Bellona report 2012

Nuclear Fissile Materials

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(management practices, technologies,
problems, and prospects)

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TRANSLATOR'S NOTE:

Names of Russian companies and locations, as well as personal names mentioned in this report, have been rendered in English in accordance with common Russian-English transliteration rules. Certain exceptions, however, have been made for a number of companies or locations, and names may appear as they are spelled on the respective companies' websites or in corporate documents, such as annual reports. English translations are provided for company names in certain cases.

Foreword

The first edition of *Nuclear Fissile Materials* was prepared and published by Bellona's experts in late 2011. The report sparked an interest among the general public and specialists in the field, who offered Bellona their comments and suggestions regarding additional information and amendments for the report.

This is the second and updated edition of the report *Nuclear Fissile Materials*. In this revised version, a new chapter, *Thorium*, has been added to the report, and the chapter *Safety and Environmental Issues of Handling Nuclear Fissile Materials* has been expanded significantly. The authors have also decided to remove the previous edition's chapter on economics and issue it as stand-alone publication.

Structurally, the present edition is divided into seven chapters with information on uranium, uranium oxide and MOX fuels, spent nuclear fuel, weapons-grade plutonium, highly enriched uranium, and thorium. Each chapter contains brief information on the technologies and sources of production (generation) of nuclear materials, their chemical, physical, and other properties. These chapters also include information on the management (application, storage, transportation, decommissioning, etc.) of nuclear fissile materials.

Additionally, the report presents information on the major companies and enterprises engaged in production and enrichment of uranium, fabrication of various kinds of fuel, reprocessing of spent nuclear fuel, and management of accumulated stockpiles of plutonium and enriched uranium. Issues of international practices in managing nuclear fissile materials, and the policies that the top nuclear nations have adopted in this domain, are examined as well.

Our hope is that the information offered in this report will give the public a more detailed view of the nuclear fissile materials accumulated in the world, the varying practices of managing these materials, and the policies of various nations – including Russia – in this field. We deem it important that the information gathered in this report might be used in order to form opinions, proposals, and signals for political and public initiatives where issues of management of nuclear fissile materials are concerned.

LIST OF ABBREVIATIONS

AGR	Advanced gas-cooled reactor
APWR	Advanced pressurized water reactor
BWR	Boiling water reactor
FR	Fast reactor
GCR	Gas-cooled reactor
HEU	Highly enriched uranium
HM	Heavy metal
IAEA	International Atomic Energy Agency
ISL	In-situ leaching
IUEC	International Uranium Enrichment Center
LDM	Low dispersible materials
LEU	Low-enriched uranium
LMR	Liquid metal cooled reactor
LWGR	Light water graphite-moderated reactor
LWR	Light water reactor
MOX fuel	Mixed uranium-plutonium oxide fuel
NDA	Nuclear Decommissioning Authority, Great Britain
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PHWR	Pressurized heavy water reactor
PWR	Pressurized water reactor
R&D	Research & Development
SEU	Slightly enriched uranium
SFA	Spent fuel assembly
SNF	Spent nuclear fuel
SWU	Separative work unit
TNR	Thermal neutron reactor
TUK	Transport cask (for Russian *transportny upakovochny konteiner*)

Russian reactor designs:

AMB	Water-cooled graphite-moderated channel-type reactor (for Russian *atom mirny bolshoi*)
BN	Fast neutron reactor (for Russian *fast neutrons*)
EGP	Water-graphite heterogeneous channel-type power reactor (for Russian *energeticheskiy geterogenny petlevoi reaktor*)
RBMK	Water-cooled graphite-moderated channel-type reactor (for Russian *reaktor bolshoi moshchnosti kanalny*)
VVER	Water-cooled, water-moderated power reactor (for Russian *vodo-vodyanoi energeticheskiy reaktor*)

CHAPTER 1. **URANIUM**

Uranium is the main source material for the generation and manufacture of nuclear fissile materials. Uranium occurs as a mixture of three radioactive isotopes:

– U-238, natural abundance: 99.274%, half-life period: 4.468×10^{9} years;

– U-235, natural abundance: 0.72%, half-life period: 7.04×10^{8} years;

– U-234, natural abundance: 0.005%, half-life period: 2.455×10^{5} years.

Uranium emits alpha, beta, and gamma radiation. The specific radioactivity of U-235 in natural uranium is 21 times less than that of U-238. U-234 is not a parent isotope, but a radiogenic one. It is a member of the U-238 decay series and is a product of nuclear decay of U-238. The radioactivity of natural uranium is mainly the contribution of U-238 and U-234; in equilibrium their specific radioactivity values are equal. Natural uranium's specific radioactivity is 0.67 μCi/g (2.5×10^{4} Bq/g) and is essentially equally divided between U-234 and U-238.

In its pure form, uranium is a very heavy, silvery-white, slightly lustrous metal. It is somewhat softer than steel, malleable, ductile, and has minor paramagnetic properties. Uranium is a highly chemically reactive element. It oxidizes rapidly in air, developing an iridescent coat of uranium oxide. Water is capable of decomposing uranium – slowly at a low temperature (around 100 °C), and faster at higher temperatures. When given a forceful shake, uranium metal particles become luminescent.

1.1. Uranium in nature

Natural uranium mainly occurs in uranium ores, although 11% of this metal is extracted as a side product when developing other types of mineral deposits.

The general abundance ratio (content in percent) of uranium in the Earth's crust is approximately 2.5×10^{-4}%. It is part of all rock forming the Earth's crust and is also present in natural waters and living organisms. The lowest uranium concentrations are found in ultrabasic rocks, and the highest in sedimentary rocks (phosphate rocks and carbon shale).

It has been established that due to the natural process of radioactive decay, throughout geological history, uranium content in the Earth's crust has been gradually depleting.

1.1.1. Uranium ores

Of the 14 known geological types of uranium ores and over 100 uranium minerals, only 12 minerals are of industrial value. The primary uranium ore minerals are pitchblende, uraninite, and carnotite.

Natural uranium ore (with an average concentration of 3 g/t) is one of the most frequently occurring ores in the earth. But, from the point of view of economic viability, developing a uranium ore deposit only makes sense where the metal's concentration in the ore is at least 700 g/t (0.07%), although a number of countries in Southern Africa extract uranium from ores with only 0.01% in uranium content.

High-grade uranium ores are very seldom found. For instance, the ore extracted at the McArthur River underground uranium mine in Saskatchewan, Canada, has a uranium content of 17.96%. As a rule, however, uranium concentration values in large deposits do not exceed 1%.

The economics of uranium mining is greatly influenced by the deposit's geological location and its size, access to the ore, labor costs, and many other factors. In its classification of reserves and resources of uranium, the International Atomic Energy Agency (IAEA) uses the economic efficiency

of their development, taking the existing mining methods into account. It factors in direct costs of mining, transportation, and production of uranium concentrate (U_3O_8), costs related to geological exploration undertaken to extend the life of a mine, those incurred to ensure environmental safety during the development of the deposit and after its completion, capital costs of building new production facilities (where necessary), and non-amortization and other expenses.

Three cost categories of uranium ores are distinguished depending on the cost of producing 1 kg of uranium: <$40/kg; <$80/kg; <$130/kg. Besides the above-mentioned factors, the economic efficiency of a development during any given period of time is influenced by pricing policies and the market. Currently, development of ores with uranium mining costs of no more than $80/kg is deemed commercially viable.

1.1.2. Uranium ore reserves

Global explored uranium reserves that can be recovered at a cost not exceeding $130/kg of uranium, as per 2009 data, total around 5.4 million tons. About 96.5% of these reserves are concentrated in 15 countries (see Table 1.1).

Table 1.1. *Proven recoverable uranium reserves (as of 2009).*

№	Country	Uranium reserves, in tons	Percentage of global reserves (%)
1	Australia	1,673,000	31%
2	Kazakhstan	651,000	12%
3	Canada	485,000	9%
4	Russia	480,000	9%
5	South Africa	295,000	5%
6	Namibia	284,000	5%
7	Brazil	279,000	5%
8	Niger	272,000	5%
9	United States	207,000	4%
10	China	171,000	3%
11	Jordan	112,000	2%
12	Uzbekistan	111,000	2%
13	Ukraine	105,000	2%
14	India	80,000	1.5%
15	Mongolia	49,000	1%
	Other countries	150,000	3%
Global reserves		**5,404,000**	

Experts estimate there is also up to 0.9 million tons in proven uranium deposits recoverable at a cost of between $130 and $260 per kg of uranium. The total undiscovered – prognosticated and speculative – uranium resources, as per IAEA data, come to 10.4 million tons. Of that, 6.5 million tons are reserves that may be recovered at a cost of no more than $130 per kg of uranium, and 0.37 million tons are reserves recoverable at a cost of between $130 and $260 per kg of uranium. There are no cost estimates for the remaining 3.6 million tons. Judging by the uranium consumption rate, the total resource of 5.4 million tons, with an extraction cost of no more than $130 per kg of uranium, should last for approximately 90 years.

In Russia, the major commercial uranium deposits are concentrated in the following four areas:

Zabaykalsky (Transbaikal) Krai:

– Priargunskoye (Priargunsky Industrial Mining and Chemical Union, PIMCU, Krasnokamensk): 113,100 tons

– Olovskoye (Olovskaya Mining and Chemical Company, OMCC, Chita): 13,500 tons

– Gorno-Berezovskoye (Gornoe Uranium Mining Company, GUMC, Chita): 4,600 tons

Kurgan Region:

– Dalmatovskoye and Khokhlovskoye (Dalur, village of Uksyanskoye): 18,000 tons

Republic of Buryatia:

– Khiagdinskoye, or Khiagda (Khiagda, village of Bagdarin): 47,000 tons

Sakha Republic (Yakutia):

– Lunnoe (Lunnoe, Aldan): 400 tons

– Elkonskoye (Elkon Mining Metallurgical Plant, Elkon MMP, Tommot): 319,200 tons

As per 2005 optimistic estimates, Russia's known uranium resources total 515,800 tons, and its prognosticated resources in optimistic estimates are 830,000 tons. However, a real assessment of the economic prospects of these resources requires their evaluation in terms of cost categories.

1.2. Uranium mining

Uranium deposit figures are not, however, sufficient to reflect the real picture with the mining and production of this metal. Global uranium mining volumes in 2011 totaled 53,654 tons.

1.2.1. Uranium mining countries

The eight top uranium mining countries that recover over 1,000 tons of uranium per year on their respective territories altogether account for around 92% in global uranium production volumes. Kazakhstan, Canada, and Australia mine around 64% of all uranium recovered in the world. In 2011, Kazakhstan's share in global uranium production was 36.2% (see Table 1.2).

In 2011, global uranium production decreased somewhat in comparison to 2010, to a level of 53,495 tons (49,219 tons were mined in the eight top uranium producing countries, and 4,276 tons in the remaining uranium mining nations). An increase in uranium production in Kazakhstan almost totally compensated for a significant drop in production volumes in Namibia, Canada, Australia, and several more uranium mining countries (see Table 1.2). The declining production volumes in Australia and Namibia have to do with the decreasing grades of uranium ores mined at Australia's Ranger and Namibia's Rössing deposits, as well as a number of accidents, caused by both technogenic and natural factors, that took place at Australian mines in 2010 and 2011. Furthermore, worker strikes at Rössing in Namibia in July and September 2011 resulted in a protracted downtime at the mining enterprise. In spite of this, Namibia is still planning to reform its uranium mining industry and double uranium production by developing its new uranium deposits at Namibplaas.

New uranium producers have appeared on the map – such as the Republic of Malawi, which in 2011 began to produce over 840 tons, becoming a world leader in boosting uranium production rates, with its production levels approaching those of China and Ukraine. In 2011, demand for U_3O_8 dropped below the values of the past six years (see Table 1.2). This was likely the result of an unstable situation in the nuclear energy industry following the Fukushima disaster. Still, despite this decrease, the volumes of uranium mined in 2011 only managed to satisfy the nuclear industry's demand to 85%. The remaining demand was covered by uranium stockpiles and MOX fuel.

Table 1.2. *Uranium production from ores mined in major uranium producing countries (in tons of uranium), between 2004 and 2011.*

Country	2004	2005	2006	2007	2008	2009	2010	2011
Kazakhstan	3,719	4,357	5,279	6,637	8,521	14,020	17,803	19,452
Canada	11,597	11,628	9,862	9,476	9,000	10,173	9,783	9,145
Australia	8,982	9,516	7,593	8,611	8,430	7,982	5,900	5,983
Niger	3,282	3,093	3,434	3,153	3,032	3,243	4,198	4,351
Namibia	3,038	3,147	3,067	2,879	4,366	4,626	4,496	3,258
Russia	3,200	3,431	3,262	3,413	3,521	3,564	3,562	2,993
Uzbekistan	2,016	2,300	2,260	2,320	2,338	2,429	2,400	2,500
United States	878	1,039	1,672	1,654	1,430	1,453	1,660	1,537
Ukraine	800	800	800	846	800	840	850	890
China	750	750	750	712	769	750	827	885
Malawi						104	670	846
South Africa	755	674	534	539	655	563	583	582
India	230	230	177	270	271	290	400	400
Brazil	300	110	190	299	330	345	148	265
Czech Republic	412	408	359	306	263	258	254	229
Romania	90	90	90	77	77	75	77	77
Germany	77	94	65	41	0	0	0	52
Pakistan	45	45	45	45	45	50	45	45
France	7	7	5	4	5	8	7	6
Total:	**40,178**	**41,719**	**39,444**	**41,282**	**43,853**	**50,773**	**53,663**	**53,495**
Tons of U_3O_8	**47,382**	**49,199**	**46,516**	**48,683**	**51,716**	**59,875**	**63,285**	**63,085**
Demand for U_3O_8		**75,690**	**74,681**	**76,067**	**76,052**	**76,762**	**81,134**	**74,217**
Share of global demand	**n/a**	**65%**	**63%**	**64%**	**68%**	**78%**	**78%**	**85%**

1.2.2. International uranium mining companies

The combined share of the world's major uranium mining companies (with over 1,000 tons in production volumes) was in 2011 almost 88% of global production, accounting for 47,200 tons. In 2010, China National Nuclear Corporation (CNNC) joined the top list of leading uranium mining companies, expanding it to 11 companies with over 1,000 tons in production volumes. Ukraine's uranium mining enterprise Eastern Mining-Processing Combine (Eastern MPC) is planning in 2012 to boost its U_3O_8 production to 1,000 tons a year by exploring its Novokonstantinovsky deposit.

According to Rosatom's data, Kazakhstan's National Atomic Company Kazatomprom (NAC Kazatomprom) kept its first-place ranking among the top uranium producing companies with its 11,079 tons of uranium produced in 2011, or 20.6% of the total production volumes. Cameco ranked second, and the ARMZ-Uranium One Inc. alliance ranked third. These figures differ somewhat from the statistics offered by the World Nuclear Association (WNA) (see Table 1.3), but on the whole, both the data from Rosatom and other sources that provide information on uranium production by major uranium mining companies are commensurate in their main characteristics.

Table 1.3. *Uranium production by global international leaders in 2011.*

No.	Company	Uranium produced (in tons)	Share in global production (in %)
1	Kazatomprom	8,884	17
2	Areva	8,790	16
3	Cameco	8,630	16
4	ARMZ/Uranium One Inc.	7,088	13
5	Rio Tinto	4,061	8
6	BHP Billiton	3,353	6
7	Navoi	2,500	5
8	Paladin Energy	2,282	4
	Other	7,906	15
	Total:	**53,494**	**100**

1.2.3. Uranium production by Russian companies

The primary Russian company engaged in uranium production is the uranium mining holding Atomredmetzoloto (ARMZ), created in 1991. Besides ARMZ, several other Russian companies as well as banks – for instance, Gazprombank, Severstal, and others – own shares in uranium mining companies.

ARMZ is a daughter company of Atomenergoprom. Atomenergoprom, an integrated company consolidating all of Rosatom's non-defense-related assets, currently holds 79.98% shares in ARMZ.

In 2007 and 2008, ARMZ became the owner of practically all Russian uranium mining assets, as well as joint enterprises that explore and develop uranium deposits in Kazakhstan. Atomredmetzoloto also acquired licenses for the right to mine stand-by uranium deposits.

In addition, ARMZ is actively purchasing foreign uranium assets, creating joint enterprises with Kazakhstan, Mongolia (Central Asia Uranium Company, CAUC), Namibia (SWA Uranium Mines), and other uranium mining countries.

In 2009, the holding acquired the Dutch company Effective Energy N.V., which holds shares in Kazakhstan's uranium deposits at Karatau (50%) and Akbastau (25%).

December 2010 saw the finalization of a deal to purchase a controlling stake (51.4%) in Canada's uranium mining company Uranium One Inc., which holds shares in five uranium mining enterprises in Kazakhstan (Zarechnoye, Akbastau, Karatau, Betpak Dala, and Kyzylkum) and is also developing uranium mining projects in the United States (in Wyoming, Arizona, and Utah) and Australia (the Honeymoon project).

In June 2011, Rosatom completed a deal purchasing 100% shares in Australia's Mantra Resources Ltd., a company with uranium mining operations in Tanzania. Table 1.4 lists companies and enterprises with uranium mining assets in which Atomredmetzoloto owned shares as of early 2012.

As of the beginning of 2012, the share held by Rosatom-owned companies (ARMZ/Uranium One Inc.) in the global natural uranium market was around 13%.

In Russia, ARMZ Uranium Holding ran uranium mining operations at the following three key deposits in 2011:

– Priargunskoye (PIMCU, Krasnokamensk, Transbaikal Krai),

– Dalmatovskoye (Dalur, village of Uksyanskoye, Kurgan Region),

– Khiagdinskoye (Khiagda, village of Bagdarin, Republic of Buryatia).

Table 1.4. *ARMZ Uranium Holding's structure and total shares in the authorized capitals of uranium mining enterprises and companies.*

Atomredmetzoloto		
In operation	**New projects**	**Shares controlled via Uranium One Inc. (51.42%)**
PIMCU: 79.63%	Armenian-Russian Mining Co. (Armenia): 50%	Betpak Dala (Kazakhstan): 70%
Dalur: 98.89%	SWA Uranium Mines Ltd. (Namibia): 12.5%	Zarechnoye (Kazakhstan): 49.67%
Khiagda: 100%	CAUC (Mongolia): 21%	Akbastau (Kazakhstan): 50%
Elkon MMP:100%		Karatau (Kazakhstan): 50%
OMCC: 100%		Kyzylkum (Kazakhstan): 30%
GUMC: 100%		Honeymoon Uranium Project (Australia): 51%
Lunnoe: 50.03%		Uranium One Inc. (United States): 100%
Mantra Resources Ltd. (Australia): 100%		

PIMCU carries out underground uranium mining at four operating mines: No. 1, No. 2, Glubokiy, and Mine 6R. The ore is processed at a hydrometallurgical plant and a heap leaching unit. The enterprise's end product is triuranium octoxide (U_3O_8). PIMCO's production output has seen a decline in the past several years, as a significant portion of high-grade uranium ores in the deposit has already been extracted. In order to increase productivity, plans have been made to continue construction of Mine No. 8 and complete designing works for the construction of Mine No. 6 in 2012. Rosatom's hope is to maintain output volumes at this enterprise at a level of no less than 2,000 tons a year in the future.

Dalur carries out uranium production by in-situ leaching (ISL) at the Dalmatovskoye deposit and currently continues pilot development at the Khokhlovskoye deposit. The enterprise's end product is natural uranium concentrate (yellowcake). In 2011, the company started employing an "intensified" ISL method using an oxidizing agent (sodium nitrate) at the Dalmatovskoye deposit. As for the Khokhlovskoye deposit, in 2012, Rosatom planned to obtain an exploration and production license and start drilling works there with the subsequent installation of process well equipment.

Khiagda employs ISL to mine uranium at the Khiagdinskoye ore field. The resulting product solutions are processed at a pilot plant into a finished product – natural uranium concentrate (yellowcake). Uranium production volumes at the deposit practically doubled in 2011 over 2010 figures, reaching 266.4 tons. Rosatom plans to further increase extraction and production of uranium at this deposit in the future.

In the past five years, ARMZ Uranium Holding has essentially had the same – in fact, rather decreased – production output from the mines it operates in Russia (see Table 1.5).

On the whole, in 2011, ARMZ produced 7,088 tons of uranium. The holding's plan to boost production includes obtaining in 2012 a license to explore and develop the Khokhlovskoye deposit. Additionally, plans are in motion to continue geological exploration at the Khiagdinskoye ore field and the Lunnoe deposit. ARMZ is also pursuing ambitious plans to conduct geological exploration at the deposits developed by Uranium One Inc. in Kazakhstan, Africa, the United States, and Australia.

Table 1.5. *Uranium production methods and volumes at Russian uranium deposits in 2008 to 2011.*

Enterprise	2008 (tons)	2009 (tons)	2010 (tons)	2011 (tons)
PIMCU (underground mining at four mines)	3,050	3,005	2,920.0	2,191.0
Dalur (ISL)	410	463	507.8	535.2
Khiagda (ISL)	61	97	135.1	266.4
Total uranium produced:	3,521	3,565	3,562.9	2,992.6

1.3. Uranium ore extraction and processing technologies

Uranium ore production technologies are practically the same in all uranium mining countries. The only differences that exist have to do with the geological conditions of the recovery sites, characteristics of the ores, etc.

The first stage of uranium production is extracting the ore from the deposit by either underground or open pit mining. The particular method is chosen based on the depth of the location of the ore bed. The ore is then transported to a processing plant for ore beneficiation (sorting) and extraction of uranium. The processing plant will include the milling facility and the leaching operations. A flow chart of uranium ore processing is presented in Appendix 1.1.

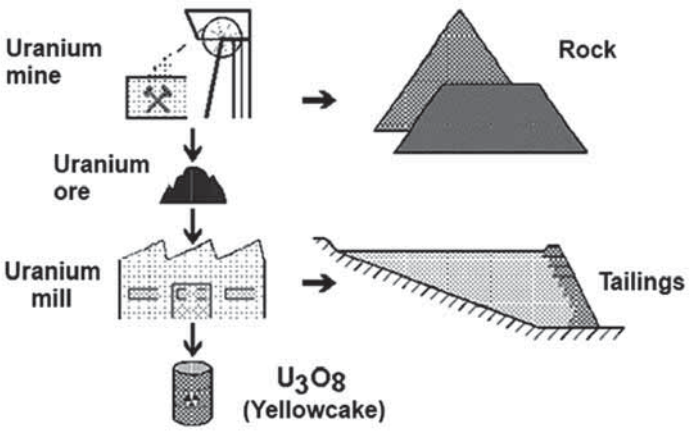


Fig. 1.1. Uranium production flow chart.

Besides the open pit or underground mining methods, with the subsequent uranium recovery at a uranium mill, the method of in-situ leaching (ISL) is at present widely used as well for production of uranium. In-situ leaching, also called in-situ recovery, or solution mining, implies selectively dissolving natural uranium compounds using a special chemical solution, which is pumped into the rock right where uranium is found within the ore, without extracting the ore from the deposit. The resulting solution is then pumped to the surface and delivered for hydrometallurgical processing. This method is considered an advanced technology.

In 2011, underground uranium mines accounted for approximately 30% of all the uranium produced in the world; 17% was produced using the open pit mining method; 46% was recovered with in-situ leaching; and the remaining 7% was extracted as a side product when developing other mineral resources.

1.3.1. Uranium milling

After being extracted from its bearing formation via either underground shafts or shallow open pits, uranium ore is delivered for processing at a mill, where it is crushed into smaller particles and sorted (dressed) by concentration. At the second stage, the ore is roasted to achieve dehydration, decomposition of organic matter, oxidation of sulfides, decomposition of carbonates, removal of arsenic and antimony, etc. Then the third stage follows – leaching the concentrate by solubilizing uranium in a potent acid solution (sulfuric acid) or alkaline solution (sodium carbonate). The uranium-containing leach solution is then separated from the undissolved particles, concentrated, and purified by sorption using ion exchange resins or by solvent extraction using organic solvents. The resulting concentrate, usually in the form of uranium oxide, U_3O_8, also called pure yellowcake uranium, is then precipitated from the solution, dried, and placed in steel containers.

1.3.2. In-situ leaching and in place leaching

Two varieties of the solution mining method are in use: in-situ leaching and in place leaching. With in-situ leaching (see Fig. 1.2), the ore deposit is accessed using a system of boreholes arranged in plan view in rows, polygonal patterns, or circles. The leaching agent (or lixiviant) – acid or alkaline solution – is pumped via injection wells into the ore body, and, percolating through the ore bed, dissolves the desired components. The resulting pregnant leach solution, saturated with uranium compounds, is pumped back to the surface via recovery wells.

In cases where uranium occurs in monolithic impermeable ore bodies, the deposit is stripped by underground mining excavations (stopes), and isolated ore blocks are broken up by drilling and blasting.

The upper level is then irrigated with the solvent, which, filtering through in a downward direction, dissolves the uranium-bearing ore. At the lower level, the uranium-containing solution is collected and pumped back up for processing.

1.3.3. Heap leaching

Heap leaching is used to extract uranium by stacking ore in a "heap" on an impermeable pad and irrigating it with leaching solutions in order to extract uranium. This process includes crushing and then agglomerating the ore, stacking, and irrigating the ore with a leaching solution. After it is crushed, the ore is first sorted by ore fraction, and stacking is done in homogeneous fractions by layers, with crush size gradually diminishing from the bottom layer up to the top layer (Fig. 1.3).

Heap leaching, just like other mining methods of uranium ore processing, does not require transportation of the extracted ore over large distances. Furthermore, employing the heap leaching method helps reduce the territory occupied by the tailings dumps.

The end product of the uranium ore processing stage of the uranium fuel cycle is triuranium octoxide – U_3O_8 (or yellowcake) – yellow or brown powder that contains some 90% of uranium oxide. Fabrication of this material completes the uranium ore mining and uranium recovery process.

In August 2012, the spot price of U_3O_8 held at a level of $49 per pound. Table 1.6 shows changes in U_3O_8 spot prices over the past ten years (with data for each year current as of the beginning of that year).

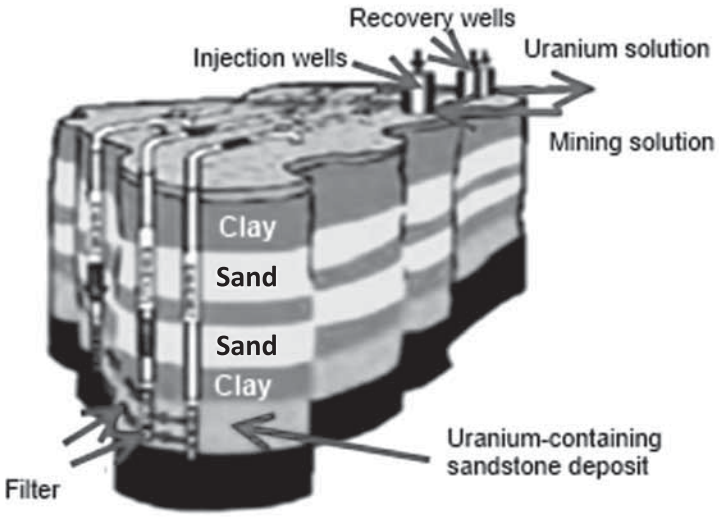


Fig. 1.2. In-situ leaching using injection and recovery wells.

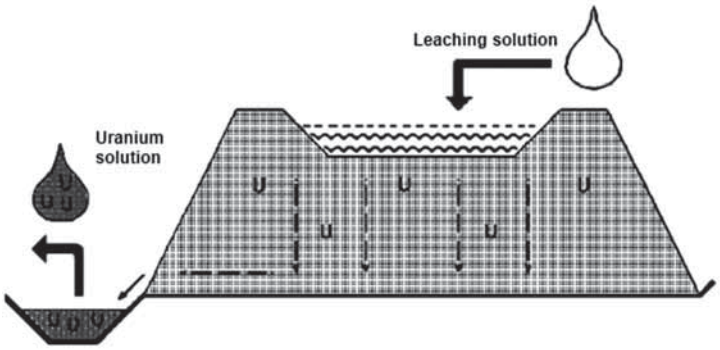


Fig. 1.3. Heap leaching of uranium ore.

Table 1.6. *Changes in U_3O_8 spot prices between 2003 and 2012.*

Year (January records)	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
U_3O_8 spot price (in U.S. dollars per pound)	10.2	15.5	21.0	37.5	75.0	78.0	48.0	42.5	62.0	52.0

1.4. Uranium conversion and enrichment

Before yellowcake is converted into uranium hexafluoride, it undergoes refining, a metallurgical process involving fabrication of high-purity uranium by segregating and removing impurities. Uranium refining begins with eliminating impurities that have large thermal neutron absorption cross-sections (boron, cadmium, hafnium, etc.). Purification and crystallization yield uranium compounds that are then delivered to a conversion facility for conversion.

1.4.1. Uranium conversion

Uranium conversion is an industrial process of chemical treatment during which natural uranium in the form of powdered triuranium octoxide (U_3O_8) is fluorinated to produce uranium tetrafluoride UF_4. Uranium tetrafluoride is either transported to a conversion facility for further fluorination to uranium hexafluoride (UF_6), or to a metallurgical plant, where it is reduced to metal.

Uranium hexafluoride (hex) has certain physical properties that are very important for the enrichment technology. It can be in solid, liquid, or gaseous state. In its solid phase, hex looks like ivory-colored crystals with a density of 5.09 g/cm^3. In liquid state, its density is 3.63 g/cm^3. Uranium hexafluoride can sublime and turn into gas, bypassing the liquid phase, within a rather wide pressure range. The reverse process – condensing uranium hexafluoride back from gas into solid crystals – requires some heat removal with the temperature and pressure kept at appropriate levels. Thus, gaseous uranium hexafluoride can be easily condensed by turning it into a solid phase. Applying heat in a vacuum achieves the goal of processing the solid product back into a gaseous phase.

In Russia, uranium conversion and uranium hexafluoride production facilities are located in Seversk (Siberian Chemical Combine), Angarsk (Angarsk Electrolysis Chemical Combine), Novouralsk (Urals Electrochemical Combine), and Zelenogorsk of Krasnoyarsk Region (Production Association Electrochemical Plant). These facilities' total combined output reaches around 20,000 to 30,000 tons of uranium hexafluoride per year. In September 2011, Rosatom head Sergei Kiriyenko announced that starting in 2012, all uranium conversion operations would be transferred to the Siberian Chemical Combine. Implementing this move will cost over RUR 7 billion in state corporation funds alone. The time frame has been set at no more than two or three years, with the transfer scheduled for completion before 2015. On December 20, 2011, the Siberian Chemical Combine's conversion plant launched the first line of the uranium oxide "dry" hydrofluorination facility.

Uranium hexafluoride makes for a very practical uranium compound to use for its further isotopic enrichment. As of June 2012, total global conversion capacity was around 76,100 tons of natural uranium a year for uranium hexafluoride (UF_6), and 4,500 tons of natural uranium a year for uranium dioxide (UO_2). Demand for UF_6 conversion was approximately 62,000 tons.

1.4.2. Isotopic enrichment

Isotopic enrichment is used to increase the percent composition of U-235, which is fissionable by neutrons of any energy, from its natural abundance level of 0.7% (natural uranium) to 2.4% or higher.

Depending on the degree of enrichment, there are three grades of enriched uranium.

