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Radioactive waste in the Russian Federation

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1 Background

The present report has been produced by Kemakta Consultants Co. under contract from the Swedish Radiation Protection Institute (SSI). The purpose of the study is to give a broad overview of the situation in the Russian Federation with regard to the production and management of radioactive waste. The report also presents an outline of possible risks for environmental and societal consequences of the current waste management practices. The study is intended to be used as a basis for discussions regarding possible international cooperative efforts for improving the waste management system in Russia.

The report is mainly based on publicly available literature. In addition,information has been obtained during a two-day visit to the Bochvar Institute and the Russian Atomic Power Ministry, MinAtom, in Moscow. Complementary information has been provided by MinAtom in response to a questionnaire that was sent to MinAtom subsequent to the visit to Moscow. Staff at the Russian embassy in Stockholm has assisted in the organisation of contacts as well as with various clarifications and translations. Some of the information in this report has not been officially confirmed by the Russian authorities.

2. Russian organisations in the nuclear field

2.1 Introduction

This chapter describes the organisation and distribution of responsibilities in the field of radioactive waste management in the Russian Federation. Due to the transient political situation and delays with the implementation of legislation to govern the responsibility distribution, it has not been possible to fully overview the situation. Also, the situation is likely to change with time as the political situation develops.

The responsibility for the radioactive waste is split on three different ministries:

- The Ministry of Atomic Power of the Russian Federation (MinAtom) has the responsibility for the waste from civilian nuclear power and from the production of nuclear weapons.
- The Ministry of Defence has the responsibility for the waste from nuclear powered naval ships.
- The Ministry of Marine Transports has the corresponding responsibility for the waste from atomic icebreakers.

MinAtom was in November 1993, through a presidential decree, given the responsibility for coordinating the waste management from all three ministries. Consequently MinAtom now acts as an umbrella organisation for the waste management.

The licensing and inspecting body in Russia is Gosatomnadzor. Gosatomnadzor is responsible for the licensing and inspection of all facilities where nuclear and radioactive materials are being handled, i.e. also military facilities.

In the following, a brief description is given of MinAtom and Gosatomnadzor.

2.2 The Ministry of Atomic Power, MinAtom

2.2.1 Overview of the organisation of MinAtom

The Ministry of Atomic Power of the Russian Federation (MinAtom) was founded in January 1992 as a successor to the corresponding organisation of the USSR. In general terms, MinAtom is responsible for [1]:

- ensuring the nuclear and radiation safety, including radioactive wastes and rehabilitation of contaminated land;
- the organisation and implementation of state regulations related to the enterprises and organisations of the nuclear complex:
- the implementation of the state scientific-technical goals, investment and structure policy in the field of nuclear power development;
- the forming and implementation of nuclear weapons programmes, including issues related to nuclear disarmament.

MinAtom's activities and responsibilities cover a scientific-industrial complex comprising technologically interconnected enterprises over a wide range of disciplines including mining of raw materials, production of fissile materials, manufacturing of products for nuclear power and of military materials, reprocessing of spent nuclear fuel with subsequent storage and burial of radioactive wastes, and also enterprises supporting the infrastructure. In total, there are about 150 enterprises associated to MinAtom, with a total number of employees of roughly 1 million.

The Head of MinAtom is Minister Victor N. Mikhailov. MinAtom is divided into 8 branches with the Minister and First Deputy Minister being head for one branch each. The remaining 6 branches are run by six Deputy Ministers. The responsibilities of the Minister, First Deputy Minister, and the Deputy Minister handling issues like radiation safety, is outlined below [2]:

The Minister: *(Mr Mikhailov)*	Strategy of industry, development strategy, implementation of the economic reform, improvement of the industrial management, international scientific and technical relations, nuclear weapons and disarmament.
First Deputy: *(Mr Konovalov)*	Nuclear fuel cycle, advances of research and development effectiveness, state oriented complex programmes of the industry, conversion of the nuclear industry, production licensing, development of the industry's export policy.
Deputy: *(Mr Egorov)*	Nuclear-chemical production, localisation of radiochemical wastes, coordination of activities in the fields of ecology, nuclear safety and radiation safety, common information policy, public relations.

A special committee for ecology that handles matters like nuclear and radiation safety, emergency situations, and radioactive waste management is organised directly under Deputy Minister Egorov. The chairman of this special committee is mr Viktor A Gubanov.

2.2.2 Important organisations associated to MinAtom

In the following, a few brief comments are made on the most important organisations and/or activities associated to MinAtom in the context of spent nuclear fuel, waste management, and research and development.

The "closed cities"

The research, development and production of nuclear weapons is organised directly under the Minister. This part of the MinAtom's activities comprises several enterprises carrying out basic and applied research, experimental and design work, full scale tests of prototypes, serial production and monitoring. This development has taken place at ten so called "closed cities" with a total number of inhabitants of about 700 000-800 000. More information about the closed cities can be found elsewhere [6,10]. Although not complete, the list below comprises some of the activities in the different closed cities:

- Arzamas-16; the capital of the archipelago of closed cities. Oriented towards research in experimental physics and development and production of nuclear charges.
- Slatoust-36; serial production of nuclear warheads and ballistic missiles.
- Krasnoyarsk-26; the 270 m deep underground Mining Chemical Combine. Reprocessing of spent nuclear fuel and production of plutonium for military purposes including three reactors. Sometimes called "Atomgrad" (atom city).
- Krasnoyarsk-45; uranium enrichment and production of ballistic missiles.
- Sverdlovsk-44; serial production of nuclear ammunition.
- Sverdlovsk-45; serial production of nuclear ammunition.
- Semipalatinsk-21; research centre with research reactors. Located in Kazakhstan.
- Tomsk-7; the Siberian Chemical Combine for reprocessing and plutonium production, uranium enrichment, production of ballistic missiles for submarines, reactors.
- Chelyabinsk-65; the Mayak Combine with reprocessing of spent nuclear fuel. Plutonium production for military purposes.
- Chelyabinsk-70; research institute for technical physics, development and production of nuclear charges.

In the closed cities a total of 13 plutonium producing reactors have been operated. Out of these 4 are still running. The plans are to decommission 2 of these in 1996 and the remaining 2 in the year 2000 [1]. As many as 75 research reactors are either operating, decommissioned or under construction in Russia [4]. Many of these are probably connected to the military programmes. Some of the reactors have been used for tritium production for thermonuclear devices.

Rosenergoatom

The Rosenergoatom-enterprise is responsible for the operation of the nuclear power plants, including the management of the waste produced. The enterprise acts as a power utility company organised within MinAtom. Rosenergoatom is also responsible for the nuclear safety at the power plants.

The Botchvar Institute

The Botchvar Institute has the main responsibility in Russia for the research concerning radioactive waste originating from all types of activities. The institute has several profiles like radiochemistry, waste management, nuclear fuel, metallurgy research, super conductors and uranium and plutonium metallurgy. The waste management department is, among other things, concerned with waste treatment (liquid waste from the Botchvar and Kurchatov Institutes), solidification of low and intermediate level liquid waste, characterisation of the solidified waste, and processing of high-level waste.

The VNIIAES Institute

The All-Union Research Institute for Nuclear Power Plants Operation (VNIIAES) is concerned with the scientific aspects of the operation of nuclear power plants. The institute also organises education of employees at the power plants. One of its departments deals with matters associated with radiochemical safety and has been involved in the development of technology for the solidification of waste at the nuclear power plants.

2.3 Inspection and licensing responsibility

Prior to 1983, the Ministry of Energy was responsible both for the nuclear power production and for the inspection of its own activities. In 1983, part of the inspection was moved to the new body Gospromatomnadzor. The major part of the work of this body was to inspect the operation of the nuclear power plants. Still, some 80-85% of the inspection activities was left within the ministry itself. By a decree of the President in 1992, the independent body Gosatomnadzor was formed. The inspection of the entire nuclear fuel cycle is now carried out by Gosatomnadzor independently from MinAtom. The complete name of Gosatomnadzor is The Russian Federal Inspection of Nuclear and Radiation Safety.

Gosatomnadzor has the overall responsibility for the inspection and licensing of all activities where radioactive material is being handled. This includes the inspection of the entire nuclear fuel cycle, the military activities and all other radiation sources. Gosatomnadzor has the legal authority to fine or prosecute those who do not follow the safety regulations. Gosatomnadzor can also give directives to shut down facilities that do not meet safety requirements.

