances in the MBA (say, requirements to the accuracy of NM balances in the MBA).

The NM A&C system functional efficiency can be also indicated by how credibly the MBA NM accounting and control system presents data on identifiers of items, TID identifiers and locations of items. This indicator value should not be below 99%. If a system model estimate fails to satisfy to the criterion chosen, it is to be changed. So, if the share of erroneous data on attributes exceeds 1%, respective automated procedures may be used instead of manual data entry/processing. Therefore, building the final NM A&C system model version is an iterative process. The number of iterations depends on how rigid the adopted design estimator is.

CHAPTER 10

CONTROL OF NUCLEAR MATERIAL

Hereinabove, attention was focused on the NM accounting system. This serves to ensure the knowledge and the integrity of nuclear material. Balance closing is the procedure which helps getting the required confidence of the knowledge. In the context of accounting, however, confidence and integrity of NM are verified exclusively through physical inventory takings which are quite periodic (e.g., annual for NM of category IV). So control of nuclear material is undertaken as a complement to accounting. NM control includes control of the NM inventory and movement; control of access to NM, equipment and information; surveillance of NM, and check of authorizations for disposition and movement of NM. Control of NM supports the integrity and proper handling of NM, as well as the confidence of our knowledge about NM [1]. The following levels of NM control will be looked at hereinafter:
Control of NM at enterprises, including organizational measures and engineered NM control features;
State control of NM through inspections by Rostekhnadzor of Russia;
International control of NM.

10.1. NM control at enterprises

Localization of NM and identification (labeling) of NM-containing objects as prerequisites of efficient control of NM

Enterprises have NM controlled involving largely the two following controls:

- Control of NM inventory. The binding requirement here is identification of facilities with NM;
- Control of access to NM. The binding requirement in this is localization of NM.

With identification aspects having been dealt with in Chapter 9, we shall take a closer look at localization of NM.

Relative inaccessibility of NM (instructions on how to produce a primitive nuclear charge can be found in Internet) is believed to be the basic reasoning behind the efforts to curb the spreading of nuclear weapons. Localization, which supports this inaccessibility, means disposition of nuclear material inside special areas and facilities. Engineered features in these enable access to NM to be controlled. Secure

areas and material access areas (MAA) are specific examples of such special areas.

Secure areas. A secure area may be a protected, an inner and a vital area. Secure areas include barriers to delay intruders into the area (security perimeter). Barriers are formed by fencing, structural elements and so on. Each secure area also includes an access control point and is equipped with respective access controls.

NM and nuclear facility physical protection regulations prescribe that:

- NM of categories 1 and 2 should be used and stored in the inner or the vital area;
- nuclear facilities should be deployed within the inner or the vital area;
- NM of category 3 should be used and stored within any secure area.

Fig. 10.1 shows an example of localization areas layout for NM of different categories.

Material access areas. Material accessibility areas are process department and NM storage areas.

A process department is where nuclear material is subject to physical and chemical changes. Most NM quantitative changes take place within process departments. Being where nuclear material is accessible directly, process departments are subject to special security regulations. This includes the requirement of permits to enter a process department to be granted only to personnel involved in running the process. The amount of the material within a department is normally limited to the quantity needed for one-day routine operations. Access control logs are kept at each process department with entries made therein on all persons granted access to the given department. This makes a starting point for anomalies to be investigated. In the absence of personnel, the intrusion detection system is active.

Apart from security features, it is important that process departments enable reliable control of the NM therein, including by way of localizing material.

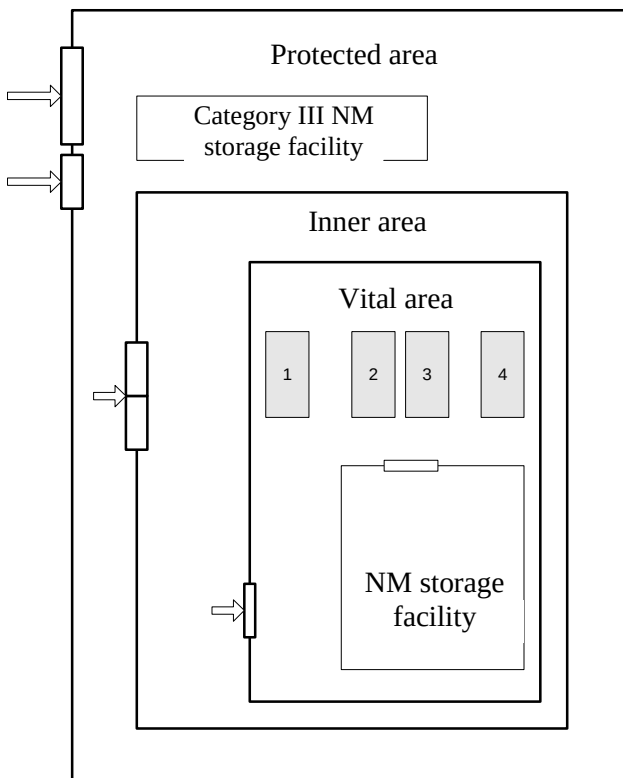


Fig. 10.1. Nuclear material localization areas:
1, 2, 3, 4 – process departments

For process departments, localization of NM suggests that NM should remain in equipment, pipelines, glove boxes, safes and containers. Therefore, material stays in these facility components when the process is run, thus making it harder to remove it in an unauthorized manner. Fig. 2.1 (Part II, Chapter 2) shows process departments for fabrication of low-enriched fuel. Each of these has nuclear material localized in equipment, safes and containers. Containers are commonly used to store NM and ensure efficient localization of bulk material (Fig.10.2). Practically, different container types are used (metal drums, cans, assemblies, packages, tanks, vessels and others).

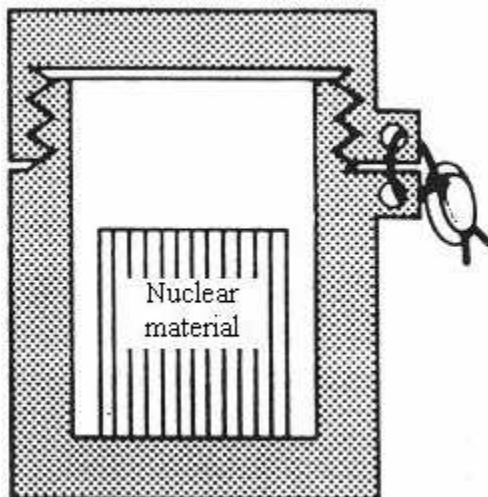


Fig. 10.2. NM localization container

Safes, stores and containers are kept locked unless immediately watched by an authorized person. The material contained therein is accessible to the smallest reasonable number of personnel. The lock codes are updated whenever situation with NM changes within the department. Thus, this is done when a container is initially received or a personnel member who knows the code is transferred or dismissed.

It is also important that nuclear security measures, which are of a prime significance to any process department with NM, have also the goal of localizing nuclear material contributing so to better NM control conditions.

Localization in storage areas. Nuclear material may be also kept in storage areas at the facility or at NM storage points outside the facility. An NM storage point is a fixed standalone installation. Fig. 10.3 shows an example of how NM can be localized in a storage facility.

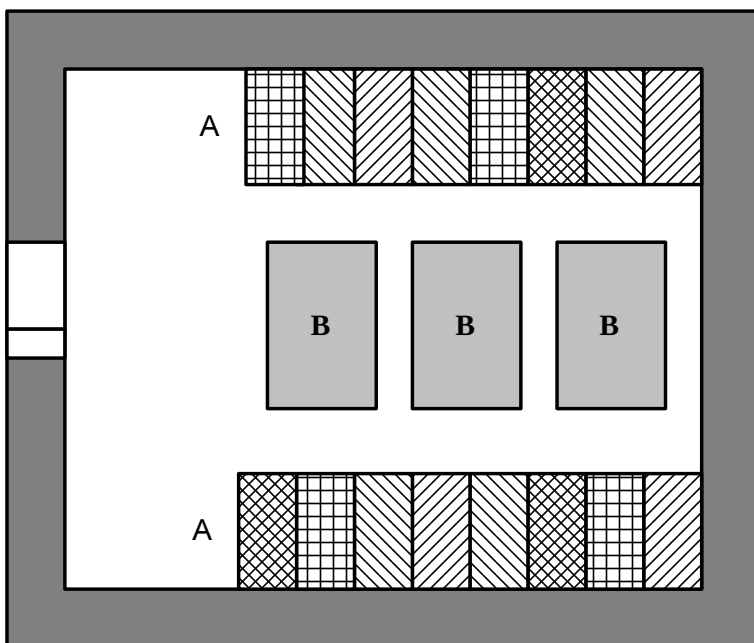


Fig. 10.3. An example of NM storage facility: A – container racks;
B – NM safes

Storage facilities offer the best NM control solutions. The major elements of the storage facility structure (floors, walls, roofing and doors) normally satisfy to top-level material localization requirements, including reinforced-concrete floor, ceiling, roofing and walls of the thickness not less 20 cm. Any openings in storage facilities that permit unauthorized intrusion thereto are equipped with barriers. It is forbidden to process material and handle same other than for the purposes of NM storage (say, for experiments involving NM) within storage facilities. It is also forbidden to lay routes to other areas of operations through storage facilities.

NM access controls

An important feature of current accounting and control systems is the maximum use of access controls. All developed countries, including Russia, have their NM accounting and control systems relying on measured material balance. Furthermore, a measurement of NM inventory is in fact a

serious physical experiment. Still there is more to that. Measurements of nuclear materials as such are rather a time-taking and hazardous procedure (especially when it comes to plutonium). So it is required to make so that NM measurements be reduced to as small scope as it can be. In this, the continuity of knowledge about NM is ensured through using NM access controls.

Access controls include two types of provisions known as surveillance and containment measures.

Surveillance. The simplest and the most commonly used surveillance type is visual surveillance. This requires continuous presence of a number of persons. A two-person rule is used for NM handling when critical operations with nuclear material are done by not less than two persons. A three-person rule can be used to handle weapon-grade material.

For NM control, many countries make an extensive use of optoelectronic surveillance (OES) via TV monitors. Fig. 10.4 shows an option of the OES camera installation in a spent fuel pool.

For years, optical surveillance of NM has been used successfully in the context of international safeguards. The IAEA uses optical surveillance to control NM movements, survey spent fuel in storage facilities and for other purposes. Photographic surveillance systems (MINOLTA) were employed by the IAEA until 1988 when these were replaced for video systems of a greater efficiency. Table 3.2 (Part I, Chapter 3) gives examples of video systems used now by IAEA, which demonstrate the increasingly great capabilities of this nuclear material control technique.

Containment. Containment ensures continuity of the knowledge about NM at rest. Containment, first of all, means use of all kinds of sensors that detect unauthorized access (tamper indicating devices or TIDs) or respond to changes in the condition or the positions of nuclear material (hybrid NM containment techniques). Thus, if a container shift is detected, the sensor generates the message of the container having been moved.

TIDs represent seals of different types.

Seals have the role of detecting unauthorized access to NM (seals are used for containers, item packages, doors and so on).

There are three properties that characterize the efficiency of seals:

- **weakness:** means that seals are easily breakable, serving so to forestall unauthorized activities with NM;
- **tamper indication:** if broken, seals are hard to replace without traces of the tamper left;

- **uniqueness:** seals should possess unique identifiers (preferably concealed).