1. Slightly enriched uranium (SEU) has a U-235 concentration within the range of 0.7% to 2%. Uranium extracted from spent nuclear fuel (SNF) also falls into this category. Global demand for this material is not significant since it is mainly used in heavy water reactors such as the CANDU series. One such reactor requires around 20 tons of slightly enriched uranium a year. Therefore, around 1,000 tons of uranium will be needed for 46 CANDU reactors a year – whereas total global capacity for fuel fabrication from slightly enriched uranium for pressurized heavy water reactors (PHWR), including the CANDU reactors, was, as of the end of 2011, around 4,000 tons of uranium per year.

2. Low-enriched uranium (LEU) has a U-235 concentration of less than 20%. This is the most common grade of enriched uranium since it is used in the nuclear energy industry for the fabrication of fuel for light water reactors, as well as research reactors of various purposes. Fuel for power-generating reactors of the VVER type has an enrichment degree of 3% to 8%. Research reactor fuel, as a rule, is enriched to between 12% and 19%. As of the end of 2011, global capacity for the fabrication of uranium fuel from LEU for light water reactors (LWR) totaled around 13,000 tons of uranium per year.

3. Highly enriched uranium (HEU) has a greater than 20% concentration of U-235. Uranium enriched to a level within the range of 20% to 85% has a status of uranium suitable for application in weapons, although in practical terms, using it for fabrication of an atomic bomb is a significant challenge. The bomb that was dropped on Hiroshima contained some 60 kg of uranium with an average enrichment level of 80%.

Highly enriched uranium that is currently **classified as *weapons-grade*** contains 85% of U-235, or more. HEU with an enrichment level of up to 85% is furthermore used to produce fuel for fast neutron or intermediate neutron reactors of various purposes – mostly, research and propulsion reactors.

1.4.2.1. Enrichment technologies

The following technologies have been developed for uranium enrichment: gas centrifugation, gaseous diffusion, laser separation, electromagnetic separation, liquid thermal diffusion, aerodynamic separation, and several other techniques.

Gaseous diffusion is currently only used in France and, to an extent, in the United States. A general trend in the enrichment capacity development is a transition from gaseous diffusion to centrifugation. This transition is expected to be completed by 2020.

The gas centrifuge technology employs a large number of spinning cylinders in series and parallel formations. Uranium hexafluoride (UF_6) gas is placed under high vacuum into a cylinder that rotates at a high speed. This rotation creates a great centrifugal force, which pushes the heavier gas molecules containing U-238 toward the outside of the cylinder, while the lighter gas molecules, which contain U-235, gather closer to the center. The flow of uranium hexafluoride with a slightly enriched U-235 content then passes into the next higher stage, while the slightly depleted stream is recycled back into the next lower stage.

The gaseous diffusion and gas centrifugation uranium enrichment methods that are currently in application were developed in the 1940s and are complex and expensive.

Recent years have seen efforts being actively directed toward perfecting laser enrichment techniques. As early as the beginning of the 1990s, an Australian company called Separation of Isotopes by Laser Excitation (SILEX) developed an enrichment technology involving laser excitation of UF_6 molecules. Under the process, U-235 is charged with greater energy than U-238 and can be separated from the latter in a much easier and more efficient way than what is afforded by the technologies in use today. Several such chambers are capable of replacing thousands of centrifuges. The SILEX technique thus promises to be much cheaper than either gaseous diffusion or gas centrifuging.

In late 2011, General Electric (GE) completed its work on the SILEX enrichment technology with a large-scale test running of the new enrichment equipment. The U.S. Nuclear Regulatory Commission (NRC) has issued a favorable decision on a licensing application by a GE-Hitachi partnership for a projected laser enrichment plant with a capacity of 3 million to 6 million separative work units (SWU). The SILEX technology is believed to be able to significantly reduce the price of fuel for commercial reactors. General Electric is planning soon to start construction of the new, SILEX-based uranium enrichment facility in Wilmington, North Carolina.

However, this technology is not without its problems – namely, that both the lasers, which are openly available for purchase, and the technology itself allow for much less sophisticated operation than centrifuges. Where it took Pakistan and India decades to develop their A-bombs – and even the USSR, with its history of extreme efficiency-boosting methods used in the push to expedite the development of the nuclear complex, spent several years on the effort – the new technology seems to be offering a much speedier process. A mere few years is all that may now be required for even a not-so-developed nation to cover the distance between commissioning a laser separation uranium enrichment facility and producing a gun-type uranium bomb (or even an implosive-type plutonium bomb). The meager land area that such a facility needs to occupy – several times less than centrifuge-based plants, according to estimates – will make it possible to enrich uranium at a site of quite compact proportions, thus hindering any detection efforts. Furthermore, experts point out, many countries have a cadre of laser experts who could work on the technology, but that expertise does not exist for centrifuges, which are a bit “esoteric.”

Waste resulting from the enrichment process commonly contains some 0.25% to 0.4% of U-235, since extracting all of the isotope content from uranium hexafluoride is not economically cost-efficient (it is cheaper to buy greater quantities of the source material). The depleted uranium that is generated in large volumes at uranium separation facilities finds little application in today’s industry, with only 5% of all the depleted uranium generated in the world being currently put to commercial use.

After enrichment, the UF_6 stream that now has a higher U-235 isotope concentration is hydrolyzed and precipitated, and the precipitate is calcined or else is converted by pyrohydrolysis and H_2 reduction to uranium dioxide (UO_2), or processed into uranium metal. The finished product is then used to manufacture fuel for production reactors, power reactors, or propulsion reactors, or to produce nuclear components for atomic weapons.

Production of 1 kg of low-enriched uranium (up to 4% in U-235 concentration) requires 7.5 kg of natural uranium and 6.5 SWU. This also means that 0.2% of U-235 will remain in so-called "tailings." Fabrication of 1 kg of weapons-grade uranium (with U-235 content enriched to up to 93%) requires 230 kg of natural uranium and 200 SWU. The "tailings" will then contain 0.3% of U-235.

1.4.2.2. Uranium enrichment facilities

The very first uranium enrichment plants were built in order to produce weapons-grade uranium for military purposes, and the first reactors, in order to produce plutonium for use in nuclear arms. Today, production of enriched uranium for civilian (commercial) purposes exceeds significantly the output of

Table 1.7. *Uranium enrichment facilities worldwide, as of 2012.*

Country	Facility	Type	Operational status	Method used*	Safeguard status	Capacity, thousand SWU per year
Argentina	Pilcaniyeu	Civilian	Resuming operations	GD	Yes	20-3,000
Brazil	Resende	Civilian	Being commissioned	GC	Yes	115-200
China	Shaanxi	Civilian	Operating	GC	(Yes)	1,000
	Lanzhou II	Civilian	Operating	GC	Offered	500
	Lanzhou (new)	Civilian	Operating	GC	No	500
France	Georges Besse I	Civilian	Shut down	GD	Yes	[was 10,800]
	Georges Besse II	Civilian	Operating	GC	Yes	7,500-11,000
Germany	Gronau	Civilian	Operating	GC	Yes	2,200-4,500
India	Ratehalli	Military	Operating	GC	No	15-30
Iran	Natanz	Civilian	Under construction	GC	Yes	120
	Qom	Civilian	Under construction	GC	Yes	5-10
Japan	Rokkasho	Civilian	Shut down	GC	Yes	[was 1,050]
Netherlands	Almelo	Civilian	Operating	GC	Yes	5,000-6,000
North Korea	Yongbyon	?	?	GC	No	(8)
Pakistan	Kahuta	Military	Operating	GC	No	15-45
	Gadwal	Military	Operating	GC	No	?
Russia	Angarsk, AECC	Civilian	Operating	GC	No	2,200-5,000
	Novouralsk (Sverdlovsk-44), UEC	Civilian	Operating	GC	No	13,300
	Zelenogorsk (Krasnoyarsk-45), PA EP	Civilian	Operating	GC	No	7,900
	Seversk (Tomsk-7), SCC	Civilian	Operating	GC	No	3,800
Great Britain	Capenhurst	Civilian	Operating	GC	Yes	5,000
United States	Paducah, KY	Civilian	Scheduled for shutdown	GD	Offered	11,300
	Piketon, OH	Civilian	Under construction	GC	Offered	3,800
	Eunice, NM	Civilian	Operating	GC	Offered	5,900
	Eagle Rock, ID	Civilian	Planned	GD	(Offered)	3,300-6,600
	Wilmington, NC	Civilian	Planned	LS	?	3,500-6,000

* GC: Gas centrifugation; GD: gaseous diffusion; LS: Laser separation.

Sources: International Panel on Fissile Materials (IPFM); the Nuclear Threat Initiative (NTI); IAEA – Nuclear Fuel Cycle Information System, NFCIS.

weapons-grade nuclear components. The main signatory nations of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) have ceased production of weapons-grade enriched uranium and plutonium for use in nuclear weapons. In expert assessments, India, Israel, Pakistan, and North Korea remain the only countries that continue to manufacture nuclear components for weapons.

The United States is planning by 2020 to create three new uranium enrichment facilities. Currently, almost all of the uranium used in commercial reactors in the Unites States is imported uranium – with about 40% of this material supplied out of Russia's blended-down weapons-grade uranium.

1.4.2.3. Russia's uranium enrichment and gas centrifugation complexes

Uranium conversion and enrichment in Russia is done at four enterprises run by the State Atomic Energy Corporation Rosatom's fuel production company, TVEL.

Novouralsk. Location: Sverdlovsk Region. The Novouralsk site is part of the Urals Electrochemical Combine and is Russia's largest enrichment facility (around 14 million SWU per year). Since 2003, eighth- and ninth-generation centrifuges have been in operation at the plant. The facility can enrich uranium to 80% U-235 (for research purposes as well as propulsion and fast neutron reactors); other facilities in the country only enrich uranium to between 7% and 20% U-235;

Zelenogorsk (Production Association Electrochemical Plant). Location: Krasnoyarsk Region. The facility's production output is around 8 million SWU per year. Some of Zelenogorsk's capacity, about 4.75 million SWU per year, is taken up with re-enrichment of uranium "tailings" to provide 1.5% enriched material for downblending Russian highly enriched uranium destined for the United States. This plant is also the site for downblending of ex-weapons uranium for sale to the United States.

A considerable portion of the capacities in use at both sites – on the order of 7 million SWU per year – is employed in the enrichment of depleted uranium (uranium "tailings");

Seversk. Location: Tomsk Region. The Seversk facility is part of the Siberian Chemical Combine. SCC's core production facilities are its four nuclear materials processing sites: the isotope separation facility, the uranium conversion plant, and the radiochemical and chemical and metallurgical plants. Seversk's main production output is enriched (5%) uranium hexafluoride, uranium hexafluoride prepared for enrichment, and related uranium enrichment, conversion, and refining services. The facility's capacity is approximately 4 million SWU per year;

Angarsk (Angarsk Electrolysis Chemical Combine). Location: Irkutsk Region. AECC's capacity is approximately 3 million SWU per year; out of the three Siberian plants, this is the smallest. The combine's core activities are production of low-enriched uranium hexafluoride, production of uranium hexafluoride, services offering conversion of U_3O_8 to uranium hexafluoride, conversion of uranium tetrafluoride to uranium hexafluoride, and uranium hexafluoride enrichment out of the source material provided by the customer.

In Angarsk, an International Uranium Enrichment Center (IUEC) has been opened at the AECC site. Two projects are being developed to boost the plant's output to 5 million SWU per year, and, by 2015, further to nearly 10 million SWU per year.

TVEL Fuel Company is the supplier that provides the above-mentioned facilities with uranium enrichment equipment, including gas centrifuges. The company's gas centrifuge manufacturing complex includes the following enterprises: Vladimir Production Association Tochmash, Kovrov Mechanical Plant, Urals Gas Centrifuge Plant, and Novouralsk Instrumentation Plant Uralpribor.

1.4.3. Global uranium enrichment market

Currently, the following countries have uranium isotopic enrichment technologies at their disposal: Argentina, Brazil, China, France, Germany, India, Iran, Japan, the Netherlands, Pakistan, Russia, Great Britain, and the United States. Israel and North Korea are suspected to have their own enrichment programs as well.

In 2011, the global uranium enrichment services market was between 47 million and 48 million SWU per year, whereas the total global enrichment capacity was approximately 60 million SWU per year.

Table 1.8. *World enrichment capacity, operational and planned (thousand SWU per year).*

Country	Companies and facilities	2010	2015	2020
France	Areva, Georges Besse I & II	8,500	7,000	7,500
Germany, the Netherlands, Great Britain	URENCO: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK	12,800	12,800	12,300
Japan	JNFL, Rokkasho	150	750	1,500
United States	USEC, Paducah & Piketon	11,300	3,800	3,800
United States	URENCO, New Mexico	200	5,800	5,900
United States	Areva, Eagle Rock	0	0	3,300
United States	Global Laser Enrichment	0	2,000	3,500
Russia	TENEX: Angarsk, Novouralsk, Zelenogorsk, Seversk	23,000	33,000	30,000-35,000
China	CNNC, Hanzhun & Lanzhou	1,300	3,000	6,000-8,000
Pakistan, Brazil, Iran	Various	100	300	300
	Total SWU (approximately)	**57,350**	**68,450**	**74,100-81,100**
	Requirements (WNA reference scenario)	48,890	56,000	66,535

Source: WNA Market Report 2009; WNA Fuel Cycle: Enrichment plenary session WNFC April 2011.

1.4.3.1. Global uranium enrichment services suppliers

The main providers of uranium enrichment services in the world are Russia's TVEL Fuel Company and Techsnabexport (TENEX), the British-Dutch-German concern URENCO, France's AREVA, and USEC in the United States. These companies together control some 95% of the market.

URENCO, with a market share of 20%, is the largest supplier of enrichment services in the Western world and the most efficient enrichment provider among TVEL Fuel Company's foreign competitors.

As of end 2011, the company's total installed capacity was around 14.6 million SWU per year. URENCO currently operates three enrichment plants in Europe: Almelo in the Netherlands, Capenhurst in the UK, and Gronau in Germany. A U.S.-based enterprise of URENCO's, an enrichment facility operated by Louisiana Energy Services (LES)/URENCO USA, went online in 2010. URENCO is steadily building up its uranium enrichment capacities, and by 2015 is planning to reach an output level of 18 million SWU per year.

AREVA has a 19% share in the world enrichment market. The company has an enrichment facility called Georges Besse I with an installed capacity of 10.8 million SWU per year and a now obsolete gaseous diffusion technology. AREVA now operates a new uranium enrichment facility, Georges Besse II, with a capacity of 7.5 million SWU per year, which enriches uranium via gas centrifugation. The new plant is slated to reach full capacity by end 2016.

USEC (United States Enrichment Corporation) accounts for 11% of the enrichment market. USEC currently operates a gaseous diffusion facility in Paducah, Kentucky. The Paducah facility is owned by the U.S. Department of Energy (DOE), which leases it to USEC for commercial enrichment operations. The plant's installed capacity is 8 million SWU per year.

USEC also acts as the executive agent of the United States government in the Megatons to Megawatts program. A core project of USEC's is construction of a gas

centrifugation plant in the U.S. – American Centrifuge Plant (ACP). This facility's projected capacity is 3.8 million SWU per year.

The dual – civilian and military – purpose for which enrichment technologies can be used is a factor that restricts entrance on the enrichment market for new major players.

1.4.4. The International Uranium Enrichment Center

The concept of an International Uranium Enrichment Center and a Fuel Bank was suggested by Russia in 2006. In 2007, the IAEA agreed to put together a working group and further develop the proposal. September 2007 saw the establishment of a new joint enterprise, Angarsk International Uranium Enrichment Center, which served as a foundation for the future IUEC and the Fuel Bank. Kazakhstan joined the IUEC the same year. Negotiations have been held on possible participation in the project with Ukraine, Armenia, South Korea, Finland, Belgium, and Mongolia. Russia has also invited India to join the project, to provide nuclear fuel supplies to India's Kudankulam Nuclear Power Plant. The IUEC's objective is to deliver low-enriched uranium for power reactors of new nuclear states and nations with small-scale nuclear programs, which will give them equity in the project but will not allow access to the enrichment technology. Russia, which owns 80% in the IUEC, remains the project's majority shareholder. The IUEC is expected both to sell uranium enrichment services (SWU) and enriched uranium products. Issues of the IAEA's involvement in the project were settled in 2009. The United States has also expressed its approval of the IUEC project in Angarsk. In 2010, Armenia and Ukraine joined Kazakhstan and Russia in the project and became IUEC members.

In December 2010, the IAEA Board of Governors authorized the establishment of an IAEA low-enriched uranium bank that will be owned and managed by the IAEA, and which will assure a supply of LEU for power generation. At the end of 2010, Rosatom completed stocking the planned 120-ton LEU reserve in Angarsk, which was placed under IAEA safeguards. As per its main objective, the IUEC stores, maintains, and sells low-enriched uranium out of the guaranteed reserve.

Plans and prospects. Experts noted no significant growth in uranium production volumes worldwide in 2011. A maximum possible increase probably did not exceed 5% over 2010 figures. Before the Fukushima disaster, the spot price of uranium was \$160 per 1 kg of U_3O_8. It dropped to \$132 following the disaster, but demand held at the same level. At the end of 2010, Rosatom announced it had secured \$20 billion worth of international contracts for export delivery of nuclear fuel and uranium enrichment services.

Fig. 1.4. International Uranium Enrichment Center's storage facility at Angarsk Electrolysis Chemical Combine.

CHAPTER 2. **URANIUM OXIDE NUCLEAR FUEL**

2.1. Terms and descriptions

Nuclear fuel will be used here to refer to two mutually related concepts:

– fissionable material (nuclides), which is capable of sustaining a chain reaction of nuclear fission and is used as a source of energy in a nuclear reactor;

– physical objects, such as fuel assemblies, that are composed of fissionable material as well as structural and neutron moderating materials and are loaded into a reactor to produce energy.

Depending on their chemical composition, the following types of nuclear fuel are distinguished: metal fuels (including alloys), uranium oxide, uranium carbide, and uranium nitride (mononitride) fuels, and other types. Uranium oxide fuel is currently the most common type used in power reactors. The nitride (mononitride) fuel can be based on either a uranium nitride (UN) or uranium-plutonium (UPuN) compounds. The latter, for instance, is planned to be used in the lead-cooled reactors of the BREST series.

As a rule, nuclear fuel is a combination of fissile material, which contains nuclei fissionable with thermal neutrons, and fertile material – nuclei that are capable, as a result of neutron bombardment, of producing other, non-naturally-occurring (artificial) fissile nuclides (such as Pu-239, U-233, etc.).

Nuclear fuel is fabricated (manufactured) using two types of material:

– natural uranium fuel, which contains fissile nuclei of U-235, as well as the fertile material U-238, which is capable of producing Pu-239 on neutron capture;

– secondary material, which does not occur in nature.

Secondary nuclear fuel includes Pu-239, produced from natural uranium fuel in a reactor on neutron capture by U-238, as well as isotopes of U-233, which are produced by neutron irradiation of Th-232.

According to its chemical composition, nuclear fuel can be metal (including alloyed fuels), oxide fuel – with uranium used in various chemical compounds that remain stable under reactor conditions (oxides, carbides, nitrides, etc.) – and mixed oxide fuel, or MOX ($PuO_2 + UO_2$).

Metal nuclear fuel is used as fuel in gas-cooled graphite-moderated reactors (the GCR type). Uranium oxide fuel is fuel composed of uranium dioxide with U-235 content enriched to 1.8% to 4% or more and sintered, under high pressure and temperature, into pellets. Uranium oxide fuel is used primarily in PWR, BWR, PHWR, LWGR (RBMK and EGP-6), and AGR reactors.

2.1.1. Certain physical, chemical, and technological properties of nuclear fuels

Uranium (and plutonium) in its pure form (as metal) is rarely used as a nuclear fuel owing to its low melting point, chemical reactivity, low resistance to corrosion, high specific energy release, and other reasons. At a temperature of 660 °C, uranium metal undergoes a phase change – a transition that changes uranium's crystal structure and is accompanied by an increase in volume. Under prolonged irradiation within a temperature range of 200-500 °C, radiation-induced expansion may occur: The irradiated uranium fuel rod expands in length. As it fissions, a nucleus produces two fission fragments whose combined volume is greater than that of the uranium (plutonium) atom. Some of the atoms – fission fragments – are fission-product gases

(krypton, xenon, and others) that accumulate in bubble-like pores in the uranium fuel, resulting in internal pressure. That, in turn, leads to fuel swelling, a process depending on the degree of burnup and temperature of the fuel rods. All this can cause damage to fuel cladding. Furthermore, using metallic uranium as nuclear fuel in power reactors is a limiting factor for burnup, which is one of the more important characteristics of reactors operating at nuclear power plants. This is why uranium metal is only used as fuel today in gas-cooled graphite-moderated reactors that serve as plutonium production reactors, since burnup needs to be minimal for the purpose of producing high-grade plutonium.

Two types of uranium are used to manufacture nuclear fuel: Uranium produced and enriched from uranium ore, and uranium separated from spent nuclear fuel as a result of SNF reprocessing – or recycled uranium. Natural and recycled uranium are different in their isotopic compositions to begin with, and different as well when the SNF cooling period is taken into account. When using recycled uranium – in contrast to natural uranium – one principal difference is especially important from the point of view of nuclear non-proliferation: Uranium separated from SNF contains around 0.5% of the isotope U-236, which, when used as part of fresh fuel, leads to increased generation of Pu-238, and this results in a lower quality of reactor-grade plutonium. On the one hand, this could be viewed as a downside, but in the context of the problem of non-proliferation, this is a positive factor. Besides, the presence of U-236 inhibits the multiplying properties of the nuclear fuel – in other words, lowers its quality.

Uranium recovered from SNF generated in PWR (VVER) reactors contains 1% of the isotope U-235, which is why it can be re-enriched and used in PWR (VVER) reactors, or diluted with depleted uranium and used in heavy-water reactors. With re-enrichment, 1 kg of reprocessed uranium yields only 0.2 kg of uranium enriched to 4.1% of U-235. Therefore, even if all fuel that is burnt in commercial nuclear reactors were to undergo reprocessing, the resulting recycled uranium would only yield 20% of fresh fuel, and the other 80% would have to be produced from natural uranium.

Nuclear fuel can also be manufactured from a blend of reprocessed uranium and uranium produced from natural uranium. In this case, the mix containing 4.1% of U-235, 0.31% of U-236, and 95.59% of U-238 can be used to produce nuclear fuel for all types of PWR (VVER) reactors. However, from the point of view of the risks of proliferation of plutonium from PWR (VVER) reactors, fuel based on recycled uranium is considered the safest, and the highest risk is associated with fuel manufactured from natural uranium.

Nuclear fuel must contain the lowest possible amount of nuclides with a high neutron absorption capacity and that are incapable of fissioning (so-called nuclear poisons). Nuclear fuel must also be compatible with the cladding of the nuclear fuel rods and have high melting and vaporization points, and high thermal conductivity. Other requirements are weak interaction with the coolant, minimal cracking or increase in volume due to irradiation (radiation-induced swelling), as well as good manufacturability properties with regard to both fresh fuel fabrication and SNF reprocessing.

Certain high-melting uranium compounds (oxides, carbides, and intermetallic compounds) make for good material for fabrication of nuclear fuel. The fuel that has come to be used most commonly in the industry is ceramic uranium dioxide (UO_2). It has a melting point of 2800 °C, and its density is 10.2 g/cm^3. Uranium dioxide fuel has no phase transitions and is less susceptible to fuel swelling than uranium alloys. This helps achieve a higher burnup by several percent. At high temperatures, uranium dioxide does not interact with zirconium, niobium, stainless steel, or other materials used in the fabrication of fuel rods. The main disadvantage of using ceramic uranium dioxide is its low thermal conductivity, at 4.5 kJ/(m·K), which limits reactor power density because of the possible excessive local heat and melting of the fuel rod. Besides, when heated, ceramic fuel is quite brittle and prone to cracking.

Good thermal conductivity and mechanical properties have been observed in dispersion fuels – fuels where small particles of UO_2, UC, PuO_2, and other uranium and plutonium compounds are heterogeneously embedded in a metal matrix made of aluminum, molybdenum, or stainless steel. The material of the matrix determines the fuel's resistance to radiation damage and its thermal conductivity.

The types of fuel deemed optimal for liquid metal cooled reactors are uranium nitride and mixed plutonium-uranium oxide fuels. The possibility of using a U-Pu-Zr alloy as metal fuel is also being researched, among other options.

Fuel contained in fuel rods is, as a rule, homogeneous. Dispersion, or matrix, fuels

are sometimes used, where fuel particles (more often, ceramic) are embedded into a matrix made of an inert (non-fissile) diluent material that has shown good nuclear and mechanical properties and an acceptable level of thermal conductivity.

2.2. Nuclear fuel handling

Fresh fuel arrives at a nuclear power plant in the form of nuclear fuel assemblies. These assemblies are transported in special containers developed to IAEA standards specifically for the delivery of fuel assemblies from the manufacturer to NPPs. Natural radioactivity of fresh fuel in fuel assemblies is quite low; practically no human exposure nor any significant area contamination occurs even in case of a transportation accident.

In Russia, the guidelines currently in use – the Rules of Safety During Storage and Transportation Of Nuclear Fuel At Sites Of Application Of Nuclear Energy (NP-061-05), which came into effect on May 1, 2006 – apply to nuclear power plants, including stand-alone storage facilities located on NPP premises, nuclear fuel storage facilities located outside NPP sites, research reactors, and onshore and floating storage facilities accommodating nuclear fuel used on ships and other watercraft.

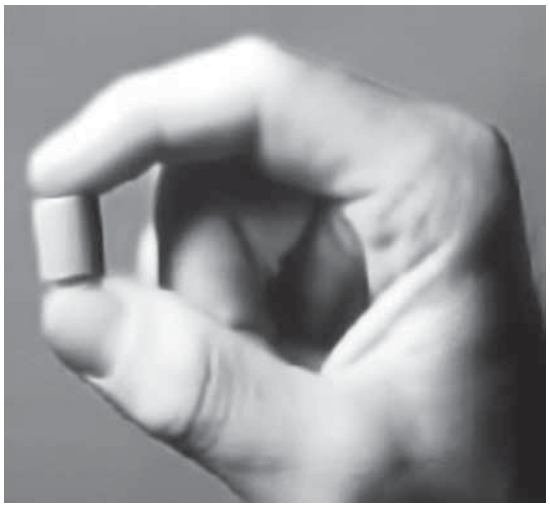


Fig. 2.1. A uranium fuel pellet.

Fig. 2.2. A VVER-1000 fuel assembly.

Each nuclear power plant uses a special system for transportation and storage of fresh nuclear fuel. The main operations that are performed with fresh fuel at a nuclear power plant are receipt, storage, preparation for loading, and loading of fresh fuel into the reactor. Upon delivery in railroad cars, containers with fresh fuel assemblies are unloaded into the NPP's fresh fuel area, where the assemblies are removed from their transport containers and placed in special packing sets for fresh fuel.

As per their current characteristics, fresh fuel areas at nuclear power plants are classified as Class 3 storage facilities. Fresh fuel areas are equipped with an emergency pump-out pump and a sump water level alarm, an alarm system to detect and alert in case of a spontaneous chain reaction, security and fire alarms, and ventilation and stand-by lighting systems.

Fresh fuel assemblies are delivered to the reactor building in packing sets transported on a special interbuilding platform.

2.2.1.Fabrication of nuclear oxide fuel

At nuclear fuel fabrication sites, the process of preparing uranium for the manufacturing of nuclear oxide fuel takes place in two stages: production of UF_6 and conversion of UF_6 or UO_3 into UO_2.

Nuclear oxide fuel fabrication is a process in which uranium dioxide (UO_2) is used to manufacture fuel pellets (Fig. 2.1), which are then used to make nuclear fuel rods (Fig. 2.2).

Following conversion, the UO_2 concentrate or powder needs to undergo several more treatments before it can be processed into fuel pellets. These include homogenization, during which the UO_2 is mixed to ensure uniformity; blending, where, to aid final pellet structure and density, some recycled U_3O_8 may be added to the mix; and granulation, during which the powder is "slugged" (pressed into a coin shape a few centimeters across) and then granulated (passed through a screen) to obtain the desired particle size and flowability characteristics.

Burnable poisons may be incorporated into the fuel at this stage to compensate for

the build-up of neutron absorbers among fission products. Burnable poisons are materials such as gadolinium and erbium that have a high neutron absorption cross-section and which are converted into materials of lower absorption cross-section by neutron irradiation. They enable much longer fuel life without compromising safety by allowing higher fuel enrichment without excessive initial reactivity and heat in the core.

Incorporation of beryllium oxide (BeO) into the fuel can improve its thermal conductivity and hence durability, since UO_2 has relatively poor conductivity.

In order to maximize the efficiency of the fission reaction, fuel cladding and all other structural parts of the assembly must be as transparent as possible to neutrons. Different forms of zirconium alloy, or zircaloy, are the main materials used for cladding. This zircaloy includes small amounts of tin, niobium, iron, chromium and nickel. Hafnium, which typically occurs naturally with zirconium deposits, needs to be removed because of its high neutron absorption cross-section.

Pellets manufactured out of enriched uranium are fabricated by cold pressing and sintering. They are then stacked in a column inside a thin-walled tube (fuel cladding) manufactured from such materials as a zirconium alloy or stainless steel. These fuel rods are then bundled into fuel assemblies (see Appendices 2.1, 2.2). Helium is used to fill the fuel cladding gap in order to increase the conduction of heat from the pellets to the cladding, and the fuel rods are sealed at each end. The fuel rods are kept in place inside a bundle by grids spaced at certain intervals along the assembly's length. This affords the entire structure a degree of flexibility by compensating for changes in size and allowing the coolant to circulate freely along the fuel rods.

2.3. Uranium oxide fuel fabrication worldwide

Fabrication of nuclear fuel accounts for no more than 8% of the final fuel cost, which determines nuclear power plants' low sensitivity to the fuel price.

On the nuclear fuel fabrication market, nuclear fuel is traded in fuel assemblies. The particular fuel assembly design is commonly approved by the national regulator and must meet specifications for use in the corresponding reactor model. Various fuel assembly designs differ in terms of efficiency of energy generation (i.e., the quantity of enriched uranium needed to produce the desired amount of energy).

In 2011, the nuclear fuel market totaled around 12,000 tons of heavy metal (tHM). Yearly demand for fuel fabrication services for LWR reactors is 7,000 tHM. In WNA estimates, by 2015, demand for nuclear fuel for light water reactors is expected to grow to 9,700 tHM. Demand for fuel fabrication for heavy water reactors such as CANDU reactors is today 3,000 tHM per year. Overall, demand for nuclear fuel fabrication services may grow, if nuclear generation shows a corresponding growth.

New fuel fabrication facilities are planned in China, South Korea, Ukraine, and Kazakhstan. In Kazakhstan, a new facility with a projected capacity of 400 tons of enriched uranium per year is being built jointly by Areva and Kazatomprom. The plant is slated to come online in 2014. In 2010, three deconversion facilities were taken online: two in the United States (Paducah, Kentucky, and Portsmouth, Ohio), and one in Russia (Zelenogorsk, Krasnoyarsk Region). In 2010, total global deconversion capacity was 60,000 tons per year.

Nuclear reactor vendors are the main customers of fuel fabrication services since these are the companies that supply nuclear power plant fuel for both the initial and subsequent loads.