In the central organisation of Gosatomnadzor the head quarters in Moscow, roughly 500 persons are employed, 300 of which at a research centre. Apart from this there are roughly 1500 employees in seven regional units. About 400 persons in some 50 groups are engaged in inspection activities.

3. Sources of radioactive waste in Russia

3.1 General

The use of nuclear and radioactive material in Russia principally involves the following sectors of the society:

- Civilian power production,
- Nuclear propulsion of civilian and military vessels (icebreakers, submarines and surface combatants),
- Various uses within industry, research and medicine, and
- Military programmes (production of nuclear warheads, etc).

Due to the strategy chosen to be self-supporting in all parts of the nuclear power production, radioactive waste derives from all the many different types of facilities involved in a complete nuclear fuel cycle ranging from the mining of uranium to the reprocessing of spent nuclear fuel.

In Figure 3.1 the locations of the nuclear power plants and some other significant facilities handling nuclear and radioactive materials are indicated. On the map the catchment areas of the seas surrounding Russia are shown as coloured areas to indicate possible recipients for dispersion of radioactive leakages from the different facilities.

In the following an overview is given of different sources of radioactive waste in the Russian Federation. The production of nuclear weapons has not been included in this overview. This industry is described in the Nuclear Weapons Handbook [6].

3.2 Civilian power production

The electricity production in Russia is based mainly on fossil fuel (roughly 75%) and hydro power (roughly 15%). The remaining 10% are covered by nuclear power. The consumption of nuclear-generated electricity is unevenly distributed over Russia. In the central European part and the north-western part it amounts to 20-25%. The consumption of electricity in Siberia and the far east is largely covered by fossil fuels like oil and gas with no or little contribution from nuclear power.

The commercial nuclear power production for civilian purposes started in the 1960-s, when the two first reactor units were installed [7]. About half of the currently operating units were commissioned during the 1970-s and the remaining half during the 1980-s. Table 3.1 gives an overview of the reactors in Russia with years of commissioning and decommissioning indicated; see also the map in Figure 3.1 for the locations of the reactor sites.

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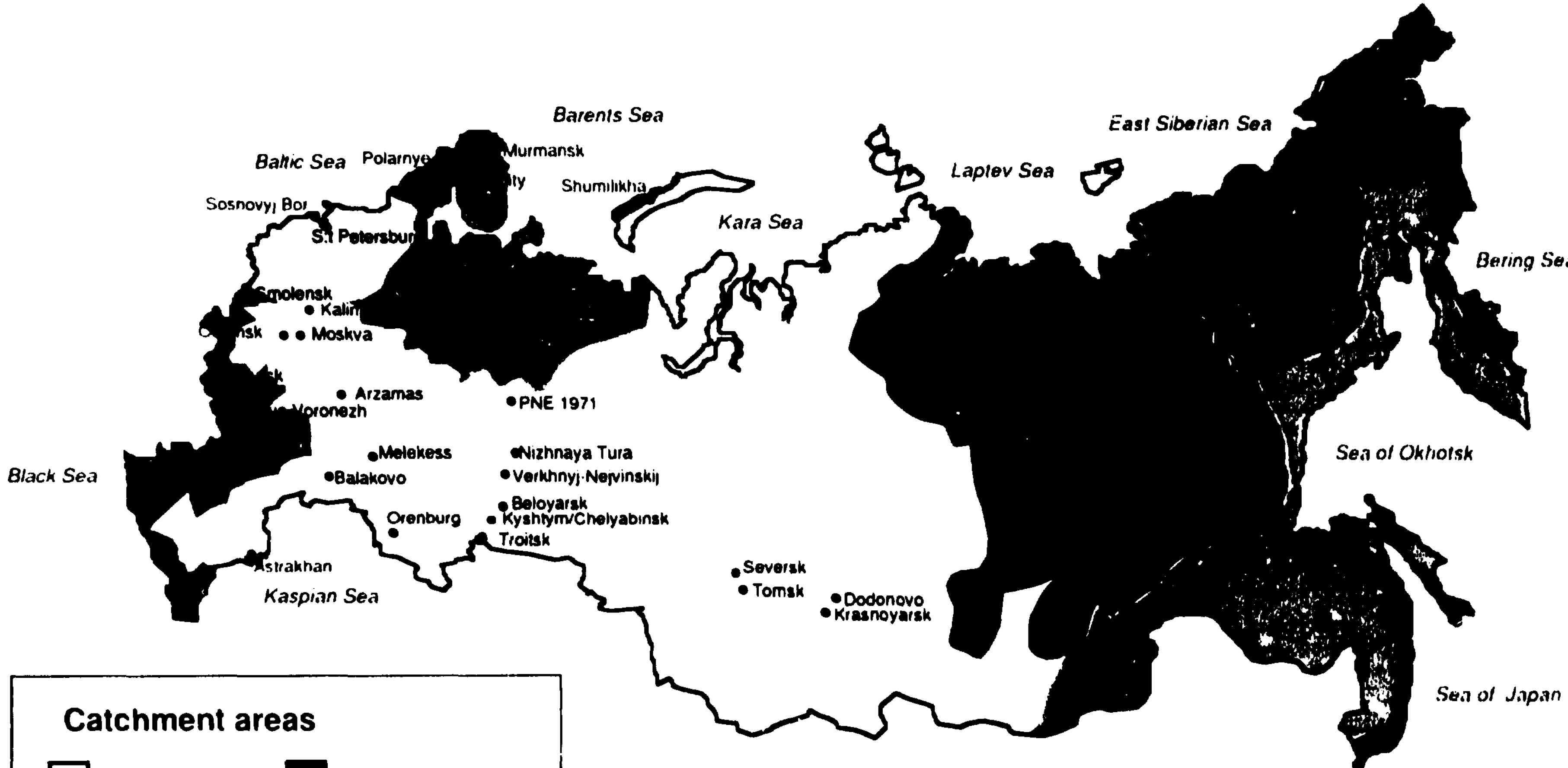

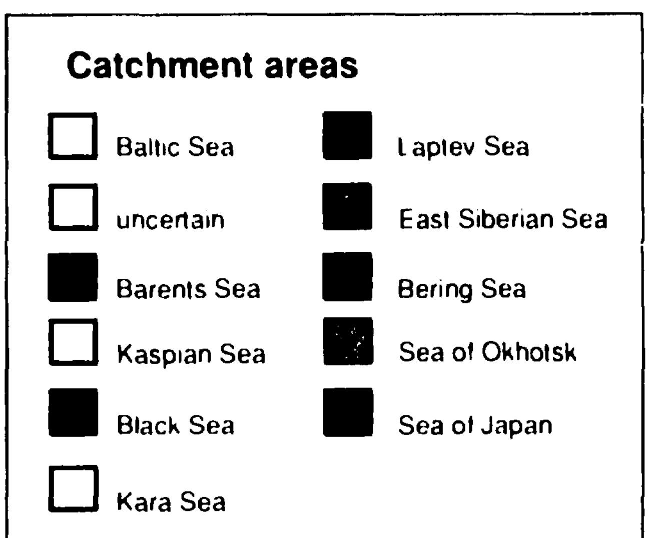

Figure 3.1 Map over the Russian Federation illustrating catchment areas for the major rivers in Russia, their recipients and locations of different facilities where radioactive waste is produced or treated.

During and after the build-up period by the end of the 1960-s, the following three reactors types were abandoned after research, testing and evaluation:

- the 0.750 MW Abrus prototype at the Melekess research centre at Dimitrovgrad which was cooled and moderated by a hydrocarbon and reached full power in 1963,
- BWRs, the first of which came into service at Melekess in 1966, and
- graphite-moderated pressurised water reactors; six 100-MW units at Troitsk in Western Siberia were commissioned between 1958 and 1962 using enriched uranium fuel.