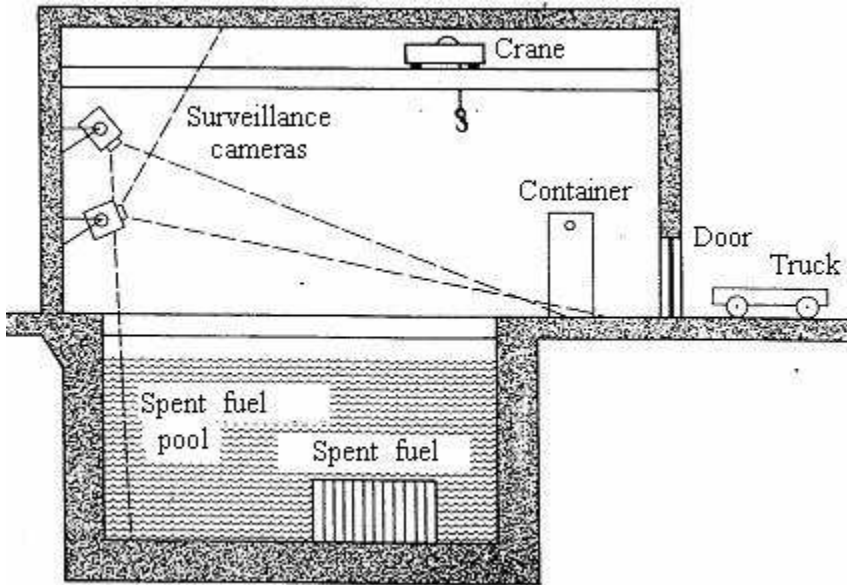


Fig. 10.4. An option of the OES camera installation in a spent fuel pool

Fig. 10.5 – 10.9 show examples of various seal types used in practical NM handling: E-cup, PS360 loop seal, Multi-lock, Cobra and Vacoss.

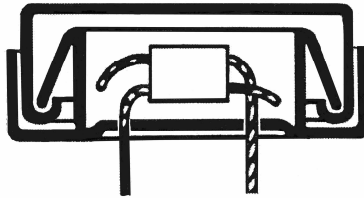


Fig. 10.5. Cup-E seal design



Fig. 10.6. A plastic loop seal (PS360 model)

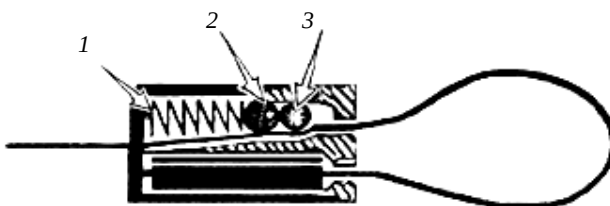


Fig. 10.7. Multi-Lock seal design: 1 – spring; 2 – aluminum ball; 3 – steel ball

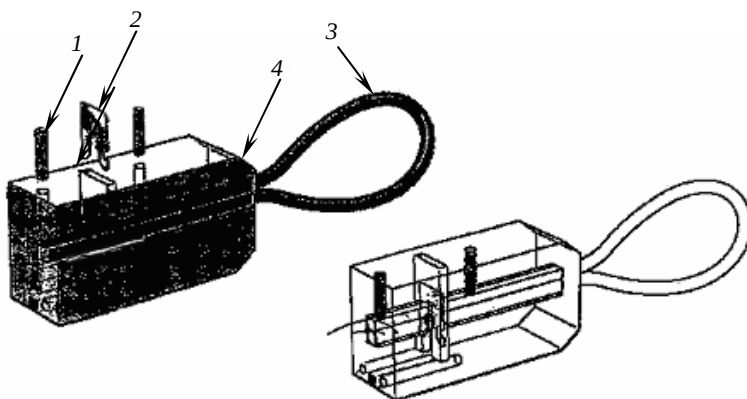


Fig. 10.8. Cobra seal design:
1 – compression rod; 2 – shearing razor; 3 – fiber optic cable; 4 – seal body

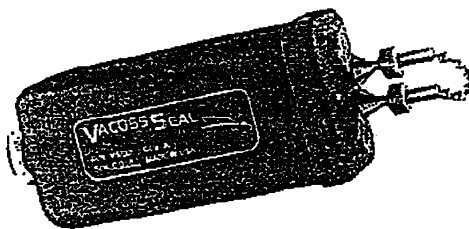


Fig. 10.9. Reusable Vacoss seal design by Aquila, the USA

Adhesive seals (stamps). These seals have a paper, vinyl or lavsan base with an adhesive applied to it on the inside. Adhesive seals may contain one or more base layers.

Paper or vinyl adhesive seals have a single-layer base. After placement, these seals are hard to remove without traces of the tamper left because:

- paper seals are based on rice paper so they can be broken easily when removed;
- vinyl seals have cross cuts made along the entire base length, which makes it much more difficult to remove a seal without breaking it.

A lavsan seal has a transparent outer layer and a colored metallized inner layer. The inner layer bears a drawing and the ordinal number. The colored base layer of a lavsan seal has a seal breaking sign (the words Void or Open for example) preprinted across the base length on the adhesive side. When a seal is removed, this sign appears on the container surface and the stretched colored base fails to match the image left on the container.

Adhesive seals are used to seal containers with NM.

Hybrid containment techniques

Access control techniques include also US-developed hybrid methods used now also in Russia. These are gamma image memorization techniques. A detector is placed beneath a container with NM (e.g. HEU) for continuous gamma ray detection. The gamma ray spectrum comes further to the computer and is compared to the reference spectrum, i.e. the spectrum that was recorded when the material was placed under control. If the comparison fails to confirm the identity of the spectra, an alarm is on. A gamma image technology is used, which also ensures the confidence of knowledge about the status of nuclear material.

Daily administrative control of nuclear material

Custodians and the facility's top officials control NM as the persons responsible for the integrity of NM. Administrative controls include systematic checks of NM performed by custodians or the persons authorized so by the facility administration for the NM inventory to be verified or anomalies and infringements in NM handling, accounting and control rules at workplaces to be timely detected. This form of control checks the NM inventory and disposition at authorized locations, the NM integrity (tamper indicating devices), alarms and so on.

10.2. Intrastate and international control of NM

Rostekhnadzor of Russia

Russia has state controls implemented in the form of supervision by a special organization, Rostekhnadzor of the Russian Federation. The functions of this cover all aspects of national nuclear safety and security, and are governed by the atomic energy law. This law authorizes Rostekhnadzor to:

- develop federal standards and regulations;
- license NM uses by organizations;
- enforce NM accounting and control regulations within organizations;
- enforce NM physical protection regulations within organizations;
- supervise nuclear, radiation, technical and fire safety.

Emphasis in this is placed on supervision of NM accounting and control within organizations. Rostekhnadzor inspectors carry out audits of all documents on the NM in each of the MBAs that exist at the enterprise, perform verifying measurements of their own and make a statement with respect to the status of NM accounting at the given enterprise. Subject to Rostekhnadzor supervision are all enterprises and organizations in Russia that possess nuclear material (except those operated by the Russian Defense Ministry).

International control of nuclear material

International controls are implemented for the nuclear proliferation resistance purposes. International NM control is based on the Nuclear Weapons Nonproliferation Treaty the parties to which are practically all countries of the world. This nuclear material control is described in Part I (Chapter 3).

Part III

PHYSICAL PROTECTION OF NUCLEAR MATERIAL AND NUCLEAR FACILITIES

CHAPTER 1

GENERAL DESCRIPTION OF THE OBJECTIVE OF PHYSICAL PROTECTION

Physical protection of nuclear material and nuclear facilities, as defined by the Russian atomic energy law [1], is a nuclear activity directed at ensuring security of nuclear installations (NI) through protection of these against a particular type of threats (theft of nuclear material, acts of sabotage at nuclear facilities and so on).

Physical protection is involved in all phases and stages of the nuclear facility (NF) lifecycle and in handling of nuclear material (NM), including transportation thereof.

Russian regulatory documents [1, 2] establish requirements to ensuring the physical protection of NIs, which, among other factors, take into account international obligations of the Russian Federation in uses of atomic energy. Regulations of the Russian Federation prohibit nuclear activities without physical protection being ensured.

Noteworthy is the hierarchical structure of physical protection measures taken at the state, industry and nuclear installation levels.

These measures are implemented by respective physical protection systems.

The state system of physical protection comprises government authorities and agencies, as well as federal executive power bodies carrying out state administration with respect to uses of atomic energy and government regulation with respect to security of installations making use of atomic energy, other federal executive power bodies and organizations involved in ensuring physical protection.

This level also includes oversight with respect to the fulfillment of physical protection requirements as declared in respective regulatory documents.

A specific objective of the state system of physical protection is to reduce the likelihood of NM being trespassed on by preventively detecting the actions prepared for and limiting the capabilities of potential attackers to make so that the adversary would not have respective materiel, e.g. armored vehicles, missile launchers, helicopters and so on, as well as information on the physical protection measures taken at particular NIs.

An agency system of physical protection combines and coordinates the efforts taken by installations within the authority of the respective agency to ensure physical protection thereof, as well as guidance, funding and control of their activities.

The agency level involves guidance with respect to the specified type of activities at all installations within the respective agency's control given the specific nature of the industry concerned, procedural assistance and logistic support to the establishment (perfection) of the physical protection system (PPS) at installations, and internal control of physical protection at NIs. To this end, management structures are formed within the respective executive power bodies to be in charge of these functions.

A system of physical protection at a nuclear installation level (installation-level PPS) implements the above complex of provisions immediately at the installation concerned. It is exactly the installation-level PPS that forms an essential, key link in the entire spectrum of physical protection activities. The responsibility area thereof is the installation's site, as well as all buildings, structures and, clearly, nuclear material proper and critical components of nuclear facilities this includes. It is exactly here that particular tasks in protection of nuclear material against theft and nuclear facilities against acts of sabotage are addressed.

A separately addressed task is protection of nuclear material in the process of transportation (movements between installations).

The activities at all levels are essential and contribute to the overall task of ensuring physical protection of nuclear material and nuclear facilities.

The state and agency systems of physical protection address general political, organizational and financial problems. Most research, engineering and practical problems arise in ensuring physical protection immediately at the level of installations. It is exactly these problems and ways to resolve these that we shall discuss below.

There is an important point to the PPS construction as a complex human-machine system, which involves competitive interests of the parties concerned (the attacker and the protection system). The human link in the PPS, made up of persons making and persons implementing decisions (emergency response teams and so on), as well as the need for addressing the task in an uncertain environment (no prior awareness of the adversary's intents) limit the applicability of analytical research techniques. Mathematical modeling (simulation), as shown below, offers the most attractive solution.

A very important question is how this complex system can be built so that it would be efficient. To find the answer, one cannot avoid using a systems approach to enable, by defining the overall objective of the PPS as protection of the installation, the requirements to its separate subsystems to be formulated.

It is also important to analyze the PPS establishment (perfection) process as such, which requires a systems approach as well to coordinate the work performed at separate stages and steps.

The recent trend in the evolution of modern NI physical protection systems has been towards an increasingly comprehensive use of technology therein. The technological innovations in the PPS field include, not being limited to, new types of intruder detection sensors and systems, including for novel applications (water area, low-flying targets, detection of introduced items), as well as systems automating some of the functions implemented earlier by the physical protection personnel. Use of hardware improves the performance of the NI physical protection systems by reducing the human factor effects thereon and promotes so safety and security culture at NIs.

The questions answered to in the subsequent chapters are what the PPS is, what this is composed of, and what roles its separate subsystems and components (hardware, response force, structural elements and others) are assigned to. Further we shall dwell on how this system can be built, what its lifecycle stages and phases are, and what procedures and techniques can be used to support the establishment (perfection) and operation of the PPS.

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CHAPTER 2

REGULATORY AND LEGAL FRAMEWORK OF PHYSICAL PROTECTION

Physical protection is a complex and critical task, which requires a regulatory and legal framework to be formed for this to guide activities in the field.

NM physical protection activities are governed by respective Russian laws and regulatory documents. Requirements and recommendations in a number of international documents should be also taken into account. We shall start from these.