In the European Union, a rule is in effect that stipulates that every nuclear power plant is to have at least two nuclear fuel suppliers. In line with this regulation, the U.S.-Japanese Toshiba-Westinghouse has developed the production of fuel for reactors of the VVER and RBMK types and is supplying limited shipments of fuel assemblies to Finland, the Czech Republic, and Ukraine. Previously, only Russian-produced fuel was used in all reactors of Russian design.

Table 2.1. *Nuclear fuel fabrication cost structure.*

Process	NEI Estimate	UxC Estimate
Uranium production	58%	47%
Uranium enrichment	31%	36%
Fabrication	7%	8%
Conversion	4%	4%
Spent fuel disposal	-	5%

Sources: Nuclear Energy Institute (NEI), 2007 (TradeTech, 2009), UxConsulting Company (UxC), 2009.

The global nuclear generation market has recently seen a consolidation of forces, with four fuel fabrication giants now representing the industry that supplies fuel assemblies for PWR and VVER reactors, the backbone of today's nuclear power generation capacity. These four major market players – Toshiba-Westinghouse, AREVA NP-MHI, TVEL Fuel Company, and Hitachi General Electric – together meet 85% of fuel demand.

The top two contenders for market domination are the U.S.-Japanese Toshiba-Westinghouse and the French-Japanese Mitsubishi Heavy Industries-Areva. For Russia's TVEL, these two represent the main competition on the global market. A lesser rival is Hitachi General Electric. Additionally, the following companies are present in the market, producers that manufacture nuclear fuel exclusively for their respective country's domestic needs:

– Industrias Nucleares do Brasil, INB (Brazil),
– CNNC (China),
– Nuclear Fuel Industries, NFI (Japan),
– KNFC (South Korea),
– Nuclear Fuel Complex, NFC (India).

Table 2.2. *LWR fuel fabrication capacity worldwide, in tHM per year (current as of September 2011).**

Country	Producer	Location	Conversion	Pelletizing/ granulation	Fuel assembly bundling
Belgium	AREVA NP FBFC	Dessel	0	700	700
Brazil	INB	Resende	160	160	280
China	CNNC	Yibin	400	400	450
France	AREVA NP FBFC	Romans	1,800	1,400	1,400
Germany	AREVA NP ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (BWR) NFI (PWR) Mitsubishi Nuclear Fuel GNF J	Kumatori Tokai Mura Tokai Mura Kurihama	0 0 475 0	360 250 440 750	284 250 440 750
Kazakhstan	ULBA	Ust-Kamenogorsk	2,000	2,000	0
South Korea	KNFC	Daejeon	600	600	600
Russia	Mashinostroitelny Zavod (MSZ) NCCP	Electrostal Novosibirsk	1,450 250	1,200 200	120 400
Spain	ENUSA	Juzbado	0	300	300
Sweden	Westinghouse AB	Västeras	600	600	600
Great Britain	Westinghouse	Springfields	950	600	860
United States	AREVA Inc. Global NF Westinghouse	Richland Wilmington Columbia	1,200 1,200 1,500	1,200 1,500 1,500	1,200 750 1,500
Total:			**13,433**	**14,858**	**11,582**

* 1) Data on fuel fabrication capacity in Kazakhstan may be inaccurate since Kazakhstan's fuel fabrication capacity has never been utilized in full. In UxC estimates, Kazakhstan's fuel fabrication industry produces 300 tHM per year, or only 15% of the stated 2,000 tHM per year; 2) Light water reactors account for 86% of the global nuclear reactor fleet (numbering a total of 376 reactors).

Table 2.3. *Heavy water reactor fuel fabrication capacity worldwide, in tHM per year (current as of September 2011).*

Country	Producer	Location	Fuel assembly bundling
Argentina	DIOXITEK SA & ENACE	Cordoba & Eizeiza	160
Canada	Cameco GE		1,500 1,200
China	CNNC	Baotou	200
India	DAE Nuclear Fuel Complex	Hyderabad	435
Pakistan	PAEC	Chasma	20
South Korea	KEPCO	Taejon	400
Romania	SNN	Pitesti	240
Total:			**4,155**

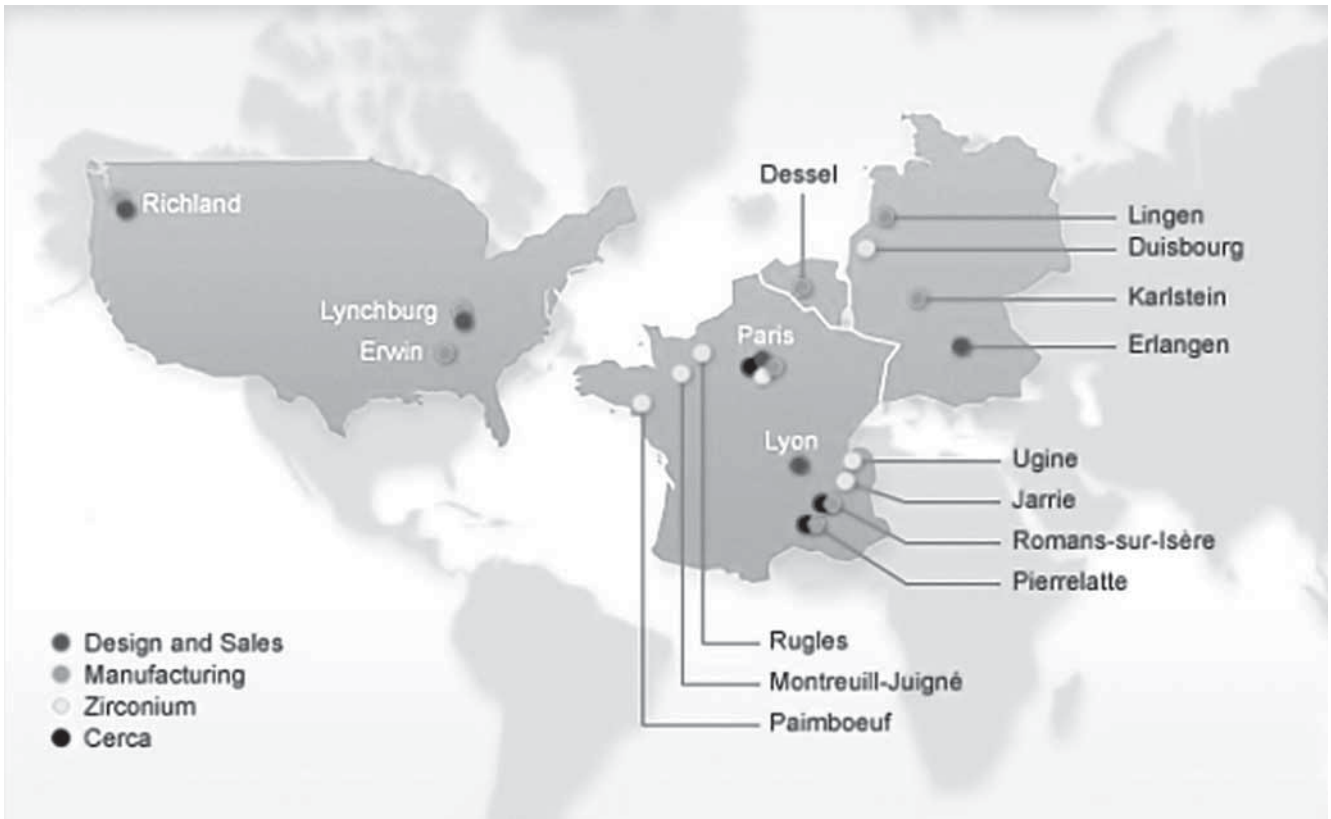


Fig. 2.3. Nuclear fuel manufacturing facilities in Europe and the United States.

Table 2.4. *AREVA Group's fuel fabrication enterprises.*

Enterprise	Operator	Capacity* Powder/Pellets/ Fuel assemblies (in metric tons of uranium per year)	Fuel type
Romans, France	AREVA NP-FBFC	1,800/1,400/400	PWR
Dessel, Belgium	AREVA NP-FBFC	0/700/700	PWR
Lingen, Germany	AREVA NP GmbH-ANF	800/650/650	PWR, BWR
Richland, U.S.	AREVA Inc.	1,200/700/700	PWR, BWR

* Nameplate capacity.

Table 2.5. *Westinghouse's fuel fabrication enterprises.*

Enterprise	Capacity* Powder/Pellets/Fuel assembly (in metric tons of uranium per year)	Fuel type
Columbia, SC, United States	1,500/1,500/1,500	PWR, VVER
Västeras, Sweden	600/600/400	PWR, BWR
Springfields, Great Britain**	440/440/0	Powder export
ENUSA, Juzbado, Spain	0/400/400	PWR, BWR

* Nameplate capacity.
** Total capacity: 700 metric tons of uranium per year (260 metric tons of uranium for AGR reactors and 440 metric tons of uranium for LWR reactors).

AREVA Group (formerly, Framatome Advanced Nuclear Power, FANP)

AREVA Group, majority-owned by the state, is a leading producer of fuel assemblies for PWR, BWR, and VVER reactors. AREVA has a 30% share in the global fuel fabrication market. Fuel assemblies for pressurized water reactors (PWR and VVER reactors) account for two thirds of this segment, with fuel produced for boiling water reactors (BWR) making up the remaining one third.

AREVA Group mostly supplies nuclear fuel to customers in Western Europe, but the company maintains a presence in the U.S. and Asia-Pacific markets as well.

AREVA Group owns five fuel fabrication enterprises: FCF and SPC in the United States, ANF in Germany, and FBFC in Belgium and France (see Table 2.4).

Westinghouse Electric Company (WEC)

WEC's majority shareholder is Toshiba. The company's share in the fuel fabrication market is 31%. The company has at its disposal the technologies needed to produce nuclear fuel for all types of light water reactors (PWR, BWR, and VVER). The United States and Western Europe are WEC's major sales regions, but the company is actively seeking ways to enter and gain a foothold in the VVER fuel segment – the markets in Slovakia (VVER-440) and Ukraine (VVER-1000) – and is the main competition for Russia's TVEL. WEC is headquartered in Monroeville, Pennsylvania, with key enterprises located in Columbia, South Carolina, and Västeras in Sweden.

WEC's fuel fabrication capacity is concentrated at its production site in Columbia and at enterprises operated by affiliated companies (see Table 2.5).

Global Nuclear Fuel (GNF)

A joint enterprise owned by GE, Hitachi, and Toshiba, GNF is composed of two enterprises: GNF-J, which supplies the Japanese market, and GNF-A, which supplies all other markets. GNF only produces fuel for BWR reactors. Its share in the nuclear fuel fabrication market is 17%.

2.3.1. Nuclear fuel fabrication in European countries

Uranium oxide fuel is produced in Europe in the following countries:

Germany: An AREVA Group daughter company, the Lingen plant produces UO_2 powder (uranium oxide), as well as pellets, fuel rods, and fuel assemblies. It has fabricated more than 20,000 fuel assemblies since operations began in 1977;

Belgium: The Dessel plant manufactures assemblies for PWRs, fuel pellets and rods, a full range of small assembly components, and assemblies of MOX fuel rods;

France: The Pierrelatte plant (Tricastin) manufactures grids for PWR assemblies; the Romans plant (Romans-sur-Isère) produces uranium oxide (UO_2), fuel pellets, nozzles, fuel rods, and assemblies for PWRs;

Great Britain: The Springfields facility produces triuranium octoxide (U_3O_8) powder, fuel pellets, and fuel assemblies;

Spain: The Juzbado plant produces fuel pellets and fuel assemblies.

2.3.2. Nuclear fuel fabrication in the United States

Five power reactor fuel fabrication sites operate in the United States, manufacturing fuel by granulating and pelletizing enriched

uranium for fuel rod production. These facilities, located in Virginia, Washington state, North Carolina, and South Carolina, are operated by Areva, Westinghouse, Babcock & Wilcox, and General Electric.

In December 2010, Areva and Mitsubishi announced the creation of a joint APWR fuel fabrication enterprise at a site in Richland, Washington state. The facility produces uranium dioxide (UO_2), fuel assemblies for PWRs and BWRs, and burnable poison rods (boron carbide). The site in Erwin, Tennessee, converts low-enriched uranyl nitrate into enriched uranium oxide and delivers it to the Richland plant to be transformed into pellets for fuel production.

2.3.3. Nuclear fuel fabrication in Russia

In Russia, nuclear reactor fuel is produced at enterprises run by TVEL Fuel Company, which was founded in 1996. TVEL's fuel fabrication facilities supply fuel to 76 power reactors in Russia and in 15 countries in Europe and Asia, as well as to 30 research reactors worldwide. TVEL is the sole supplier of fresh nuclear fuel for nuclear power plants in Bulgaria, Hungary, and Slovakia, and also supplies nuclear fuel to all European countries that operate nuclear power plants built to Russian (Soviet) designs.

TVEL's nuclear fuel fabrication complex comprises four enterprises: Mashinostroitelny Zavod (Elektrostal, Moscow Region); NCCP (Novosibirsk Chemical Concentrates Plant, Novosibirsk); Chepetsk (Chepetsky) Mechanical Plant (Glazov, Udmurtia); and Moskowsky Zavod Polimetallov (Moscow Polymetals Plant, Moscow). These enterprises manufacture nuclear fuel for light water reactors of Russian (VVER-1000, VVER-440) and Western (PWR, BWR) designs, uranium-graphite reactors (RBMK-1000, EGP-6), as well as research reactors, fast neutron reactors (BN-600), and marine nuclear propulsion systems.

Mashinostroitelny Zavod is Russia's leading fuel assembly supplier. The core of the enterprise's production program is fabrication of nuclear fuel supplied as fuel assemblies for use in practically all commercial reactor types (VVER-440, VVER-1000, RBMK-1000, RBMK-1500, BN-600, EGP-6, PWR) and research and marine nuclear reactors, and also as fuel components (uranium dioxide powder and fuel pellets). The plant operates the entire fuel fabrication cycle from converting uranium hexafluoride into uranium dioxide powder to manufacturing fuel assemblies.

MSZ manufactures nuclear fuel on a per order basis as requested by the parent companies that supply fuel assemblies to nuclear power plants in Russia and abroad. As part of its cooperation with AREVA NP (AREVA Group), the plant produces nuclear fuel for PWR and BWR reactors operating in Western Europe.

MSZ has lately been upgrading its production technologies in an effort to use them as a springboard for expansion into international competitive markets. In 2010, the plant perfected a new powder compaction technology based on equipment developed by Hosokawa, which was used to produce 140 tons of fuel pellets. MSZ has also introduced into operation uranium dioxide powder production based on the ADU process (a ceramic uranium dioxide (UO_2) fabrication technology involving UO_6 conversion to UO_2 using ammonium diuranate).

Novosibirsk Chemical Concentrates Plant mostly produces nuclear fuel for VVER-440 and VVER-1000 reactors. Additionally, NCCP manufactures nuclear fuel for a number of research reactors, and produces lithium and lithium compounds as well. In 2010, NCCP assembled and commissioned a new production line to manufacture ceramic-grade uranium dioxide powder with the help of high-temperature pyrohydrolysis. A new stainless steel precision casting shop has also been created, and technologies brought to commercial scale for the production of castings meeting quality standards with regard to the product's chemical composition and mechanical properties.

Chepetsk Mechanical Plant is Russia's only producer of zirconium, zirconium alloys, and nuclear-quality zirconium alloy products, as well as products manufactured from natural and depleted uranium. Natural uranium is processed at the plant to produce uranium metal ingots, uranium metal powder, uranium dioxide, and uranium tetrafluoride.

Moscow Polymetals Plant serves as the head organization leading the research into, and manufacture of, control and protection systems for nuclear power reactors, nuclear marine reactors operating on board of nuclear-powered fleet, as well as research and production reactors. The enterprise supplies products used in control and protection systems of 42 reactors operated at nuclear power plants in Russia and abroad, including power plants in Ukraine, Bulgaria, and China.

Table 2.6. *Effective output at TVEL Fuel Company's nuclear fuel fabrication enterprises in 2007 to 2011, by specific fuel type.*

Product	2007	2008	2009	2010	2011
VVER-1000 fuel assemblies	1,373	1,289	1,398	1,498	1,289
VVER-440 fuel assemblies	1,790	1,834	1,577	1,808	1,769
RBMK-1000, RBMK-1500 fuel assemblies		3,530	3,360	3,630	3,210
BN-600 fuel assemblies	282	236	223	249	405
EGP-6 fuel assemblies			144	144	144
Research reactor fuel assemblies	71	96	465	445	630
PWR fuel assemblies	n/a	n/a	n/a	326	116
Total fuel assemblies:	**3,516**	**6,985**	**7,167**	**8,100**	**7,563**
Total ceramic pellets, in tons uranium:	**-**	**1,042.1**	**1,289.0**	**1,463.5**	**1,583.0**

In 2010, TVEL's fuel assembly output increased by 8% (not taking PWR assemblies into account), and the output of ceramic fuel pellets grew by 13%.

2.3.4. Russian nuclear fuel producers' international integration

The nuclear fuel manufactured by TVEL's enterprises is supplied to the following companies: Rosenergoatom Concern (Russia), NNEGC Energoatom (Ukraine), Armenian Nuclear Power Plant (Armenia), Natsionalna Elektricheska Kompania (National Electric Company, Bulgaria), MVM Hungarian Electricity (Hungary), Slovenské elektrárne (Slovakia), Fortum Power and Heat Oy (Finland), ČEZ (Czech Republic), China Nuclear Energy Industry Corporation and Jiangsu Nuclear Power Corporation (China), Department of Atomic Energy, Government of India (India), and the Atomic Energy Organization of Iran (Iran).

In addition to complete fuel assemblies, TVEL also exports nuclear fuel components – such as fuel pellets that the company supplies to India. Furthermore, TVEL is working on developing mixed uranium and plutonium oxide (MOX) fuel.

The company's goal in the immediate term is to make an entrance on the global market with an offer of fuel assemblies for commercial power reactors of Western designs. As of 2010, TVEL's annual export had exceeded $1 billion.

Russia–Ukraine–Kazakhstan. In 2008, TVEL and Ukraine's NNEGC Energoatom signed a licensing agreement, with TVEL transferring to Ukraine its technologies for fabrication of stainless steel components for fuel assemblies. In October 2010, TVEL and the Ukrainian Nuclear Fuel State Concern signed a deal envisioning the creation in Ukraine of a fuel fabrication site for the production of VVER-1000 reactor fuel. During the first stage of the project, Russian nuclear fuel manufacturing technologies will be gradually transferred to the joint enterprise, starting from uranium reconversion and up to fuel assembly production. The construction of the fabrication plant is the second stage of this cooperation. The full fuel assembly fabrication cycle is slated to be ready for commercial-scale operation by 2020. By 2013, the plant is expected to have successfully started production of nuclear fuel assemblies, with other technologies – for fuel tubing manufacture, uranium reconversion, and sintering of fuel pellets – to follow. 2010 also saw the inking of a nuclear fuel delivery contract – a deal by which Russia will supply fuel assemblies to Ukrainian NPPs for the duration of the Ukrainian reactors' useful life terms, including operating extensions. As per the contract terms, all reactor units operating at Ukrainian nuclear power plants will be supplied with nuclear fuel manufactured exclusively to Russian technologies starting from 2016.

Russia–Czech Republic–Slovakia. In April 2010, TVEL and Slovakia's Slovenské elektrárne signed a contract for the delivery of nuclear fuel and associated services to Reactor Units 3 and 4 currently under construction at Mochovce Nuclear Power Plant. The deal provides for the delivery, starting in 2012, of fuel assemblies for the initial loading of both reactors, with further delivery of fuel for five subsequent reloads for each unit. In the Czech Republic, a full fuel reload was completed in August 2010 at Temelin Nuclear Power Plant's Reactor Unit 1, during which U.S.-produced fuel, then in use in the reactor, was replaced with

Russian-made fuel ahead of a scheduled reload. Temelin's Reactor Unit 2 was switched over to Russian fuel in 2011. Additionally, TVEL is showing an interest in new nuclear fuel fabrication facilities in Slovakia and the Czech Republic.

Cooperation with AREVA NP. TVEL and AREVA NP's German division are engaged in joint production of fuel assemblies of Western design. As of 2010, over 2,600 fuel assemblies had been made, with fuel deliveries shipped to nuclear power plants in Germany, the Netherlands, Switzerland, and Great Britain.

2.3.5. Nuclear fuel fabrication in China

China intends to become self-sufficient in most aspects of the fuel cycle, but currently, China's nuclear energy industry still relies to a considerable degree on imported uranium as well as conversion, enrichment, and fabrication services from other countries.

China National Nuclear Corporation (CNNC) is responsible for fuel fabrication, utilising some technology transferred from Areva, Westinghouse, and TVEL.

CNNC's main PWR fuel fabrication plant at Yibin, Sichuan province, was set up in 1982 (based on a 1965 military plant). It is operated by CNNC subsidiary China Jianzhong Nuclear Fuel (JNF), with its subsidiary China Nuclear Fuel South. By the beginning of 2013, its fuel assembly production was to grow to a total of 800 tons of uranium per year, with plans to further increase production to 1,500 tons of uranium per year by 2015. It has certified Kazakhstan's Ulba Metallurgical Plant as a source of pellets.

VVER fuel fabrication at Yibin began in 2009, using technology transferred from TVEL under the fuel supply contract for Tianwan. (First core and three reloads for Tianwan's Units 1 and 2 were from Novosibirsk Chemical Concentrates Plant in Russia – 638 fuel assemblies, under the main contract.) By August 2010, Yibin had produced 54 VVER-1000 fuel assemblies which were being loaded into the Tianwan units. In November 2010, TVEL contracted with Jiangsu Nuclear Power Corporation (JNPC) and the China Nuclear Energy Industry Corporation (CNEIC) to supply six fuel reloads for Tianwan's Unit 1, and the technology for fuel to be produced at Yibin thereafter.

CNNC set up a second civil fuel fabrication plant run by China North Nuclear Fuel Co Ltd at Baotou, Inner Mongolia, in 1998, based on a military plant there dating from 1956. This plant fabricates fuel assemblies for Qinshan's CANDU PHWRs (200 tons of uranium per year) and some PWRs – 200 tons of uranium per year from 2010, expanding to 400 tons of uranium per year. In 2012, it became the North Branch of China Nuclear Fuel Co Ltd.

In 2008 SNPTC agreed with both fuel companies (China Jianzhong Nuclear Fuel and China North Nuclear Fuel Co Ltd) to set up CNNC Baotou Nuclear Fuel Co Ltd to make fuel assemblies for China's AP1000 reactors (first cores and some re-loads of the initial units will be supplied by Westinghouse). In January 2011, a contract was signed with Westinghouse "to design, manufacture, and install fuel fabrication equipment that will enable China to manufacture fuel" for AP1000 units. A plant is being set up at Baotou, initially at 200 tons of uranium per year from 2013, but likely to grow to 2,000 tons of uranium per year.

China is aiming to be able to cover its nuclear fuel needs with domestic production, but for the time being, fuel for the nuclear power plant under construction in Taishan, for instance – two first cores and 17 reloads – will be supplied by France's Areva.

Areva has announced the prospect of a joint venture with CNNC to produce zirconium alloy tubes for nuclear fuel assemblies. The joint venture, CNNC Areva Shanghai Tubing Co. (CAST), was expected to start production at a plant in Shanghai at the end of 2012.

Two industrial parks focused on nuclear power were announced in 2010. The first, near Nanjing in Jiangsu province, is a nuclear technology base, part of the China Nuclear Binjiang Production Base, which includes a research facility for nuclear-grade concrete and will feature a factory for pre-assembled structural and equipment modules for CPR-1000 and Westinghouse AP1000 reactors (the modules will weigh up to 1,000 tons each). Currently AP1000 modules are made at a Shandong enterprise that has the capacity to support construction of two reactors per year.

Following the disaster at Fukushima Daiichi, the Chinese authorities halted issuing construction licenses for new CPR-1000 projects, though projects that had already been started were allowed to continue.

CPR-1000 is a pressurized water reactor design, the Chinese version of the French M310. With the CPR-1000 plans abandoned, China intends to build AP1000 units.

Two EPR units are also being built in China, and development is under way of the 1,000 MW ACPR-1000, which may with time

become a joint project with France's EDF. Another project being developed in China is the CPR-1700, which is supposed to become China's adaptation of the EPR-1600, with an increased power capacity.

The second industrial base is launched by CNNC in Zhejiang province, about 120 km from Shanghai. The new site is expected to have these main areas of work: development of the nuclear power equipment manufacturing industry; nuclear training and education; and applied nuclear science industries (medical, agricultural, radiation detection and tracing, etc.).

As well as these major industry centers, there is a factory for AP1000 modules set up at Haiyang and another in Hubei province to support inland AP1000 projects and later the CAP1400 derivatives.

A further centre, the Taishan Clean Energy (Nuclear Power) Equipment Industrial Park, opened in February 2010 in Guangdong province, is expected to become a centre for nuclear power equipment manufacturing, initially supplying hardware and services to nearby nuclear power projects. Targets call for manufacturers at the park to have 45% of the nuclear equipment market in Guangdong by 2020.

2.3.6. Nuclear fuel fabrication in Japan

Currently the only producer of nuclear fuel for both boiling water reactors and pressurized water reactors in Japan, NFI (Nuclear Fuel Industries, Ltd.) was founded in 1972 by integration of the nuclear power businesses of Furukawa Electric Co., Ltd. and Sumitomo Electric Industries, Ltd. NFI develops, designs, and produces various types of nuclear fuel, including for high-temperature gas reactors and fast breeder reactors. In May 2009, Westinghouse Electric Co. acquired a majority stake in Nuclear Fuel Industries. NFI supplies nuclear fuel to such customers as Japan's major energy companies TEPCO (Tokyo Electric Power Company) and KEPCO (Kansai Electric Power Company).

By 2013, a new facility for the production of uranium dioxide powder is slated for completion in Ibaraki prefecture, an addition that is expected to more than double the already existing fabrication capacity – currently, at 450 tons a year. The plant, part of a joint venture established by Areva, Mitsubishi Corporation (MC), Mitsubishi Materials Corporation (MMC), and Mitsubishi Heavy Industries Ltd. (MHI), in which the French company holds 30 percent, will process enriched uranium into uranium dioxide.

2.3.7. Nuclear fuel fabrication in Kazakhstan

In Kazakhstan, nuclear fuel is produced at Ulba Metallurgical Plant (UMP, Ust-Kamenogorsk, Kazakhstan).

The plant was built in 1949 and for some time at first specialized in uranium metallurgy. Then UMP produced HEU-beryllium alloys for use as fuel in marine nuclear reactors. The plant's main mission, however, was supplying beryllium metal products to the Soviet nuclear and aerospace industries. In 1976, Ulba Metallurgical became the leading producer of uranium dioxide powder and fuel pellets for VVER and RBMK power reactors.

At present, UMP supplies the following products on the global market:

– triuranium octoxide;
– ceramic-grade uranium dioxide powder;
– fuel pellets for VVER, RBMK, and PWR reactors, including pellets with incorporated burnable poisons – erbium oxide and gadolinium oxide;
– fuel pellets for assemblies of the AFA 3G type for PWR reactors of AREVA NP design;
– services for processing hard-to-recover uranium-containing materials.

UMP's production includes the following facilities:

– beryllium production: fabrication of beryllium metal, alloys, ceramics, and processed beryllium products;
– tantalum and superconductor facility: fabrication of tantalum products as well as electronics and high-quality superconducting devices;
– nuclear fuel fabrication plant.

Two fuel production lines are in operation at the nuclear fuel fabrication facility, manufacturing fuel for RMBK and VVER reactors. The plant receives enriched uranium hexafluoride from Angarsk Electrolysis Chemical Combine. The material is converted to uranium dioxide powder, which is then granulated using an organic binding agent, compacted to pellets, and sintered. The fuel pellets are shipped for subsequent fuel rod and fuel assembly manufacture at the fuel fabrication facilities in Elektrostal (VVER-400 and RBMK-1000 reactor fuel) and Novosibirsk

(VVER-1000 fuel). The plant has an output capacity of 2,650 tons of fuel per year.

Ulba's technology enables production of uranium dioxide powder and fuel pellets for commercial reactors using not just uranium hexafluoride enriched to 4.95% U-235 but also uranium oxides, uranyl salts, uranium tetrafluoride, uranium ore concentrates, uranium metal, and various uranium-containing scrap materials such as ash and insoluble residues, including those containing burnable absorbers (erbium and gadolinium), which are difficult to reprocess with traditional methods.

In 2010, Ulba Metallurgical Plant and Japan's NFI signed an agreement to produce nuclear fuel components for the Japanese market.

2.3.8. Planned and existing nuclear fuel fabrication projects in other nuclear power countries

It should be noted that, based on the history of nuclear energy development worldwide, a distinction is called for between nuclear power generation at power plants and the creation of a nuclear fuel cycle serving to supply these power plants with fuel, since nuclear power development does not always imply developing a national nuclear fuel cycle. For instance, a number of countries that are actively developing civilian nuclear power programs, such as Switzerland, Finland, Sweden, Belgium, South Korea, Mexico, South Africa, and Taiwan, are not planning on creating a domestic nuclear fuel cycle industry or have concluded that doing so would be impractical and opted not to pursue this path.

Ukraine has been developing plans to emerge as a new producer of nuclear fuel. In December 2006, the Ukrainian government made a decision to create a concern called Ukratomprom by merging the state-owned NNEGC Energoatom and a number of nuclear fuel cycle enterprises into one vertically integrated company. It was to include Vostochny GOK (Eastern Mining and Processing Complex), Pridneprovsky Metallurgical Plant, Polimin, Smoly, Tsirkony, and departments of the National Science Center "Kharkov Institute of Physics and Technology." The new concern was expected to develop nuclear fuel fabrication capacity to serve Ukraine's open nuclear fuel cycle needs. The government's decision, however, was abolished in 2007, though a new company, Nuclear Fuel State Concern, was created in April 2008 with apparently the same goal.

Iran is a country with an ambition to create its own nuclear fuel cycle. Iran has the capability to enrich uranium on an industrial scale. Thousands of centrifuges have been installed and are in operation. Recently, Iran has started uranium enrichment at some 3,000 new centrifuges in Natanz. In early 2011, reports said a new fuel plate fabrication facility had been completed at the nuclear industrial complex in Isfahan, to produce fuel apparently for the needs of the Teheran Research Reactor. Furthermore, the Isfahan Nuclear Technology Center has the capacity to manufacture zirconium sponge (50 tons per year), tubing (10 tons per year), and strip and bar (2 tons per year). According to some data, this facility became operational as long back as 2004, though current output numbers remain unknown.

The particular nature and depth of Iran's nuclear program is becoming progressively harder to measure. In November 2011, the IAEA said it had information that Iran was engaged in activities that had the goal of developing nuclear weapons (see Appendix 2.3).

CHAPTER 3. **MOX FUEL**

MOX (mixed oxide) fuel is nuclear fuel composed of a mix of uranium and plutonium dioxides.

The main reason that the nuclear energy industry today is pursuing the path of using MOX fuel is the goal of disposing of the stockpiles of excess plutonium by burning it in reactors. MOX fuel fabrication involves using depleted or natural uranium, in the form of uranium dioxide, and reactor-grade or weapons-grade plutonium.

MOX fuel proponents thus forward these two arguments: Firstly, we get rid of the excess plutonium; and secondly, we burn uranium that is unusable in thermal reactors, while producing energy as well.