From the 1960-s and onward, three reactor designs have been developed on a major industrial scale:

- RBMK graphite-moderated reactors in which boiling water flows through pressurised tubes containing enriched uranium fuel. Two units of 100 MW_e and 185 MW_e commissioned at Beloyarsk in the mid 1960-s, paved the way for the development of major power reactors comprising twin 1000-MW_e units. Four 11-MW_e reactors in Bilibino (East Siberia) were commissioned in the mid 1970-s to generate electricity and feed a district heating network;
- WWER reactors (pressurised-water reactors) were initially developed for propulsion of icebreakers and submarines. Following two reactors commissioned at Novo Voronezh in the 1960-s, the capacities adopted for the plant series was 440 MW_e and 1000 MW_e;
- Fast breeder reactors using plutonium as fuel and liquid sodium as coolant. The first reactor was Obninsk BR5, a 5-MW_e loop-type reactor that was commissioned in 1954. Another reactor is the 550-MW_e BN 600 plant commissioned at Beloyarsk in 1980. This pool-type reactor is one of the most powerful breeder reactors in the world. An intermediate-size fast breeder reactor is located at Shevchenko on the eastern shore of the Caspian Sea in Kazakhstan.

As of today, there are 9 nuclear power plants with 29 units in operation in Russia. Their total capacity is about 20 500 MW_e. In addition, 4 units (two at Beloyarsk and two at Novo Voronezh) have been decommissioned.

Out of the operating 29 units, 15 are of RBMK type, 13 are of WWER type, and one is a fast breeder reactor. As a majority of the units currently in operation were started during the 1970-s and the 1980-s and have an expected life-time of 30 years, they are likely to be shut down by the second decade of the next century. Plans exist for a continued exploitation of nuclear power. This is described below in Section 4.2.4.

Apart from the reactors, the fuel cycle in Russia comprises facilities for uranium mining, fuel fabrication, spent-fuel storage and spent-fuel reprocessing including vitrification of high-level waste.

Table 3.1 Overview of the nuclear power plants in Russia, see Figure 3.1 for locations.

Power plant	Reactor type	Capacity MW_e	Year of commissioning	Year of decommissioning
Beloyarsk 3	BN	600	1980	2010
Bilibino 1	RBMK	11	1974	2004
Bilibino 2	RBMK	11	1974	2004
Bilibino 3	RBMK	11	1975	2005
Bilibino 4	RBMK	11	1976	2006
Kursk 1	RBMK	1000	1976	2006
Kursk 2	RBMK	1000	1979	2009
Kursk 3	RBMK	1000	1983	2013
Kursk 4	RBMK	1000	1985	2015
Leningrad 1	RBMK	1000	1973	2003
Leningrad 2	RBMK	1000	1975	2005
Leningrad 3	RBMK	1000	1979	2009
Leningrad 4	RBMK	1000	1981	2011
Smolensk 1	RBMK	1000	1982	2012
Smolensk 2	RBMK	1000	1985	2015
Smolensk 3	RBMK	1000	1990	2020
Balakovo 1	WWER	1000	1985	2015
Balakovo 2	WWER	1000	1987	2017
Balakovo 3	WWER	1000	1988	2018
Balakovo 4	WWER	1000	1993	2023
Kalinin 1	WWER	1000	1984	2014
Kalinin 2	WWER	1000	1986	2016
Kola 1	WWER	440	1973	2003
Kola 2	WWER	440	1974	2004
Kola 3	WWER	440	1981	2011
Kola 4	WWER	440	1984	2014
Novo Voronezh 3	WWER	440	1971	2001
Novo Voronezh 4	WWER	440	1972	2002
Novo Voronezh 5	WWER	1000	1980	2010

The uranium mines exploited by the USSR authorities were largely located in the southern republics of the union outside of the present Russian territory [2]. The only uranium-producing corporation in Russia is the Priargunska Mining Chemical Combine in the Streltsov area east of the Lake Baikal. Although Russia's geology is poorly investigated, it is believed that significant ore bodies can be found within the borders of Russia.

Enrichment of uranium takes place at least at four sites [6]; the Ural Electrochemical Combine (Sverdlovsk-44) near Verkh-Neyvinsk, the Siberian Chemical Combine (Tomsk-7), the Electrochemical Combine (Krasnoyarsk-45) and the Electrolysing Combine at Angarsk north of Irkutsk near Lake Baikal. The plants at Sverdlovsk-44 and Angarsk are the only plants capable of converting yellowcake to uranium hexafluoride which is used as feed in the enrichment plants.

The fuel used in the power production reactors is manufactured at three principal fuel fabrication facilities. Enriched uranium hexafluoride is transported to the Ul'binsky Metallurgical plant at Ust'-Kamenogorsk (Kazakhstan) where it is reduced to uranium dioxide powder which is subsequently granulated, compacted into pellets and sintered. Most of the UO_2-powder and pellets used in Soviet-designed power reactors are produced at Ust'-Kamenogorsk.

The pellets are shipped from Ust'-Kamenogorsk to the Khimconcentrate Plant in Novosibirsk and to the Machine Building Plant in Electrostal 30 km east of Moscow where fuel pins and assemblies for WWER 440/1000, RBMK, ship reactors and research reactors are produced. The annual production comprises 4 000 assemblies for Russian reactors and 5 000 assemblies for foreign Soviet-built reactors.

The design of the back-end of the fuel cycle varies depending on the fuel type. The fuel from WWER-440 reactors, ship reactors, research reactors and fast breeder reactors is intended to be reprocessed at the Mayak Combine at Chelyabinsk-65. The fuel from the WWER-1000 plants is planned to be reprocessed at the RT-2 reprocessing plant which is under construction at Krasnoyarsk-26. At the RT-2 site a spent-fuel storage facility is operating and receives fuel from the WWER-1000 reactors.

Due to the low enrichment of the fuel for the RBMK reactors, there are no plans to reprocess this fuel. It is currently stored in pools at the reactor sites. These pools are designed to host the fuel for up to 30 years. There are plans to build a federal storage facilitv that could host the fuel for 80-100 years. This facility would be based on the dry storage concept.

3.3 Nuclear propulsion of civilian and naval vessels

Fleets of ice breakers and military vessels equipped with nuclear reactors for propulsion contribute to the production of nuclear waste. The three major base areas for these fleets are on the Kola peninsula, on the Kamchatka peninsula and in the Vladivostok area.

At the peak of its activities the Soviet navy operated more than 300 reactors installed on nuclear submarines and surface combatants [6]. According to [8] a total of 457 reactors have been installed on naval vessels, 8 on cruisers of the Kirov class and the rest on different types of submarines, from 1957 through 1993. Most of the vessels are powered by dual reactors. The capacities of these reactors have been estimated to be 185 and 370 MW_{th} [6] depending on the type of vessel.

The activities of the navy are decreasing and some of the reactors have been decommissioned. It is estimated [8] that about 100 operating nuclear submarines currently are based at the largest base area on the Kola peninsula. In addition, about 60 phased out submarines have been laid up at these bases.

The number of operating civilian nuclear powered ships is currently 8 and one more ice-breaker is ordered [8]. Each ship is equipped with one or two reactors in the capacity range 135-170 MW_{th}.

3.4 Various uses within industry, research and medicine

Within the former USSR the use of radioactive substances for various industrial, research and medical purposes has been widespread. For example, there are about 75 research nuclear reactors in operation, shut down or under construction [4]. Furthermore, in excess of 2000 organisations in the central parts of Russia through their every-day activities create low and intermediate-level waste that needs to be managed in an appropriate manner [10]. According to [15] as many as 130 000-200 000 organisations in the former USSR use different types of radiation sources.

The radioactive waste from industry, research and medicine is collected, stored and treated in 15 special plants, Special Combines or Spetskombinats. Up to 1994 the responsibility for the Special Combines is within the State Committee for Municipal Economy. At the same time these facilities are subordinate organisations to the local administrations. The Russian government is presently considering the question of transfer of responsibility for Special Combines to the Moscow facility as it has the best possibilities and the greatest operational experience.

4. Waste amounts and handling system

4.1 General

In this chapter an overview is given of the waste amounts generated by the nuclear power production, by the use of nuclear-powered ships as well as from various industrial, medical and research applications. The chapter also gives a very brief description of the technological system for the management of the waste generated.

4.2 Civilian power production

4.2.1 Introduction

The principles for treating different types of spent nuclear fuel in Russia have been described in Section 3.2. In the present section further details of the treatment and management of wastes from the fuel cycle are given. The emphasis has been put on wastes arising from the treatment of spent fuel and from the operation of reactors. Table 4.1 gives an overview of the estimated total amounts of waste from various sources in Russia [2]. There are of course large uncertainties associated with some of the data in the table.