There is an IAEA-developed document [1] which forms a conceptual physical protection basis for different countries possessing nuclear material and nuclear facilities. This views physical protection in each particular country as a national problem to be addressed given the country's specific features (geopolitical environment, peculiarities of nuclear installations, crime rate in the given country and so on).

The second international document is the Convention on the Physical Protection of Nuclear Material (1989). Also taking physical protection as a national-level issue, this document places emphasis on international NM transport.

The atomic energy law is the underlying Russian law [2]. Some of the chapters and sections therein do deal with physical protection issues, still, as is clear, in the most general terms.

More detailed regulation of physical protection is provided in another federal document [3]. This defines the functions of executive power bodies and sets forth major requirements for physical protection of nuclear sites, as well as for nuclear material and facilities during transport.

Law, clearly, simply outlines different aspects of physical protection activities and provides only general guidance on how this to be ensured. Therefore, a vital task is to generate industry (interindustry) regulations to take into account the specific features of nuclear installations and the need for carrying out interbranch activities.

The above instruments govern necessary procedures and impose requirements upon the PPS, its components and types of activities. A number of documents at this level describe the techniques of carrying out some activities (e.g. site vulnerability analysis, PPS performance assessment, PPS testing and others). One example to consider is Rosatom's system of the PPS industry documents as discussed in [4, 5].

An essential part of the PPS regulatory framework is site-level regulations (bylaws, instructions and so on). These contain more detailed requirements to PP with regard for the specific features of this very NI. Such documents are developed and employed directly at the level of installations.

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CHAPTER 3

STRUCTURE AND COMPONENTS OF THE PHYSICAL PROTECTION SYSTEM (PPS)

Nuclear material and nuclear facilities are contained in respective buildings and rooms within the protected area confined by a perimeter. Figure 3.1 shows a standard layout of a physically protected site.

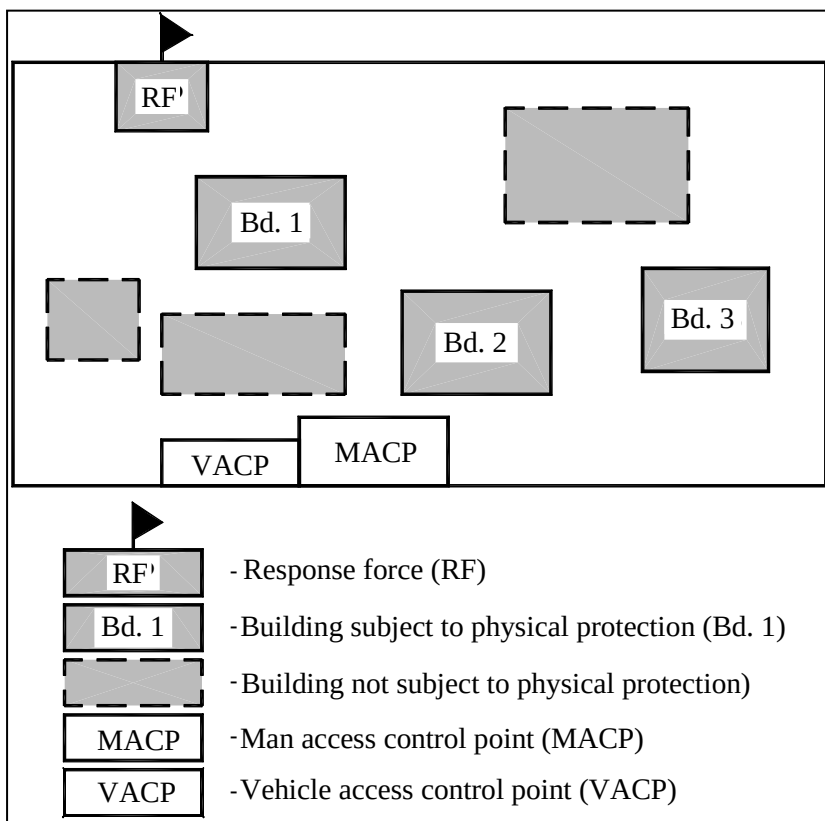


Fig. 3.1. Standard layout of a physically protected site

A note should be made that only some of the buildings that accommodate NM and critical NF components require physical protection, while the presence of others affects physical protection tasks only indirectly (limited visibility, onsite movement routes and so on). This will be given

more detailed consideration in Chapter 5 where principles of the PPS zonal arrangement will be discussed.

Onsite forces and features are responsible for the physical protection at the level of nuclear installations. These are chiefly a response force as well as engineered physical protection features (EPPF).

Collectively, physical protection forces and features form a **physical protection system** (PPS), which represents an interlinked set of organizational, administrative and legal provisions, physical protection personnel and engineered features intended to ensure the physical protection of a particular nuclear site.

The PPS is a complex man-machine system an analysis whereof requires such techniques as systems engineering and operations research [1].

An analysis of such systems requires these to be first decomposed (subdivided) into subsystems. This makes it easier to get an insight into the hierarchical structure of the system as the whole and its individual components.

We shall decompose a PPS into respective subsystems. When doing this, one should keep in mind that a lower-level system is a subsystem of a higher-level system. Thus, in turn, the PPS is a subsystem of the whole NI safety and security system, which also includes other systems (nuclear safety, fire safety, NM accounting and control, etc.).

The PPS structure is shown in Fig. 3.2.

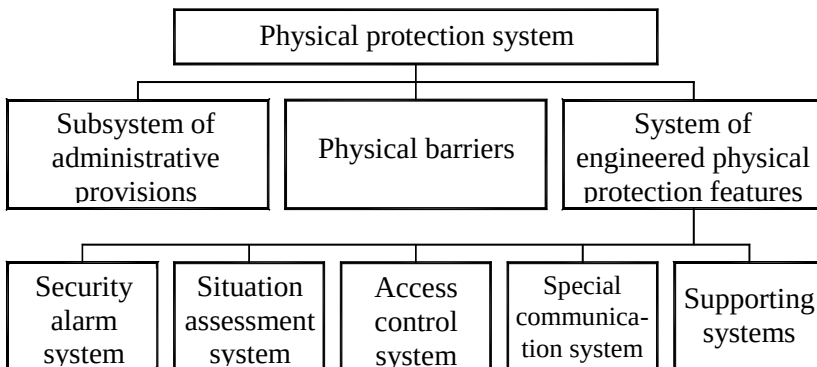


Fig. 3.2. Structure of a physical protection system

As can be seen in Fig. 3.2, the PPS has three key components, the functions whereof will be discussed hereinafter.

The prime objective of engineered physical protection features is to acquire information on unauthorized activities to be further used to produce respective control responses.

Physical barriers have the purpose of making it more difficult for attackers to carry out the actions planned.

Administrative provisions establish the onsite PP procedures (rules). The guard force response to suppress the above attacker actions is a sort of an “actuator” for the PPS and makes it possible to reach the final objective of the NI protection.

A note should be made that the PPS subsystems at all levels should be balanced and contribute to the overall goal of the NI protection against unauthorized activities of potential attackers.

Separate subsystems and their respective functions are described hereinafter.

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CHAPTER 4

GENERAL DESCRIPTION OF THE PPS SUBSYSTEMS

4.1. Engineered physical protection features

As mentioned above, a better understanding of a system is achieved through decomposing it. Separate systems are described below as subsystems of a system of engineered physical protection features (SEPPF) [1, 2].

Security alarm system

Essential to the construction and operation of the PPS is acquisition of information on the committed (attempted) unauthorized activity. This function is performed by detection sensors, which are part of the security alarm system (SAS).

A detection sensor is a device designed for automatic signal generation in the event of an unauthorized activity within its responsibility area.

A security alarm system is a combination of detection sensors, call alarms and the PPS data acquisition, handling and display system.

The following detection sensor classes may be identified.

By conditions of application:

- outdoor (perimeters, local areas);
- indoor (buildings and rooms).

By action:

- electric-contact;
- optical (including infrared);
- capacitive;
- inductive;
- vibration;
- seismic;
- acoustic (including subsonic);
- radio beam;
- radar;
- leaky-wave;
- combined;
- others.

The physical classification of detection sensors is based on interactions of the detection object (attacker) with different physical fields.

Essential to the SEPPF design are characteristics of its individual components, including detection sensors.

The following is normally chosen as the major detection sensor characteristics:

- detection probability;
- mean operating time to false response;
- mean operating time to failure;
- mean time to recovery;
- cost.

Probability of detection is what determines the efficiency of the PPS as the whole.

Operating time to false response or frequency thereof is the performance characteristic defining to what extent the SEPPF causes nuisance to the guard personnel. Psychologically, an important point is also a decrease in confidence in signals and a lower level of alert as the result of frequent false alarms.

Operating time to failure and time to recovery are the robustness characteristics also determining the efficiency and operability of the SEPPF.

Cost is an important characteristic to be taken into account in the SEPPF design.

Fig. 4.1 presents simple examples of detection sensor applications on the NI site perimeter and inside the NI.

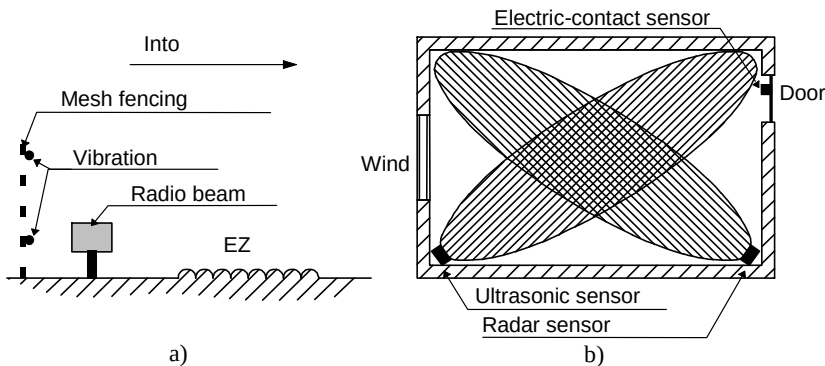


Fig. 4.1. Examples of detection sensor applications: a) – on the NI perimeter; b) – inside the NI.

The signals from the detection sensors installed for various NI applications (perimeter, outdoor, indoor) are sent over the communication lines to the physical protection system control panel (panels). The panel operators analyze the signals, after which the person responsible for decision-making chooses the algorithm for the response force actions to suppress the attackers and protect NM and the NF.

The combination of detection sensors, communication lines and control panels (that handle and display information from centers) forms the security alarm system.

Situation assessment subsystem

The false response problem leads us to thinking about how to raise the level of confidence in the DS response signals. One proven but outdated technique is the arrangement of exclusion zones (EZ) around the NI site on which the intruder's traces will be left. Seals are used for indoor alarm acknowledgement.

A more recent alarm acknowledgement technique is application of video monitors and video surveillance systems (VSS).

All of the above features, both old and new, may be collectively viewed as a collection of situation assessment features and systems that improve reliability of primary data from detection sensors, as well as, in some cases (TV), make it possible to obtain more information on the intruder (number, intruder movement direction and so on) so that adequate countermeasures could be undertaken.

Seal designs are also improved (barcodes, optic seals, etc.).

Access control subsystem

The NI operations require authorized personnel and vehicle admission into the installation site and its separate areas, so each NI has a special subsystem established to identify "friends" (NI personnel, authorized visitors and so on) and "foes" (intruders) using a set of specific features.

Here are some of the definitions concerned with this.

Clearance: a duly issued permit for a person or a vehicle to enter any guarded area for the purpose of carrying out activities or receive any documents or data.

Access: realization of the possibility to stay in a guarded area, obtain information and documents, operate nuclear materials and so on.

One example of this subsystem's element is a guard who performs the access-related functions. A recent trend is to use automatic devices instead of guards.

Essential elements of the access control system (ACS) are also devices that prevent prohibited items (weapons, explosives, nuclear material, etc.) from being taken into or out of the NI.