3.1. A brief review of MOX fuel fabrication technologies

Several MOX fuel fabrication technologies are in use today. Fig. 3.1 shows a general flow sheet of a typical MOX fuel fabrication process. There are significant differences in the MOX fabrication technologies depending on whether weapons-grade or reactor-grade plutonium is being used. The practice of converting weapons-grade plutonium to reactor-grade fuel involves the use of two non-aqueous methods: Pyrochemical, or producing PuO_2 by hydrogenation of plutonium metal and subsequent oxidation in one reactor; and pyroelectrochemical, where plutonium metal is dissolved in a chloride (NaCl+KCl) melt, with subsequent precipitation of crystal PuO_2 in one electrolyser.

Three methods are employed to manufacture MOX fuel pellets for fuel rods used in power reactors:

1) mechanical mixing of uranium and plutonium dioxide feed powders;

2) chemical co-precipitation of UO_2 and PuO_2 powders using surfactants;

3) direct production of MOX powders from a uranium nitrate and plutonium nitrate solution.

When using the mechanical mixing method, an important part of the process is fine grinding (micronization) of the UO_2 and PuO_2 powders, a step essential to achieve densification of powder particles to a desired degree and quality. The blending takes place in a high-energy mill, where a homogeneous solid $(U\text{-}PuO)_2$ structure is produced in a short time. This technology produces a lot of dust, which constitutes a significant disadvantage. Furthermore, MOX fuel fabrication results in the generation of plutonium-contaminated waste materials and scrap fuel residues.

The second method involves co-precipitating uranium and plutonium salts from a solution, a technique that produces granules which generate little dust (the AUPuC process). This method is similar to that used to produce uranyl tricarbonate, but the uranium and plutonium are precipitated simultaneously as $(NH_4)_4(U\text{-}Pu)O_2(CO_3)_3$, in aqueous solution. The precipitate is a homogeneous solid solution which, after calcination at 600 °C, produces a free-flowing powder of $U\text{-}PuO_2$, a product which is soluble in boiling HNO_3. This process requires the transportation of plutonium in aqueous solution if the MOX plant is not situated near the SNF reprocessing plant. The advantage of this method lies in the absence of dust throughout the production process. But its drawbacks include the danger of occurrence of a spontaneous chain reaction, a risk inherent to any aqueous plutonium processing method, as well as increased amounts of radioactive waste, and the potential risk of theft, since the uranium and plutonium used in the process are in separated and purified form.

The third UO_2-PuO_2 fabrication technology is co-conversion of a uranium-plutonium nitrate solution, a technique based on

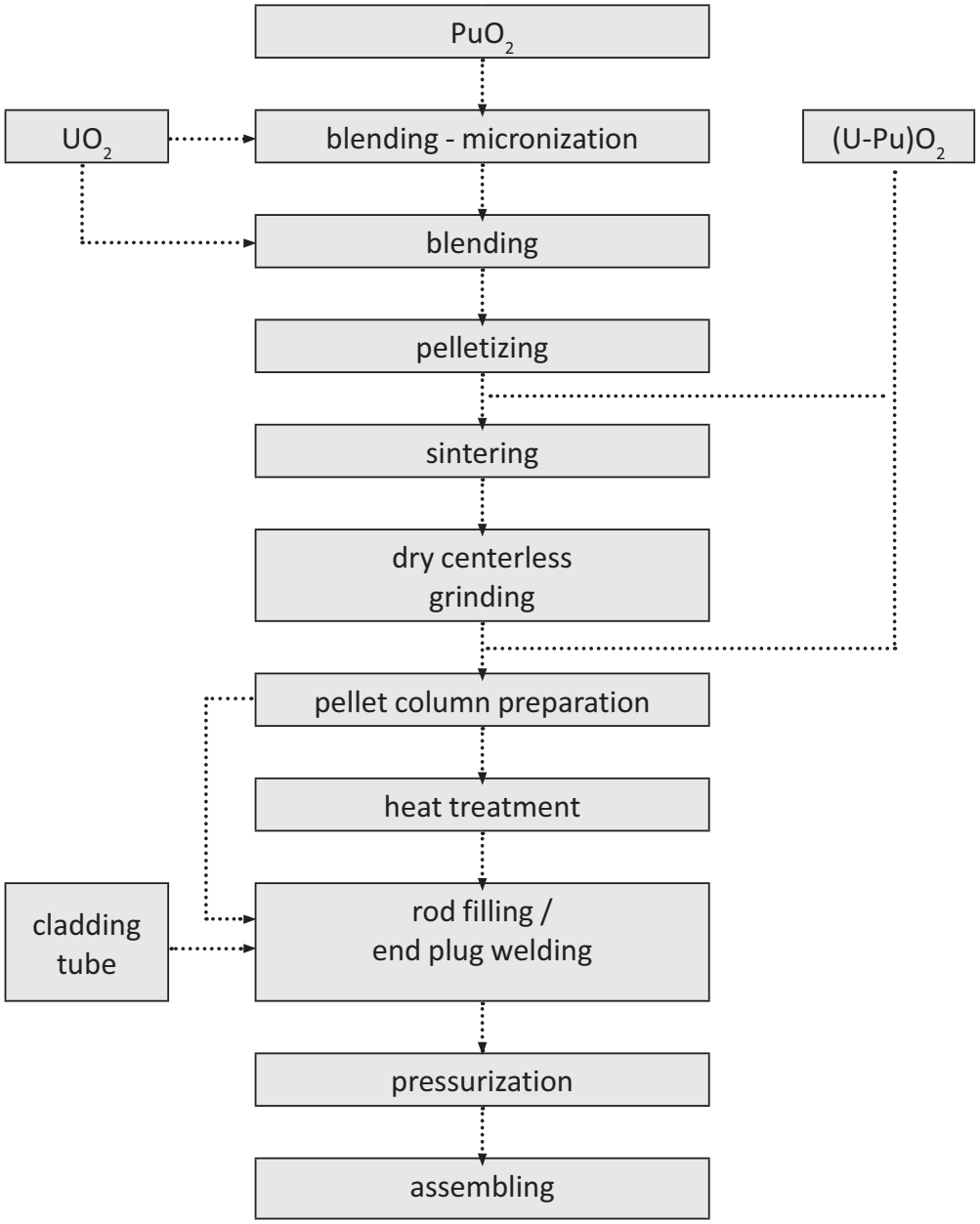


Fig. 3.1. A typical MOX fuel fabrication process.

dehydration and denitration of product solutions by microwave heating. The flow sheet of this process represents a mid-way between the full dry-powder process (BN-COGEMA) and the aqueous precipitation process (AUPuC) (see Fig. 3.2). This technology requires a very efficient off-gas treatment unit but lends itself very well to automation and operation in shielded glove boxes.

A number of other technologies have also been tested at various times for the production of MOX fuel. Studies conducted in Russia, for instance, focused on using the sol-gel process to obtain granulated MOX fuel which was then pressed into pellets. However, this manufacturing process made it impossible to achieve a high and stable pellet quality, so a decision was made to revert to the technique of ammonia co-precipitation of uranium and plutonium. Twelve fuel assemblies were made for the BN-600 design using this technology, and most of these have completed reactor tests.

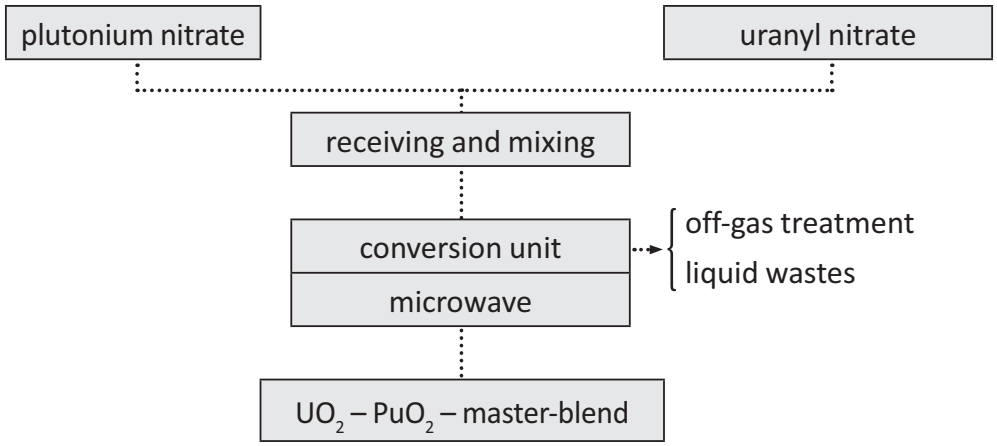


Fig. 3.2. Direct production of MOX powders from a uranium and plutonium nitrate solution.

Table 3.1. *Existing and planned MOX fuel fabrication capacity worldwide (in tHM).*

Country	2010	2015
France, Melox	175	195
Japan, Tokai	10	10
Japan, Rokkasho	0	130
Russia, Mayak, Ozyorsk	5	5
Russia, Mining and Chemical Combine, Zheleznogorsk	0	60
Great Britain, Sellafield	40	0
India	20	20
Total:	**250**	**420**

3.2. Global MOX fuel fabrication and processing (burning) capacity and MOX fuel prospects after the Fukushima disaster

MOX fuel has been used in thermal neutron reactors for over 30 years. Currently, MOX fuel is used in 33 thermal reactors worldwide. Over 2% of nuclear fuel used in reactors today is MOX fuel.

Several MOX fuel fabrication facilities are in operation in the world. Current global MOX fuel fabrication capacity and prospects to 2015 are shown in Table 3.1.

Today's global mixed uranium and plutonium oxide fuel fabrication capacity totals around 250 tHM. The main MOX fuel fabrication facilities are located in France, Great Britain, and India, and several plants with lesser capacities are in operation in Russia and Japan. In October 2010, Japan Nuclear Fuel Ltd (JNFL) started construction of a new 130 tHM MOX fuel production plant in Rokkasho, Aomori Prefecture. The project is slated for completion in March 2016. A similar facility is planned in Russia, in the town of Seversk in Tomsk Region. Russia also plans to build a commercial MOX fuel fabrication plant with a capacity of 60 tons per year as well as a 14-ton-a-year facility to produce mixed (dense) nitride fuel for fast neutron reactors. A new MOX fuel fabrication plant is being constructed at the MOX fuel production site in Sellafield, Great Britain. The United States is planning to create additional MOX fuel fabrication capacity in order to utilize excess weapons-grade plutonium. In 2010, Japan started to use MOX fuel at Ikata (Reactor Unit 3) and Fukushima Daiichi (Reactor Unit 3) Nuclear Power Plants.

The consequences of the nuclear disaster at Fukushima Daiichi may affect global MOX fuel programs. A limited number of mixed uranium and plutonium oxide fuel assemblies had been loaded into the core of the nuclear power plant's Reactor Unit 3. Even though this had little effect on the progression of the accident, the use of MOX fuel in the reactor sparked new debate over MOX fuel prospects both in Japan and the rest of the world.

3.2.1. MOX fuel in Europe

MOX fuel was first used in Europe at the Belgian BR3 reactor in Mol, Belgium, in 1963. Starting in 1974, MOX fuel was also used in the now shut down Chooz A reactor in France. Belgonucléaire and COGEMA began producing MOX fuel jointly at two small plants in Dessel, Belgium (which started operation in 1973), and Cadarache, France (which started operation in 1970), with capacities at 35 tons and 15 tons of MOX fuel per year respectively for the two plants.

France and Belgium

Today, 16 out of 28 French reactors are licensed to use MOX fuel. As per the guidelines enforced by the French nuclear safety regulator, in France, MOX fuel assemblies may not constitute more than 30% of the fuel assemblies loaded into the reactor core. The content of plutonium in the fuel may not exceed 5.3%.

In Belgium, in December 1993, a permission was granted to load two reactors with only up to 20% MOX core, but with a 7.7% plutonium content.

The second wave of MOX development for light water reactors resulted in 1995 in the creation of a new fabrication facility in Marcoule, France, with a capacity of 115 tons of fuel a year.

In France and in Belgium, much as in the rest of the world, MOX fuel producers face a number of technological challenges involved in the fuel's fabrication and storage, which results in higher costs affecting the MOX fuel industry. These are such factors as:

- the presence of strong alpha emitters and of americium-241, which is a highly radioactive gamma emitter;
- limited storage period of 2 to 3 years for plutonium extracted for the production of MOX before its use;
- a greater enrichment of fuel necessary in order to increase the time fuel rods can remain in a reactor: With 4.2% enrichment for uranium fuel and 8% for MOX, and France's limit of maximum allowed plutonium content in MOX not exceeding 5.3%, MOX fuel produces 30,000 megawatt-days per 1 metric ton of heavy metal, while uranium fuel produces 47,000 megawatt-days per 1 metric ton of heavy metal;
- tests of reprocessing spent MOX fuel have produced a form of plutonium with a large amount of impurities and which, as a result, was less fissile than plutonium recovered from reprocessed uranium fuel. Further purification of this plutonium implied increased reprocessing costs. Reprocessing spent MOX fuel – in contrast to reprocessing uranium fuel – yields higher concentrations of transuranic elements, and, by extension, higher levels of radioactivity. This was one of the reasons why in August 1996, France's energy giant EDF (Électricité de France) announced that it wanted to store spent MOX fuel rather than reprocess it.

Thus, so far there is no policy regarding what to do with spent MOX fuel in the future.

A conclusion that can be drawn from the above is that the suggested path of MOX fuel application, regarded by some as a way to reduce plutonium stocks, may entail many more problems than the plutonium itself. If one added MOX fuel's mediocre economic performance to the nuclear – and in particular, the plutonium – industry's already manifest environmental impact, then France might re-classify and regard plutonium as

waste. In that case, there might be some hope that future generations will have less plutonium to manage than what is envisioned in COGEMA's reprocessing projects.

One of the first consequences of the Fukushima disaster was the indefinite postponement of new deliveries of French MOX fuel to Japan.

France's Areva is contracted by Japanese energy companies to reprocess Japanese SNF and manufacture MOX fuel. Four Japanese reactors were partially switched to MOX fuel prior to the disaster at Fukushima Nuclear Power Plant, with the accident leaving just three. On August 3, 2011, World Nuclear News reported that Areva had announced the cancellation of orders for uranium and nuclear fuel amounting to €191 million as a result of the shutdown of reactors in Japan and Germany.

Great Britain

Similarly, it now remains under question whether the high-level radioactive waste generated as a result of SNF reprocessing at Great Britain's nuclear complex in Sellafield will be returned to Japan. According to statements from Great Britain, a shipment of high-level radioactive waste that was planned for 2011 was canceled. The Fukushima accident affected Great Britain's MOX-related plans, with the Nuclear Decommissioning Authority announcing it would stop MOX fuel fabrication at Sellafield "at the earliest practical opportunity."

In an August 2011 press release, the NDA said it had "assessed the changed commercial risk profile for" Sellafield MOX Plant (SMP) and "concluded that in order to ensure that the UK taxpayer does not carry a future financial burden from SMP that the only reasonable course of action is to close SMP at the earliest practical opportunity."

SMP's only customers were ten Japanese utilities.

The troubled Sellafield MOX Plant was built in the 1990s and designed to handle foreign, mainly Japanese, plutonium dioxide that had been recycled from spent fuel by a facility in the same location, at Sellafield.

A Sellafield spokesman said that Japan's plans to close one nuclear power plant in particular, at Hamaoka, were instrumental in sealing the Sellafield MOX plant's fate.

A second MOX plant at Sellafield is now under consideration by the UK government, a project that the government regards as a way of solving the problem of storage (utilization) of Britain's civil plutonium stockpile – the biggest in the world. If a second MOX plant goes ahead, it is possible the Japanese plutonium could be converted into nuclear fuel and burned in new British reactors designed to take this type of fuel. In its August 2011 press release, the NDA said it "will continue to store Japanese plutonium safely and securely […] and further develop discussions with the Japanese customers on a responsible approach […]."

3.2.2. MOX fuel in Japan

Since the Fukushima disaster, the Japanese MOX fuel program has been experiencing significant difficulties as it came under pressure from local authorities.

In May 2001, in a referendum held in Niigata Prefecture, residents voted against the use of MOX fuel at Kashiwazaki-Kariwa Nuclear Power Plant – one of the world's largest reactors designed to burn this type of fuel. The residents' protests were first and foremost caused by lacking guarantees with regard to MOX fuel's safety. Such concerns are not without merit: Between 1986 and 2011, more than ten rather serious accidents took place at Japanese nuclear power plants, injuring over 500 people. But despite the protests against the use of MOX fuel, the government was intent on expanding the country's MOX program. If all of Japan's fuel reprocessing projects are brought to completion, the country's plutonium stockpile will in ten years already become the world's largest, reaching 80 to 90 tons – with 30 tons accounted for by export from Europe, six tons resulting from SNF reprocessing at the Tokai plant, and another 50 tons coming from the reprocessing facility at Rokkasho.

Situated on the coast some 200 kilometers off Tokyo, Hamaoka Nuclear Power Plant sits astride the junction of two major geological faults, prompting this description by seismologist Katsuhiko Ishibashi at Kobe University in Japan: "a kamikaze terrorist waiting to explode." In May 2011, wary of the risk of a magnitude 8.0 quake in the next 30 years, the Japanese government ordered it to close for an indeterminate period while a massive sea wall is built around the plant.

Currently under construction in Japan is a 1,383 MW advanced boiling water reactor (ABWR), a project implemented by EPDC and intended to be the first in Japan designed specifically for the use of MOX fuel containing recycled plutonium.

MOX fuel is used at two reactor units – KEPCO's Mihama-3 and Takahama-4. The operation of these two units suffers regular disruptions. On August 9, 2004, the third unit

at Mihama was closed following an accident that killed five people, and only resumed operation two and a half years later. This incident served to prompt a freeze on a project that envisioned using MOX fuel at Takahama-4, even though the permission to switch the reactor to MOX fuel was issued by authorities in Fukui Prefecture, where the reactor is operated, as early as March 2004. KEPCO now has to prove that Mihama-3 is safe to operate in order to continue to use MOX fuel in its reactors.

Before Fukushima, many Japanese utilities were planning to use MOX fuel in their reactors. For instance, in 2006, Shikoku Electric Power Co. and Kyushu Electric Power Co. were granted permission from local authorities to use MOX fuel at one of their reactors starting in 2011, with MOX fuel constituting 25% of the reactor core.

Japan has started decommissioning the first MOX-fuel reactor, at Fugen Nuclear Power Plant. The unit was shut down in March 2003. The decommissioning and dismantlement process is scheduled for completion by 2028, at a total decommissioning cost of JPY 70 billion (around EUR 700 million).

3.2.3. MOX fuel in the United States

In the United States, where an ambivalent attitude toward plutonium had shaped well before the Fukushima accident, the only major potential client indicating an interest in MOX fuel was TVA, a company with established ties with the federal government.

The joint enterprise Shaw-Areva MOX Services is building a MOX fuel fabrication facility in South Carolina. The plant is slated to start commercial operation in 2018. Before the Fukushima disaster, a willingness to discuss the prospect of using MOX fuel was expressed by TVA and Energy Northwest. TVA could become the largest – or one of the major – customer of MOX fuel assemblies for as many as two of its nuclear power plants. So far, no changes have been formally announced by the company with regard to its position. But the comments made by its representatives sound non-committal. TVA still expects its final decision – whether or not to agree to a partial switch over to MOX fuel – to be made in 2012, though it does not specify any precise time frame. The company first wants to study what happened with the MOX fuel used at Fukushima. “We're still investigating the potential use,” said TVA spokesman Ray Golden. “We are very interested in the ongoing events in Japan and there likely will be lessons learned.”

TVA is said to have started an independent safety study on the use of MOX fuel. One of the documents subject to review is an environmental impact study.

In order to expand the pool of potential clients, the U.S. Department of Energy wants to redesign its mixed oxide fuel plant to make nuclear fuel for a wider variety of reactors. Changes are now proposed that will enable the facility, planned to make fuel for PWR reactors only, to also make fuel for BWR reactors and the next generation of light water reactors, such as AP1000.

3.2.4. Russia’s MOX fuel concept and experience

Russia’s research into using plutonium as nuclear fuel dates back to the second half of the 1950s.

Two reactor cores containing weapons-grade plutonium have been tested in Russia in the BR-10 experimental fast reactor. Batches of MOX fuel pins made using a variety of technologies with plutonium of various isotopic compositions have been tested in the BOR-60 research reactor. This reactor has been in operation for many years recycling its own plutonium.

The prototype reactors BN-350 and BN-600, which were primarily fueled with enriched uranium fuel since the reactors were launched, were used for expanded tests of MOX fuel previously tested in the BR-10 and BOR-60 research reactors. In the BN-350 reactor, the tests were performed with the subsequent investigation and chemical reprocessing of test fuel subassemblies with MOX fuel (350 kg of weapons-grade plutonium). More than 2,000 such fuel elements were built and tested in the BN-350 and BN-600.

To experimentally substantiate the technology of plutonium utilization in fast reactors, the semi-industrial plant dubbed Paket was built at PA Mayak, capable of producing up to 10 plutonium fuel subassemblies a year. Work is under way at Mayak to backfit the Granat and Paket plants in order to meet Rostekhnadzor’s latest industrial and environmental safety requirements.

Russia is currently engaged in designing and building a small – 3- or 4-unit – series of BN-800 power fast reactors at South Urals and Beloyarsk Nuclear Power Plants.

The main purpose of the BN-800 design was to utilize civil plutonium accumulating at Mayak, the product of chemical processing of uranium reactor spent fuel. The BN-800 reactor design is described with a breeding ratio of 1, that is, it was expected that these reactors will use plutonium from thermal reactors as fuel for their first loading only, changing to their own plutonium in the future.

Further estimates showed, however, that not only the civilian plutonium accumulated at the RT-1 reprocessing facility but also all ex-weapons plutonium released during the dismantlement of nuclear weapons could be handled with the help of the BN-800. It would only be necessary to postpone chemical reprocessing of the BN-800 reactor spent fuel until a considerable portion of already released civilian and weapons-grade plutonium has been disarmed – i.e., converted into spent MOX fuel. Reprocessing spent MOX fuel will thus become a deferred problem.

Construction has started of a MOX fuel plant to produce up to 900 subassemblies per year as fuel for BN-800 reactors. The project is expected to be completed in 2014, simultaneously with the launch of the BN-800 unit at Beloyarsk NPP. The MOX fuel plant will comprise several facilities. The Mining and Chemical Combine in Zheleznogorsk (Krasnoyarsk Region) will handle the preparation of feed materials – granulated uranium and plutonium, while the actual fabrication of fuel elements will take place in Ulyanovsk Region, at the State Scientific Center "Research Institute of Atomic Reactors" (NIIAR). Annual weapons-grade plutonium consumption for the fabrication of fuel subassemblies for one BN-800 reactor is about 1.6 tons. In other words, if the BN-800 reactor commissioning program is fulfilled, then all civil and all released weapons-grade plutonium accumulated at Mayak could be transformed into spent fuel within 20 or 30 years. In order to reduce the content of plutonium in the spent fuel and cut spent MOX fuel storage costs, an improved BN-800 design without breeding blankets and with a total breeding ratio of about 0.8 is also under consideration.

The possibility of using MOX fuel in VVER reactors has not yet been proven and is currently only being researched and experimented with as part of analytical validation studies. The goal of this work is to understand the advantages and disadvantages of this direction in plutonium utilization, while taking Western European experience into account. Construction of a critical assembly called SUPR (for *mixed uranium-plutonium lattices*) has started at the State Scientific Center "Alexander Leipunsky Institute for Physics and Power Engineering" in Obninsk for an experimental study of safety characteristics of light water reactors using fuel containing plutonium, including weapons-grade plutonium. Reactor safety significant properties of MOX fuel, as compared to those of uranium fuel, are listed in Appendix 3.1.

In order to make a decision with regard to potential MOX fuel application in VVER reactors, the compatibility requirements for the reactor design and MOX fuel assemblies will have to be determined and at least a dozen more important safety and economic characteristics researched.

First and foremost, these are neutronic characteristics, since the neutronic behavior of the core differs greatly depending on whether MOX fuel or uranium fuel is loaded into the reactor. The neutron spectrum resulting from MOX fuel is harder than that from UO_2 fuel. This reduces the worth of the soluble boron and control rod absorbers, which results in an increase in the soluble boron concentration, increased use of burnable absorbers, and a modification to the control rods to use enriched boron. Furthermore, the delayed neutron fraction and prompt neutron lifetime are smaller in MOX cores, while the moderator temperature coefficient of reactivity and the Doppler coefficient of reactivity in MOX cores are more negative than in UO_2 cores – differences that have to be taken into account when analyzing any impacts on reactor safety.

Differences are also found in the thermophysical properties of MOX fuel and those of UO_2 fuel. Thermal conductivity is lower in MOX fuel, which results in a higher MOX fuel temperature (about 50-100 K centerline) and energy stored as compared to UO_2 fuel at the same power levels. MOX fuel has a lower melting temperature than UO_2 fuel. Additionally, its decay heat is larger than UO_2 decay heat in the long term, which may be detrimental in severe accidents and in the cooling pond when compared to UO_2 fuel.

Researchers at the Leipunsky Institute believe continued studies are needed into the criticality and dose rates of fresh and irradiated MOX fuel. Fresh MOX fuel has significantly larger neutron and gamma sources than fresh UO_2 fuel, as well as a significantly higher alpha activity than UO_2 fuel. The cladding is sufficient to contain this activity and protect the personnel where

intact and undamaged fuel is concerned. However, different storage standards will be required for damaged fuel.

Irradiated MOX fuel has a larger neutron emission rate. During spent MOX fuel transportation, the dose rate at the cask surface, because of the larger neutron source, is three times larger compared to spent UO_2 fuel.

Apart from the concerns listed above – problems that warrant further study and respective conclusions – there are other reasons that demonstrate that using MOX fuel in Russian light water reactors today is too dangerous and lacks sufficient rationale.

Firstly, none of the thermal reactors in Russia was designed with the possibility of using MOX fuel in mind. Both the safety record and safety specifications of most VVER reactors currently in operation – even considering that these reactors burn uranium fuel – do not meet the prospective standards required of newer-generation reactors with enhanced safety characteristics. Because of this, the likelihood that a permit (license) will be issued to replace part of the uranium fuel assemblies in operating VVER reactors with MOX fuel assemblies is practically zero.

Second, the issue of spent fuel radiotoxicity is also essential. The presence in spent MOX fuel of long-lived isotopes of plutonium, americium, neptunium, and curium is known to considerably complicate both the MOX fuel recycling technology and dealing with the challenge of long-term waste disposal. To a great extent this is attributed to the accumulation in spent MOX fuel of Pu-241 – an isotope whose specific radiotoxicity is 40 times higher than that of the basic isotope, Pu-239. During storage, the Pu-241 isotope is transformed into the even more toxic Am-241, which has a half-life of 433 years. This isotope is the main contributor to the radiotoxicity of transuranium elements in spent fuel after the decay of short-lived fission products.

During the operation of light water reactors with uranium, about 250 kg/GW(e)/year of reactor-grade plutonium are built up. About 30 kg of this mass is Pu-241. Burning up MOX fuel fabricated from weapons-grade plutonium in light water reactors increases the annual build-up of plutonium-241 three-fold, or to around 100 kg.

Thirdly, the burning of MOX fuel based on weapons-grade plutonium at VVERs – as compared with the VVERs using uranium-based fuel – may produce several times more minor actinides with radiotoxicity more than three times as high as that of transuranium elements that accumulate at a uranium-fuel-burning VVER of the same power capacity.

The situation is quite different, however, if weapons-grade plutonium is used in BN-type reactors: The radiotoxicity of disarmed plutonium does not, for all practical purposes, exceed that of the initially loaded plutonium.

As for the economic efficiency, fast reactors – and the related auxiliary technologies – come at a much higher cost than thermal reactors. In Russia, the electricity generated by the first production BN-600 fast reactor is 40% more expensive than that of a VVER-1000. The cost of the BN-800 has been reduced somewhat by decreasing the metal consumption factor to 80% as compared to that of the BN-600 project. The economic characteristics of the fuel cycle have also been improved in the BN-800 project by the transition from uranium fuel, which is ineffective for fast reactors, to MOX fuel, and by further improvement of the burnup factor.

The main argument to substantiate and rationalize the Russian MOX-burning fast reactor development program, therefore, boils down to the need to dispose of weapons-grade plutonium and plutonium accumulated as a result of reprocessing operations at PA Mayak. There are no other serious or favorable arguments offered by proponents of MOX fuel application today. It must be noted especially that as of today, no country in the world, including Russia, has fast reactors that can be used to full capacity for the purpose of plutonium utilization. And the goal of utilizing the accumulated plutonium stockpiles in thermal reactors running on full MOX core loads will require either twice as many reactors or twice as much time compared to burning plutonium in fast reactors of the same power capacity. This is the result of differences in annual plutonium consumption rates for fuel fabrication with regard to VVERs and fast reactors, respectively. With the limitation of one third of the core loaded with MOX fuel, as at French reactors, the required number of VVERs will increase six-fold compared to fast reactors.

3.3. MOX fuel transportation

As other nuclear fissile materials, MOX fuel is transported by sea, air, and land. The design of transport casks used to ship MOX fuel is not publicly available.

It is known that IAEA standards and guidelines do not specifically prescribe any

additional safety measures for MOX fuel casks shipped by sea. Moreover, no scenarios or specially developed measures exist to handle a sinking accident involving a vessel with a MOX fuel shipment on board. The IAEA's position regarding such a risk is that it will result in insignificant damage to the environment and minimal human exposure to radiation.

Air shipments are not uncommon today as a way to transport MOX fuel in Europe. For instance, Swiss MOX rods assembled in the UK have been flown from an airport in Carlisle (in northern England near the Scottish border) to Zurich. There have also been MOX transports by air from Germany to Scotland.

The USA has a stricter safety standard (NUREG-0360) on air transports in general and is rather unlikely to allow plutonium or Pu-containing MOX fuel to fly over its territory. It was disclosed in 1987 that the air shipment plutonium container that had been developed by Japan's Power Reactor and Nuclear Fuel Development Corporation (PNC) jointly with the U.S. Battelle-Columbus failed the crash tests conducted at the Sandia National Laboratory. This led to a hot debate in the U.S. Congress and a proposal to toughen the National Regulatory Commission's safety criteria for licensing transport packages for air transport of plutonium so that the packages could withstand even the worst aircraft accident. Essentially, this proposal is tantamount to laying a ban on foreign plutonium overflight from US airspace.

A Kyodo News report of June 10, 1997 revealed that BNFL was considering a possibility of air shipment of spent fuel from Japan, Switzerland, and Germany to THORP, Sellafield, sending processed plutonium back to these countries also by air. According to BNFL, air shipment was one of the possibilities and that the choice is to be made primarily by the overseas utilities with which they are contracted.

MOX containers for air transport would be categorized as Type C. A cask of Type C is supposed to withstand "enhanced accident conditions," including 90 m/s (or 324 km/h) impact and one-hour fire at 800 °C separately (not in succession). But these "enhanced accident conditions" only cover 85-90% of air crashes, so the "regulations vs. reality" problems arise here again. The IAEA asserts that the 90 m/s standard would only be exceeded in 5% of air crashes, whereas Greenpeace claims that this happens in 50% of air crashes. It is recognized in IAEA's data that 10% of aircraft fire lasted over 60 minutes. Notably, the IAEA Type C standard is even less strict than the one required for ordinary aircraft flight recorders, which are to survive a crash speed of 138 m/s (or 496 km/h) and one-hour fire at 1,100 °C (not separately, but consecutively, i.e. withstanding an accident when the crash is directly followed by fire, which is not the case with IAEA's Type C test). In fact, there have been cases with black boxes getting destroyed in actual aircraft accidents. The US standard for a Pu container in air transport is 282 m/s (or 1,015 km/h). Neither Type B nor Type C containers as specified by the IAEA meet the US standards.