4.2.2 Spent fuel and waste from reprocessing

The spent fuel from WWER-440 plants is kept in pools at the power plants for cooling period of about three years being transported to the Mayak Combine at Chelyabinsk-65 for reprocessing. The period during which the spent fuel is kept in pools at Mayak is decided by the technological scheme for each fuel batch.

The Mayak plant is also used for the reprocessing of spent fuel from the fast breeder reactors at the Beloyarsk plant and at Shevchenko in Kazakhstan, as well as for reprocessing of spent fuel from icebreaker reactors and from reactors on nuclear naval ships [6]. Spent fuel from reactors in former USSR-republics, from former eastern Europe, and from Finland, is also reprocessed at Mayak. The uranium that is obtained as a result of the reprocessing is used for the production of fuel for the RBMK-reactors. The plutonium obtained is stored on the site.

The spent fuel from the WWER-1000 plants is partly stored at the power plants and, since 1985, partly at Krasnoyarsk-26 where the RT-2 reprocessing plant is under construction. This type of fuel cannot be reprocessed at Mayak because the design of the fuel elements is incompatible with the equipment installed at Mayak.

The construction of RT-2 was first halted in 1989 following a decision by the Ministry for Nuclear Science. This decision was prompted by strong local opposition against the plans to dispose of liquid high and intermediate-level waste in deep geological formation. A completely new system for the treatment of high-level waste was designed, including vitrification and subsequent controlled storage of the vitrified waste.

Table 4.1 Broad overview of sources to radioactive waste and the amounts and activities of the waste from these sources.

Source	Type of waste (L, S, Sol)	Activity class	Amounts (m^3, tonnes)	Activity (Ci)	Place of storage
Uranium mines	Ore waste (S)	LLW	60 000 000	600 000	Mine tailings
Enrichment plants		LLW	1 600 000	93 000	Open storage
Power plants	L	LLW, ILW	83 700	40 000	At all power plants
	S	LLW, ILW	67 300	1 500	At all power plants
	Bitumenised (Sol)	LLW, ILW	12 000	2 000	At the power plants Leningrad and Kalinin
	Spent RBMK-fuel	HLW	5 325	350 000 000	At NPP
	Spent WWER-440 fuel	HLW	940	200 000 000	At NPP for three years prior to reprocessing
	Spent WWER-1000 fuel	HLW	1 100	150 000 000	Partly at NPP and partly at Krasnoyarsk (RT-2)
Reprocessing plants including military activities	Spent fuel from WWER-440, BN-350, BN-600	HLW	3 500	9 500 000	Mayak Combine at Chelyabinsk
	Vitrified high-level waste from reprocessing of WWER-440, BN-350 and BN-600 fuel (Sol)	-	1 000	150 000 000	Mayak Combine at Chelyabinsk
	L	ILW, HLW		550 000 000	Mayak Combine at Chelyabinsk, steel tanks
	L	ILW		125 000 000	Mayak Combine at Chelyabinsk, Lake Karachay
	Equipment, construction material (S)	LLW, ILW, HLW	730 000	12 000 000	Mayak Combine at Chelyabinsk, solid waste burial
	L	ILW		126 000 000	SChK at Tomsk, basins
	L	HLW		400 000 000	SChK at Tomsk, rock caverns
	L	-		8 400 000	GChK at Krasnoyarsk
	L	HLW		500 000 000	GChK at Krasnoyarsk, rock caverns

Notes: L means liquid waste, S means solid waste, Sol means solidified waste, LLW means low level waste, ILW means intermediate level waste, HLW means high level waste; GChK means Mining-chemical Combine at Krasnoyarsk-26, SChK means Siberian Chemical Combine at Tomsk-7.

Due to a lack of financial resources the construction of RT-2 was stopped again at the beginning of 1991, and it was decided to preserve the construction site for 5 years. It has been estimated that the available storage capacity of roughly 6000 tonnes at the site will be sufficient until the year 2004-2005.

Due to the low residual enrichment of the spent RBMK-fuel, there are currently no plans to reprocess this fuel. The spent fuel from RBMK-reactors is stored for 3-5 years in pools located in the reactor hall. After this initial cooling period the fuel is transferred to pools in separate storage buildings on the reactor sites [14]. Such storage facilities are in operation at the Leningrad and Kursk nuclear power plants and under construction (1993) at Smolensk [6]. The storage capacity of the current facilities is 17 500 fuel elements per power plant corresponding about 2000 tonnes which is sufficient for 10 years operation of a plant with four RBMK-1000 units. Plans exist to expand the current facilities to allow for 30 years of storage time.

There are plans to construct a federal storage with air cooling of the spent fuel. This facility will be designed for a storage time of 80-100 years. This extended dry storage of the spent RBMK-fuel is intended to give time to decide on the ultimate fate of the fuel. MinAtom currently favours final disposal of the spent RBMK-fuel in permafrost. It is believed that it would be easier to get political acceptance for such disposal at Novaya Zemlya than in northern Siberia.

The fuel elements in the RBMK-reactors have a length of about 11 m. There are currently no transportation casks available that are licensed for transportation of such long fuel elements on public roads. The RBMK-fuel assemblies are designed to make it possible to cut them in halves to reduce their lengths and facilitate the transportation.

The liquid high-level waste from reprocessing of fuel from WWER-440, BN-350 and BN-600 is being stored at the Mayak Combine in single walled steel tanks housed in steel-lined concrete canyons [6]. The total number of tanks at Mayak is reported to be 99. Since the waste from the reprocessing of civilian spent fuel is mixed with waste from military activities, it has been difficult to get a good handle on the waste volumes and activities in store. The data in Table 4.1 have been gathered from [2], [6] and [10]. The table has also been commented by MinAtom.

A vitrification facility is in operation at the Mayak Combine. At the start of the operation of the first facility in 1986 mainly waste with a high aluminium content, probably from highly enriched fuel from naval reactors, was solidified. In the current facility, which was put into production on 25 June 1991, waste from reprocessing of fuel from BN-reactors and WWER-440 reactors has been treated.

The glass produced in the vitrification process is a phosphate glass. It is cast into 200 l metal vessels. Subsequent to cooling, three such vessels are put together in a metal container (0.63 m diameter and 3.4 m height). The activity concentration in the glass is currently about 400 Ci/l. With the present capacity of 1 tonne of glass per day it will take approximately 10 years to solidify the liquid high-level waste stored at Mayak.

The glass blocks are planned to be disposed of in either granite or salt. Suitable sites are being looked for in the southern Ural area.

At the Mayak Combine there are 227 solid waste burial sites comprising an area of 30 ha (the sites occupy 21.3 ha) [6,10]. The total volume of waste disposed is approximately 730 000 m^3. The waste disposed of at these sites is a mixture of HLW (25 000 tonnes), ILW (350 000 tonnes) and LLW (150 000 tonnes). The metallic waste constitutes 30% of this waste amount. The total activity content of about 450 PBq is totally dominated by the HLW. The solid waste is normally dumped into the burial sites because of a lack of proper conditioning methods.

About 10 of these sites still receive waste. The sites are usually located where the groundwater table is at least 4 m below the bottom of the burial. The LLW and ILW are disposed in trenches dug in the ground. After being filled, the trenches are covered with clay to reduce the infiltration of rain water. The bottom and walls of the trenches are lined with clay in order to give further hydraulic isolation. The solid HLW is placed in concrete structures that are hydraulically tightened with bitumen, steel and clay linings. These HLW burials are equipped with monitoring equipment and signalling systems.

It is well known (e.g. [6,8,10,11]) that the operation of the radiochemical complexes in the south Ural region and in Siberia has caused substantial radioactive contamination of the environment, in particular of the Ob and Yenisey river systems. Most of the contamination took place during the 1940-s and 1950-s when radioactive waste from the plants were discharged directly into adjacent rivers and lakes. It has been estimated [12,13] that the rivers Ob and Yenisey have discharged roughly 1200 TBq of ^{90}Sr and ^{137}Cs to the Kara Sea. The sources of this activity are the discharges from the radiochemical plants in the river catchment areas and the wash-out from land areas contaminated by accidents such as the Kyshtym (1957), the Lake Karachay (1967) and the Chernobyl (1986) accidents. Moreover, it is known that radioactivity infiltrates into the groundwater system from Lake Karachay that is used by the Mayak Combine as a storage reservoir for intermediate-level waste [10]. The contaminated groundwater system covers 80 km^2 and the contamination front moves some 80 m per year. Ongoing remedial activities including filling the lake med soil are primarily designed to avoid dispersion of radioactivity by wind erosion rather than to protect the groundwater system.