The access control system is a PPS subsystem that supports the NI protected area access control tasks.

To perform all these functions, external and internal access control points are established for the NI.

The access control systems and facilities are designed for the following applications:

- external personnel access control points;
- external vehicle and railway access control points;
- internal personnel access control points;
- entrances to restricted rooms;
- storage rooms for physical protection articles (safes, etc.).

Examples of personal identification techniques:

- based on the features assigned:
 - coded pass;
 - digital code;
- based on personal features:
 - hand geometry;
 - eye structure;
 - voice;
 - signature dynamics;
 - appearance (a computer photograph);
 - others.

Examples of the ACS elements:

- man traps for external (local area entrance) and internal access control points;
- turnstiles at entrances to detached guarded areas;
- door terminals for control of access to guarded rooms.

Also, access control points may include devices to prevent introduction of prohibited items as listed above.

The devices to be installed and the installation points thereof within the facility site are determined in the process of the PPS design.

Examples of the major ACS characteristics are as follows:

- probability of detecting an admission procedure violation (identification features, etc.);
- probability of a false detection of said violation;
- mean operating time to failure;
- mean time to recovery;
- cost.

The first characteristic is what the efficiency of the PPS as the whole depends on.

The second characteristic determines the ACS maintainability. Of note is the ACS capability to regulate access to the installation's separate guarded areas and segregate human and vehicle flows between these. The ACS ensures authorized access of personnel exactly to those areas they are permitted to enter.

The same can be said about the last three of the presented characteristics as with respect to detection sensors.

The ACS also has roles in countering insider actions.

Thanks to a great deal of capabilities opened up by advanced computer technology, a trend is observed towards integrating the ACS with security alarm systems and building integrated access control and security alarm systems (IACSAS).

Tendencies are also showing up towards integrating the PPS with NM accounting and control systems. The ACS is the major "interface" element in such integrated systems.

There are also other access control devices to consider in detail. These are, primarily, controlled locks that can be used in the ACS components, e.g. in cabins, or installed separately (door locks). In the latter case, these are to be logically viewed as controlled physical barriers to be described below.

Special communication system

A communication system is a facility for controlling the response force (RF) and ensuring communication within the NI and with the outside (relative to the installation): superior organizations, police stations, etc.

Regulatory documentation contains the requirement that there should be two communication channels (wire telephone and radio facilities).

Thanks to modern computer capabilities, it is possible to organize a communication network and control it in a flexible manner depending on the situation at hand.

The term “special communication” is used chiefly because of the need to protect information in the communication system.

Supporting systems

The term “supporting systems” gives a good notion of what these systems are.

One illustrative example is the power supply system which is essential for operations of all the systems discussed above.

Another example is the lighting system which supports operations of the video surveillance system components (TV cameras).

More examples of supporting facilities and systems are the system of cable ducts that connect individual components in the above key systems, and structural elements (zone cabinets, etc.).

4.2. Physical barriers and organizational subsystem of the PPS

Physical barriers

Physical barriers (PB) have an important role in the PPS. A physical barrier is a physical obstacle that ensures the intruder delay to slow down the attacker’s movement to the target within the protected area.

In fact, it is not enough to receive an unauthorized action signal from a detection sensor or a component of the ACS. Another condition needs to be fulfilled to make so that the attacker action time (T_a) be longer than the response force action time (T_{rf}). It is important that the response force has a slack margin, that is, that the condition $T_a > T_{rf}$ or $\Delta T_{rf} = T_a - T_{rf} > 0$ is fulfilled, where ΔT_{rf} is the response force slack time.

Physical barriers have the purpose of delaying the attacker in every way possible and increasing T_a .

Physical barriers may be fixed and controlled.

Specifically, the following classes of physical barriers may be identified:

- existing onsite physical barriers:
 - structural elements of buildings (walls, ceilings, doors);
 - elements of the terrain and vegetation;
- artificial physical barriers:
 - perimeter and local area fencing;
 - locks, meshes and reinforced doors in buildings and rooms;
 - anti-ram facilities at vehicle access control points;

special physical barriers (sound-and-light, smoke-discharge, foaming, etc.).

There are also techniques of influencing the intruder (electric shock, gas discharge and others), though onsite uses of these are subject to authorization by respective law.

Response force

The response force (RF) is responsible for the ultimate suppression of the intruder actions. This means that the RF starts to act as information is received from facilities or the guard on duty about an attempted intrusion into the site or into some of its protected areas. The choice of the response tactics depends so on respective regulatory requirements and on the situation at hand.

The RF comprises several units, each of which is assigned to the task of its own. Thus, the alarm unit moves to the DS response point, the reinforcement unit heads for the site's most vulnerable points to tighten security thereof and so on.

As will be shown below, time relations depend on the tactics chosen. Thus, we reduce T_{rf} by redeploying the RF and getting it closer the potential action points.

Organizational arrangements

Lastly, it is very important that all PPS components act coherently. We shall dwell on how to build and operate the PPS below, when consideration will be given to design and optimization of physical protection systems. Now just a note should be made that the order should be kept within the installation in the course of the PPS operation as established earlier through organizational arrangements. These arrangements include:

- NI personnel actions in standard and emergency situations;
- interactions among the onsite PP-related services and of these with the "outside world" (municipal authorities, superior organizations and security agencies);
- maintenance of engineered physical protection features.

The arrangements taken should be governed by regulations (bylaws, instructions, etc.). This makes the PPS operations less dependent on subjective factors. For example, where no regulatory documents exist, the decision in some situations will be made by an executive officer at the respective level, that is, the decisions taken will be much determined by his/her personal qualities. A hard and adamant security service leader will

create a great deal of problems to the normal site operations, while, in contrast, an excessively mild leader will cause poorer control of the NI, which will ultimately make it less physically protected.

A note should be made that modern physical protection systems have an increasingly great number of organizational functions vested nowadays in their hardware. Thus, modern AC systems rely on a “two-person rule” based on a collective responsibility principle (including with respect to the opening of rooms and the activation of security modes for these) when a person watches the actions of another person to reduce the probability of unauthorized activities.

Here is one more example. A timer is built in the data acquisition and processing system, which is triggered the moment the alarm unit (AU) responds to an alarm. When reaching the destination, the AU should report so to make it possible to know the exact guard personnel movement times and, accordingly, the final time of T_{rf} .

References

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CHAPTER 5

GENERAL CONCEPTS OF THE PPS DESIGN

The creation of complex systems is based on general concepts representative of systems of any nature, as well as on a number of specific principles that reflect the features of the given class of systems. The PPS features, as discussed hereinabove, define the set of specific concepts which are set forth below [1].

Zoning – defense in depth. This concept suggests the establishment of a system of guarded onsite areas enclosed one into another: a protected area, an inner area and a vital area (Fig. 5.1).

The protected area (PA) means the whole of the NI territory surrounded by physical barriers subject to continuous guarding and surveillance with access thereto being restricted and controlled. The inner area is inside the protected area (there may be more than one inner area). The inner area respectively includes the vital area (there may be also several vital areas). Safeguard measures become tougher from the outside to the physically protected items (PPI).

Here are some examples of such areas. If, as mentioned above, the protected area is the entire installation territory, the inner area (IA) may consist of buildings or separate parts of buildings within this territory, while rooms (clusters of rooms) inside buildings may be viewed as the vital area (VA).

The boundaries of the areas are equipped with engineered features with dedicated passages (drives) arranged therein for the authorized personnel access to the site. Clearly, requirements differ for the equipment of the areas and the boundaries thereof with engineered features and organizationally. Depending on the category of the physically protected item, this should be held within a particular area. For example, regulations require HEU to be held within the IA or the VA.

Of note is that areas may include additional EPPF-equipped barriers that are not on the area boundary and do not change the area status.

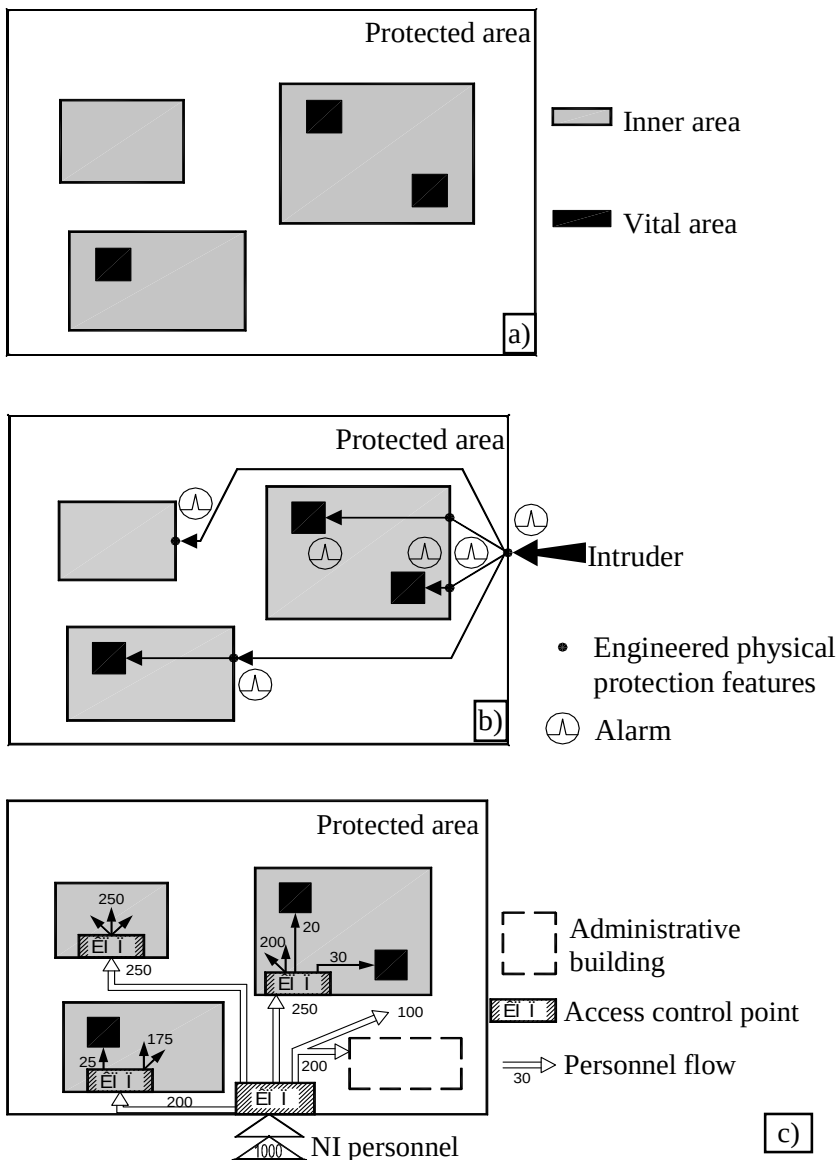


Fig. 5.1. PPS zoning principle: a) – guarded areas;
b) – defense-in-depth barriers; c) – differentiated personnel access to guarded areas

Zoning helps establish a defense-in-depth system to detect the intruder's attempts to defeat separate barriers (area boundaries) and predict the intruder's movement path and targets (Fig. 5.1, b).

In addition, zoning makes it possible to differentiate personnel access into some areas and, additionally, be fully aware (with an accuracy up to an area) of where the NI personnel are (Fig. 5.1, c).

Adequacy of the PPS to assumed potential threats and models of potential intruders.

The concept of the PPS adequacy to threats relates to the necessity of having the PPS “tuned” exactly to the threats assumed. Where the system is designed to deal with a milder potential threat, no protection will be ensured. Where, contrarily, the PPS is redundant (just in case), excessive capital and operating costs may be involved.

The PPS structure, composition and operation so depend on the potential threats and potential intruder models assumed.