Type C packages are yet to be developed, and their application can be expected to greatly increase the cost of MOX transport. It is thus not surprising that nuclear fuel industry representatives have pressed for permission to use other types of packaging for shipping MOX fuel by air. A 1996 revision of the IAEA safety standards introduced an exemption from Type C package: the so-called "low dispersible materials" (LDM) exemption. Apparently, MOX fuel assemblies are regarded as qualifying for the LDM category, since MOX fuel is firmly sintered into pellets and the pellets are contained in fuel rods made of solid alloy.

It does not follow directly, however, that the existing Type B casks may be used to transport MOX by air. The revised edition of safe transport regulations, approved by the IAEA in September 1996, allows the use of Type B casks for plutonium and MOX shipments, provided transporters can demonstrate that radionuclides will not be dispersed even following a severe accident that ruptures the cask. This is a fairly high threshold test, since the enhanced accident conditions similar to those for testing Type C packages would be applied to LDM cargo itself, rather than its casks. At the moment, it seems quite difficult for the nuclear industry to meet this condition.

LDM exemption of MOX fuel from Type C packaging in air shipment will have to be approved by the International Civil Aviation Organization (ICAO). But none of the IAEA Type B containers has ever been tested in a plane crash.

Packages for air transport containing fissile materials (such as MOX fuel) will also be subject to "enhanced accident conditions" similar to those for Type C, and will be required to maintain subcriticality. Meeting these standards will be a challenge.

Land shipments of MOX fuel, by rail or by road transport, have been used in shipments

between France and Belgium. Likewise, MOX fuel may possibly be transported on land from MOX fabrication plants in Japan to the country's nuclear power plants licensed for MOX.

With regard to land transport of MOX fuel, the first problems to consider are those of radiation exposure of transport workers and the threat of terrorism. Serious consequences could also occur in severe accidents that go beyond the test conditions required for Type B cask. Highways in Japan cross quite a lot of bridges: almost 10% of the total distance of national highways is elevated, more than half of them being higher than 9 meters. It is, therefore, a prudent approach to consider "hypothetical" accident conditions exceeding the IAEA standards for the Type B cask.

3.4. Certain issues of the MOX fuel economics

Fabrication of MOX fuel is several times more expensive than manufacturing fuel from the more common enriched uranium – twenty times as costly in the case of Japan, for instance, and five times more expensive in the case of France. According to the Japanese Atomic Energy Commission's October 2008 data, using MOX fuel will increase the cost of 1 kWh of electricity by 40%. But a transition to MOX fuel serves to solve two major tasks: utilizing accumulated plutonium and introducing uranium-238 – an isotope that constitutes over 99% of natural uranium and 95% of spent nuclear fuel – into the nuclear fuel cycle. In other words, the MOX fuel technology is undoubtedly expected to boost the Japanese nuclear energy industry's energy resource potential and let it break free from its dependency on imported enriched uranium. But today's global market is well supplied with cheap natural uranium. What also should be noted is the relative inexpensiveness and accessibility of uranium enrichment. These two factors contribute to the rather low price of enriched uranium. If the price of natural uranium is taken to be $40 per kg, and enrichment is assumed to cost $100 per SWU, then enriched uranium will cost around $1,100 per kg. By contrast, the cost of fabricating MOX fuel elements is much higher, reaching between $1,300 and $1,600 per kg of MOX fuel at a minimum. The effective cost of MOX fuel fabrication, however, is higher still when it includes expenses incurred on measures to ensure safety during storage and transportation of plutonium – costs that exceed noticeably those involved in uranium fuel fabrication.

Table 3.2 shows cost calculations performed in Russia with regard to standard RBMK uranium fuel assemblies as compared to the corresponding data on standard uranium fuel assemblies for light water reactors and mixed uranium and plutonium oxide fuel assemblies for light water reactors, with equivalent burnup. The calculations were done based on current global SNF recycling prices.

Table 3.2. *Cost of mixed uranium and plutonium oxide fuel, in US dollars per kgHM.*

Costs	Enriched uranium	MOX fuel
RBMK fuel assemblies		
Natural uranium	200	-
Uranium enrichment (up to 2.4% U-235)	250	-
Separating plutonium from SNF	-	5,600
Re-use of regenerated uranium (enrichment to 0.65% U-235)	-	140
Fabrication of fuel assemblies	200	1,300
Total:	**650**	**7,040**
VVER fuel assemblies		
Natural uranium	400	-
Uranium enrichment (4.4% U-235)	600	-
Separating plutonium from SNF	-	5,600
Re-use of regenerated uranium (enrichment to 1.2% U-235)	-	420
Fabrication of fuel assemblies	300	1,300
Total:	**1,300**	**7,320**

As follows from Table 3.2, the cost of one MOX fuel assembly for RBMK and, by extension, the cost of power generated by it, is approximately 10 times greater than that of a standard uranium fuel assembly with an equivalent burnup. The costs associated with separating plutonium from SNF contribute the bulk of the cost of producing a fuel assembly based on mixed oxide fuel. This is why the cost of a fuel assembly containing uranium and plutonium recovered from VVER spent fuel, which contains higher plutonium concentrations, will exceed the cost of standard uranium fuel by a fewer number of times – just five-fold. Costs involved in storage of spent uranium fuel assemblies – which are absent with SNF reprocessing – will slightly reduce the described ratios to 8 in the case of RBMK and 4, in the case of VVER.

The cost of initial core loads for future fast reactors may reach $800 million per one

reactor unit (about 4 tons of fissile plutonium per 1 GW).

A 1995 U.S. National Academy of Sciences report estimated the cost of processing and fabricating low-enriched uranium oxide reactor fuel (4.4% enrichment) at about $1,400 per kg in 1992 dollars, assuming a natural uranium price of $55 per kg. The costs of MOX fuel fabrication, assuming that the plutonium was free (that is, obtained as surplus from the nuclear weapons program), would be about $1,900 per kg in 1992 dollars, exclusive of taxes and insurance. The higher cost of MOX means that annual fuel costs for a full MOX core would be approximately $15 million more than uranium fuel per year for a 1,000 MW reactor, or about $450 million over its operating life (in 1992 dollars), even if the plutonium were free. This amounts to about $500 million in 1995 dollars. Further, the costs of disposing of MOX spent fuel are likely to be higher than those for uranium spent fuel because MOX spent fuel will be more radioactive and contain two to three times more residual plutonium than uranium spent fuel.

It is clear that so long as uranium prices are relatively low, the use of MOX fuel is uneconomical even under the most favorable circumstances: when the plutonium itself is free and uranium is assumed to be more expensive than current spot market prices. The cost difference is even greater when the cost of reprocessing is taken into account, because reprocessing would add hundreds of millions of dollars to lifetime fuel costs for each reactor.

CHAPTER 4. **WEAPONS-GRADE FISSILE MATERIALS**

The notion of **weapons-grade fissile materials** first appeared during the time of the development and manufacture of nuclear weapons. Weapons-grade fissile materials include highly enriched uranium (85% U-235 or higher) and weapons-grade plutonium.

4.1. Highly enriched uranium

Highly enriched uranium (HEU) that nowadays is classified as "weapons-grade" contains 85% or more of U-235. Typically, the manufacture of modern nuclear weapon components requires the use of uranium enriched to even higher levels – 90% or higher. In practical terms, a bomb could be manufactured using uranium enriched to 20% or more, but such a weapon would be too large in size to allow problem-free delivery or use. The lesser the degree of enrichment, the more uranium and more traditional explosive will be needed to produce a bomb. A modern uranium bomb would commonly require some 20-25 kg of weapons-grade HEU.

In Russia, weapons-grade HEU for nuclear warheads used to, and still can, be produced at four facilities: Urals Electrochemical Combine (UEC, Novouralsk, Sverdlovsk Region), Production Association Electrochemical Plant (Zelenogorsk, Krasnoyarsk Region), Siberian Chemical Combine (Seversk, Tomsk Region), and Angarsk Electrolysis Chemical Combine (Angarsk, Irkutsk Region).

Since the mid-1990s, Russia's HEU stockpile has been shrinking, as, pursuant to

Table 4.1. *National stocks of highly enriched uranium as of 2011, in metric tons.***

Country	Stockpile available for weapons	Naval (fresh)	Naval (irradiated)	Civilian material	Excess (mostly for blend-down)	Eliminated
China	16*					
France	26			4.6		
India	2*					
Israel	0.3*					
Pakistan	2.75*					
Russia	616*	20*	10*	20*	71	446
United Kingdom	11.7	8.1		1.4		
United States	260	130	100	20	100	135
Non-nuclear weapon states				20		

* IPFM estimates. For Russia, an ± 120 MT uncertainty is assumed.

** The numbers for the United Kingdom and United States are based on their publications. The civilian HEU stocks of France, the United Kingdom are based on their public declarations to the IAEA. Numbers with single asterisks are IPFM estimates, often with large uncertainties. HEU in non-nuclear weapon states is under IAEA safeguards. A 20 % uncertainty is assumed in the figures for total stocks in China and for the military stockpile in France, about 30% for Pakistan, and about 40% for India. The 446 tons of eliminated Russian HEU include 433 tons from the 500-ton HEU deal and 13 tons from the Material Consolidation and Conversion (MCC) project. About 4 tons of HEU remain for blend-down within the MCC project. About 10 tons of HEU in non-nuclear weapon states is irradiated fuel in Kazakhstan with an initial enrichment of about 20%.

a U.S.-Russian agreement, highly enriched uranium is being diluted to low-enriched (reactor-grade) uranium for use at U.S. nuclear power plants. In 1993, the U.S. and Russia signed a government-to-government agreement that started the so-called HEU-LEU (Megatons to Megawatts) program. In 2011, in accordance with the contract that was concluded as part of the HEU-LEU agreement between Russia's Techsnabexport and the U.S. USEC, about 834 tons of low-enriched uranium was shipped to the United States. The value of these uranium deliveries to the U.S. in 2011 totaled $1.01 billion. The 20-year HEU-LEU program envisioned by this agreement has now been completed to 88%. In preliminary estimates, Russia's overall revenue from the Megatons to Megawatts program may total $17 billion, including the remaining shipments planned before the program's completion in 2013.

As of end 2011, the combined worldwide stockpile of highly enriched uranium – including but not limited to the weapons-grade category – covered by IAEA safeguards was estimated at around 1,470 tons. However, in expert assessments, the IAEA does not control over 10% of the total global HEU stockpile.

4.1.1. Highly enriched uranium for naval use

Fast (and intermediate) liquid metal cooled reactors were used in the USSR as propulsion reactors on board of nuclear-powered Alfa class submarines. The Soviet Union built seven such vessels. These submarines' reactors were loaded with approximately 175 kg of fuel enriched to 90% of U-235. Thus, in the 1970s, around 1.5 tons of HEU enriched to 90% was altogether produced in the USSR for use in these reactors. In the 70 reactor-years that these nuclear submarines remained in operation, there had been no core reloads (with the exception of one or two emergency reloads). At the end of the 1990s, the Alfa submarines were decommissioned, and the reactor fuel was unloaded and shipped to Dimitrovgrad (Ulyanovsk Region), where Russia operates the only test facility capable of accommodating this type of cores.

HEU of various levels of enrichment is also used for nuclear marine propulsion in various types of shipboard light water reactors, in Russia and other countries alike. The enrichment level of the fuel used in these reactors is lower than of that intended for liquid metal cooled reactors, but is higher than 20%. In their reliance on highly enriched uranium as fuel of choice for reactors on board of submarines and surface vessels, the United States, France, Great Britain, and Russia are guided by the goal of ensuring that the core's energy generating capacity is enough to support its operation throughout the vessel's entire service period. This can be achieved with highly enriched uranium and high-quality materials used in the manufacture of the reactor core. The United States Navy currently requires around 2 tons of weapons-grade uranium per year, and 128 tons of excess weapons-grade uranium – an amount sufficient for 5,000 nuclear weapons – is reserved in the U.S. for prospective use in naval reactors.

4.2. Plutonium

Plutonium (Pu) is an artificial transuranic radioactive chemical element of the actinide series with atomic number 94 in Group III in Mendeleev's Periodic Table of the Chemical Elements.

After plutonium was first synthesized in a laboratory, attempts were made to discover it in nature. Trace amounts of plutonium have been detected in microscopic quantities (0.4-15 parts Pu per 10^{12} parts U) in uranium-bearing minerals. It was established that all plutonium isotopes have half-lives that are much shorter than the Earth's age, so all of the primordial plutonium that existed on the planet at the time the Earth was formed has completely decayed. Extremely small quantities of primordial Pu-244 – the longest-lived plutonium isotope, which has a half-life of 80 million years – have been detected in cerium ores, where they have apparently remained since they were formed during the creation of the Earth. Infinitesimal quantities of Pu-239 are also constantly forming as a result of beta decay of Np-239, which, in turn, is yielded when uranium undergoes a nuclear reaction as its atoms are hit by neutrons (for instance, those present in cosmic radiation). The amount of natural plutonium that is found in the accessible part of the Earth's crust, therefore, does not exceed a few dozen kilograms.

All of the remaining plutonium – measuring hundreds of tons worldwide – is man-made, i.e. it is of artificial origin. Plutonium is produced from uranium-238 in nuclear reactors. As a U-238 nucleus captures a neutron, a newly formed U-239 nucleus

beta-decays into Np-239, which, in its turn, is transformed by beta decay into Pu-239.

First plutonium production reactors were built in the 1940s – in the United States at first, and then in the Soviet Union. These reactors were capable of producing plutonium in amounts sufficient for the manufacture of a nuclear explosive device.

The first nuclear military production complex with uranium-fueled graphite-moderated reactors and a facility for chemical separation of plutonium from irradiated fuel was built in the United States near Richland, Washington state, at what is known as the Hanford Site, or Hanford Nuclear Reservation. In 1943, the United States first yielded plutonium metal in powder form which was then sintered into ingots. In 1945, the U.S. produced its first three plutonium bombs. One was detonated on July 16, 1945 in a nuclear test at a site in New Mexico, another was dropped on Nagasaki on August 9, 1945, and the third one was never used. At the height of the Cold War, the U.S. nuclear weapons complex comprised 18 facilities, including 14 production reactors.

In the USSR, the first plutonium production reactors were built at a site in Chelyabinsk Region (Production Association Mayak, Ozyorsk). Five more plutonium-producing reactors were subsequently built at the Siberian Chemical Combine (Seversk, Tomsk Region) and three more at the Mining and Chemical Combine (Zheleznogorsk, Krasnoyarsk Region). The USSR's first nuclear weapon with a plutonium core was tested on August 29, 1949 at a test site near Semipalatinsk. Two of the 18 production reactors built in the Soviet Union are still in operation.

Later, England, France, and China created their own plutonium production facilities, with Inida, Pakistan, and Israel joining the nuclear weapons club in the following years. In October 2006, North Korea performed its first underground nuclear bomb test, with a yield of around 1 kiloton. North Korea's next atomic bomb test was conducted in May 2009, yielding an estimated 12 kilotons.

4.2.1. Physical and chemical properties of plutonium isotopes

Plutonium is a very heavy metal with a silvery luster. It has a density of 19.8 g/cm^3 at a temperature of 25 °C. It is chemically reactive – much more so than uranium. It quickly develops an iridescent tarnish, initially of a pale yellow that eventually progresses into a dark purple. With severe oxidation, a coat of olive-green oxide powder (PuO_2) forms on the surface.

Plutonium is characterized by a vast variety of specific properties. It has the lowest thermal conductivity among all metals and its electrical conductivity is lower than any metal but manganese. In its liquid phase, it is the most viscous of metals. And when exposed to temperature changes, it undergoes the most extreme and bizarre density changes (allotropic transformations). It can be as brittle as glass and as malleable as aluminum. It expands as it solidifies, much like water freezing into ice. Because of its high radioactivity levels, plutonium is warm to the touch. A large piece of plutonium that is thermally insulated can develop a temperature exceeding the boiling point of water.

Plutonium has 15 well-researched radioactive isotopes ranging in mass number from 232 to 246. Table 4.2 lists the most significant plutonium isotopes used for the manufacture of nuclear weapons or fabrication of nuclear fuel.

Table 4.2. *Plutonium isotopes.*

Nuclide	Half-life (in years)	Radiation	Specific radioactivity (×10^9 Bq/g)
Pu-238	87.74	α (γ)	630
Pu-239	24,113	α (γ)	28.2
Pu-240	6,570	α (γ)	8.4
Pu-241	14.6	β (α)	3,680
Pu-242	375,000	α	0.141

The isotopes listed in Table 4.2 are present in any plutonium material produced in a nuclear reactor. The specific isotopic composition of the produced plutonium material depends to a considerable degree on the fuel's burnup, the level of initial enrichment of U-235, as well as the type of the nuclear reactor, which determines the particular properties of its neutron spectrum.

The following categories are used to classify plutonium:

– *weapons-grade plutonium (WGPu)* is defined as plutonium material containing no more than 7% Pu-240;

– *fuel-grade plutonium (FGPu)* is defined as plutonium material containing between 7% and 18% Pu-240;

– *reactor-grade plutonium (RGPu)* is defined as plutonium material containing over 18% Pu-240.

As follows from this classification, the main factor determining the grade of plutonium material is the content of the isotope Pu-240.

4.3. Plutonium isotopes

Plutonium-238 was the first plutonium isotope to be discovered. Its nuclei – as the nuclei of all plutonium isotopes with even mass numbers – are not fissile, so it cannot be used to generate nuclear energy. During radioactive decay (5.1×10^6 fissions/g-hr), Pu-238 has a very high heat output, at 567 W/kg. It emits very high levels of alpha radiation (283 times higher than Pu-239) and can be a source of neutron emission from the α, n reaction. The Pu-238 content in total plutonium composition typically does not exceed 1%. Pu-238 is currently widely used as a power source for equipment used in space technologies and in medicine. Plutonium-238 has an alpha decay energy of 5.5 MeV. A power source fueled by 1 kg of plutonium-238 develops a thermal capacity of 560 W. The maximum thermal capacity of an electrochemical cell of identical mass is 5 W. Because Pu-238 is not a strong emitter of gamma rays from the α, γ reaction, it can be used as a power source in medicine, for instance, to power artificial heart pacemakers.

Plutonium-239 is essentially the most important isotope formed by a U-238 nucleus upon neutron capture in this reaction:

$$^{238}U(n,\gamma)\,^{239}U \xrightarrow{\beta,\,23\ min} {}^{239}Np \xrightarrow{\beta,2.33\,days} {}^{239}Pu \xrightarrow{\alpha,24{,}065\ years} {}^{235}U.$$

Pu-239 today is the chief component in almost all nuclear weapons since its production technologies are simpler, more economical, and more promising than the technologies needed to enrich the concentration of U-235 in natural uranium to weapons-grade levels. Furthermore, Pu-239 has larger scattering and absorption cross-sections than uranium, and a larger number of neutrons per fission, and, correspondingly, a lesser critical mass. One kilogram of Pu-239 is equivalent to 22 million kWh of thermal energy. When exploded, one kilogram of Pu-239 produces a yield equivalent to 20,000 tons of TNT.

Weapons-grade plutonium, being distinct from its fuel-grade and reactor-grade counterparts, does not differ from them so much in the enrichment degree and chemical composition as it does in its isotopic composition, which depends in complicated ways both on the duration of uranium bombardment by neutrons and on the plutonium's storage period after irradiation.

It should be noted that an atomic bomb can be created using material with any concentration of Pu-240. This is why the very term "weapons-grade plutonium" serves more to describe an economic characteristic – in other words, how it affects the cost of the bomb design, which could be implemented at various technical and technological levels – than it does to characterize the plutonium material that can be used to manufacture a bomb. On the one hand, the cost of the plutonium decreases the larger the share of Pu-240 in its composition, but on the other, the presence of Pu-240 increases the critical mass, which drives up the cost of the material. However, it should also be kept in mind that the key parameter that has a bearing on the risk of nuclear proliferation is not the amount of Pu-240 in the plutonium material but its Pu-241 content and, to an extent, that of Pu-238. These isotopes have rather short half-lives (T1/2 Pu-241 = 14.4 years, T1/2 Pu-238 = 86.4 years), and, as they are transformed by beta and alpha decay into other isotopes (Am-241 and U-234, respectively), they alter considerably plutonium's isotopic composition and, correspondingly, impact its suitability for use in nuclear weapons.

The United States has built 14 reactors for the production of weapons-grade plutonium – nine at the Hanford Site in Washington state and five at the Savannah River Site in Georgia. The last of these reactors was shut down in 1988.

In Russia (Soviet Union) weapons-grade plutonium was produced at 18 reactors of different types (Table 4.3).

Table 4.3. *Russian (Soviet) plutonium production reactors.*

Facility	Reactor name	Reactor type*	Reactor generation	Startup year	Shutdown year
Production Association Mayak, Ozyorsk (Chelyabinsk-65)	A	UGK	I	1948	1987
	AI-IR	UGK	I	1951	1987
	AV-1	UGK	II	1950	1989
	AV-2	UGK	II	1951	1990
	AV-3	UGK	II	1952	1990
	OK-180	TVK	I	1951	1966
	OK-190	TVK	I	1955	1965
	OK-190M	TVK	I	1966	1985
	Ruslan	VVR	I	1979	In operation
	Lyudmila	TVK	II	1986	In operation
Siberian Chemical Combine, Seversk (Tomsk-7)	I-1	UGK	I	1955	1990
	EI-2	UGKTs	II	1958	1990
	OK-140	UGKTs	III	1961	1992
	OK-204	UGKTs	III	1964	2008
	OK-205	UGKTs	III	1965	2008
Mining and Chemical Combine, Zheleznogorsk (Krasnoyarsk-26)	OK-120	UGK	II	1958	1992
	OK-135	UGKTs	III	1962	1993
	OK-206	UGKTs	III	1964	2010

* Reactor type abbreviations stand for: UGK: uranium-fueled graphite-moderated channel-type reactor; TVK: heavy water vessel-type reactor; UGKTs: dual-purpose uranium-fueled graphite-moderated reactor; VVR: water-cooled water-moderated reactor.

As shown in Table 4.3, only two production reactors, of the types VVR and TVK, remain in operation. All uranium-graphite production reactors have been shut down, though as yet not decommissioned. The last plutonium production uranium-graphite reactor, ADES-2, which had been in operation at the Mining and Chemical Combine for over 46 years, was shut down on April 15, 2010.

State Corporation Rosatom has developed a decommissioning concept for uranium-graphite production reactors involving the option of radioactively safe disposal in a repository on site. The total cost of measures envisioned for these purposes is earmarked at RUR 4.8 billion in the Federal Target Program for Nuclear and Radiation Safety for 2008 and for the Period through 2015, while the cost of decommissioning one reactor is estimated at RUR 2 billion alone.

Weapons-grade plutonium can furthermore be extracted from spent nuclear fuel during reprocessing, which is done at Mayak using the two reactors that remain in operation.

Plutonium-240 is the major contaminant of concern in plutonium intended for weapons use. Pu-240 is fairly fissile, more so than U-235. Nonetheless, high concentrations of Pu-240 raise the required critical mass, thus aggravating the neutron background problem.

Plutonium-241 is about as fissile as Pu-239, has a low neutron emission rate, and a moderate heat production rate, and thus does not adversely affect weapon usability of plutonium directly. It decays with a short 14-year half-life into americium-241, which is non-fissile and does produce a great deal of heat: 106 W/kg. Pu-241 does not emit much heat (only 3.4 W/kg) because of its weak beta emission decay mode.

Plutonium-242. Pu-242 has a high neutron emission rate, at 8.4×105 fissions/sec-kg – or twice that of Pu-240, and is non-fissile. A substantial concentration of Pu-242 thus increases both the critical mass and neutron background. With its long half-life, and a relatively low neutron capture cross-section, Pu-242 tends to accumulate in recycled reactor plutonium.

4.4. Plutonium stockpiles

With the exception of Russia, all major nuclear weapon states have declared the amount of weapons-grade plutonium accumulated in their arsenals. However, exact data are unavailable for certain nations such as Iran, Israel, North Korea, and others, which is why expert estimates are used in related publications.

According to these estimates, the global stockpile of weapons-grade plutonium accumulated by all nations totals around 300 tons.

The United States has over 50 years produced more than 100 tons of weapons-

grade plutonium. All production reactors in the United States are currently shut down. As of end 2010, the U.S. weapons-grade plutonium inventory totaled 99.5 tons, of which 54 tons has been declared by the U.S. government as excess to national security needs.

Russia, in expert estimates, currently owns between 123 and 200 tons of weapons-grade plutonium. Russia has declared 34 tons – and potentially up to 50 tons – of its weapons-grade plutonium as excess for its defense purposes.

The combined weapons-grade plutonium stock accumulated in other countries totals around 18 tons. Of these, the United Kingdom owns about 7 tons; France, 6 tons; China, 2 tons; and the rest belongs to India, Israel, and other nuclear nations.

Table 4.4. *National stocks of separated plutonium (as of 2011), in metric tons.***

Country	Military stockpile	Excess military material	Additional strategic stockpile	Civilian stockpile stored in country	Civilian stockpile stored outside country
China	1.8*				
France	6*			56	
Germany				2	5.6
India	0.52*		4.2*	0.24	
Israel	0.8*				
Japan				9.9	35
North Korea	0.03*				
Pakistan	0.14*				
Russia	88*	34	6*	48.4	
United Kingdom	3.2*	4.4		86.8	0.9
United States	38	53.9			
Others					10.7

* IPFM estimates.

** Civilian stocks are based on the most recent INFCIRC/549 declarations for December 2010 and are listed by ownership, not by current location. Weapon stocks are based on non-governmental estimates except for the United States and United Kingdom, whose governments have made declarations. Uncertainties of the military stockpiles for China, France, India, Israel, Pakistan, and Russia are on the order of 10-30%. The plutonium India separated from spent heavy water power reactor fuel has been categorized by India as "strategic," and not to be placed under IAEA safeguards. Russia has 6 tons of weapon-grade plutonium that it has agreed to not use for weapons but not declared excess.

Table 4.5. *Uranium and plutonium content in spent nuclear fuel of one reactor core, in kilograms.*

Material	Light water reactors	Fast reactors
Uranium	960	856
Plutonium	7	103

Table 4.6. *Total amount of SNF accumulated in Russia, including forecast to 2050, and plutonium content, in tons.*

	2000	2010	2025	2050
SNF	15,000	23,000	33,000	50,000
Plutonium content	90	140	240	500

4.4.1. Commercial (civilian) plutonium

Civilian plutonium is produced in nuclear reactors burning uranium fuel and is separated from the spent nuclear fuel using technologies similar to those employed to produce weapons-grade plutonium.

One kilogram of nuclear fuel burnt in a light water reactor contains around six grams of plutonium. This value is much larger in the case of fast reactors. Table 4.5 lists data on uranium and plutonium content in spent nuclear fuel burnt in light water and fast reactors.

Table 4.6 shows changes in the total amount of SNF accumulated in Russia and forecast to 2050, as well as plutonium content in that SNF.

If a nuclear power plant is operated according to nameplate power generation capacity, then the typical isotopic composition of the plutonium generated in the reactor fuel will be different than that of weapons-grade plutonium. Table 4.7 shows the approximate isotopic composition of plutonium generated in a VVER-type light water reactor, with fuel burnup at 33 MWd/kg.

The lesser the amount of Pu-239 in civilian plutonium, and the more the content of Pu-240, the less attractive it is for the purpose of manufacturing nuclear weapons, as compared to weapons-grade plutonium.

Yet, civilian plutonium can be used to manufacture a nuclear explosive device – which, all other conditions being equal, will simply have larger dimensions, a more complicated design, and a considerably lesser yield.

Nuclear tests performed in 1962 in the United States in Nevada (and later, in India, in 1974) used weapons that had civilian plutonium as the fissile core. The tests confirmed earlier theoretical calculations that held that civilian plutonium could be used to manufacture nuclear weapons. This effectively made civilian plutonium a subject of non-proliferation policies. A report on this finding was presented at an IAEA conference in 1971. According to a finding by the Lawrence Livermore National Laboratory, "Virtually any combination of plutonium isotopes ... can be used to make a nuclear weapon," which is why plutonium with any isotope content should be regarded as strategically important and dangerous material. The IAEA furthermore determined that 25 kg of U-235 in highly enriched uranium and 8 kg of plutonium were substantial amount of fissile materials – i.e. amounts sufficient to manufacture a first-generation implosion-type bomb of the kind that was dropped on Nagasaki.

Taking into account the plutonium contained in SNF that has not yet been reprocessed, overall, more than 1,200 tons of plutonium (both civilian and military) has been produced worldwide. This figure continues to rise annually by an estimated 75 tons.

In expert estimates, the global stockpile of separated (pure) plutonium, both civilian and military, totals around 500 tons. Storage facilities of nuclear weapon states contain over 250 tons of separated civilian plutonium not including the plutonium that Russia and the United States have declared as excess – 34 tons and 54 tons in Russia and the U.S., respectively. Over 80% of the global stockpile

Table 4.7. *Approximate isotopic composition of plutonium generated in a VVER-type light water reactor.*

Plutonium isotope	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Content, %	1.4	56.5	11.28	2.95	1.42

of separated civilian plutonium is stored at three sites in Europe – La Hague, Marcoule, and Sellafield – and in Russia, at Production Association Mayak. Various data also indicate that around 7 to 10 tons of plutonium has been dispersed across the globe as a result of nuclear weapons tests, losses during production, and accidents at various nuclear facilities.

Separated civilian plutonium belongs to countries that remain engaged in spent nuclear fuel reprocessing or that have concluded reprocessing contracts. There are countries such as Germany, Italy, the Netherlands, and Switzerland, that also own small national plutonium stocks that they store on their respective territories.

The U.S. owns a relatively small stock of civilian plutonium produced at a radiochemical enterprise in West Valley, New York, a site closed in 1972.

Great Britain separates civilian plutonium from spent nuclear fuel burnt in British and foreign reactors. In storage in the United Kingdom is currently around 100 tons of civilian plutonium. Plutonium from foreign-generated SNF is to be reprocessed into MOX fuel and returned to the respective client states. The country is yet to determine its policy with regard to its own civilian plutonium.

France has accumulated around 70 tons of civilian plutonium, of which 30 tons is owned by foreign customers.

Japan has started plutonium separation at a facility in Rokkasho, where by the end of 2010, around 10 tons of separated civilian plutonium had been produced.

Russia submitted to the IAEA in May 2010 its annual declaration on the total amount of civilian plutonium in the Russian Federation. The communication contains information on the Russian stock of civilian plutonium as of December 31, 2009, compared to the figures current as of December 31, 2008.

According to this communication, as of the end of 2009, the total amount of unirradiated separated plutonium at Russian SNF reprocessing enterprises was 46.3 tons. At the end of 2008, Russia had 45.2 tons of this type of plutonium.

Plutonium contained in unirradiated MOX fuel assemblies or other fabricated products

at reactor sites or elsewhere amounted to 300 kg of civilian plutonium. The figure for this category is the same as that stated for 2008. The amount of plutonium identified in the communication as "unirradiated separated plutonium held elsewhere" stood in 2009 at 1,100 kg over the figure of 1,000 kg reported for 2008.