Liquid high and intermediate-level waste has been disposed of by injecting it into deep groundwater aquifers at least at three sites within Russia. The concept is based on injection into pervious geological layers overlain by hydraulically tight clays. The actual volumes and activity contents of the wastes injected are unknown. According to information from MinAtom, the waste injected at the above mentioned sites has had an activity content of less than 37 GBq/l. It has been claimed by MinAtom that evidence from more than 30 years of environmental monitoring show that the deep injection method is ecologically safe. There is currently no international consensus on this view.

At the Mining Chemical Combine at Krasnoyarsk-26 injection is performed into an aquifer at a depth of about 270 m [6,10] at the so called northern testing ground which is to be closed down by the year 2000. Specialists employed at the plant have said that there are no plans of abandoning this disposal scheme before the year 2000. At the Siberian Chemical Combine at Tomsk-7 injection into a formation at 180-210 m depth has taken place. The town with its 500 000 inhabitants gets part of its water supply from wells that are 240-260 m deep. It cannot be excluded that the injected radioactive waste finds its way to the aquifer constituting the water supply. According to MinAtom, injection of liquid waste has also taken place at Dimitrovgrad in the Volga region.

4.2.3 Low and intermediate-level waste from the power plants

The radioactive waste generated at the power plants mainly consists of low and intermediate level waste with half-lives less than 30 years. The waste is either liquid or solid. At all the power plants there are either existing or planned facilities for the storage or treatment of both the liquid and solid low level waste. The types of facilities for the local treatment of the low and intermediate level liquid and solid waste at the different power plants are shown in Tables 4.2 and 4.3, respectively. Tables 4.4 and 4.5 show the waste amounts stored and the fraction of the storage capacity utilised. The tables also include a column indicating the percentage of the theoretical operational life-time that the power plant has been in operation. This value is intended to give an impression of the future amounts of waste to be expected from the power plant in question.

The liquid waste is stored in special tanks of stainless steel located on the site of the power plant. The waste is then transferred from the storage tanks for evaporation followed by bitumenisation. The bitumenised waste is stored on the NPP site either in special containers or in 200 l iron drums.

A solidification process based on cementation has been developed by the Bochvar institute. This process has not yet been implemented at any reactor. Since cementation is regarded as a safer solidification method than bitumenisation, plans exist to implement cementation at most power plants.

Solid low and intermediate-level waste is collected in storage facilities on the sites of the power plants. It is kept without packaging in special storage compartments of reinforced concrete. In these compartments, low-level, intermediate-level, high-level and burnable wastes are stored separated from each other.

In all, the amounts of low-level and intermediate level waste that will be produced at the nuclear power plants up to the year 2010 can be estimated to roughly 700 000 m^3 as liquid waste and roughly 500 000 m^3 as solid waste. Since facilities for a long term disposal for the waste from the power plants are lacking, the waste is stored at or close to the power plant sites.

4.2.4 Future radioactive waste

The Russian Federation has issued plans for the future exploitation of nuclear power. These plans are concerned with the construction of nuclear power plants within Russia up to the year 2010. The plans include the completion of ongoing projects, replacement of decommissioned existing reactors, and the development and construction of a new generation of reactors with improved safety. In addition, there are plans to evaluate the conditions for the construction of nuclear power plants and nuclear heating power plants (including low power reactors) in distant parts of the country. The programme includes construction and commissioning of about 25 reactor units with an installed power of some 17 000 MW_e until the year 2010. The plans for the completion of ongoing projects and the replacement of decommissioned reactors for the years 1993-2010 are summarised in Table 4.6

Table 4.2 Facilities for the local treatment of the liquid low level radioactive waste stored at the nuclear power plants.

Power plant	Bitumenisation plant	Cementation plant	Amount waste treated (m³)	Volume of solidified waste (m³)
Beloyarsk BN-600		Planned 1998		
Bilibino RBMK 4×11		Planned 1994		
Kursk RBMK 4×1000	Planned	Planned 1997		
Smolensk RBMK 3×1000	Planned	Planned 1997		
Leningrad RBMK 4×1000	Two plants in operation, a third planned 1995		14000	9000
Kola WWER 4×440		Planned 1995		
Novo Voronezh WWER 2×440, 1×1000	One plant in operation (1993)	Planned 1996	No information available	No information available
Kalinin WWER 2×1000	One plant in operation, a second planned 1995	Planned 1998	250	160
Balakovo WWER 4×1000	One plant in operation (1993)	Planned 1994	No information available	No information available

Table 4.3 Facilities for the local treatment of the solid low level radioactive waste stored at the nuclear power plants.

Power plant	Incineration plant	Compression plant	Notes
Beloyarsk BN-600	In operation	Planned 1996	
Bilibino RBMK 4×11	Planned 1995	Planned 1995	
Kursk RBMK 4×1000	In operation	Planned 1998	
Smolensk RBMK 3×1000	Planned 1998	Planned 1995	
Leningrad RBMK 4×1000	In operation 1995	Planned 1995	Waste is transported to the Lenspets Combine
Kola WWER 4×440	In operation	In operation	
Novo Voronezh WWER 2×440, 1×1000	Planned 1999	Planned 1999	
Kalinin WWER 2×1000	Planned 1996	Planned 1996	
Balakovo WWER 4×1000	Planned 1995	Planned 1994	

Table 4.4 Amounts of liquid low and intermediate level waste being stored at the power plants in operation by 1992.

Power plai..	Amounts stored by 1992 (m^3)	Used present storage capacity by 1992 (%)	Theoretical operational lifetime by 1992. Percent of total
Beloyarsk BN 1×600	7000	95	40
Bilibino RBMK 4×11	800	70	54
Kursk RBMK 4×1000	27000	42	37.5
Smolensk RBMK 3×1000	7400	63	21
Leningrad RBMK 4×1000	21000	98	50
Kola WWER 4×440	6144	72	47
Novo Voronezh WWER 2×440, 1×1000	7970	51	53
Kalinin WWER 2×1000	3400	94	23
Balakovo WWER 4×1000	3000	79	13

Table 4.5 Amounts of solid low and intermediate level waste being stored at the power plants in operation by 1992.

Power plant	Amounts stored by 1992 (m^3)	Used present storage capacity by 1992 (%)	Theoretical operational lifetime by 1992. Percent of total
Beloyarsk BN-600	16000	90	40
Bilibino RBMK 4×11	185	19	54
Kursk RBMK 4×1000	18400	84	37.5
Smolensk RBMK 3×1000	6500	33	21
Leningrad RBMK 4×1000	see note	see note	50
Kola WWER 4×440	3500	62	47
Novo Voronezh WWER 2×440, 1×1000	20300	83	53
Kalinin WWER 2×1000	650	13	23
Balakovo WWER 4×1000	1800	30	13

Note: The waste is transported to the Lenspets Combine

Table 4.6 New reactors that will be commissioned until the year 2010 according to the Russian programme for the development of nuclear power.

Reactor	Type	Power (MW$_e$)	Year of commission			
			1993-1995	1996-2000	2001-2005	2006-2010
Ongoing constructions to be completed						
Kursk 5	RBMK	1000	x			
Kalinin 3	WWER	1000	x			
Beloyarsk 4	BN	800		x		
Reactors replacing those to be decommissioned						
Bilibino 5	RBMK	32			x	
Bilibino 6	RBMK	32			x	
Bilibino 7	RBMK	32				x
Novo Voronezh 6	WWER	1000			x	
Novo Voronezh 7	WWER	1000			x	
Kola 5	WWER	630			x	
Kola 6	WWER	630			x	
Kola 7	WWER	630				x

Low and intermediate level waste

Assuming that waste continuously will be generated with the same amounts per year and per MW installed, the future waste generation can be estimated from the amounts presently in store. The estimated future amounts of liquid and solid low and intermediate-level waste from nuclear power plants are shown in Figures 4.1-4.2. The projections include the existing reactors, see Table 3.1, and those planned, see Table 4.6, assuming the reactors will be operated at full capacity for 30 years. These figures indicate roughly the future need for storage capacity at the power plants.