We shall introduce some of the terms and definitions used in the field.

Threat - a potential of an act of sabotage or an NM theft.

External threat - a threat coming from an external attacker.

Internal threat - a threat coming from an insider.

Attacker model - a combination of qualitative and quantitative characteristics of an intruder used to analyze the resistance to sabotage, formulation of requirements to the PPS and appraisal of the PPS efficiency.

External attacker – an attacker out of the number of persons without the right of access to the protected area.

Insider – an attacker with the right of unescorted access to the protected area.

Examples of major threats to an NI are:

- a theft of NM or NM-based items;
- sabotage at a nuclear facility (NF) or within an NM storage facility;
- a terrorist act;
- nuclear blackmail.

As an act of nuclear blackmail requires the intruders to seize NM or the NF's key components, protection against this threat is reduced to ensuring physical protection against the two first types of threats.

Now we shall look at major intruder types as the “bearers” of the above threats.

The classification of intruders is given in Fig. 5.2.

Further we need to build models of potential intruders which can be divided into “macromodels” and “micromodels”.

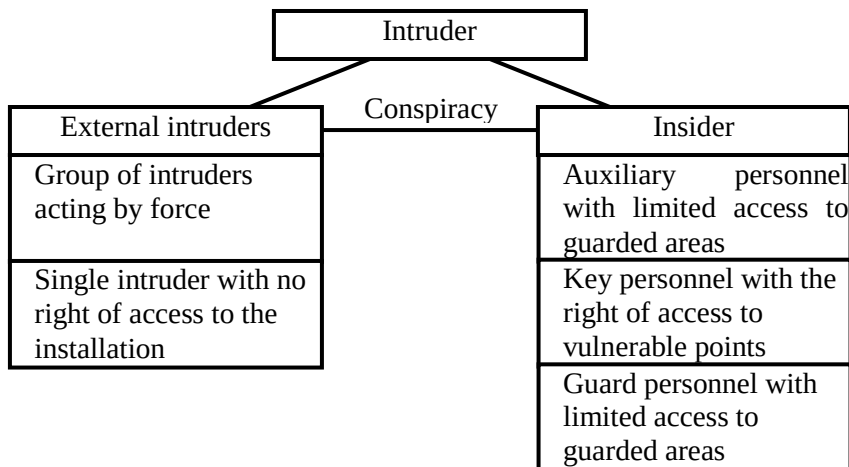


Fig. 5.2. Classification of intruders

A macromodel contains the following data:

- intruder type;
- anticipated act;
- target;
- number of intruders (where there is more than one intruder);
- awareness;
- preparedness;
- equipment, if any;
- weapons.

A micromodel contains the following data:

- techniques to defeat physical barriers and detections sensors (DS);
- speed of movement within the DS detection area;
- appliances at hand, if any;
- dedicated facilities intended, e.g., to disable DSs, if any.

Macromodels are used primarily to conceptualize the PPS design in general, while micromodels help formulate requirements, say, to the detection sensors and physical barriers on the perimeter, in local areas, within buildings and rooms, etc.

Practically, an intruder model for a particular NI is formed for the installation after its vulnerability is analyzed by filling in respective questionnaire forms.

Of note is that the intruder model should be revised on a regular basis. The reason for this may be a change in the political situation in the country or in the region or an onsite change (redeployment, relocation of NM, a change in the NI infrastructure and so on).

Timely countermeasures.

Timelines of countermeasures is defined by the fact that, whatever is the scenario under consideration, the relation $T_i \geq T_{rf}$ is to be fulfilled, where T_i is the time required by the intruder to accomplish his objective and T_{rf} is the time needed by the response force to suppress the said action in response to alarms from respective facilities.

Balanced strength of the PPI protection given the PPI value (attractiveness), potential consequences of unauthorized activities and the potential of any scenarios to be realized by the attacker.

The definition is absolutely clear so no comments on this are needed.

Adaptivity.

This suggests the PPS capability to adapt to changes in:

- threats and intruder models;
- the installation's layout and the boundaries of the guarded areas;
- locations of physically protected items;
- types and techniques of guarding;
- seasonal and climatic conditions.

Frequency of performance monitoring. Continuous monitoring serves the purpose of detecting any deviations from onsite routine, e.g. supervision as to correctness of the procedure performance by the PPS personnel. Because of large amounts of information that circulates in the PPS, current PPSs cannot do without automation of the monitoring process.

Physical protection is monitored at the agency level and at the level of the NI as such (self-monitoring).

General technical concept of the PPS design suggests ensuring reliability, survivability and unification of the PPS components, mutual compatibility thereof and so on. This is typical of many complex man-machine systems.

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CHAPTER 6

PPS CREATION (PERFECTION) PROCESS. STAGES AND PHASES

The lifecycle of the physical protection system for a nuclear installation involves the creation of the PPS and support of its onsite operations. If we deal not with an installation under design but with an active installation where the PPS already exists, it makes more sense to talk about perfection rather than creation of the PPS.

The PPS lifecycle stages are shown in Fig. 6.1. The “feedbacks” between stages reflect the need for the work to be redone given a variety of factors (changes in threats, intruder models, site layout, locations and compositions of physically protected items, constraints on the feasibility of proposed decisions, etc.).

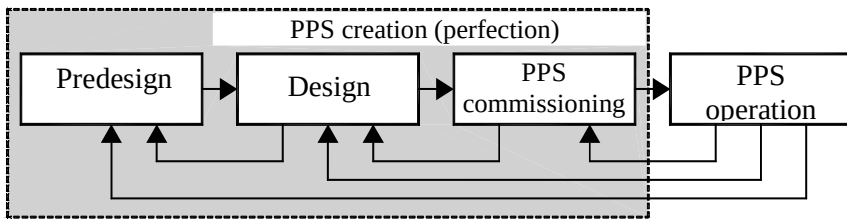


Fig. 6.1. Lifecycle of a physical protection system.

The **PPS creation (perfection)** process comprises the followings stages:

- pre-design;
- design;
- PPS commissioning.

The **pre-design stage** includes the following phases:

- NI vulnerability analysis, including analysis of threats and potential attacker models;
- categorization of physically protected items (PPI), including nuclear material and critical components of nuclear facilities;
- performance assessment of the existing PPS;
- conceptual design of the PPS;
- feasibility study, including prioritization of investments, crediting, etc.;

- development of technical specifications for the PPS creation (perfection), including individual technical specifications for technical subsystems.

The **design stage** includes:

- design of engineered physical protection features (EPPF);
- development of engineering documentation for EPPFs;
- development of organizational and technical documentation.
- The **PPS commissioning stage** includes:
- order placement for and supply of equipment (under design documentation);
- construction and erection;
- startup;
- development of operating documentation;
- run-up;
- training of the PPS personnel;
- development of required site-level regulations;
- initial tests of engineered physical protection features (EPPF);
- pilot operation of the PPS;
- acceptance tests of the PPS;
- acceptance of the PPS.

A note should be made that the design and commissioning stages are fairly standard and typical of many PPS-like complex systems, while predesign takes into account the specific features of the physical protection system.

The work to create (perfect) the PPS for an NI begins with the installation vulnerability analysis. The items to be subject to physical protection¹ (PPI) and the potential intruder models for each PPI are identified at this stage.

The PPIs are then categorized and the NI PPS efficiency is assessed (actual physical protection status for active installations) given the PPI categorization results and other factors. Weaknesses in the PPS are identified.

Proposals are further developed on removing the detected weaknesses and raise so the security status of nuclear material. These proposals are concerned with the structure and composition of engineered physical protection features (types and arrangement of detection sensors, situation

¹ The NI vulnerability analysis and the PPS efficiency assessment are discussed in more details in the chapters that follow.

assessments, access control, control panels and so on), the structure and composition of physical barriers (perimeter, onsite, buildings and rooms) and tactics of the response force. The efficiency of the options is assessed, and the materials and workforce needed to implement these are identified.

The site security service examines the options and chooses the most feasible one. This takes into account not only the efficiency and the cost of the option in question but also practical considerations relating to the NI operations (installation retrofit plan, etc.).

The scope of the work for the most complex PPS creation phases (NI vulnerability analysis and PPS efficiency assessment) is considered below. A note should be made that a vulnerability analysis should be conducted on a periodic basis to track down potential changes in threats, intruder models, onsite NM configurations and the PPS structure and composition. The PPS efficiency is subject to assessment not only at the predesign stage but at all subsequent stages as well, including during the PPS operations following the commissioning.

CHAPTER 7

NI VULNERABILITY ANALYSIS

A vulnerability analysis shall be performed early into the predesign stage and include, primarily, determination of the external and internal threats the installation may be exposed to and the vulnerability areas to be subject to physical protection.

The NI vulnerability analysis results are taken as the input for the NI conceptual design.

The key phases of a vulnerability analysis are:

- formation of an expert team to conduct the analysis;
- development of the analysis program;
- acquisition of initial data on the NI vulnerabilities and the items to be subject to physical protection;
- determination of threats and attacker models;
- finalization of the analysis results.

As defined by the “Physical Protection Rules ...”, a vulnerability analysis is undertaken by the NI administration involving, where required, specialized organizations (security agencies, research and design organizations specializing in the field of the given NI, etc.).

Determination of the NF vulnerability areas is the process of identifying the NF elements that may be potential targets of an attacker and the locations thereof.

In terms of NM thefts, the NI vulnerabilities are locations within the guarded areas where NM is stored or used.

NM-related vulnerabilities are more apparent. These are NM locations. Identifying vulnerabilities of an NF requires a special analytical work. For example, the answer to the question if failure (collapse) of an NF component (pump, vessel, pipeline, control system cable, etc.) leads to severe radiological effects is not altogether obvious and needs rather in-depth studies, NF simulations and so on.

The NF vulnerabilities may be identified using logic schemes and the mathematical graph-theory apparatus.

A logic scheme is an efficient tool of identifying vulnerabilities when considering potential threats of NM theft or acts of sabotage at the NF.

Let us consider an example of a hazardous aftermath (event), i.e. radioactivity escape as the result of an act of sabotage with respect to a component of a WWER-type reactor.

Normally, for an analysis, a tree of failures from sabotage (TFS) is built (Fig. 7.1).

It can be seen from Fig. 7.1 that the end event “Radioactivity escape” is expanded into intermediate events of level 1, level 2 and so on until we arrive at the initial events. Fig. 7.2 gives an example of the event “Escape during power operation” (level 3) expanded into 3 more levels.