The total stock of unirradiated separated civilian plutonium stored in Russia therefore increased in 2009 to 47.7 tons over the 46.5 tons stated for 2008.

Of this total amount, 0.3 kg of plutonium stored in Russia belonged to "foreign bodies." Additionally, 0.6 kg of Russia-owned plutonium was in 2009 "held in locations in other countries" and was thus not included into the total Russian stock.

The communication also contained information on the total amount of civilian plutonium that was accumulated in spent nuclear fuel in Russia. These figures were rounded to tons: Plutonium in spent fuel that was stored at civil reactor sites amounted to 71 tons, or three tons more than in 2008; plutonium contained in spent fuel that had been transported to reprocessing plants totaled four tons, or one ton more than in 2008; and plutonium contained in spent fuel held elsewhere was 47 tons, or two tons more than at the end of 2008.

Overall, Russia's total stock of civilian plutonium, all categories included, is estimated to have been 169.7 tons as of end 2009, having increased by 7.2 tons over 2008 figures.

4.5. Plutonium management and disposition

Two perspectives have developed today in the world regarding further management of accumulated plutonium. In the United States, most experts favor the option of disposing of plutonium in deep geological formations, mixed with high-level radioactive waste and in vitrified form. Russia regards plutonium primarily as an energy resource that can be used as mixed uranium and plutonium oxide (MOX) fuel for nuclear power plants. Studies that have started in the 1960s focusing on application of pure plutonium as fuel in fast reactors have yielded little success and are likely to discontinue.

In March 2011, the government of the Russian Federation adopted a protocol amending a bilateral U.S.-Russia agreement on the disposition of plutonium declared as excess to defense needs, plutonium management, and cooperation in that field. The protocol was signed in Washington on April 13, 2010 and served as an amendment to the bilateral government-to-government agreement on the disposition of excess weapons-grade plutonium signed in 2000.

Under the agreement, each of the countries committed to dispose of 34 tons of accumulated excess weapons-grade plutonium. Also according to the agreement, the U.S. is to allocate up to $400 million to the Russian excess weapons-grade plutonium disposition program. The Russian government will contribute RUR 2.5 billion toward the implementation of this program.

Excess weapons-grade plutonium is accumulated in the process of decommissioning nuclear weapons. The dismantlement of nuclear warheads in Russia takes place at the same enterprises where these weapons were manufactured: Urals Electrochemical Combine (Novouralsk, Sverdlovsk Region), Penza Instrument-Making Plant (Zarechny, Penza Region), and Instrument Manufacturing Plant (Trekhgorny, Chelyabinsk Region). When operating to full capacity, these enterprises are capable of disassembling up to 2,000 warheads a year. The cost of dismantling one warhead is between $10,000 and $15,000 depending on the design complexity. During the dismantlement, the nuclear core material – so-called pit, in which uranium-235 (enriched to 90%) and plutonium-239 (enriched to over 90%) are used – is removed from the warhead. The fissile materials, uranium and plutonium, that are extracted from the warheads during dismantlement are not just a national-level problem, but also an international one, both from the environmental point of view and that of non-proliferation goals.

In December 2003, PA Mayak commissioned a unique site of strategic importance: the Fissile Material Storage Facility (FMSF). This development came as part of the U.S.-Russia Cooperative Threat Reduction program. The FMSF is the only site of this kind in Russia and is intended to be used for 100-year storage of weapons-grade uranium and plutonium released in the process of the nuclear arms reduction effort and nuclear weapon component disposition. According to the information available, the facility is mainly filling up with weapons-grade plutonium packed in special containers. The total stock of plutonium – weapons-grade and civilian – that is already in storage at Mayak reaches over 60 tons (see Table 4.8).

Table 4.8. *Characteristics of plutonium in storage facilities at Production Association Mayak.*

Facility	Purpose	Weight, in tons	Activity, in mCi
Fissile Material Storage Facility	Storage of weapons-grade plutonium	25	130
Reactor A building	Storage of civilian plutonium	38	Over 100,000

Total activity: over 100,000 mCi (3.7×10^{12} Bq)

According to a number of specialists and analysts, using one single facility for storage of dangerous nuclear materials runs counter to the principle of distributed storage of such materials and allows for an unprecedented concentration of radioactive substances in one place. Officially, Rosatom insists that the list of possible emergency situations developed for the project documentation for the FMSF provides for all realistically possible emergency events. But the list still offers no clear answers to a number of questions that arise with regard to the risks associated with force majeure events – risks that have become pertinent considering the facts of the Fukushima catastrophe in Japan. The major questions are: Do the designs of the FMSF and the building housing the first production reactor, Reactor A, guarantee the intactness of the material in storage under the various scenarios involving a nuclear attack or an attack with a modern "bunker-busting" bomb of the GBU-28 type or similar? What will happen should these buildings be hit with a modern airliner (jumbo jet), with an in-flight weight of 200 tons and a speed of over 800 km/h (the parameters adopted for a crashing aircraft scenario in the FMSF project are on par with those of a WWII bomber)? Keeping in mind the 100 years as the expected storage period at the FMSF, even the most infinitesimal possibility of such threats must be duly considered.

When the siting decision for the Fissile Material Storage Facility was being made, one option under discussion was transferring Russia's plutonium stockpile into a deep underground facility, for instance, at the Mining and Chemical Combine (Zheleznogorsk, Krasnoyark Region), where it could be accommodated on the unoccupied production areas of some of the sites where operations have been discontinued. This proposal received a favorable state environmental impact assessment. Other, suitable deep-underground siting options could possibly be developed by specialists for the FMSF project so as to ensure the safety of the materials in storage against all possible threats.

4.6. Weapons-grade fissile materials and international policies and safety

Nine countries currently own nuclear weapons. These are: the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan, and North Korea.

At the height of the Cold War, the USSR's nuclear warhead inventory numbered, in some estimates, around 30,000 nuclear weapons. In line with international strategic and tactical nuclear arms reduction agreements, the country was to dismantle between 16,000 and 18,000 nuclear weapons. By 1997, Russia, as the USSR's successor, had already disassembled around 50% of the warheads. In April 2010, the Russian and U.S. presidents signed a treaty on Measures for the Further Reduction and Limitation of Strategic Offensive Arms, or New START, which entered into force on February 5, 2011, replacing the START I treaty, which had expired in December 2009. The treaty is to last ten years with an option to renew it upon mutual agreement of the parties for a further five years. The treaty provides for the following limits: 1,550 nuclear warheads and 700 deployed inter-continental ballistic missiles, submarine-launched ballistic missiles, and heavy bombers equipped for nuclear armaments. Information on the cumulative numbers of nuclear weapons in the two countries' arsenals has been made public under the New START treaty. As of early 2010, Russia's operative nuclear arms included 2,504 warheads, while the U.S. nuclear arsenal numbered 1968/2468 warheads (the second figure reflects the 500 warheads carried by Tomahawk cruise missiles with a range in excess of 600 km, submarines, and unguided bombs – weapons that fall outside the scope of the treaty).

CHAPTER 5. **SPENT NUCLEAR FUEL**

Spent nuclear fuel (SNF) refers to nuclear material and fission products contained in spent (irradiated) nuclear fuel assemblies unloaded from a nuclear reactor after their use (irradiation).

Strictly speaking, spent nuclear fuel represents a homogeneous-heterogeneous highly radioactive mix of structural materials (which have lost their durability and leak resistance and have become radioactive) and a mix of radionuclides (the remainders of the initial and newly generated nuclear fissile material). This mix can no longer be nuclear fuel per se. The term "spent nuclear fuel," used to designate what can be called a "maximally radioactive conglomerate" of a different isotopic composition, in contrast to the original nuclear fuel configuration, was coined in order to be able to artificially classify this material as falling outside the category of radioactive waste. That this "radioactive conglomerate" can be used to extract, at great cost, new nuclear fissile materials, only proves that there is no waste that cannot be used to extract something valuable – it is only a matter of the cost of the technology needed to do it. However, because *spent nuclear fuel* remains the generally accepted term, it will be used in this report despite its true meaning, described above.

Table 5.1. *Major radionuclides contributing to SNF radioactivity and toxicity.*

Time period (in years)	Main radioactivity contributors
Up to 100	Fe-55, Co-58, Ni-59, Sr-90, Ru-106, Cs-134, 137, Ce-144, Pm-147, Eu-154, 155
Between 100 and 1,000	Sm-151, Co-60, Cs-137, Ni-59, 63
Between 1,000 and 10,000	Pu-239, 240, Am-241
Between 10^4 and 10^5	Np-237, Pu-239,240, Am-243, C-14, Ni-59, Zr-93, Nb-94
Over 10^5	I-129, Tc-99, Pu-239

SNF is the most potentially dangerous product arising from the application of nuclear energy, because it contains up to 98% of all radioactivity concentrated in all the materials of the nuclear fuel cycle.

The radioactivity of 1 kg of SNF on the first day following its unloading from a reactor at a nuclear power plant is between 26,000 and 180,000 Ci (9.6-67×10^{14} Bq). A year later, its activity will have decreased to 1,000 Ci (3.7×10^{13} Bq), and over the course of 30 years, to 260 Ci (9.6×10^{12} Bq). Owing to the decay process of short-lived radionuclides, within one year after its unloading from a nuclear reactor, the radioactivity level of spent nuclear fuel will drop by 11-12 times, and, after 30 years, it will have dropped by 140-220 times, slowly decreasing further over hundreds of years.

Fission products that are generated as a result of nuclear reactions are elements with mass numbers ranging from 72 to 161, i.e. from zinc to dysprosium. Additionally, a share of the total radioactivity of SNF is contributed by radionuclides of iron (55), cobalt (58, 60), nickel (59), and other elements – radionuclides that are generated in the structural materials of fuel assemblies as a result of neutron irradiation. Nuclear fission and radioactive decay result in the generation in spent nuclear fuel of several hundred radionuclides with half-lives ranging from thousandths of a second to millions of years. The main radionuclides contributing to the radioactivity and toxicity of spent nuclear fuel are listed in Table 5.1.

The necessary component present in SNF is the newly generated isotopes of the following actinides: uranium (232, 236), plutonium (239, 240, 241, 242), americium (241, 242, 243), curium (242, 243, 244), and neptunium (237).

After it is unloaded from a reactor, spent nuclear fuel contains 96% of U-235 and U-238, 1% of Pu-239 and Pu-240, and 3% of

radioactive fission fragments (see Appendices 5.1 and 5.2).

The chemical and physical properties of spent nuclear fuel depend on the type of the original fuel and the level of its enrichment, reactor type and power capacity, the irradiation period, the duration of the cooling period following unloading, and a number of other parameters.

When extracted from a nuclear reactor, SNF is characterized by significant decay heat – the result of beta and gamma decay of the fission products accumulated in the fuel assemblies over the course of the fuel's life cycle in the reactor, as well as of alpha and beta decay of the actinides.

The presence in spent nuclear fuel of "old" and "new" nuclear fissile materials, the increased toxicity of the radionuclides, and the decay heat require enhanced safety measures and special technologies needed to handle the material. The possibility to transport this material, transfer it to "dry" storage, reprocess it, or perform any other operations with it only becomes available after the SNF has been held in "wet" storage in a cooling pond for a period of three to five years.

5.1. Accumulation, storage, and transportation of spent nuclear fuel in Russia and abroad

The most accurate data available on the accumulation of spent nuclear fuel in various countries can be found in national reports that are submitted to the IAEA by the respective governments of these countries in accordance with the requirements of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

As of early 2011, around 250,000 tons of SNF (expressed as tons of heavy metal) had been accumulated in the world. The amounts of SNF (current for the same period) held in the world's top ten nuclear countries, where over 80% of the global nuclear potential is concentrated, are listed in Table 5.2.

According to the IAEA, in operation in the world today are: 331 GW in combined LWR capacity; 23 GW in combined CANDU capacity; and 19 GW in combined RBMK capacity.

Total global annual SNF accumulation figures for each of these reactor types are listed in Table 5.3 (with one reactor assumed as operating at 90% of nameplate capacity of 1 GW).

Table 5.2. *Spent nuclear fuel accumulated in the world's top ten nuclear countries (as of early 2011).*

Country	Spent fuel inventory (tHM)	Spent fuel policy
Canada	37,300	Direct disposal
Finland	1,600	Direct disposal
France	13,500	Reprocessing
Germany	5,850	Direct disposal
Japan	19,000	Reprocessing
Russia	22,000	Partial reprocessing
South Korea	10,900	Storage, future options undecided
Sweden	5,400	Direct disposal
United Kingdom	5,850	Reprocessing, but future unclear
United States	64,500	Direct disposal

Table 5.3. *Annual global SNF accumulation.*

Reactor type (1 GW capacity)	Typical fuel burnup (GWd/tHM)*	Average annual SNF generation from one reactor (tons)
LWR (light water moderated)	50	20
CANDU (heavy water moderated)	7	140
RBMK (graphite moderated)	15	65

* Average fuel burnup is understood to be the ratio of the amount of energy generated to the amount of fuel loaded.

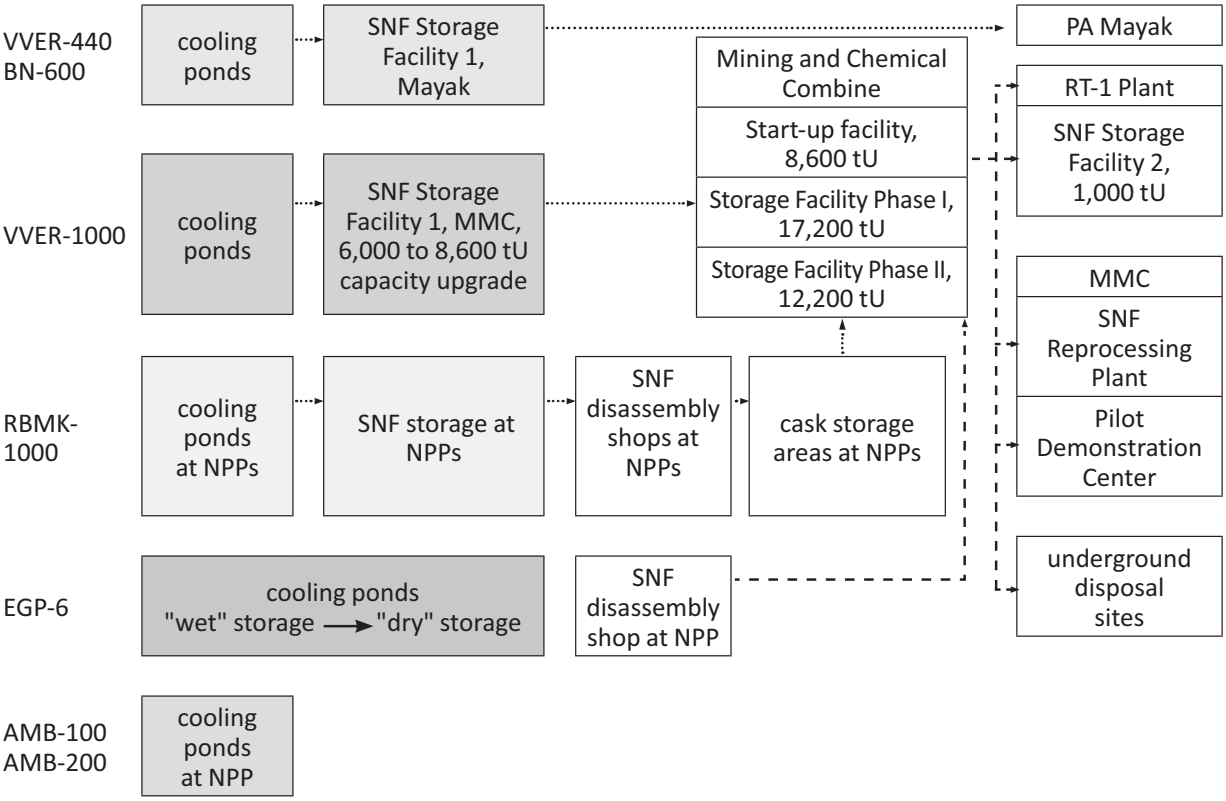


Fig. 5.1. Management of spent nuclear fuel from power reactors of Russian (Soviet) design.

A typical flow sheet representing the management of SNF of power reactors of Russian (Soviet) design is shown in Fig. 5.1.

5.1.1. Storage of spent nuclear fuel

Of all spent nuclear fuel accumulated in the world, 90% is stored in "wet" facilities, and the balance is held in "dry" casks. The annual spent nuclear fuel generated globally is approximately 10,500 tHM per year, with roughly 8,500 tHM going into long-term storage and the remainder allocated for reprocessing but much of it in interim storage.

The IAEA does not prescribe any particular standards with regard to storage methods or duration periods, but points out that the period of "dry" SNF storage may reach hundreds of years. It falls upon the nuclear states themselves to regulate the issues of storage duration periods and methods. For instance, the U.S. Nuclear Regulatory Commission (NRC) has made the decision that spent fuel could be stored in "dry" casks for 60 years after the fuel has been unloaded from the reactor. Russia has no established SNF storage standards. But the problem of long-term – indefinite – storage of spent nuclear fuel remains the predominant one for the global nuclear industry.

"Wet" storage ensures the removal of decay heat in the SNF and reduces radioactivity levels considerably. Furthermore, the "wet" storage method allows for the possibility to control the fuel's condition, including by visual means. The period needed for the heat output to lower to the required levels ranges between one and five years depending on the fuel's type and burnup.

The principal risk associated with storing spent nuclear fuel in cooling ponds is a loss of cooling water. The disaster at Fukushima Nuclear Power Plant has demonstrated just how catastrophic the consequences of such an event could be in terms of radiation danger.

Another risk that accompanies SNF storage in cooling ponds is that of a spontaneous nuclear chain reaction, which may occur if spent fuel assemblies are stored in a "densified" mode – packed closely together – since water serves as a moderator. This is possible either due to a mistake made by reactor operators or as a result of an accident, such as, for instance, the accident that involved the storage pond in Russia's Andreyeva Bay (Zaozyorsk, Murmansk Region).

"Dry" storage implies using air or inert gas instead of water. Several design options exist for storage facilities based on the "dry" storage technology: cask-based storage facilities, reinforced concrete silos, concrete modular units, etc. "Dry" casks serve a variety of functions: storage proper, packing for transportation, or final disposal. There

are, furthermore, a rather large number of designs suggested for dual-purpose casks. The issue most critical for "dry" storage is that of acceptable storage temperature: it must not exceed 380-410 °C for zirconium alloys in an atmosphere filled with inert gas.

The "dry" storage method does not have the same disadvantages that are characteristic for "wet" storage, but it does nonetheless present a greater hazard in terms of radiation risks since the absence of water increases radiation exposure levels inside and outside the storage facilities.

Interim storage implies storage of spent nuclear fuel in temporary storage facilities at the reactor sites or elsewhere. These facilities could be both cooling ponds and "dry" modules that could allow for SNF transportation outside the reactor site. Interim storage facilities can have operational lifetimes well in excess of 50 years. In Russia, all nuclear power plants operating RBMK reactors, as well as Novovoronezh NPP, have interim storage facilities for accommodation and storage of spent nuclear fuel for periods of no less than 10 years. These facilities are located on NPP premises in separate buildings.

One other example of an interim SNF storage facility is the "dry" storage facility operated by Atomflot in Murmansk. Placed in storage there is spent nuclear fuel unloaded from the reactors of nuclear-powered submarines, naval cruisers, and icebreakers.

Geological disposal. No country regards long-term above-ground storage of spent nuclear fuel as a safe option suitable for long (over 100 years) periods of time. Spent fuel management policies adopted in France, Great Britain, Russia, and Japan are structured around the goal of researching and implementing options that would make it possible to close the nuclear fuel cycle – i.e. these countries lean toward SNF reprocessing. Other countries assume that spent fuel will have to be disposed of in geological repositories built hundreds of meters deep underground.

Many analysts believe spent fuel should be accommodated in geological repositories in special containers and within a controlled environment. Great uncertainties remain, however, with regard to all of the geological disposal options under consideration. The primary challenge is that it will be difficult to predict the short-term (first 100 years) behavior of the spent fuel placed in a repository. This is why the projects that have made the most progress investigating the geological disposal approach (for instance, research by Sweden's SKB) provide for easy retrieval of the fuel from its storage containers (see Appendix 5.3).

Building geological disposal facilities at three- to five-kilometer depths has today become possible with the advances made in the deep-hole drilling technologies. The challenges that arise with implementing this option – such as the need to ensure complete insulation of the fuel to protect it from groundwater, as water penetration can occur even in a granite monolith – can, theoretically, be solved. For instance, Sweden's SKB employs in its container manufacturing process special alloys that calculations show should resist the impact of increased humidity levels, temperature fluctuations, and corrosion for one million years. The long-term geological disposal technologies will thus likely continue in this trend since disposing of spent nuclear fuel in underground geological facilities is a safer option than holding SNF in storage in above-ground facilities.

5.1.2. Spent nuclear fuel accumulation and storage in Russia

Russia's spent nuclear fuel inventory is estimated at around 22,000 tHM, with some 850 tHM in new SNF generated each year. The forecast for future accumulated spent nuclear fuel in Russia is shown in Fig. 5.2.

Spent nuclear fuel varies in its isotopic composition. The typical isotopic compositions of spent fuel burnt in VVER-440 and VVER-1000 reactors are shown in Appendix 5.4.

The main contributors to Russia's SNF stock are currently: 32 reactors operating at

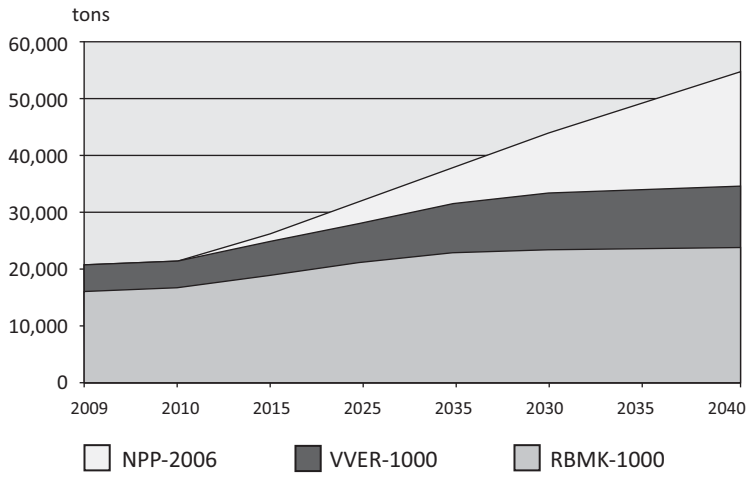


Fig. 5.2. Forecast growth in Russia's accumulated SNF inventory to 2040, with breakdown by reactor type.

Table 5.4. *Spent nuclear fuel (in tons) of various reactor types in storage at State Corporation Rosatom's enterprises (as of January 1, 2008).*

VVER-440		VVER-1000			RBMK-1000				BN-600	AMB	EGP-6	VVER-440, AMB	VVER-1000	Propulsion reactors
Kola NPP	Novovoronezh NPP	Novovoronezh NPP	Balakovo NPP	Rostov NPP	Kalinin NPP	Kursk NPP	Leningrad NPP	Smolensk NPP	Beloyarsk NPP	Beloyarsk NPP	Bilibino NPP	PA Mayak	Mining and Chemical Combine	Atomflot
75.4	73.9	138.5	400.3	98.2	222.1	4,612.0	4,485.2	2,372.1	35.9	190.9	140.9	463.6	4,871.6	5,541.0 SFAs

nuclear power plants (including ten VVER-1000s, six VVER-440s, eleven RBMK-1000s, four EGP-6s, and one BN-600); eight reactors operating on board of nuclear icebreakers; 20 to 30 nuclear-powered submarine and naval cruiser reactors; and around 53 (as of 2009) research reactors.

Detailed information on spent nuclear fuel generation at various reactors in operation and under construction in Russia is given in Appendix 5.5.

Temporary storage of spent nuclear fuel of various types is done in Russia at the nuclear power plants in operation (storage at the reactor sites and interim storage facilities), at the special storage facility operated by Production Association Mayak (Ozyorsk, Chelyabinsk Region), and at the "wet" and "dry" storage facilities run by the Mining and Chemical Combine (Zheleznogorsk, Krasnoyarsk Region). Russia's accumulated SNF is mostly concentrated at nuclear power plants and other Rosatom enterprises (see Table 5.4).

Production Association Mayak

The SNF storage facility at PA Mayak was commissioned in 1969. The facility is designed to accommodate and store spent nuclear fuel of propulsion reactors, reactors of the types VVER-440 and BN-600, and research reactors, with subsequent transfer of this SNF for reprocessing. Mayak's storage facility also holds spent nuclear fuel of AMB reactors, which is not suitable for reprocessing. At present, a total of around 500 tons of SNF has been accumulated at the facility. The site is operated by Mayak's SNF reprocessing plant (RT-1) and is part of its spent fuel preparation area.

Mining and Chemical Combine

In 1986, a storage facility with a capacity of 6,000 tons (uranium) was built at the Mining and Chemical Combine to store SNF from VVER-1000 reactors. At present, this facility is all but filled to capacity. Delivered here for storage is spent nuclear fuel from Russian nuclear power plants – Novovoronezh, Balakovo, and Kalinin NPPs, and the possibility is provided for accommodation of SNF from Rostov NPP. Additionally, the facility accepts for storage foreign spent nuclear fuel: SNF from Bulgaria (Kozloduy NPP) and Ukraine (South-Ukraine, Zaporizhzhya, Khmelnitsky, and Rivne NPPs). The facility's capacity is planned to be expanded to 8,600 tons.

As part of its plans regarding the Mining and Chemical Combine's near future, Rosatom is looking to commission there in 2015 a large "dry" air-cooled centralized storage site with a capacity of almost 26,510 tons to accommodate spent nuclear fuel from RBMK-1000 and VVER-1000 reactors. Fig. 5.3 shows a forecast for future placement of RBMK spent fuel for storage in this centralized facility. Filling of the site's start-up complex with spent nuclear fuel began in 2011. The removal of spent fuel from Russia's nuclear power plants and transportation to Zheleznogorsk's new storage facility is expected to take place throughout a period of over 20 years.

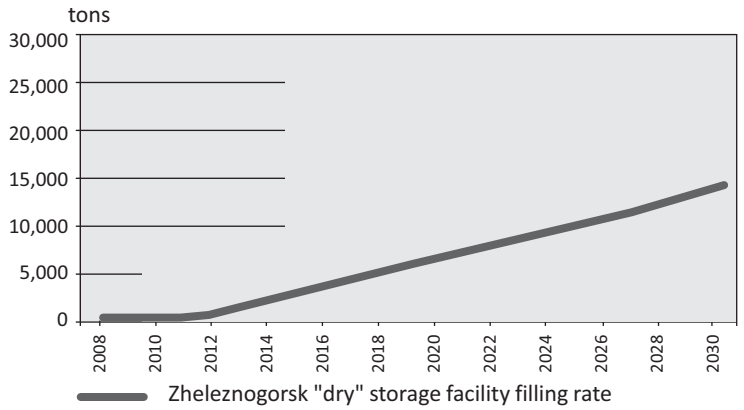


Fig. 5.3. Projected storage space filling rate at the Mining and Chemical Combine's "dry" storage facility, starting with its planned commissioning date.

5.1.3. Spent nuclear fuel transportation

Railroad is the main means of transportation used to ship spent nuclear fuel on the territories of nuclear states. According to the IAEA and national nuclear and radiation safety agencies, railroad SNF shipments provide sufficient safety during transportation. However, it is acknowledged that certain problems still warrant further consideration – such as those that may be associated with the threat of terrorism and the issues of shipping spent nuclear fuel across densely populated regions.

Maritime shipments are used when SNF is transported between nations or continents, such as between Japan and Europe, between mainland Europe and Great Britain, as well as between Russia and European countries. Certain countries ship their spent nuclear fuel by special vessels with routes lying along these countries' coastlines (for instance, Sweden).

IAEA rules do not prescribe against transporting SNF by aircraft, but they list a number of additional safety requirements, since an accident involving an aircraft with spent nuclear fuel on board may have much more severe consequences than one where land transport or a marine vessel is used. Estimates show that air shipments of spent nuclear fuel are rather rare and are only undertaken when failing to obtain approval for, or when it proves impossible for other reasons to arrange, cross-border delivery of the hazardous cargo by rail, or in similar extreme circumstances.

SNF transportation in Russia is done using all means of transportation: by rail, sea, air, and land. Each year, around 30 shipments of nuclear and radiation hazardous cargoes take place in Russia. Transportation risks have to do, first and foremost, with the poor condition of the country's roads. Russia's accident statistics for land, marine, and air transport are at least twice as high as those of developed nations. Furthermore, transport connections demonstrate a real vulnerability to terrorist risks. This is confirmed by the numerous terrorist attacks that have involved all means of transportation in use in Russia, including railroads. Additional risks arise with shipments carried out on routes that go near major cities and densely populated areas.

In railroad shipments, each kind of spent nuclear fuel is transported in the type of container car specifically designed to carry it. Altogether, 59 different container car designs are used for the transportation of spent fuel. SNF transportation routes involve, as a rule, deliveries from nuclear power plants to PA Mayak and to the storage facility in Krasnoyarsk. Additionally, some 700 kg (uranium) of spent fuel is moved annually to Mayak from the storage facilities of the Northern and Pacific Fleets. A general overview of shipping casks used for SNF transportation is given in Appendix 5.6.

Railroad shipments are expected to expand in the next several years as Rosatom is planning massive removal of spent fuel from storage facilities at nuclear power plants and its transportation to the Mining and Chemical Combine and Mayak. An effort of similar scale – no fewer than 35 special delivery trains – is also planned in Russia's north as part of an SNF removal project in Andreyeva Bay (SevRAO, Branch No. 1), where some 21,000 spent fuel assemblies from submarine reactors have accumulated in storage.

SNF transportation by sea is done in Russia's Northwest and in the Far East, as Russia's nuclear-powered submarines and surface ships are stationed in these regions. These shipments usually proceed between naval bases and shiprepairing yards located along the coastline. In the north, these are short-distance routes: Polyarny (Shiprepairing Yard 10), Snezhnogorsk (Shiprepairing Yard Nerpa), Zaozyorsk (SevRAO, Branch No. 1), Ostrovnoi (SevRAO, Branch No. 2), with the port of Murmansk as the destination. Transportation has been carried out both by Atomflot's civilian nuclear support vessels (*Lepse, Imandra, Lotta,* and *Serebryanka*) and by the Navy's floating maintenance facilities.

The first SNF shipment that was sent along the Northern Sea Route was done in 1998 on board of the motor ship *Kandalaksha* (Murmansk Shipping Company) from the port of Dudinka to Murmansk. The cargo, packed in TUK-19 transport casks, was 71 spent nuclear fuel assemblies from a research reactor operated by Norilsk Nickel. The vessel did not have the required class certification for transportation of hazardous cargoes as per the Russian classification standards, nor according to any of the standards of the international INF Code (as per the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships, or the INF Code, vessels are to be issued an International Certificate of Fitness to be assigned one of three INF classes to transport such cargoes (see Appendix 5.7); the Russian equivalent of this international certificate is the designation «ОЯТ» (for SNF)).