The amount of solid waste stored at the plant in Novo Voronezh is far greater than average per MWa, possibly because waste from the decommissioned reactors Novo Voronezh 1 and 2 is stored on the site. The projected solid waste generation for Novo Voronezh is therefore based on average values for the other reactors of the same type. Note also that the solid waste generated at the Leningrad plant is transported to the Lenspets Combine.

It is evident from the figures that there is an acute need for expansion of the storage capacity at several power plants.

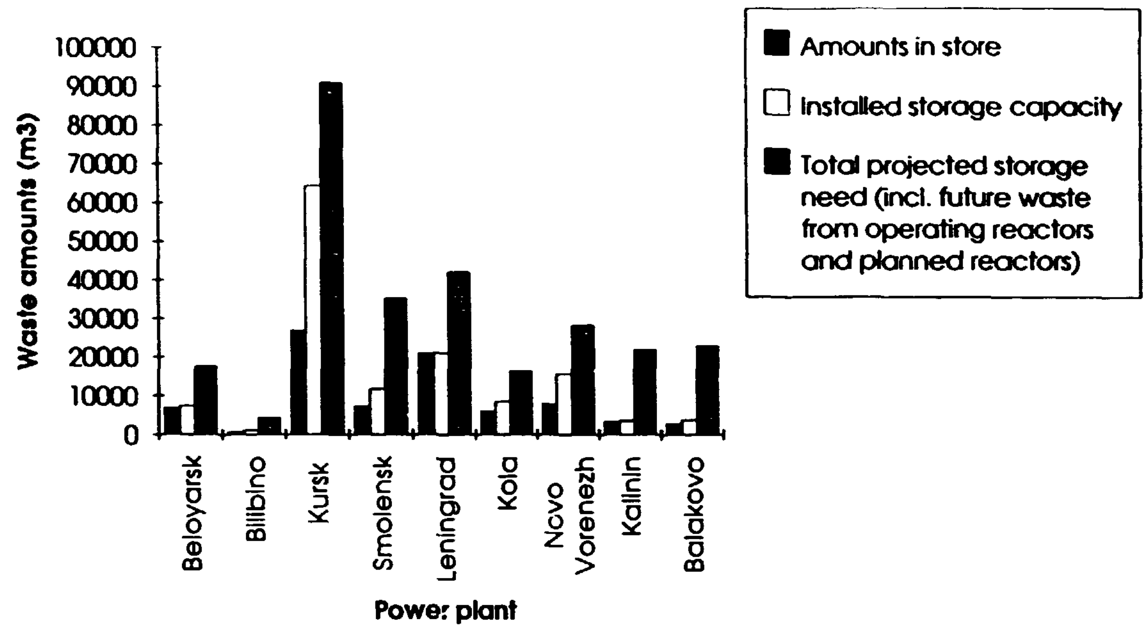

Figure 4.1 Forecast of waste generation for on site disposal of liquid low and intermediate level waste.

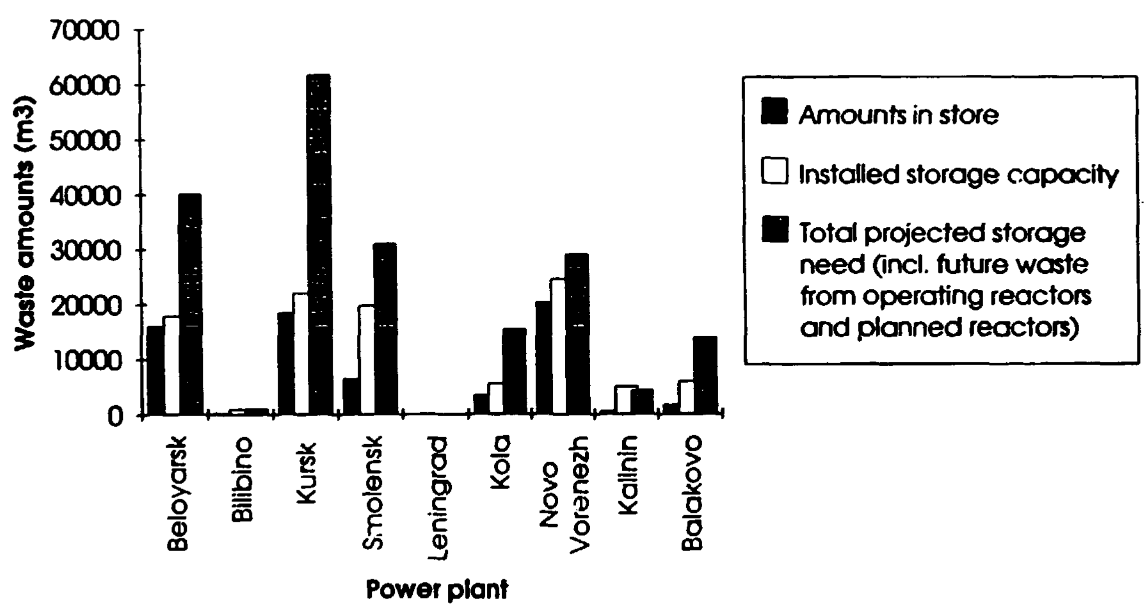

Figure 4.2 Forecast of waste generation for on site disposal of solid low and intermediate level waste.

Spent fuel

The amounts of spent fuel that will be generated from the power plants presently in operation and from those planned, see Table 4.6, are shown in Figure 4.3. The estimate is based on a steady-state assumption regarding the fuel throughput in the reactors The annual fuel throughput has been has been assumed to be 12.5 MTU (tons of uranium) for WWER-440, 21 MTU for WWER-1000 and 50 MTU for RBMK-1000 [14]. The spent fuel from fast breeder reactors is not included in the figure. The expected amounts of such fuel are small compared to the amounts of fuel from the other reactors.

The data are somewhat uncertain as the core physics of the different reactor types may have been modified. For example, the enrichment of the fresh RBMK fuel has been increased subsequent to the Chernobyl accident in order to improve the stability of the reactors. It is therefore likely that the estimated amounts of spent RBMK fuel in Figure 4.3 are overestimated. The figure does not account for effects from special designs of the initial cores and possible burn-in problems in conjunction with and subsequent to the commissioning of the reactors. The data in Table 4.1 on amounts of spent fuel in storage 1993 are 20-30% lower than those in Figure 4.3, except for WWER-1000.

The total estimated amount of spent RBMK fuel produced by the year 2030 is about 18 000 tonnes out of which 90% derives from the existing reactors. For WWER-440 the amount produced is not quite 4000 tonnes out of which 60% comes from currently operating reactors. The corresponding numbers for WWER-1000 are 6000 tonnes with 70% coming from the currently operating reactors.

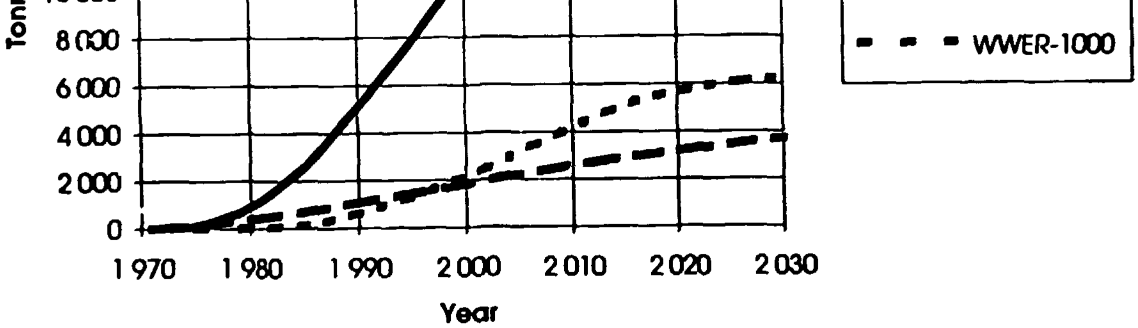

Figure 4.3 Forecast of generation of spent fuel.

4.3 Nuclear propulsion of civilian and naval vessels

As mentioned in Section 3.3, the Kola peninsula hosts bases for both naval and civilian nuclear-powered vessels. This area has the worlds largest concentration of nuclear vessels including about 100 operative submarines and 8 nuclear ice-breakers. In addition, about 60 phased-out submarines are laid up in the area. About 20 of these phased-out submarines have been emptied from their contents of spent fuel whereas the remaining 40 lie at different harbour areas with their reactors and fuel inventories intact. It is expected that another 30 submarines will be phased out before 1998 [8]. The total number of reactors on phased-out submarines on the Kola peninsula will then be 180 out of which 140 will be fuelled.