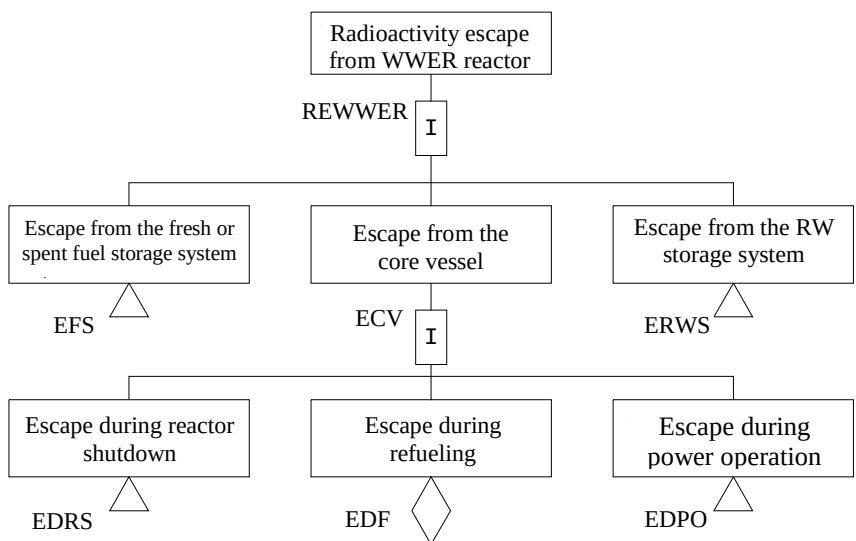


Fig. 7.1. Upper part of the TFS for WWER reactor

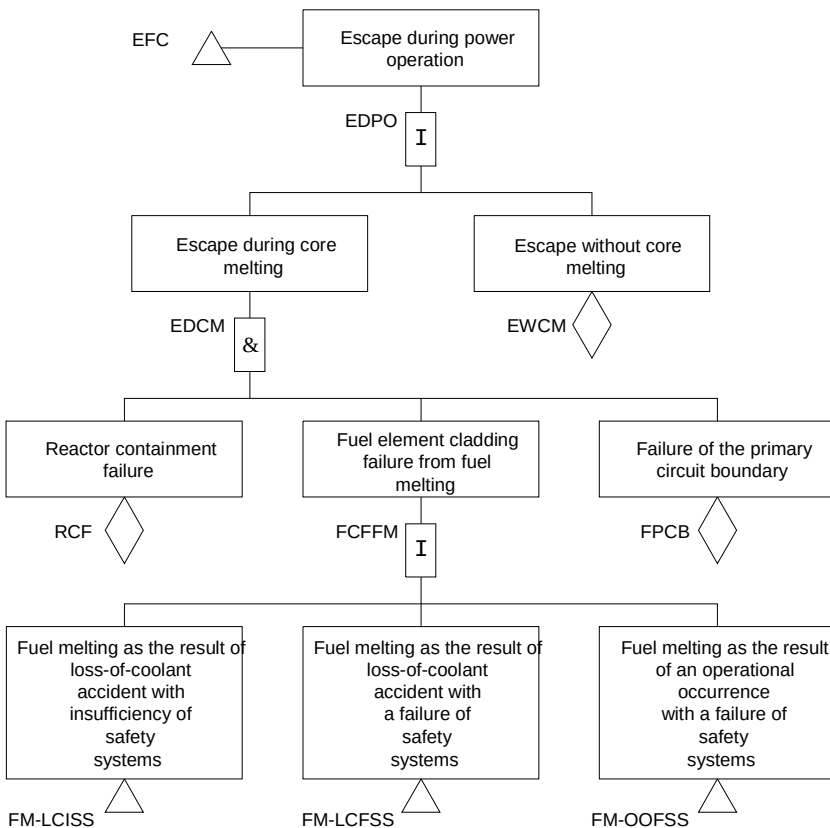


Fig. 7.2. Expansion of a level 3 event (Note: EFC – escape from core)

The next step in defining the protected area is to locate the NF component which, if failed, may induce the given event. To do this, the tree of events (Fig. 7.3) should be transformed into a tree of locations.

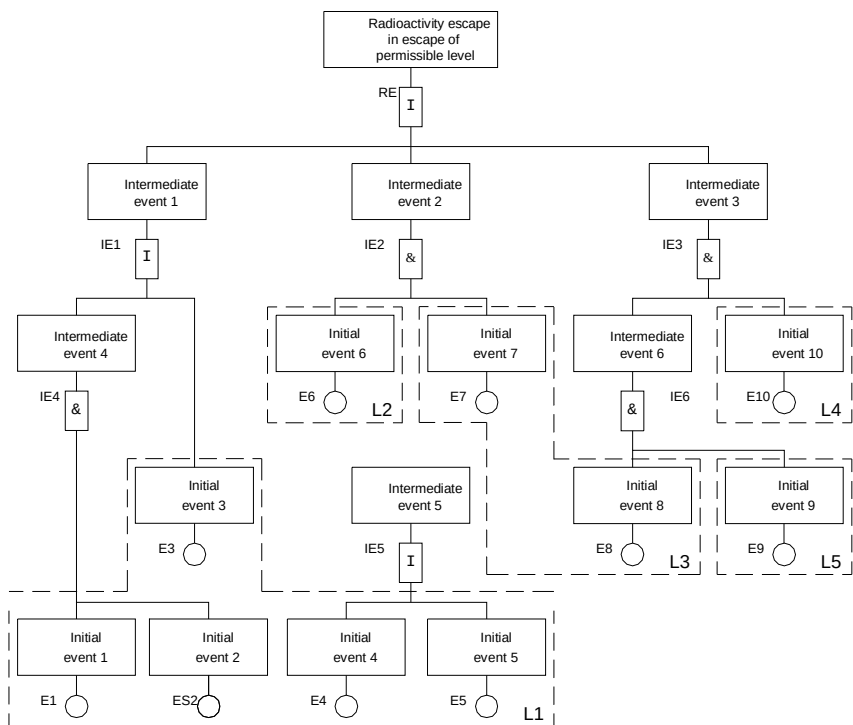


Fig. 7.3. Example of an event tree

Let us assume that the locations L1...L5 match the initial events E1...E10.

The initial events E1...E5 may occur at the location L1, E6 at L2, E7 and E8 at L3, E9 at L5 and E10 at L4. By analyzing the diagram we find that for the end event (the top one in the diagram) to occur, it will be enough to have any of the following six groups of events to take place:

1. E3.
2. E4.
3. E5.
4. E1 and E2.
5. E6 and E7.
6. E8, E9 and E10.

To transform the tree of events into a tree of locations, one needs to identify which locations match the given events. For example, the group of events numbered 6 (E8, E9 and E10) matches the locations L3, L4 and L5. Therefore, the locations that match the obtained six groups of events are:

1. E3 – L1.
2. E4 – L1.
3. E5 – L1.
4. E1 and E2 – L1.
5. E6 and E7 – L2 and L3.
6. E8, E9 and E10 – L3, L4 and L5.

This means that acts of sabotage that may lead to the said end event may take place either at the location L1 or at L2 and L3 (at a time) or at L3, L4 and L5.

Now the tree of locations is plotted. The next step is to identify the smallest possible groups of locations (smallest possible critical groups) the protection of which will prevent the said end event (hazardous consequence) from taking place. One of such groups is, say, the combination of L1 and L3. This group is distinctive in that it shares members with all of the earlier identified groups, the location of which may be initiated by the accomplishment of the end event, i.e. with groups:

1. L1.
2. L2 and L3.
3. L3, L4 and L5.

An analysis shows that no radioactivity escape will occur if the attacker access to any of the following three groups of locations is excluded:

1. L1 and L3.
2. L1, L2 and L4.
3. L1, L2 and L5.

These groups are called the protection groups.

When choosing a particular group for taking provisions for its physical protection requires the cost of these and their influence on the NF operation to be taken into account.

Similar though simpler examples may be also given for the case of NM theft.

CHAPTER 8

PPS EFFICIENCY ASSESMENT*

To objectively assess a system for being fit to perform the tasks it is assigned to, one needs to possess an **efficiency assessment technique** for this system. Such techniques may have a quality basis but are preferably to be based on quantitative indicators which enable different system versions to be compared [1].

As a property of a particular class of systems, efficiency depends on the specific features of these systems. Thus, in particular, the following definition may be used as applied to physical protection systems.

Efficiency, as applied to a PPS, is a property of the system which consists in the PPS capability to counter the attacker acts with respect to nuclear material, nuclear facilities, other NI vulnerabilities and physically protected items given the threats and the attacker models identified in the NI vulnerability analysis. The desired PPS efficiency level is achieved through a combination of activities undertaken to monitor and analyze the PPS operations in accomplishing its tasks of ensuring physical protection and define the ways for improving the PPS efficiency or maintaining same as required.

For a unified approach to efficiency assessment, respective procedures are developed.

To be determined, the efficiency of a PPS needs its capability to suppress unauthorized attacker acts to be assessed. Terminologically, “**to suppress**” means the guard force timely reaching the objective (the point) for the attacker to be neutralized.

The efficiency assessment has the following objectives:

- identification of the PPS elements by defeating which the attacker has the best capability to commit an act of sabotage or NM theft;
- consideration and identification of the most credible scenarios of the attacker actions for committing acts of sabotage or NM theft;
- identification of the PPS points which are vulnerable though, formally, meet regulatory requirements;
- analysis of the causes for the PPS vulnerabilities to emerge;
- estimate of the probability for any attacker acts to be suppressed by the guard force in response to an external or internal threat alarm;
- selection of the best designs at the PPS creation and upgrading stages;

* A contributor to this chapter was D.A. Skvortsov.

- formulation of proposals for the NI administration and guard force to perfect the PPS and its separate structural elements.

PPS efficiency assessment is mandatory at the PPS design stage in the PPS creation or perfection process. The quantitative indicator of efficiency may be used in the PPS design for comparing alternative PPS designs, including for supporting the feasibility of the PPS upgrade. To this end, the performance characteristics of the current PPS and the proposed PPS design are compared.

The efficiency of the existing PPS is assessed in full, involving a specialized organization, where no earlier PPS performance assessment data is available, including in the event that:

- onsite changes are planned to the NI PPS;
- the NI vulnerability analysis data requires so;
- new NI vulnerabilities have been identified by state supervision or agency or onsite security control.

The above may have the form of both a complete PPS efficiency assessment and an update of the efficiency assessment data obtained during the PPS design.

The basis for carrying out the efficiency assessment in view of the scheduled site or NI PPS changes may be:

- a change in the facility structure or the NI vulnerabilities and PPI array;
- a change in the type or technique of guarding;
- a change in the number of guard units;
- relocation of guard forces;
- other factors caused by a change in the guard force time of response to alarms;
- a change in the structure or composition of engineered physical protection features.

The basis for carrying out the efficiency assessment based on vulnerability analysis data, as well as on the NI security government supervision or agency or onsite control results may be:

- update of the attacker models;
- update and identification of new vulnerabilities and PPIs as may be subject to unauthorized activities;
- identification of new threats to the NI and ways for these to be realized;
- a change in the NI processes;
- identification of the PPS components failing to meet the requirements thereto;

- identification of the PPS components the defeat of which makes it possible for the attacker to commit acts of sabotage or theft of NM or other PPIs;
- other factors rendering NM, the NF and other PPIs more vulnerable.

As mentioned above, the key PPS efficiency assessment criterion is assumed to be the PPS capability to suppress unauthorized attacker acts. The PPS efficiency is estimated by the quantitative indicators that define the **probability of unauthorized attacker acts to be suppressed** by the guard force in response to the alarm.

Performance indicators depend on the threats, attacker models and vulnerabilities identified by the NI vulnerability analysis. The PPS efficiency is estimated using:

- a **differentiated efficiency indicator** that takes into account the probability of the attacker act against one target to be suppressed;
- an **integrated indicator** that represents the PPS efficiency indicator, as averaged given the significance of targets, for the NI as the whole.

Efficiency assessment takes into account:

- the probability of the attacker detection by engineered physical protection features (EPPF);
- the time of the attacker delay by physical barriers (PB);
- the time of the guard force and attacker movements over the nuclear site;
- the mutual arrangement of facilities (probability of determining the attacker movement direction);
- the presence of visual surveillance systems and facilities;
- the presence of intrusion identification facilities (exclusion zones, seals);
- the tactics of the guard force actions;
- the equipment used by the attacker (vehicles, tools, weapons and so on).

Efficiency assessment is based on an **event and time analysis** of the conflict developments in the “guard – attacker” system during an external and an internal threat.

The attacker targets are assumed to be only fixed.

The PPS efficiency shall be assessed for two types of the attacker acts:

- a theft of NM and other physically protected items;
- an act of sabotage against NM, the NF or an NM storage point.

Two steps are involved in efficiency assessment. Step 1 is a preliminary PPS efficiency assessment based on an engineering analysis. Step 2 is the final PPS efficiency assessment using dedicated software.