In 2003, the government of the Russian Federation approved the following list of sea ports authorized to accept for entry and exit vessels and other watercraft transporting nuclear materials, radioactive substances, and cargoes containing such substances, in TUK transport packages (handling Class 7 hazardous cargoes): Arkhangelsk, Bolshoi Kamen, Vysotsk, Dikson, Dudinka, Kaliningrad, Kandalaksha, Murmansk, Pevek, Provideniya, St. Petersburg, and Ust-Luga. In 2010, the ports of Vostochny and Vanino were added to this list. Of the ports named above, Murmansk is the only port meeting all the safety requirements, since its harbor includes terminals operated by Atomflot, which has the necessary railroad access lines, cargo-lifting equipment, and physical security systems at its disposal.

Transportation of spent nuclear fuel by sea between Russia and other states is carried out today, mostly, in accordance with international contracts that require the repatriation of spent fuel from nuclear power plants and research reactors built by Russia (Soviet Union) in other states back to the Russian Federation.

In the fall of 2008, as part of the repatriation program of Russian-design research reactor SNF, a first shipment of SNF was delivered by sea from Slovenia's Koper to Murmansk. The spent fuel from a research reactor in Hungary was delivered by the vessel *Lynx* (Class INF 2 certificate), flying the flag of Denmark. The SNF (1.7 tons) was packaged in transport casks of the type SKODA VPVR/M, which, in turn, were tommed off inside 20 ft reinforced ISO containers. In late 2010, the vessel *Puma*, also flying the flag of Denmark, used the same route to deliver to Murmansk 2.5 tons of spent fuel from the Serbian RA research reactor in Vinča. In 2009, the Russian vessel *MCL Trader* was retrofitted to comply with the international Class INF 2 requirements for transportation of spent nuclear fuel. In 2009 and 2010 this vessel was used to carry out five maritime shipments of spent nuclear fuel (25.5 tons) from Polish research reactors from Poland's Gdynia to Murmansk. These shipments were handled by the Russian shipping company ASPOL Baltic Corporation.

In August 2011, Atomflot took delivery of a new ice class vessel, *Rossita*, a ship designed specifically to transport spent nuclear fuel and radioactive waste (see Appendix 5.8). The vessel was built by the Italian shipbuilding company Fincantieri and is expected to transport cargoes in the North Atlantic region as well as the Barents and White Seas between Murmansk, Andreyeva Bay, Sayda Bay, the closed administrative territorial entity Ostrovnoy, and Severodvinsk. *Rossita* should be able to fully accomplish the task of shipping spent nuclear fuel and radioactive waste for the period of cleanup and remediation works in Russia's Northwest.

Russia is also developing the option of transporting hazardous cargoes by seagoing train ferries, using the roll-on/roll-off method, or of retrofitting vessels to meet the equivalent requirements. River-sea ships are also under consideration for their potential use in the transportation of spent nuclear fuel and radioactive waste, as operating combined navigation vessels along the Northern Sea Route could reduce shipping distances substantially.

The risks of transporting spent nuclear fuel by sea are rather significant. For instance, in December 2001, due to difficult weather conditions and violent wind, the floating maintenance facility *Imandra*, while crossing the harbor of the shiprepairing yard Nerpa (Snezhnogorsk, Murmansk Region) with a cargo of spent nuclear fuel on board, fell on board a decommissioned nuclear submarine moored at the dock and sustained a hole at the waterline as a result. The crew of the *Imandra* and the rescue services managed to prevent the more severe consequences of the collision.

Air deliveries of spent fuel into Russia (PA Mayak) took place in 1993 and 1994 and involved shipments of spent fuel from the Iraqi IRT-5000 research reactor. These were shipments warranted by the extraordinary circumstances caused by the 1991 Gulf War.

In June 2009, a first certified shipment of spent fuel by air transport delivered SNF from Romania's VVR-S research reactor. An AN-124-100 transport plane brought the 70 spent fuel assemblies (around 25 kg uranium) from Romania in 18 TUK-19 transport casks accommodated in six special-purpose 20 ft ISO containers. The total cost of the project was over $10 million. A similar shipment of spent fuel was carried out in 2009, when 26 spent fuel assemblies were delivered from Libya's IRT-10 reactor. Shipments by air have apparently been done in other cases as well when spent fuel had to be repatriated from land-locked countries – such as from Hungary, but data on these deliveries are not available.

Using air transport to ship spent nuclear fuel in any regular manner is undoubtedly a very expensive option, which is unlikely to see broad application in the near future unless a delivery by this method is necessitated by an emergency.

Road transport for SNF shipments is used primarily on short-distance routes – for instance, between nuclear power sites, where the TUK shipping packages are loaded, and transshipment points, where they are transferred onto a special-purpose train or vessel, or plane. Trucking heavy and hazardous cargoes such as spent nuclear fuel requires special equipment and additional safety and security means.

Deliveries of SNF carried by trucks through city streets, even with police escort, present a grave risk – though such shipments have taken place in Russian regions (for instance, up to the mid-1990s, trucks used to transport spent nuclear fuel in Murmansk to distances of around 5 km, including routes crossing residential city blocks, carrying the shipments from Atomflot's premises to the railroad loading docks).

5.2. Spent nuclear fuel reprocessing

Spent nuclear fuel reprocessing began with the goal of separating plutonium for use in nuclear weapons. But in the 1960s, many countries with nuclear power programs regarded reprocessing their spent fuel as a way to use the recovered uranium and plutonium for fabrication of fresh fuel. Proponents of reprocessing argued vigorously that natural uranium reserves were being depleted, and that the uranium and plutonium retrieved from spent fuel during reprocessing would be the main source of fuel for nuclear power plants. Today, with uranium reserves evaluations revised, these arguments have faded.

Before the Fukushima disaster, only five nations – France, Great Britain, Russia, Japan, and India – intended to remain committed to their SNF management policies, geared toward SNF reprocessing and closing the nuclear fuel cycle.

The catastrophe at Fukushima Daiichi caused Japan to revisit its nuclear policy, and the government has announced it was closing its fast reactor program, and that it would subsequently phase out nuclear energy completely before the year 2050. The fate of the Rokkasho facility, which was supposed to be commissioned in 2012, is now left suspended.

Great Britain is reducing its reprocessing capacity. In August 2011, the Nuclear Decommissioning Authority (NDA) said it would soon shut down the MOX fabrication facility in Sellafield. The main reason was the enterprise's unprofitability. The post-Fukushima closure of nuclear power plants in Japan is expected eventually to affect reprocessing volumes at Sellafield.

India has limited SNF reprocessing capacity and unclear prospects of expanding it in the future.

Russia is pursuing a hardline SNF reprocessing policy, with plans to build the reprocessing plant RT-2 and introduce a spent nuclear fuel management bill where this policy would be codified on a legislative level. The position of Rosatom's current leadership is based on the rationale that reprocessing spent nuclear fuel in Russia is a promising international business project. In reality, a lot will depend on the economic situation and on how successful the technologies that Russia intends to use first at its Pilot Demonstration Center, and then, at RT-2, prove to be.

The data listed in Table 5.5 show design-basis capacities of SNF reprocessing facilities worldwide, though none of these enterprises have, as a rule, ever achieved outputs matching their stated capacities.

Table 5.5. *Global SNF reprocessing capacity.*

SNF type	Country	Facility	Capacity, in tons per year
SNF from light water reactors	France	UP2, UP3, La Hague	1,700
	Great Britain	THORP, Sellafield	900
	Russia	RT-1, Mayak, Ozyorsk	400
	Japan	Rokkasho	800*
SNF from other reactor types	Great Britain	Magnox, Sellafield	1,500
	India	PHWR, Tarapur	330
Total (estimates):			**5,630**

* Commissioning expected in late 2012.

Overall, around 4,000 tons of spent nuclear fuel unloaded from commercial reactors is currently reprocessed worldwide. The amount of SNF reprocessed to date is estimated at 90,000 tons (out of a total of 250,000 tons already accumulated). The SNF accumulation rate is not declining, but is in fact likely to grow. With the current capacity of the world's reprocessing facilities, the global stockpile of SNF may reach up to 400,000 tons by 2030, including 60,000 tons stored in the United States, 69,000 tons accumulated in Europe, and 40,000 tons in Russia.

5.2.1. Spent nuclear fuel reprocessing technologies

The world has been developing and applying a variety of spent fuel reprocessing technologies for over 60 years. The reprocessing techniques used by different countries mostly differ in the decladding methods (separating the fuel composition from the fuel cladding) and extraction methods, the latter used to separate the needed components of the fuel composition.

A general flow sheet of reprocessing irradiated uranium fuel is shown in Fig. 5.4.

The existing decladding methods fall into two categories: those where the fuel assembly is mechanically opened to free the fuel section from the cladding material (mechanical method) and methods that do not involve mechanically separating the cladding from the fuel composition inside (aqueous chemical methods).

The mechanical decladding method implies the removal of the fuel cladding and other structural materials before dissolving the nuclear fuel inside. The process takes place in several stages: First, the top and bottom nozzles are cut off from the fuel assembly, and it is disassembled into separate fuel rod bundles and then into individual rods, then the fuel cladding is mechanically removed from each of the fuel rods.

Aqueous chemical methods allow for the dissolution of the cladding material in acids or acid mixtures without affecting the fuel stacks in the fuel rods. Fuel rods fabricated for modern reactors have cladding made of corrosion-resistant, poorly soluble materials – zirconium, zirconium-tin and zirconium-niobium alloys, or stainless steel. Selective dissolution of these materials

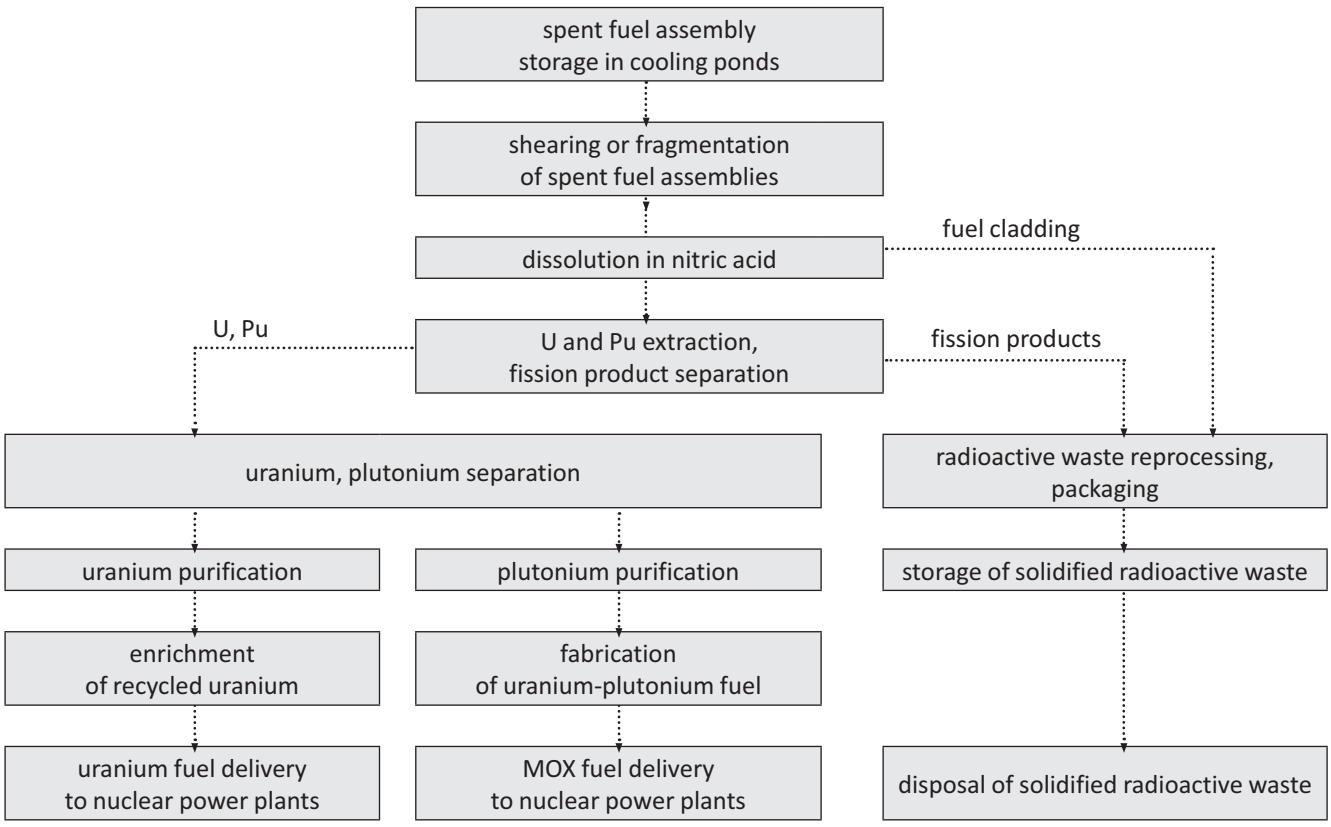


Fig. 5.4. A simplified SNF reprocessing flow chart.

is only possible using highly aggressive environments. Zirconium is dissolved using hydrofluoric acid, or by mixing it with oxalic acid or nitric acid, or in a NH_4F solution. A stainless steel cladding is dissolved in boiling sulfuric acid H_2SO_4.

The main disadvantage of the chemical decladding process is the generation of large amounts of high-salinity liquid radioactive waste. In order to reduce this decladding waste and have it generated already in solidified form, and thus better suited for long-term storage, methods are being developed where decladding is done using non-aqueous reagents at high temperatures (pyrochemical processes).

Besides the methods mentioned above, a combined fragmentation/dissolution method is currently applied (see Appendix 5.9): Fuel assemblies are sheared into small pieces, and the fuel composition thus becomes accessible for treatment by chemical reagents and dissolution in nitric acid. The undissolved cladding fragments are scrubbed to remove the remainders of the leach solution and disposed of as scrap.

For **solvent extraction**, i.e. separation of the fuel components, two processes are used: PUREX (for "plutonium-uranium recovery by extraction") and REDOX (for "reduction-oxidation"). Under these processes, the feed nitrate solution of uranium, plutonium, and fission products undergoes treatment with solvent extractants in order to separate uranium and plutonium from the bulk of the fission products.

The next stage is a second extraction cycle, during which uranium and plutonium are further purified from fission products, neptunium, and from each other to levels meeting the required fuel cycle specifications. The uranium and plutonium are then transformed into commodities suitable for subsequent use.

The Civex process is an extraction process where nuclear fuel is recycled without separating plutonium. Under this SNF reprocessing method, plutonium is not at any stage fully separated from the uranium and fission products in the treated spent fuel, which complicates significantly the possibility to use it for military purposes.

In order to reduce the ecological burden of SNF reprocessing, non-aqueous technological processes are being developed. The advantages of the non-aqueous alternative are that these processes are compact, do not involve the use of large quantities of solvent extractants or generate large amounts of liquid radioactive waste, and are associated with a lesser impact from the radiation decomposition processes. The resulting waste is in solidified form and occupies much less space.

This approach to spent nuclear fuel reprocessing is expected to be used at future reprocessing facilities under construction or development, such as Russia's RT-2 plant and Japan's Rokkasho.

5.2.2. Spent nuclear fuel reprocessing in Russia

In Russia, spent fuel assemblies unloaded from commercial reactors are reprocessed at radiochemical facilities operated by these three enterprises: Siberian Chemical Combine (radiochemical plant), Mining and Chemical Combine (mining and chemical plant), and Production Association Mayak (radiochemical plant).

The only plant that reprocesses spent nuclear fuel from power, research, and propulsion reactors is the RT-1 plant at Mayak (Ozyorsk, Chelyabinsk Region), a facility that came online in 1977. In all the years of operation, the RT-1 plant has never reached full design-basis capacity (400 tons per year); in 2008 and 2009, reprocessing throughput was 66 tons and 94 tons, respectively.

The aqueous extraction process flow used at RT-1 for SNF reprocessing is similar to a classical version of the PUREX process (see Fig. 5.5).

SNF reprocessing is done with the purpose of producing plutonium oxide, triuranium octoxide, and uranyl nitrate hexahydrate melt $[UO_2(NO_3)_2 6H_2O]$. From the "wet" storage pond, spent fuel assemblies arrive for disassembly – where the end fittings of the fuel rods are cut off (electric arc cutting) – and then are transferred further on for fragmentation. The resulting mix of fuel and metal cladding pieces is fed to a dissolution apparatus, which yields the process solution – a slurry consisting of many components. The clarification and filtering stages follow. Separation of the desired components is done using multi-stage extraction processes with subsequent precipitation of the required chemical compounds of uranium, plutonium, and neptunium. This is the process flow used to recycle spent nuclear fuel from VVER-440 reactors. Similar processes are used at reprocessing facilities in France and Great Britain.

The uranium and plutonium produced as a result of reprocessing at RT-1 are currently

used for fabrication of fresh nuclear fuel, including MOX fuel.

Radiochemical treatment of spent nuclear fuel at the RT-1 plant is an environmentally dirty process, which is associated with radiation hazards and results in the generation of the bulk of Russia's solid, liquid, and gaseous radioactive waste of various levels of activity (see Table 5.6). Liquid high-level radioactive waste makes up 95% of the generated waste's total radioactivity; solid waste accounts for 1%; the share of liquid intermediate-level waste in total waste's radioactivity is around 5%; and low-level liquid waste contributes 0.01%. The radioactivity of reprocessing waste is due, primarily, to the content of such radionuclides as strontium-90 and cesium-137.

Since it started operations, RT-1 has reprocessed a total of around 4,500 tons of spent nuclear fuel from VVER-440 reactors, as well as research and propulsion reactor SNF. The overall amount of radioactive waste generated during reprocessing totals over 1.5 million cubic meters in high-level liquid radioactive waste, over 4 million cubic meters of intermediate-level waste, and around 54 million cubic meters of low-level waste. As of end 2011, Mayak was holding in storage around 6,000 tons of vitrified high-level waste with a total radioactivity of around 637 Ci (2.4×10^{19} Bq).

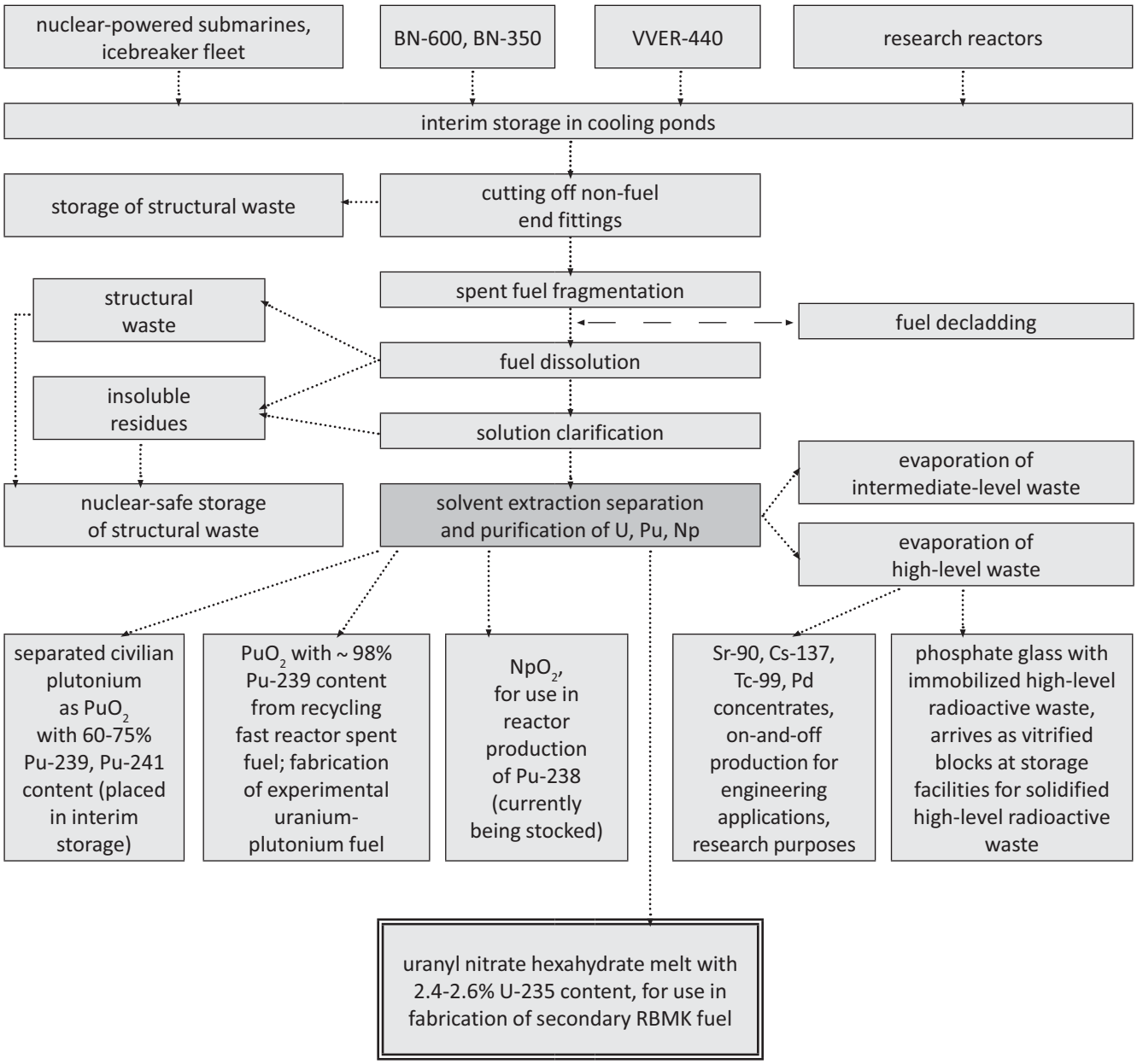


Fig. 5.5. A flow sheet of spent nuclear fuel reprocessing in Russia.

Table 5.6. *Specific volumes of liquid radioactive waste generated per one ton of regenerated fuel (RT-1 Plant).*

SNF type	LRW type	Average LRW volume, m^3/t	Standard deviation, m^3/t
VVER-440	Low-level LRW	2,000.0	707.1
	Intermediate-level LRW	150.0	12.4
	High-level LRW	45.0	2.3
BN	Low-level LRW	1,552.0	413.0
	Intermediate-level LRW	59.0	9.38
	High-level LRW	31.0	14.4

The design of the reprocessing plant RT-2, intended to handle spent VVER-1000 fuel, was developed by the VNIPIET institute. Construction of the plant started in 1979. A complex of SNF management facilities was created for the transportation, reception, and storage of spent fuel, of which the main one is the "wet" (water-cooled) SNF storage facility with a design-basis capacity of 3,000 tons. In December 1985, the cooling pond accepted its first delivery of VVER-1000 SNF from Novovoronezh NPP. The storage facility became part of the RT-2 plant among other RT-2 facilities in operation. Other RT-2 sites were also at various stages of completion. Since 1991, construction was repeatedly halted due to funding difficulties and was eventually abandoned.

Currently under development at RT-2 is the Pilot Demonstration Center, a facility expected to introduce innovative SNF reprocessing technologies and become the basis for a future SNF reprocessing plant with a reprocessing capacity starting at 1,500 tons a year. The first stage of the new facility, with an annual capacity of 100 tons, is slated for commissioning in 2017.

The technologies being developed for use at the Pilot Demonstration Center are deemed to be third-generation technologies that ensure a considerable – potentially, ten-fold – reduction in the generation of low-level radioactive waste, as this waste remains today the major problem.

It is claimed that the future Pilot Demonstration Center will base its operations on technologies that are unrivaled anywhere in the world, such as:

– thermochemical fragmentation of spent nuclear fuel assemblies (so-called Khrust);

– SNF voloxidation for tritium removal and spent oxide fuel activation;

– two-loop evaporation of liquid radioactive waste resulting from SNF reprocessing, complete with isolation of the tritium-containing stream;

– two-stage uranium and plutonium separation process, with plutonium withdrawn from the main cycle in the form of concentrated uranium-plutonium stream;

– mass transfer separation processes;

– purification by isohydric crystallization of uranyl nitrate.

The technologies currently being tested at the Mining and Chemical Combine are the Simplified PUREX Process – which is being used as a baseline process for SNF reprocessing – as well as thermochemical fragmentation, high-level waste vitrification etc.

Based on the results of studies and projects conducted in the course of the Pilot Demonstration Center's activities, a decision is expected to be made (no earlier than 2020) on the possible construction of a full-scale production facility for radiochemical treatment of spent nuclear fuel (the RT-2 plant), with the Pilot Demonstration Center subsequently used for reprocessing of damaged spent fuel as well as for the development and testing of radiochemical technologies of various purposes.

Full confidence is lacking, however, within Rosatom as to whether these technologies prove to be a success.

5.3. SNF management policies and economic aspects

For most countries with nuclear energy programs, the development and application of policy strategies designed to deal with spent nuclear fuel have been a constant priority for a great many years. All countries understand that if the task of safely isolating nuclear and radioactive waste is not solved, then they will have to shrink their nuclear programs or even shut them down entirely. This is why nuclear nations today are working toward achieving two major objectives:

ensure that spent nuclear fuel is managed in an environmentally acceptable manner and that nuclear materials regenerated out of this spent fuel are reincorporated into the nuclear fuel cycle.

The first of these problems concerns every country that uses nuclear energy. The second is only relevant in countries that are still engaged in spent nuclear fuel reprocessing – i.e., France, Great Britain, Russia, Japan, and India. China, too, intends to build a commercial SNF reprocessing facility, and is currently building a pilot reprocessing plant, where hot tests were performed in late 2010.

An environmentally acceptable SNF management concept implies that nuclear countries, first and foremost, will have to agree on the main principles regarding the transportation, storage, and disposal of spent fuel. An important step toward finding solutions to this problem was made when the Council of Europe adopted the Radioactive Waste and Spent Fuel Management Directive, which establishes radioactive waste and spent fuel safety standards enforceable in the European Union. According to the Directive, the fourteen European Union member states that have nuclear energy programs are to develop and present by 2015 national programs with specific descriptions of the radioactive waste and spent nuclear fuel storage and reprocessing options that they deem preferable. The Directive received a mixed public response since it includes a regulation permitting (with certain provisos) transportation of radioactive waste across national borders. The position endorsed by non-governmental organizations is unequivocal: Countries that use nuclear energy must bear their own costs, including costs incurred with accumulating radioactive waste and spent nuclear fuel.

Any business related to the transportation, storage, or disposal of nuclear and radioactive waste in countries that do not produce this waste is unacceptable for society. A discussion, therefore, continues with regard to the possibility of creating international storage facilities or repositories for spent nuclear fuel. It is obvious that the idea of creating such a site has dim prospects because it will entail strong public opposition and face the same problems that nuclear nations encounter when building their own domestic storage facilities (situations of this kind have been observed in the United States, Germany, and other countries). Almost all states will first have to secure the approval of their municipal authorities and the public. Finland's Nuclear Energy Act, for instance, entitles the country's municipalities to the right to veto siting decisions regarding any nuclear facilities, including storage sites, in their areas.

At the same time, there is practically no doubt that the task of disposing of spent nuclear fuel calls for the use of geological repositories. The biggest advances in this field have been made by Scandinavian countries, which, finding that they could not rely on a prospect of seeing international storage facilities built, started to make steps toward developing their own. In March 2011, the Swedish Nuclear Fuel and Waste Management Company (SKB) applied for a license to build a spent nuclear fuel geological repository, to be sited in Östhammar. The construction is expected to start in 2015, and disposal operations to begin in 2025. In Finland, at the Olkiluoto NPP site, a 4,570-meter tunnel completed at the end of 2010 leads to a facility called Onkalo, located at the final disposal depth of 434 meters. Initially, the Onkalo facility is planned to be operated as an underground laboratory to study the properties of the hard rock at the site and determine the site's suitability for the purpose of geological disposal. Later, the access tunnel and Onkalo's other underground facilities will be used for disposal of spent nuclear fuel. A licensing application to begin construction of the repository is expected to be submitted in 2012, and the process of securing an operating license for the site will start after 2020.

Still, Sweden and Finland remain the world's only two countries to have made some progress toward finding solutions to the problems of controlled geological disposal of spent nuclear fuel. In other states, the development of spent nuclear fuel repositories or disposal facilities remains a task deferred at least by a few decades into the future.

Certain countries are favoring the option of creating near-surface facilities for interim – decades-long – storage of nuclear and radioactive waste. For instance, Spain decided to build in the municipality of Villar de Cañas a central storage facility to accommodate spent nuclear fuel and radioactive waste from eight Spanish reactor units. Spain's national SNF and radioactive waste management entity Enresa said the storage facility is intended to hold for a period of up to 100 years 6,700 tons of spent nuclear fuel, 2,600 m^3 of intermediate-level waste, and 12 m^3 of high-level radioactive waste generated as a result of reprocessing

in France of spent nuclear fuel from the gas-graphite reactor Vandellòs I. The project is estimated at EUR 700 million.

Less than 25% of spent nuclear fuel unloaded from nuclear reactors worldwide is allocated for reprocessing; in Russia, that share is less than 15%. The amount of spent nuclear fuel accumulated in the world is rising drastically; and the SNF already accumulated will have to be stored for longer periods than initially intended, with storage periods in interim "dry" cask storage exceeding 100 years. This, in turn, will result in the need to step up research into SNF integrity for the duration of long-term storage periods and in the need for additional studies of spent nuclear fuel's behavior in "dry" storage facilities.

As regards the issues of import and export of spent nuclear fuel, France, Great Britain, and Russia import spent fuel from other countries, including for reprocessing and storage (in Russia's case only). France and Great Britain, in most cases, send reprocessing products (including uranium, plutonium, and radioactive waste) back to the country of origin, since laws adopted both in France and Great Britain contain the requirement that no radioactive waste – either from other countries or that generated during reprocessing of foreign SNF or radioactive waste – shall remain in storage after handling in these countries. No spent nuclear fuel or radioactive materials may be imported into France or Great Britain other than for the purpose of reprocessing, research, or transit transportation between states.

Russia imports, for storage, disposal, and reprocessing, spent nuclear fuel discharged from reactors built by Russia (the USSR) abroad without sending back the radioactive waste generated during reprocessing. At least, there is no openly available information on repatriation of radioactive waste back to the countries where the spent nuclear fuel has been imported from.

Nuclear policy strategies are dictated by the world's key nuclear players that continue, or intend to continue in the near future, to reprocess spent nuclear fuel (France, Great Britain, Russia, Japan, India, and China), countries that are planning direct disposal of spent nuclear fuel (Canada, Germany, the United States, Finland, and Sweden), as well as South Korea, which has yet to adopt a clear SNF management policy.

France is reprocessing its spent uranium fuel and using the recovered plutonium in MOX fuel for light water reactors. The spent MOX fuel is being stored pending commercialization of fast breeder reactors. France is planning a geological repository for its high-level, long-lived waste in a clay formation at Bure, aiming for a start up of repository operations by 2025.

The **United Kingdom** has been reprocessing all the uranium-metal spent fuel from its gas-cooled graphite-moderated reactors, the last of which are to be shut down by 2012. It is also reprocessing a significant quantity of the uranium-oxide fuel discharged from its second-generation advanced gas-cooled reactors. There are no final plans on how to manage the UK's approximately 100 tons of separated plutonium: It might be used as MOX fuel in a proposed new generation of LWRs. A new MOX fuel fabrication facility is being built at Sellafield for this purpose. The UK has for many decades been struggling with site selection for an interim (100 years) SNF storage facility to hold the high-level, long-lived radionuclides generated during reprocessing.