A nuclear submarine will normally be refuelled twice and phased out when there is a need for a third refuelling. A refuelling cycle is about 7 years, but for newer submarines it can by 9-10 years. Each submarine will during its life consume about 1000 fuel elements. In order to serve the operating fleet, it is estimated that the Russian navy needs a capacity to handle 4000-5000 fuel elements per year. Further capacity is needed to handle the fuel from phased-out vessels. The emptying of phased-out submarines from fuel is a major problem. The northern navy presently has the capacity to empty two submarines simultaneously. As the time required for one submarine is about three months it has been estimated [8] that it will take about 10 years to empty all submarines that will be phased out until 1998.

The intended management scheme for the spent fuel from the navy and the ice-breaker fleet is similar to the scheme used for the WWER-440 reactors. This means that the fuel is stored for three years at the bases before it is transferred to the Mayak Combine at Chelyabinsk-65 for reprocessing. It is known that the fuel transfer has been disturbed due to economical and/or technical problems. According to MinAtom the transfer is now in full operation, and mainly damaged fuel that cannot be transported to the Mayak Combine is stored at the bases. Plans exist to bury the defect fuel in underground repositories.

On the Kola peninsula the Russian navy has stored about 21 000 fuel elements from normal refuelling while about 4 500 fuel elements have accumulated from the operations of the ice-breaker fleet [8]. At the naval bases on the coast of the Pacific Ocean roughly 9 000 spent fuel elements are estimated to be in store. In addition, it is estimated that 10 000 spent fuel elements are still in the reactors of the phased out submarines. The annual accumulation of spent fuel is said by the Russian authorities to be 2 000 elements [8]. The fuel elements, that are considerably smaller than the elements used in commercial power reactors, can be assumed to contain 1.5 kg uranium each. The total amount of spent fuel in store should thus be about 60 tonnes which is less than the inventory of one commercial reactor.

Spent fuel from the navy is partly stored in phased-out submarines, partly in floating storage on board ships and partly in storage facilities on ground. Some of the phased-out submarines are in a such a bad shape that they threaten to sink. Spent fuel from the ice breakers is stored on service and maintenance ships (e.g. the repair ship Lepse and the mother ship Imandra) that lie at harbours with frequent ship traffic and located near population centres in the Murmansk area.

The ice-breaker fleet produces about 600-800 m^3 of liquid radioactive waste per year which is purified at "sorption plants" in Murmansk. Within the northern naval fleet 4000-5000 m^3/year of liquid waste is produced with an activity of less than 10^{-5} Ci/l. Until 1993 this waste was dumped into the sea. Currently this waste is collected in tanks and tankers which have been filled up to 90% of their capacity. During 1994 it is planned to build a special water purification plant in Murmansk. This plant will purify liquid radioactive waste from the ice-breaker fleet and the navy, as well as liquid radioactive waste from the utilisation of nuclear submarines (the capacity will amount to 150 000 m^3 liquid waste per year).

The northern fleet produces about 3500 m^3 solid radioactive waste yearly. The solid waste is stored at the base areas and at dockyards. It is planned to start the erection of facilities for compaction and incineration of solid radioactive waste at the dockyards and at the base of the ice-breaker fleet "Atomflot".

4.4 Various uses within industry, research and medicine

As mentioned in Section 3.4, there is a widespread use of radioactive isotopes in the Russian society for industrial, research and medical applications The collection, processing, storage and disposal of this waste is performed at special facilities called Spetskombinats or Special Combines. Altogether there are 15 such plants within the present Russia. One of these is the Murmansk plant which now has been shut down following directives from Gosatomnadzor as it did not meet the safety requirements.

Due to the diversity of the waste and the multitude of collection and storage facilities used, it has not been possible within the present study to obtain an overview of the amounts of waste handled and stored nor of the activity contents of the waste or the technology used at the individual facilities.

Today only the Moscow and Leningrad (the Lenspets Combine) plants are equipped with facilities for conditioning of the waste before storage. In order to give some view of the technology used at these facilities some impressions from a study trip to the Lenspets Combine are given below [9].

The Lenspets Combine is equipped with facilities for incineration and evaporation of the waste as well as for solidification with bitumen and cement. Most of the waste received is solid, burnable waste, but also liquid waste and ion exchange resins are received. After processing the waste is stored above ground in two types of storage buildings. The older type consists of open-top concrete cells that are filled from the outside using different types of cranes. When the cells have been filled they are covered with a plate roof.

The second and newer type is similar to the old type but equipped with a roof made of plate and the filling is made from the inside. The risk for activity leakage during the filling period is thus lower for the new type than from the old type.

The volume of waste stored at the Lenspets Combine was in September 1992 about 40 000 m^3. The activity leakage from non-closed storage buildings is said to be measurable but nor exceedingly great. A part of the area is contaminated with i.a. ^{137}Cs to a level of 40-200 Bq/m^2. Contributions to this contamination come from the facility itself, from the Leningrad nuclear power plant (which is located about a kilometre from the Lenspets Combine) and from the Chernobyl accident.

Solid radioactive waste corresponding to 4000 m^3 annually is transferred from the Leningrad nuclear power plant to the Lenspets Combine. No radioactive waste from any other Russian nuclear power plants is transferred to the "Spetskombinats".

At the naval base in Kaliningrad some tens of TBq have accumulated. Waste from this source was previously transferred to Lithuania for treatment and storage. After the breakdown of the USSR this operation has been discontinued.

It is obvious that the extensive use of radioisotopes in Russia is associated with certain risks. It has been admitted by Russian authorities that there is a certain risk for unauthorised export of radioactive materials due to the lack of an appropriate regulatory system and the difficulty to maintain an efficient inspection.

5. Summary and conclusions

General

Radioactive waste is accumulating within the territory of the Russian Federation. The waste derives from the operation of power-producing nuclear reactors, from facilities in the nuclear fuel cycle, from the operation of nuclear-powered naval vessels and ice-breakers and from an extensive use of radioactive isotopes in different sectors of the society including industry, research and medicine. Although a significant effort is spent on research and on the development of methods to manage the waste accumulating, financial limitations often delay the practical implementation of the solutions developed, or impede proper maintenance causing equipment and facilities to deteriorate to the degree that obvious threats to the environment are created.

Another consequence of the lack of financial resources is that the personnel at the power plants sometimes don't get their salaries. This could potentially threat the sense of responsibility and the morale of the personnel possibly influencing the safety at the facilities.

One reason for the lack of financial resources is that much of the power production never is payed for as the power distribution company does not get payed by their clients. It has been said that it is not possible according to Russian law for the utility companies to turn off the electricity to those clients that do not pay.

The creation of Gosatomnadzor as a body responsible for the inspection of all facilities handling nuclear or radioactive materials within the country is an improvement of the regulatory situation. Gosatomnadzor has the authority to fine or prosecute operators violating the regulations and ultimately to order the shut down of facilities that don't meet the safety requirements. However, the efficiency of the inspection is in practice limited by a lack of legislation. It has also been difficult in the short time since the formation of the authority to locate qualified personnel to the regional outfits where the inspection is performed.

Waste from nuclear power production

At many nuclear power plants the available facilities for low and intermediate-level waste are near full. The plants for bitumenisation of liquid waste that exist at some of the power plants cannot treat ion exchange resins due to design related problems. As a consequence the resins have to be stored in tanks. Cementation is regarded as a safer solidification process and a conceptual design of a cementation plant has been developed. Plans exist to implement cementation at most power plants. However, delays are foreseeable because of lack of financial resources. If proper solidification cannot be performed, liquid waste will continue to accumulate in tanks. There is an obvious risk that temporary and possibly inadequate solutions to the storage problem can emerge with consequent poor radiation hygiene at the plant.

Treatment facilities for solid low and intermediate level waste exist only at the Kursk (incineration), Leningrad (incineration) and Kola (incineration and compaction) power plants. At the other plants the solid waste is stored in special concrete cells without packaging with a consequent risk for contamination of personnel and equipment as well as of the environment.

At the RBMK plants the capacity for spent fuel storage needs to be expanded to allow for the 30 years of interim storage included in the current waste management plans. In particular at the Leningrad power plant and possibly at Kursk the time at which the expansion is needed is coming closer. It should be noted that the RBMK fuel elements are very long, about 11 m, and that there are currently no suitable transportation casks available that are licensed for off-site transportation. There is thus no possibility to utilise unused storage facilities at other plants when the capacity at a plant is fully used.