The work sequence is as follows:

- formation of the work unit and a meeting of experts on the NI PPS efficiency assessment;
- acquisition of initial data for the NI PPS efficiency assessment;
- development of a formalized NI description;
- NI PPS efficiency assessment as applied to an external threat;
- NI PPS efficiency assessment as applied to an internal threat;
- formulation and analysis of the NI PPS efficiency assessment results.

The PPS efficiency is assessed separately for external and internal threats.

For external threats, the PPS efficiency is assessed as applied to all NI vulnerabilities, given the attacker models developed in the NI vulnerability analysis and updated at the initial data acquisition and formalized site description stages.

When the efficiency indicator is estimated, it is assumed that the attacker, to defeat each PPS barrier, is free to choose one of the two following options:

- option 1 – the external attacker, where possible, defeats a PP barrier by stealth. This option is characterized by a low probability of detection and a long PB defeat time;
- option 2 – the external attacker, where possible, defeats a PP barrier rapidly, including using special force tools or explosives to destroy the PB. This option is characterized by a high probability of detection and a short PB defeat time.

For external threats, the PPS efficiency shall be assessed for both of the attacker action options.

The integrated indicator of the NI PPS efficiency for an external threat (P_{ext}) is estimated from the expression:

$$P_{\text{ext}} = \sum_{j=1}^J \square_j * P_{\text{ext}j}, \quad (8.1)$$

where J is the number of the attacker targets within the nuclear site; $\square_j$ is the weight factor that reflects the significance (category) of the j -th target;

and $P_{\text{ext}\cdot j}$ is the differentiated PPS efficiency indicator, i.e. the probability of the attacker act against the j -th target to be suppressed.

The weight factor $\square_j$ is determined by the work unit using the expert evaluation method.

The differentiated PPS efficiency indicator is estimated from the expression:

$$P_{\text{ext}\cdot j} = 1 - \prod_{k=1}^K (1 - P_{\text{ext}\cdot jk}), \quad (8.2)$$

where K is the total number of separate response force groups (the perimeter alarm group and others) involved in the conflict developments when the nuclear site is intruded; and $P_{\text{ext}\cdot jk}$ is the probability of the external attacker act against the j -th target to be suppressed by the k -th response force group.

Where several scenarios of the attacker actions against the j -th target are considered, the differentiated indicator of its protection efficiency is assumed to be equal to the minimum value for all considered scenarios.

The attacker action scenario that matches the value of the minimum probability of the action against the j -th target to be suppressed is assumed as critical.

The probability of the external attacker act against the j -th target to be suppressed by the k -th response force group is in a general case the function of:

$$P_{\text{ext}\cdot jk} = f(Pd_{jl}, P_{\text{seiz}\cdot jkl}) \quad (l = 1, \dots, L), \quad (8.3)$$

where L is the total number of the PPS lines to be defeated by the outside attacker to reach the j -th target; Pd_{jl} is the probability of the attacker act against the j -th target at the l -th PPS layer to be detected; and $P_{\text{seiz}\cdot jkl}$ is the probability of the attacker committing an act against the j -th target to be seized by the k -th response force group acting in response to signals starting with the l -th PPS layer.

The probabilities of detection are assumed to be equal to the values of performance characteristic for the respective EPPFs as shown in specifications.

The probabilities of the attacker to be seized are determined from the following condition:

$$\Delta T = T_{rf} - T_a < 0 \quad (8.4)$$

for the respective operational situation. Here, ΔT is the guard force slack time; and T_{rf} and T_a are the response force and attacker action times (from the alarm signal arrival time) respectively.

The probabilities of seizure are assessed by the expression

$$P(\Delta T = T_{rf} - T_a < 0) = F(-x), \quad (8.5)$$

where $F(x)$ is the standard normal random quantity distribution function; and x is the mathematical expectation of the given response force slack time found from the expression:

$$x = \frac{M[T_{rf}] - M[T_a]}{\sqrt{D[T_{rf}] + D[T_a]}}, \quad (8.6)$$

where $M[T]$ and $D[T]$ are the mathematical expectation and the variance of the response force and attacker times respectively.

The attacker and response force time values are combined out of the components relating to different phases of their actions (PB defeat time for the attacker, and assembly time, movement time, perimeter length examination time and others for the response force). The mathematical expectations and variances of the attacker and response force action times are calculated based on the relation for the sum of independent random

quantities according to which, where $T = \sum_{i=1}^I ti$, we have:

$$M[T] = \sum_{i=1}^I M[ti], \quad (8.7)$$

$$D[T] = \sum_{i=1}^I D[ti], \quad (8.8)$$

where ti , $i=1,...,I$ are separate random values; and $M[ti]$ and $D[ti]$ are mathematical expectations and variances of quantities ti .

The PPS efficiency for an internal threat is assessed as applied to all NI vulnerabilities, given the powers of different site personnel groups. A personnel group shall be understood as a group of the nuclear site staff members having similar rights of access.

Efficiency should be estimated separately for each personnel group.

When the efficiency indicator is calculated, it is assumed that the insider, to defeat each PPS layer, may choose any of the following two options:

option 1 – the insider clears a PP layer by virtue of his/her capacity using authorized access routes. In doing this, for a lower probability of the act suppression, the insider may attempt to throw prohibited items out of/into the PP area via channels not accessible to humans (piping, upper-story windows, mesh holes and so on);

option 2 – the insider defeats a PP layer “by force” using the same unauthorized intrusion channels as the external intruder. It is assumed that the attacker defeats the subsequent PP layers also “by force”.

The PPS efficiency is assessed for an internal threat assuming that the attacker action scenario consists of two steps: he/she first enters a PP area by virtue of his/her capacity and then breaks through “by force”. Sometimes, the attacker action scenario may not include step 2.

Different combinations of tools and materials the attacker may carry into the site and use to break through to the target or to commit an act are considered during the assessment.

It is assumed during the assessment that the attacker, to commit an unauthorized action, may employ tools and materials present at the site for production or other purpose.

For each of the targets, the integrated indicator of the NI PPS efficiency as applied to an internal threat ($P_{\text{int.}}$) is estimated from the expression:

$$P_{\text{int.}} = \sum_{i=1}^I \gamma_i P_{\text{int.}i} \quad (8.9)$$

where I is the number of the onsite personnel groups attached to the target under consideration; γ_i is the weight factor equal to the relation of the number of the persons in the i -th group to the total number of the site personnel; $P_{\text{int.}i}$ is the differentiated indicator of the PPS efficiency as applied to an internal threat, i.e. the probability of an act by anyone in the i -th access group against the target under consideration to be prevented.

The differentiated NI PPS efficiency indicator is estimated from the expression:

$$P_{\text{int},i} = 1 - \left(\prod_{l=1}^L (1 - P_{\text{int},il}) \right) \cdot (1 - P_{li}), \quad (8.10)$$

where L is the number of the PP layers cleared by the insider by virtue of his/her capacity; $P_{\text{int},il}$ is the probability of the insider carrying prohibited or stolen items on him/her to be detained at the access control point of the l -th PP layer; and P_{li} is the probability of the insider acting “by force” from a sector beyond the l -th PP layer to be detained.

Where more than one scenario of the insider acts against the j -th target are considered, the differentiated indicator of its protection efficiency is assumed to be equal to the minimum value for all considered scenarios.

The probability of the insider carrying prohibited items or materials to be detained at an access control point is estimated, in a general case, from the expression:

$$P_{\text{int}}^* = 1 - (1 - P_{\text{sear}}^* \cdot P_{\text{sear}}) \cdot (1 - P_{\text{met}}^* \cdot P_{\text{met}}) \cdot (1 - P_{\text{exp}}^* \cdot P_{\text{exp}}) \cdot (1 - P_{\text{NM}}^* \cdot P_{\text{NM}}), \quad (8.11)$$

where P_{sear}^* is the probability of the insider to be searched; P_{sear} is the probability of prohibited items to be detected by search; P_{met}^* is the probability of the insider to be searched with the aid of a metal detector; P_{met} is the probability of metallic items to be detected with the aid of a metal detector during the search; P_{exp}^* is the probability of the insider to be searched with the aid of an explosive detector; P_{exp} is the probability of explosives to be detected with the aid of an explosive detector; P_{NM}^* is the probability of the insider to be searched with the aid of an NM detector; and P_{NM} is the probability of NM to be detected with the aid of an NM detector.

Note. If the insider does not have a prohibited material or item on or with him/her, the probability of detection for the respective detector is assumed to be equal to “0”.

The probabilities of the insider acting “by force” to be seized (P_{li}) are found in the same way as the probabilities of seizing the outside intruder. This does not take into account the PP layers cleared by the insider

officially (the insider is believed to have reached a sector which is beyond the *I*—the PP layer undetected).

The PPS efficiency indicator is the key quality indicator that characterizes the PPS application for the purpose it is designed for. Still, practically, any system is also characterized by other indicators. Thus, an important factor is the system creation and operation cost. Other properties of the system (reliability, noise resistance and others) are also important.

An assessment of the PPS for each of these properties requires:

- selection of the quantitative indicator that characterizes the given property;
- development of the assessment procedure;
- existence of needed initial data.
- For example, the quantitative indicator of expenditures is the cost of the necessary PPS equipment and the work to equip the nuclear site with engineered physical protection features. Cost estimate is a fairly simple and traditional technique of calculating cost indicators. The dimension of this indicator (ruble or USD) is also clear.

The reliability of a system of EPPFs, as of any other engineered system, is characterized by indicators of fail-safety (mean operating time to failure and others), maintainability (mean time to repair and others), etc.

Noise resistance is normally characterized by such indicator as mean operating time to false actuation of equipment.

Indicators that describe such “fine” properties of systems as the alarm deployment speed (for mobile equipment), masking capabilities and others can be also used.

Respective techniques exist which enable these indicators to be qualitatively estimated. Also there are respective source databases.

A note should be made that the work to acquire necessary initial data, prepare for calculations and assess immediately the PPS efficiency requires a great deal of routine operations and computations. Furthermore, efficiency is assessed more than once in the conceptual design process as the best (reasonable) decisions are chosen. These and many other factors inevitably lead to the necessity of **automation** of the PPS efficiency assessment procedure and, consequently, **development of dedicated computer programs** being recognized. The technological revolution in creation and application of personal computers has made this task both vital and feasible.

There is a range of US dedicated PPS efficiency assessment codes widely known in Russia, including the following:

- **EASY, SAVI** – MS DOS programs intended to assess the PPS efficiency as applied to an “external” threat [2];
- **ET** – an MS DOS program intended to assess the PPS efficiency as applied to an “internal” threat;
- **ASSESS** – a WINDOWS program intended to assess the PPS efficiency as applied to an “external” or an “internal” threat or a conspiracy between an outside intruder and an insider, and to calculate the probability of neutralizing an armed adversary [3].

ASSESS, a code delivered to Russian nuclear operators in the framework of international cooperation, is the most popular of such programs in Russia. It has a number of significant advantages as compared to earlier US dedicated computer programs.

However, a number of shortcomings limiting the program application in Russia were found in ASSESS by Russian experts in the process of its operation and as practical experience was acquired. One of these is the rigid response force tactics built in ASSESS, which is not comprehensively applicable to specific conditions of Russia. Apart from this, ASSESS does not have a database on real performance of EPPFs and PBs with respect to classified information.

Dedicated PPS efficiency assessment codes are also developed in Russia with utmost emphasis laid on applications specific to Russia. One example is **БЕГА–2**, a computer program designed to assess the PPS efficiency for both external and internal threats and enabling calculations based on analytical methods and simulations [4].

Of special note is БЕГА–2’s software solution that offers a more flexible description of the response force and potential attacker tactics, makes an allowance for the target designation function of detection sensors (essential to sites with a branched tree of attacker targets), makes it possible to estimate contributions from the closed-circuit television system at different PP layers, etc. БЕГА–2 is continually perfected and upgraded given its practical onsite operations.

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CHAPTER 9

PPS INTERACTIONS WITH THE NM ACCOUNTING AND CONTROL SYSTEM

Though differing greatly, the above physical protection systems and NM accounting and control systems are assigned to the same task of ensuring security of nuclear material.

A question arises of whether these can interact to ensure a higher level of NM security. This, quite reasonably, suggests that the “autonomy” of interacting systems should be however maintained so that not to disturb the established organizational structures typical of Russian nuclear sites.

The following types of interactions between PPSs and NM A&C systems may be discussed:

- technical;
- organizational;
- informational.

Technical interactions suggest that one and the same elements are used by the systems to address the tasks they are assigned to. Thus, one and the same TV camera can be used both for the NM control and containment in the NM A&C system and for the situation assessment purposes in the PPS.

Room door seals are also examples of such shared components.

Still, such sharing of components brings to life a great deal of organizational problems, e.g. relating to the division of responsibilities for the operation of the given element and so on.

Organizational interactions of the PPS and the NM A&C system require personnel of these systems to interact in various situations, which is to be set forth in respective regulatory documents (instructions, bylaws, programs).

Modern PP and NM A&C systems are expected to include a **computerized data handling** function, so **informational interactions** between them can be achieved at the level of each system’s databases.

Here is an example to illustrate this. Suppose there is a need for an authorized NM movement between two material balance areas (MBA) within the same site. A request is made out with the NM A&C system handling it and “informing” the PPS of the forthcoming transaction (place, time, personnel with respective permits).

The PPS then formalizes respective clearing procedures (admission to the building, to the NM storage room and so on), these to be further realized via respective walks-through.

A simplified example of a procedure to transfer NM between two MBAs is shown in Fig. 9.1. It can be seen that both systems operate alternately, ensuring so integrated control of the nuclear material handling operations. The security system will take any deviation from or omission in an action as a situation of alarm.

If materialized, this approach helps raise the security status of NM.

No.	Action	Hardware function	Facility	System responsible for operation
1	NM receivers enter building 1	Check of receivers' identification tags at the internal access control point of building 1	ACS booth	PPS
2	Receivers meet with the NM custodian in building 1	Check of the right to receive NM (order)	Custodian panel	NM A&C system
3	The custodian and receivers enter NM storage room	Check of identification tags and execution of the "two persons" rule to permit the entry into NM storage room	ACS terminal door	PPS
4	Formalities are fulfilled to transfer NM from custodian to receivers	Check of NM conformity to request and update of NM location data	Storage room terminal	NM A&C system
5	The custodian and receivers exit the NM storage room	Note of joint exit	ACS terminal door	PPS
6	Receivers exit building 1	Check of identification tags including for presence of NM	ACS booth	PPS
7	Onsite NM transportation to building 2	Guarding of NM en route	Guard and communication facilities	PPS
8	Receivers enter building 2	Check of identification tags at the internal access control point of building 2	ACS booth	PPS
9 ...	Further: actions 2 - 6 are repeated in building 2 (the only difference is that NM is not removed but placed in storage at building 2)			

Fig. 9.1. Simplified example of an authorized NM transfer between two MBAs (from building 1 to building 2)

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The definitions of the terms have been taken from “Dictionary of Terms on Accounting, Control and Physical Protection of Nuclear Material” (Moscow, TsNIIatominform, 2000).

- Access** – entry into NM location areas.
- Access point control** – a point on the perimeter of the protected area equipped with engineered features and systems to ensure authorized access thereto.
- Access controls** – equipment designed to detect unauthorized actions with NM and intrusions into restricted areas. Divided into surveillance systems and tamper indicating devices.
- Access control system** – a PPS subsystem that supports the tasks of controlling access to guarded areas.
- Accounting measurements** – measurements of parameters of an NM batch the results of which (including measurement errors) are entered in accounting records and certificates.
- Accounting of NM** – a combination of measures and equipment enabling sufficiently confident determination of the NM inventory and NM flows.
- Accounting records** – documents showing data on presence, composition, location and state of NM using which this is accounted for.
- Administrative control** – control by the nuclear site administration.

Anomaly	– a nonconformity of the physical inventory to accounting record data.
Attributes	– data that unambiguously determines the presence or absence of any NM property.
Balance of NM	– the relation between the book inventory and the physical inventory.
Barcode	– representation of data as a combination of parallel variably spaced bars of different thicknesses.
Batch data	– data on the total mass and the element and isotopic composition of NM.
Batch of NM	– a collection of single-type NM-containing articles the parameters of which are determined in one set of measurements.
Bookkeeping NM	of – strictly deterministic accounting of NM as expressed in cash or in kind.
Bulk form of NM	– NM in the form of liquid, gas or powder, or a large quantity of solids that do not have individual identifiers.
Cask	– a package for NM.
Category of nuclear material	– a quantitative characteristic of the significance of nuclear material in the context of its special handling.
Certificate of item	– a document enclosed with an item and containing data on its basic parameters.

Checkout of NM	– check of the physical inventory in an MBA for conformity to accounting data.
Clearance	– issuance, in due manner, of the permit to enter/drive in guarded areas, performance of work and obtainment of documents or information.
Control of nuclear material	– measures taken to prevent unauthorized uses of NM.
Conversion time of NM	– the period of time needed under optimal conditions to convert the given NM form into metal components of a nuclear explosive.
Custodian	– an employee of the enterprise with the responsibility for the storage of all NM in an MBA.
Delay of intruder	– the taking of measures towards slowing down the intruder movement to the target over the guarded area.
Destructive analysis	– characterization of NM by its sample taking and analysis.
Detection monitor	– a device designed to trigger an automatic alarm in the event of an unauthorized activity in the area for which it is intended.
Discard	– loss of NM in processing, long-term storage or tests as estimated by calculations.
Efficiency system	of – a property of a system showing the extent to which it has been adapted to the tasks it is assigned to.

Fertile NM	– a nuclear material which can be converted into a fissionable material through capture of a neutron.
Fissile material	– a fissionable material the nuclei of which can undergo, efficiently, fission by neutrons of small energies.
Form of NM	– a physicochemical state of NM (metal, solution, gas, powder, etc.).
Forms of accounts and reports	– established model forms for documentation of NM accounting and control data.
Handling of NM	– a nuclear activity relating immediately to NM.
Highly enriched uranium (HEU)	– uranium with an enrichment of not less than 20% in U-235.
IAEA safeguards	– a system of provisions employed by the IAEA under its charter and the Nonproliferation Treaty (NPT) for the purpose of nonproliferation of nuclear weapons.
Identification of item	– matching of identification tags to accounting record data.
Identification tags	– unique features inherent in or artificially rendered to anything.
Integrated system	– a combination of several systems existing in the conditions of interdependent operation.
Intruder (attacker)	– a person who has committed or attempting to commit an unauthorized act, as well as a

person who assists in this.

Inventory change report (ICR)	– a report showing changes in the inventory of nuclear material in an MBA.
Inventory difference	– the difference between the book and physical inventories in an MBA.
Inventory difference limit	– a determined quantity of the inventory difference exceeding which is viewed as an anomaly.
Inventory listing	– a list of the inventory of nuclear material showing the quantities thereof and based on accounting data.
Invoice	– the accompanying document that contains basic accounting data on the transferred NM.
Item	– an identifiable NM-containing article (having an individual number or another identifier) that has its integrity invariable over the specified period of time.
Key measurement point	– a place within an MBA equipped for measurements of NM parameters and attributes.
Ligature mass of NM	– the mass of a material containing a chemical or physical composition of NM with an inert substance.
Loss limit	– a justified and approved quantity of NM the loss of which in a process is tolerable.
Low-enriched uranium (LEU)	– uranium with an enrichment of less than 20% in U-235.

Material balance area (MBA)	– an administratively established enclosed area where all inputs and outputs of nuclear material and, on a periodic basis, the inventory thereof are determined based on the quantities measured.
Material balance period (MBP)	– the period of time between two consecutive physical inventory takings.
Material balance report (MBR)	– a report on the physical inventory and the balance of nuclear material in an MBA over the material balance period.
Measurement error	– a deviation of a measurement result from the true value of the measured quantity.
Nondestructive assay (NDA)	– characterization of NM without violating the integrity of NM-containing articles.
Nonproliferation safeguards	– a system of provisions that ensure nonproliferation of nuclear weapons.
Nuclear activity	– an activity relating to fabrication, use, storage and transportation of NM, as well as to design, construction, operation and decommissioning of nuclear facilities.
Nuclear facility	– a facility which uses or contains nuclear material
Nuclear material	– material that contains or is fertile for fissionable (fissile) nuclear material.
Nuclear safety and	– properties of a nuclear facility that

security	determine the impossibility of a nuclear accident.
Operator	– an organization that has been acknowledged to be fit to operate a nuclear facility and handle NM.
Physical barrier	– a physical impediment that ensures the intruder delay.
Physical inventory listing	– a list of the physical inventory of nuclear material showing the quantities thereof and defined by the physical inventory taking.
Physical inventory taking	– determination of the physical inventory of nuclear material by measurements.
Physical protection system	– a system of organizational, administrative and legal arrangements and engineered features intended to ensure physical protection of NM and nuclear facilities at a nuclear site.
Protected area	– the nuclear site area surrounded by physical barriers subject to continuous guarding and surveillance, the access to which is limited and controlled.
Random test of NM	– control of NM in which the conclusion is made based on results of a random sampling from the overall quantity of items.
Reference NM	– a specimen of NM characteristics whereof have been determined with the specified accuracy intended to test instruments and measurement techniques.
Reports	– documents containing NM data and

submitted to superior, inspecting and/or supervising authorities.

Representative sample

– a sample taken from NM-containing articles with definite typical characteristics for the collection of such articles.

Sabotage

– any deliberate act directed against NM, nuclear facilities, NM storage points or NM carrying vehicles and transport nuclear facilities which could directly or indirectly lead to an accident and endanger human health by exposure to radiation and radioactive contamination of the environment.

Safety of NM

– conditions that exclude unauthorized activities with NM.

Sampling

– selection of NM samples according to a particular rule.

Seal

– a device designed for indication of tamper by identifying integrity thereof.

Security alarm system

– a collection of detection monitors, call alarms and the data acquisition collection, processing and display system in the PPS.

Shipper/receiver difference

– the difference between the NM quantity stated by the shipper (certificate data) and the quantity received by the receiver as established by verifying measurements.

Significant quantity

– the quantity of NM with respect to which no probability of a nuclear explosive to be

created, with regard for any conversion process, can be excluded.

Special non-nuclear material – material that does not contain NM or is not fertile, but can be used in nuclear explosives.

Stratum – a collection of individual items or batches of NM with similar or close physical and chemical characteristics.

Supervision of the NM accounting and control system – a form of control to verify the compliance with the established standards and rules of NM accounting and control.

System of accounting for and control of NM – a system intended for timely obtainment of confident information on presence, location, quantity and use of NM, as well as for timely detection of unauthorized use of NM.

Tamper indicating device – a device designed to detect unauthorized access to nuclear material (seals).

Theft of NM – unauthorized removal and movement of NM to beyond the protected area.

Transfer of NM – procedures of NM measurements and formalization of accounting records during NM movement from the shipper to the receiver.

Two (three) person rule – a form of surveillance with mutual observation between two or three NM co-handlers.

Unauthorized access – access without a documented right to same.

**Unauthorized
action**

– an act or an attempted act of an NM theft, unauthorized access to NM, tampering, sabotage, smuggling of prohibited items, or disabling of NM accounting, control and physical protection equipment.

**Verifying
measurements of
NM**

– measurements of parameters or attributes of an NM batch for the purpose of verifying earlier accounting data.

**Video surveillance
system**

– an NM control, intrusion detection and situation assessment facility.

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