The management plans for the RBMK fuel include a federal air-cooled storage facility that can host the fuel for up to 100 years. This solution also requires that transportation casks and handling systems are developed. There are provisions in the fuel design to cut the fuel assemblies in halves in order to facilitate transportation. However, it is unclear whether this has been tested with irradiated fuel and if this would lead to contamination and radiation hygiene problems.

For the spent WWER-440 fuel, one problem seems to be the long transportation routes from the reactors, in particular from Kola, to the Mayak Combine. It is known that financial and/or technical problems have caused interruption of these transports. The WWER-1000 fuel continues to accumulate awaiting the finalisation of the construction of the RT-2 reprocessing plant at Krasnoyarsk-26. The construction is currently interrupted due to a lack of finances, and the construction site has been preserved for 5 years. Information about the status of the development of special storage facilities for WWER-fuel at the power plants has not been available in the present study.

Waste from the fleets of nuclear powered vessels

The conditions under which spent fuel and radioactive waste is stored at the bases for the nuclear naval vessels and ice breakers are inadequate. Significant amounts of spent fuel are stored on maintenance ships and phased out submarines docked at harbours near population centra on the Kola peninsula and on the coast of the Pacific. Also, liquid low and intermediate-level waste is stored in tanker ships at the bases. Some of the ships used for storage of spent fuel and radioactive waste are in such a bad shape that there is a significant probability that one of them sinks. It is estimated that 90% of the available storage capacity is already utilised.

Despite 35 years of operation of the nuclear fleets, the waste management situation remains virtually unresolved. Plans exist to build treatment facilities at the support bases of the fleets, but it is uncertain when the plans can be implemented. There is a significant probability for accidents in storage facilities at naval or ice-breaker bases causing radioactive contamination of the marine environment.

Management of miscellaneous radioactive wastes

The use of radioactive isotopes for various industrial, research and medical applications has been extensive in the former USSR. Trying to get an overview of the uses of the handling of different types of radioactive materials is associated with considerable difficulty. According to one source about 2000 organisations in the central part of Russia have in their ordinary activities created low and intermediate-level wastes which need proper management. Other sources indicate that as many as 130 000-200 000 organisations in the former USSR use different types of radiation sources.

There is a worry in the western world that materials exported from the former USSR may contain or be contaminated by radioactive isotopes. This risk appears to be largest with materials from the industrial, research and medical applications, since this sector, in view of its diversity and size, is difficult to regulate and control. The Russian authorities claim that the control in the nuclear power production as well as in the military complex is strict enough to minimise the risk for radioactive materials to come astray. Despite this, Russian authorities in the spring of 1994 confiscated a couple of kilograms of enriched uranium in S:t Petersburg on its way to be illegally exported.

Within Russia there are currently 15 regional facilities, so called Spetskombinats (Special Combines) for the collection and storage of such wastes. However, only two of them (the Moscow facility and the Lenspets Combine at Sosnovy Bor west of S:t Petersburg) have facilities to condition the waste by incineration, compaction, evaporation and solidification before storing it.

The waste storage at the Spetskombinats is intended to be retrievable should that be required. However, some of the waste has been solidified with bitumen in situ in the storage tanks. It is presently uncertain if this waste can be economically feasibly retrieved assuming the maintenance of good radiation protection standards. At the Lenspets Combine part of the ground within the facility has been contaminated by Cs isotopes leaking from the waste. The operation of the facility at Murmansk has been discontinued following directives from Gosatomnadzor as it did not meet the safety requirements.

Waste from the military nuclear complex

Although it has been beyond the scope and possibilities of this study to include materials from the fabrication and handling of nuclear weapons, it should be noted that significant amounts of radioactive waste and other materials are handled in the military complex. A total of 120 tonnes of weapon-quality plutonium is estimated to have been produced within the former USSR. As a comparison the amount of pure plutonium from reprocessed commercial fuel is estimated to be 40-90 tonnes, but the degree of reprocessing is unknown.

The total nuclear arsenal is estimated to comprise 40 000 devices. Due to maintenance requirements and the disarmament process an estimated 2000-3000 devices are dismantled every year. Awaiting permanent storage facilities, the plutonium from the weapons dismantling is currently put in temporary storage facilities. The amount of plutonium stored is estimated to several dozens of tonnes [1].

Large amounts of tritium have been produced for thermonuclear devices. The inventory is estimated to be 55 kg [16] and the production continues, probably at the same facilities as the plutonium production.

Environmental contamination

Some of the activities within the nuclear complex of the former USSR have caused significant radioactive contamination of the environment. There have been several major accident causing substantial dispersion of radioactive substances. The best known are probably the Chernobyl reactor accident in 1986, the Lake Karachay accident in 1967 when wind erosion dispersed radioactivity from a lake that was used as an open reservoir for intermediate-level waste from the Mayak Combine, and the Kyshtym accident in 1957 when a tank containing liquid high-level waste exploded. In addition, the operation of radiochemical plants in particular in the Chelyabinsk area, the Tomsk area and the Krasnoyarsk region has caused significant contamination of large parts of the Ob and Yenisey river systems. Limited amounts of radioactivity have been reported to be discharged by these river systems into the Kara Sea.

Testing of nuclear weapons and peaceful applications of nuclear explosives have caused contamination in many areas. As many as 115 peaceful explosions have been carried out mainly for different civil engineering and research purposes.

Substantial sea dumping of radioactive waste has been performed in the Barent and Kara Seas as well as in the Pacific. The dumping of 16 reactors, six of them loaded with spent fuel (cores from submarines and the sinking of whole ships with reactors, fuel and all) has been much mentioned. According to the results of the environmental sampling and measurements carried out jointly by Russian and Norwegian scientists in 1992 as well as the findings from the International Arctic Seas Assessment Project, IASAP, launched by IAEA in 1993, there is yet no health hazard from these dumping operations.

Some remarks on costs

Based on the present study it is probably impossible to estimate of the total cost for a waste management system in Russia designed to meet safety criteria of the same type that are used in western Europe. The size of the Russian nuclear power generation system is comparable to that in Germany. It should therefore be possible to compare with estimated costs for the German waste management system.

The German disposal costs are discussed in [5] where it is stated that the planning, construction and licensing for two repositories intended for high-level waste and low and intermediate-level waste respectively amounts to about 1-2% of the electricity generation cost. This corresponds to a total cost of about 2000-4000 million German marks for each of the two repositories. The expected yearly cost for the continued operation of the post-closure phase is estimated to about 50-100 million German marks. Both sites are based on a deep geological burial system, one in a salt formation, the other in an abandoned iron ore mine.

The total cost for the management of waste from the Swedish 12 nuclear reactors (10 GW_e) is estimated to 50 000 million Swedish crowns (about 10 000 million German marks) [17]. This cost includes a transportation system, a central underground interim storage facility for spent fuel, an underground repository for low and intermediate-level waste from reactor operation, an encapsulation plant for spent fuel, a deep repository for spent fuel and other long-lived waste and a final repository for decommissioning waste. The first three parts of the system are already in operation while the latter three are in the planning stage.

When estimating the costs total costs for a radioactive waste management system in Russia it is important to remember that the implementation of waste treatment technology, reprocessing, management of the waste from nuclear-powered ships, etc should be added to the German and Swedish systems mentioned above. It is likely that these costs are substantial. For instance, the decommissioning of one single nuclear submarine is estimated in the western world to cost about 200 million Norwegian crowns (about 40 million German marks) [8]. In Russia about 90 submarines are expected to be phased out by 1998. This cost alone could thus be in the same order of magnitude as the costs for the total disposal system for waste from the civilian nuclear power production.

It has been estimated by Russian authorities [10] that the costs for completion of a first step of the RT-2 reprocessing plant at Krasnoyarsk-26 would require 3-4 billion roubles plus the inflation from 1991 to present day. According to the same source, a similar facility in France required the investment of some 8 billion US dollars. There have been negotiations between Russia and South Korea about Korean financial support for the finalisation of the plant in exchange for possibilities for Korea to utilise the facilities. There has, however, been protests from the local population against the creation of an international nuclear waste dump in the area. The present situation is unclear.

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