Japan, after the disaster at Fukushima Daiichi, announced that its prospective nuclear policy would provide for continued construction of those nuclear power plants that are already at the last stages of completion, but that no new NPP projects would be initiated. Furthermore, according to the decision made by Japan's parliament and government, the country is to phase out nuclear energy completely before 2050. Regardless of whether these decisions are carried out, it seems apparent that the prior policy, geared as it was toward speedy development of nuclear energy and SNF reprocessing, is in for significant adjustments. The SNF reprocessing plant and "dry" cask storage facility at Rokkasho should have been commissioned in 2012, but there is yet no information on whether that in fact happened. Japan is also looking to select a suitable location for geological disposal of its high-level waste.

China (Taiwan) today is the site of the most vigorous NPP construction. As of end 2010, 28 reactor units were under construction in China, and construction of ten of these had also started in 2010. At the same time, having little experience operating nuclear power plants – 111 years/13 reactors – China has yet to determine a clear future policy regarding spent nuclear fuel management. China currently has no long-term (100 years) storage facilities or repositories for its spent nuclear fuel or radioactive waste, but it is building a pilot SNF reprocessing plant and is also planning to build a commercial SNF reprocessing facility,

with the latter project being at the moment only at the site selection stage.

Germany is in the process of nuclear phase-out. Its accumulated SNF is collected at an interim storage site in Gorleben, where it will be stored pending ultimate disposal. No site for a geological repository has been selected yet.

Canada stores its spent nuclear fuel at the reactor sites. In 2010, after specific criteria and requirements had been developed for a geological SNF repository, a site selection process began and a search for a community willing to host the future site.

Sweden and Finland are planning to use a shared approach of disposing of their spent nuclear fuel in casks made of special alloy and placed inside deep geological repositories, where the waste is expected to remain in a controlled environment.

The United States has been trying, with no success, to find a suitable repository site for its spent nuclear fuel and radioactive waste since 1970.

Approximately $15 billion was spent preparing the technical basis for a license application for a site at Yucca Mountain, Nevada, but in 2010 the Obama Administration halted the project. Currently, almost all spent fuel remains at the reactor sites, with "dry" cask storage for older spent fuel being deployed as the cooling ponds fill up. In January 2010, as a first step toward establishing a new U.S. spent fuel policy, a special commission was created to conduct a comprehensive review of current policies and to produce a report with recommendations for developing a safe, long-term solution for the management of the country's spent nuclear fuel and radioactive waste.

5.4. The strategy for creating a national SNF management system in Russia

In November 2011, Rosatom's Governing Board reviewed the main provisions of the "Strategy for the Development of the Back End of the Life Cycle of Sites and Materials Involved in the Use of Atomic Energy until 2030."

One of the major objectives of the Back End Strategy is creating state-governed SNF and radioactive waste management systems and solving the issues of the Russian nuclear legacy. The Strategy underlines that final disposition of spent nuclear fuel requires the development of relevant infrastructure and is ultimately tied to the issue of the choice of the nuclear fuel cycle.

At the same time, Russia's nuclear industry has yet to form a unanimous opinion regarding the type of the future nuclear fuel cycle, which has a direct impact on the SNF management strategy to be settled on. The main nuclear fuel cycle alternatives are:

– open nuclear fuel cycle, which implies disposing of spent nuclear fuel in stable geological formations;

– fully or partially closed nuclear fuel cycle, which implies reprocessing spent nuclear fuel for the purpose of extracting regenerated uranium and civilian plutonium – products suitable for further use and for separation of high-level radioactive waste from them.

In order to choose its nuclear fuel cycle, Russia will need to conduct research and development work to identify promising reprocessing (storage, disposal) technologies, an analysis of the full cost of nuclear-generated power, and environmental impact assessment studies with regard to the different nuclear fuel cycle options. Furthermore, as of today, Russia has no regulatory framework governing the issues of SNF management, no legislation codifying the responsibility of entities that generate spent nuclear fuel, nor any established mechanisms of financial and economic interaction between the participants of this process. Funding allocated to projects related to SNF management, as well as to those aimed at addressing the problems of legacy spent nuclear fuel, is provided exclusively at the expense of the state budget as part of Federal Target Programs for Nuclear and Radiation Safety.

The comprehensive long-term (until 2070) National Strategy for the development of the back end of the nuclear fuel cycle, currently under development in Russia, is hoped to provide solutions to the problems of legacy SNF as well as those of creating an SNF management structure and establishing the needed regulatory framework. The main challenge posed by the search for solutions to these strategic tasks has to do with the spent nuclear fuel infrastructure – which depends entirely on the type of the fuel cycle chosen. The expanded version offers for consideration these four fuel cycle alternatives:

1) a combined closed nuclear fuel cycle based on fast reactors (FR) and thermal neutron reactors (TNR), which involves: reprocessing TNR spent nuclear fuel, fabrication of initial MOX fuel loads for

FR, reprocessing FR spent nuclear fuel, and fabrication of subsequent FR fuel loads out of reprocessing products;

2) MOX-fueled TNR cycle, which involves: reprocessing TNR spent nuclear fuel, fabrication of MOX fuel for TNR, and subsequent long-term storage or disposal of spent MOX fuel in a geological repository;
3) FR and TNR MOX cycle with plutonium incineration, which involves: reprocessing TNR spent nuclear fuel, fabrication of MOX fuel for FR (with possible fabrication of MOX fuel for TNR and reprocessing spent MOX fuel for TNR as a middle step), and subsequent long-term storage or disposal of FR spent MOX fuel in a geological repository;
4) long-term storage /disposal cycle, which involves: long-term storage of spent nuclear fuel and/or disposal of spent nuclear fuel in geological repositories with the retrieval option.

The technologies and economic assessments available today are insufficient for the effort to make a clear determination as to the type of the fuel cycle, and, by extension, the needed SNF management infrastructure. Therefore, a decision has been made that the choice of the nuclear fuel cycle for Russia will be made by clearing consecutively the following key points in the decision-making process:

– **2015:** decision with regard to the construction of a pilot series of fast neutron reactors; condition for clearing this juncture: economic and technological efficiency of the BN-1200 reactor project;

– **2020:** decision with regard to the construction of an industrial-scale TNR spent fuel reprocessing line; condition for clearing this juncture: the assessment of the full cost of SNF management based on potentially available nuclear fuel cycle alternatives;

– **2030:** decision with regard to further expansion of fast neutron reactor installed capacities; condition for clearing this juncture: factual data on the full cost of a closed fuel cycle.

State Corporation Rosatom is leaning toward a baseline scenario that relies on the first alternative, i.e. closing the nuclear fuel cycle by using the closed nuclear fuel cycle of fast reactors (Scenario 1). It is, however, stipulated that should no economically feasible technological solutions be made available before 2030 to implement Scenario 1, then the possibility must be provided for the implementation of the deferred decision (SNF disposal with the retrieval option) – i.e., moving to Scenario 4. Additionally, a plan of the following key decisions, with respective implementation dates, has been developed for Scenario 1:

– **2015:** completing design specifications and estimates for the fast neutron reactor project, with substantiation of the choice of coolant with respect to safety and an assessment of future capital costs;

– **2020:** collecting the results of tests performed with TNR spent nuclear fuel reprocessing technologies at the Pilot Demonstration Center; completing the design of an industrial-scale TNR SNF reprocessing plant; collecting the results of R&D work conducted on the TNR MOX option and technologies and on the technologies of immobilization and disposal of high-level radioactive waste, as well as results of the analysis of the full cost of electric power generated using different nuclear fuel cycle alternatives;

– **2030:** collecting the results of studies on the possibility of final SNF disposal in a geological intermediate- and high-level radioactive waste repository, results of TNR MOX fuel tests, results of operating the pilot fast reactor series, and results of developing and testing the closed FR fuel cycle reference technologies at a multifunctional radiochemical complex; completing the design of an industrial FR and/or TNR MOX fuel reprocessing and fabrication plant.

Therefore, should negative results on these activities be received in the specified time frames, Russia will have to adopt the long-term storage/disposal policy, which implies long-term storage of spent nuclear fuel and/or disposal of spent nuclear fuel in geological repositories with the retrieval option.

5.4.1. Creating business opportunities in the SNF management sector

The National Strategy provides for the possibility of developing commercial opportunities in the field of spent nuclear fuel management. Rosatom's chief goal is to become a major market player with a global presence and a focus on offering fuel leasing services for new nuclear countries, reprocessing services for countries operating VVER reactors, and sale of technologies developed for the SNF management industry. The Strategy states that if Russia successfully

develops the closed nuclear fuel cycle based on fast reactors, the main service provided in the SNF management sector will be fuel leasing (taking back spent fuel for reprocessing, with reprocessing products remaining in Russia). It is noted, however, that business development in this direction will depend on whether SNF reprocessing services will prove attractive enough economically (cost of reprocessing) for foreign customers, and the SNF reprocessing contract portfolio strong enough, to sustain the operation of an industrial-scale SNF reprocessing capacity long term.

According to Rosatom, the state will have to assume the risks associated with developing the SNF management infrastructure. The reason for that is that a large spent fuel stock was accumulated by the country's nuclear industrial complex during the Soviet era, and it is at this time impossible, both in terms of time and economic constraints, to ensure the allocation of the funding necessary to address the spent nuclear fuel problems by the enterprises of the nuclear industry.

State Corporation Rosatom anticipates that the successful implementation of the domestic fast reactor construction program will ensure Russia an SNF business market with a potential estimated at $25 billion in 2010 dollars. Currently, the gap between this potential market and the one that actually exists is only due to the lack of economically attractive spent fuel management technologies.

Rosatom considers Areva, which also owns SNF reprocessing technologies, to be its main competition on this market.

5.4.2. National spent nuclear fuel management strategy's deadlines and main anticipated results

The development of the National Back End Strategy, with stipulation of the main anticipated results and scheduled time frames, is slated for completion by 2015.

Targets for completion before 2020:

– achieving the objectives and targets of the Federal Target Programs Nuclear and Radiation Safety 1 and Nuclear and Radiation Safety 2;

– developing long-term final disposition programs for legacy SNF in line with long-term plans for the development of spent nuclear fuel management infrastructure;

– issuing all legacy SNF (each spent fuel assembly) with technical dossiers specifying deadlines scheduled for the implementation of all stages of SNF management in accordance with SNF management process flows;

– identifying funding sources for all legacy SNF, and coordinating funding distribution across funding sources and allocation periods;

– establishing target values for the activities' main key performance indicators for subsequent periods.

Targets for completion before 2030:

– finalizing reference technologies for SNF management;

– creating the infrastructure needed for the centralized management of legacy SNF, in accordance with the developed plans;

– placing all legacy SNF in centralized interim storage.

Targets for completion before 2070:

– completing final disposition of all legacy SNF (100%);

– radioactive waste generated during legacy SNF reprocessing shall be disposed of in accordance with the deadlines specified in the approved SNF management process flows.

CHAPTER 6. **THORIUM**

Thorium (Th), the isotope Th-232, is a natural radioactive element, the parent isotope in the thorium series. Just as uranium, thorium can be used in the fabrication of nuclear fuel. The chemical element Th belongs to the actinide series in Group III of Mendeleev's Periodic Table of the Chemical Elements.

As of 2012, 30 thorium isotopes are known, but natural thorium consists almost entirely of the single isotope Th-232, since, compared to other isotopes, it has the longest half-life: (T1/2 = 1.4×10^{10} years). Th-232 is an alpha emitter, its specific radioactivity is 0.109 μCi/g (4×10^{3} Bq/g). The thorium decay chain produces the radioactive gas thoron (radon-220), which is hazardous in significant concentrations. The other natural radioactive thorium isotopes, besides Th-232, include Th-227, Th-228, Th-230, Th-231, and Th-234.

Pure thorium is a silvery white lustrous metal, ductile at room temperature, and can be readily worked. In appearance its resembles platinum, and has a comparable melting point; its specific gravity and hardness are similar to those of lead. Samples of thorium metal with thorium oxide content of about 1.5% to 2% are resistant to oxidation, tarnishing very slowly to black. Thorium corrodes slowly in cold water, while in hot water, the oxidation rate of thorium and thorium-based alloys is hundreds of times higher than that of aluminum.

6.1. Natural thorium

Thorium is much more naturally abundant than uranium. Trace amounts of thorium are even found in granites. Unlike data for uranium, the data on thorium deposits in the world are not yet well systemized; nevertheless, it is generally assumed that thorium is three to four times more abundant in nature than uranium. Thorium abundance in the Earth's crust is about 8×10^{-4}% – around the same as lead. Thorium content in river water is 2.2×10^{-14} Ci/liter (8.1×10^{-4} Bq/liter), or much lower than that of uranium.

Natural thorium compounds include those with uranium, rare earth metals, and zirconium. Thorium has been discovered in over 100 minerals representing oxygen compounds – primarily, oxides, and much more seldom, phosphates and carbonates. Over 40 minerals are thorium compounds or else thorium is found in them as one of the chief components. The main industrial thorium-bearing minerals are monazite (Ce, La, Th…)PO_4, thorite $ThSiO_4$, and thorianite $(Th,U)O_2$.

Thorite, just like the mineral thorianite, is very rich in thorium – 45% to 93% in thorium content – but is just as rare. Monazite (monazite sands) is an important source of thorium, with concentrations of between 2.5% and 12%. Brazil, India, the United States, Australia, and Malaysia are known to have thorium-rich monazite placer deposits. Vein-type deposits of this mineral are found in Southern Africa.

The largest thorium deposits in Europe are believed to be in Norway (the main reserves are located in the Fen complex (Fensfeltet) in Telemark). But thorium deposits in Norway are not developed because of the insignificant concentrations of thorium in the ores – just some 0.2% on average. This complicates the extraction process and leads to the generation of a great amount of mill tailings and harmful wastes, which raises objections from the Norwegian public and the country's government.

Australia's thorium reserves total 489,000 tons (at $176 per pound), thorium deposits in the Unites States are estimated at 400,000 tons, and thorium reserves in Turkey and India amount to 344,000 tons and 319,000 tons, respectively.

6.2. Thorium production

The main source material for thorium production is monazite concentrates. Thorium extraction is a difficult process since monazite contains elements whose physical and chemical properties are similar to those of thorium – rare earth metals, uranium, etc.

The initial stage of thorium production is production of pure monazite concentrate. A variety of methods and techniques are used for monazite separation. First, monazite is separated by scrubbing and on shaking tables – a process that makes use of the differences in the minerals' density and wettability by different liquids. Further treatment to achieve finer separation includes electromagnetic and electrostatic methods. The final product contains between 95% and 98% monazite.

Of the numerous methods of extracting thorium from monazite concentrates, only two have broad commercial application: digestion with concentrated sulfuric acid at 200 °C and treatment of the finely ground concentrate by a 45% sodium hydrate (NaOH) solution at a temperature of 140 °C.

These processes yield thorium concentrates in the form of precipitates of hydroxides, basic salts, phosphates, or oxalates. They contain between 40% and 70% thorium. The products resulting from purification are mostly thorium dioxide or thorium nitrate, which can then be used to obtain other compounds necessary for the production of thorium metal (for instance, thorium fluoride or thorium chloride).

Commercially, thorium metal is produced by metallothermic reduction of its compounds (thorium dioxide and halogenide) or electrolysis of melts.

To produce particularly high-purity thorium (predominantly, for research purposes), thermo-dissociation of thorium iodide is used. In view of the high melting point, thorium is produced in powder or sponge form, which is then transformed into compact metal by powder metallurgy method or by melting.

The various complexities of thorium production are compounded by the need to ensure reliable radiation protection measures.

6.3. Using thorium in the uranium-thorium nuclear fuel cycle

Historically, investigations of a potential application of thorium (Th-232) as a fuel for nuclear power reactors started in parallel with the first studies of uranium and plutonium utilization. Thorium seemed an attractive option of nuclear material mainly due to its abundance, the opportunity to reduce the cost of enrichment in the fuel cycle, the high conversion ratios (to U-233) achievable in a thermal neutron spectrum, and also due to other neutron and thermal physical properties described below.

Thorium-232 is not naturally fissionable by thermal neutrons. Still, thorium is a source of secondary nuclear fuel (U-233), produced by the following nuclear thermal neutron reaction:

$$\mathrm{Th}^{232}(\mathrm{n},\gamma)\,\mathrm{Th}^{233}\xrightarrow{\beta}\mathrm{Pa}^{233}\xrightarrow{\beta}\mathrm{U}^{233}$$

U-233, which results from Th-232, makes for excellent nuclear fuel that can sustain the nuclear chain reaction and has a number of advantages compared with U-235 (in particular, during fission, a U-233 nucleus releases more neutrons). When comparing the fission processes that involve U-233, on the one hand, and those that involve U-235 or Pu-239, on the other, each neutron absorbed by a U-235 or Pu-239 nucleus produces 2.03-2.08 new neutrons, whereas in the case of U-233, the neutron yield is much higher: 2.37.

Among other benefits of thorium compared to uranium-235 are its high melting point, no phase transformations up to 1,400 °C, and high mechanical performance and radiation resistance of metallic thorium and a number of its compounds (oxide, carbide, fluoride). U-233 is characterized by a high multiplication factor for thermal neutrons, which enables their efficient utilization in nuclear reactors. A comparison of the absorption cross-sections of Th-232 and U-238 in thermal spectra (7.4 barns against 2.7 barns) shows that thorium is a better contributor to neutron absorption than uranium. This means that a thorium fuel reactor can ensure a lesser, percentage-wise, level of neutron loss due to parasitic absorption in structural materials – and, consequently, higher neutron multiplication parameters.

Furthermore, using uranium recycled from spent nuclear fuel from thermal neutron reactors – or plutonium from spent MOX fuel – requires, because of the presence in the fuel of significant concentrations of non-fissile isotopes U-236, Pu-240, Pu-242, a higher level of enrichment of U-235 or Pu-239 in the fresh fuel loads for thermal reactors. In the thorium fuel cycle, this is not

as critical an issue, and recycling thorium reactor spent fuel may be a more promising option economically.

There are other advantages to thorium reactors. For instance, the reactivity margin throughout the core life – the period of time that the reactor continues to operate at nominal capacity – will be changing less in thorium-fueled reactors than in reactors burning uranium or uranium-plutonium fuel. Besides, thorium reactors may allow for a more efficient use of both U-235 and/or plutonium added to fresh fuel, which offers the possibility of using the thorium nuclear fuel cycle for the purpose of disposition of the global stock of plutonium.

As for the disadvantages of thorium as a nuclear fuel, one is that thorium has to have fissile material added so that nuclear reaction is possible. To use thorium breeding to fuel reactors, a highly enriched fissile material (U-235, U-233, Pu-239) must be used as a fuel, with thorium included in the reactor for its breeding potential. On the other hand, thermal breeder reactors (slow neutron reactors) are possible using a U-233/thorium breeding cycle, especially if heavy water is used as a moderator.

Besides everything else, using thorium as a nuclear fuel is complicated by the generation of high-activity isotopes produced by side reactions. The chief of them, U-232, is an alpha and gamma emitter with a half-life of 73.6 years. U-233 with 1% U-232 content has an alpha activity that is three times as high as that of weapons-grade plutonium, and, by extension, is three times as radiotoxic.

The technologies required to convert mined thorium ore into fuel forms ready for use in a reactor involve fewer conversion processes, and, consequently, expenses, than with conversion of mined uranium into UO_2 fuel. However, today, thorium fuel fabrication technologies cannot yet be considered mature. Likewise, the knowledge accumulated to date with regard to thorium fuel's behavior under irradiation cannot be deemed sufficient. Therefore, the thorium option has yet to reach a level of development needed to allow it an assured entry on the nuclear technology market.

Of all nuclear countries, India currently is the only one with serious intentions regarding the thorium fuel cycle option. Beginning in the 1980s, India has loaded a total of around 232 thorium fuel assemblies in its heavy water power reactors.

A thorium core for VVER-1000 reactors has been patented in the United States, but is not produced commercially. The design of this core helps reduce the U-235 load through the involvement into the chain reaction of the isotope U-233, which is produced by thorium during reactor operation, and the accumulation of U-232, typical for the thorium cycles, helps denature plutonium in the core – i.e., makes it unsuitable for reprocessing using the technologies available today. This is important from the point of view of plutonium production and proliferation concerns.

For Russia, the option of partial transition of VVER reactors to a thorium cycle is, on the one hand, quite attractive. But the problem of how and where to produce U-233 remains unsolved. One scenario suggests producing U-233 in thorium blankets of fast reactors and then using the produced uranium to fuel VVERs. For enhanced radiation protection, the U-233 extracted from the blanket material can be additionally diluted with depleted or regenerated uranium, decreasing the U-232 concentration and thus solving the issue of the thorium fuel's excessive radiation hazard.

Canada is considering the option of using thorium fuel in heavy water reactors. The Canadians are researching the possibility of involving thorium into the fuel cycle by developing commercial fuel based on a homogeneous mixture of oxides of two or more heavy metals. Canada's CANDU reactors today operate on natural or slightly enriched uranium only. A transition to the thorium cycle implies that the composition of the homogeneous mixtures will, besides uranium, include thorium, plutonium, and uranium-233 oxides.

Other countries have no programs envisioning the development of thorium-based nuclear cycles for commercial use. But some states do research the possibility of using thorium in nuclear reactors. For instance, Norway's Thor Energy is planning to conduct a fuel irradiation experiment testing thorium-plutonium oxide fuel in simulated LWR conditions using the research reactor in Halden. The company's other line of work is the design and modeling of thorium-MOX and U-233-thorium fuel assemblies for boiling water reactors. Thor Energy believes thorium-fueled LWR reactors could assume some of the functions traditionally expected of fast neutron reactors.

CHAPTER 7. **SAFETY AND ENVIRONMENTAL ISSUES OF HANDLING NUCLEAR FISSILE MATERIALS**

Nuclear fissile materials, as radioactive elements emitting alpha and beta particles, neutrons, and gamma radiation (ionizing radiation) – and because of their extreme toxicity levels – are a danger to all life. If for no other reason, nuclear fissile materials are dangerous by virtue of their very existence in nature, as no rules, guidelines, or technologies are capable of fully protecting humans and the natural environment from the hazard that they pose. But since it is impossible to rid of them completely, humankind is forced to develop and implement safety measures that can, to a certain degree, prevent or mitigate the harmful effects that arise from handling these materials.

Safety in handling fissile materials is achieved through design concepts and technological and engineering solutions, physical calculations, personnel training, and measures developed to prevent the adverse effects of accidents, emergencies, natural disasters, and other force majeure events or circumstances (tsunami, earthquake, lightning, falling meteorite or crashing aircraft, etc).

7.1. Uranium (health effects and environmental impact)

Any form of uranium is hazardous for humans and the environment.

Uranium is a general cellular poison that affects all organs and tissues. Its impact is due to its chemical toxicity and radioactivity. The maximum allowable concentration for soluble uranium compounds is 0.015 mg/m^3, and 0.075 mg/m^3 for insoluble compounds.

Uranium is also a reproductive toxin. Its radiological effects are local due to the short range of the alpha particles produced by decay of U-238. Uranyl ions have been shown to cause birth defects and immune system damage in laboratory animals.

The chemical toxicity of uranium – its chemical effect on metabolism – is even a greater hazard than its radiotoxicity.

Mining uranium ore in open pits and in underground mines is accompanied by the generation of radioactive dust, radioactive gas, and large amounts of uranium-contaminated water released into the environment. Uranium mining and milling operations, therefore, have adverse health effects both on the mining enterprises' workers and the populations residing nearby, as well as detrimental environmental effects.

Some 95% of the radioactivity of uranium ore containing 0.3% of triuranium octoxide U_3O_8 results from the radioactive decay of U-238 and reaches 1.2×10^{-5} Ci/kg (4.5×10^5 Bq/kg). Uranium has 14 long-lived radioactive isotopes, each with a radioactivity of 8.7×10^{-7} Ci/kg (3.2×10^4 Bq/kg) on average (irrespective of the mass proportion).

After the ore is processed, U-238 and some U-234 (and U-235) are removed from the ore, and its radioactivity declines to 85% of the initial level. After the removal of most of U-238, its two short-lived decay products – Th-234 and Pa-234 – disappear quickly, and over the following several months the ore's radioactivity decreases further to 70% of the original level. Th-230, in its turn, then becomes the main long-lived isotope (its half-

life is 77,000 years), decaying to Ra-226 and later on to Rn-222.

The gas radon, a uranium daughter product, which is present in uranium ores and emanates from rock, is a source of radiation exposure and thus a health hazard for uranium mine workers (with lung cancer being the primary occupational illness).

During heap leaching, sulfuric acid is poured over the upper surface of the pay streak, then percolates through the ore and accumulates on an impermeable liner, with the pregnant leach solution then draining off of the bottom of the leach pad, where it is collected and transported to a processing plant.

The hazards associated with heap leaching are posed by off-site dust transport and leaching liquid seepage. After the ore processing operations cease, the environmental risks persist because of the natural leaching processes which take place due to the presence in the rock of iron sulfide (FeS_2). Natural precipitation, coupled with inflow of air, causes sulfuric acid to generate constantly within the piled-up material, a process resulting in a permanent leaching of uranium and other contaminants and poisoning of groundwater for centuries.

In warmer climates, metal sulfides, upon contact with water and air – and especially in the presence of certain bacteria – tend to undergo reactions that result in the formation of sulfuric acid and toxic heavy metals. These substances may penetrate into groundwater and may then be carried to water bodies. To date, no uranium mine site reclamation has been attempted after acid heap leaching, and ways to achieve it are unknown.

During in-situ leaching, the leaching agent – ammonium carbonate solution or sulfuric acid – is pumped into the rock through injection wells, and the uranium-saturated pregnant leach solution is retrieved via recovery wells. The uranium ore itself is not removed from the deposit. This method can only be applied if the uranium deposit is located in porous rock confined within impermeable rock layers.

The disadvantages of the in-situ leaching technology are the risk of the leaching liquid spreading outside of the uranium deposit, involving subsequent groundwater contamination; the unpredictable impact of the leaching agent on the rock surrounding the ore body; the production of waste slurries and waste water during recovery of the uranium from the leach solutions; and the impossibility of restoring natural groundwater conditions after the leaching operations have been completed.

Following the end of operations at the site, the leaching solution that remains locked in the pores of the rock begins to diffuse. This solution contains high concentrations of such contaminants as cadmium, arsenic, nickel, uranium, and other elements. The contaminated liquid may spread out beyond the leaching zone horizontally and vertically.

Large volumes of mine waste left by uranium mining operations, when combined with warm rainy climates, may lead to an outflow of significant amounts of acid-containing water – a phenomenon known as the acid mine drainage (this, for instance, happened at the uranium mill tailings dam at Australia's Rum Jungle site).

Precipitation can form erosion gullies in the tailings deposits, and floods can destroy the whole deposit. Roots and burrowing animals can intrude into the deposit and spread the radioactive material, increasing radon exhalation and making the deposit more susceptible to weathering and erosion. If the surface of the deposit desiccates, the fine sands are blown by the wind over adjacent areas.

Uranium ore is delivered to uranium mills that perform mechanical and chemical treatment of the ores during processing. The main hazard associated with the operation of these mills is the discharge of radioactive dust. Additionally, when uranium mills cease operations, the problem that emerges is that of disposing of the generated high-level radioactive waste. This waste is usually dumped with the spoil piles. The chemical reactions that occur between the depleted uranium ore, or tailings, resulting from the milling operations, and the mine waste, are accompanied by the generation of gaseous products that may exacerbate significantly the environmental situation around the deposits.

Liquid waste resulting from uranium milling is the toxic solutions that contain radium and other metals and contaminate the environment. These are usually collected in tailings ponds, set up in the available depressions or by erecting special tailings dams.

Tailings ponds containing uranium milling waste are created at uranium mines and open-pit mining sites. One such tailings dump usually occupies an area of between 300 and 500 hectares and contains between 50 million and 100 million tons of waste with a total radioactivity of $(5\text{-}14)\times10^4$ Ci ($(2\text{-}5)\times10^{15}$ Bq).

The amount of tailings is equal to the amount of processed ore. If the ore contains 0.1% of uranium, then 99.9% of it becomes

waste. Besides uranium, the tailings contain all the elements of the uranium series, i.e., 85% of the ore's original radioactivity, since they still contain long-lived uranium decay products, including the long-lived radionuclides Th-230 (with a half-life of 80,000 years) and Ra-226 (with a half-life of 1,600 years). Radium is the constant source of Rn-222, which has a half-life of 3.8 days and which, as it is a gas, easily spreads into the atmosphere.

Radionuclides contained in the tailings produce radiation (at the deposit's surface) with levels that exceed background radiation by 20 to 100 times. These levels decline with distance from the site, so the radiation is only dangerous for people who are in the immediate vicinity of the deposit. Gamma radiation is emitted primarily by bismuth and lead isotopes. The radiation emitted by radon – which is the decay product of radium, also present in the tailings – should likewise not be disregarded.

Besides radioactive elements, uranium tailings also contain other toxic substances that were present in the ore, such as arsenic, as well as the chemicals that were used during the milling. These contaminants lead to a geochemical disequilibrium in the adjacent territories and may become dangerous for the environment should the toxins spread beyond the tailings deposit.

In an arid region, contaminated salts may migrate to the surface of the deposit, where they are exposed to erosion and spread into the environment. If the ore contains the mineral pyrite (FeS_2), then acids form inside the deposit when accessed by precipitation and oxygen, triggering a continuous leaching of contaminants. Chemical interactions between the slurries and the liner under the deposit might deteriorate the performance of the liner and thus increase the release of contaminants into groundwater.

At a surface glance, the simplest decision that may seem to be the solution to the uranium tailings problem is putting them back where they came from – into the underground mines, open pits, etc. But this is not the best solution. Placing this waste back into a mine is an unacceptable approach in most cases, since then the materials present in the tailings may come into direct contact with groundwater – and these are materials containing 85% of the ore's original radioactivity, as well as all of its toxins. Furthermore, these contaminants are now much more mobile and "better equipped" to escape into the environment.

Disposal in mines is possible if it appears possible to completely rule out any contact between the waste and groundwater by ensuring natural or artificial water barriers, but this method has not so far been adopted on a wide scale. The same can be said about the idea of replacing the waste back into the open pits that were used for uranium production.

7.1.1. Uranium and its health effects

On average, approximately 90 μg of uranium exists in the human body from normal intakes of water, food, and air, though this figure may vary depending on the region. Uranium is not uniformly distributed in the body, mainly depositing and accumulating in the spleen, kidneys, skeleton, liver, and, with inhalation of poorly soluble compounds, lungs and bronchopulmonary lymph nodes. Uranium does not circulate for prolonged periods in the blood. The approximate distribution of uranium in the human body is as follows: 66% is found in the skeleton, 16% in the liver, 8% in the kidneys, and 10% in other tissues. Uranium content in the organs and tissues of animals and humans does not exceed 10^{-7} g per gram of tissue. With animals and humans, uranium enters the gastrointestinal tract with food and water and the respiratory tract with air; it also enters the body through the skin and mucosae. The daily intake of uranium is 1.9×10^{-6} g from foods and liquids and 7×10^{-9} g from the air.

Uranium's biological effects on human health may vary depending on the chemical form of the uranium to which exposure has occurred and can be triggered both by chemical and radiological mechanisms.

Irrespective of the route of intake, most of the uranium (over 95%) is not absorbed, but is eliminated with the feces and urine. But 5% of the uranium will be absorbed by the body if the soluble uranyl ion has been ingested, and only 0.5% in the case of intake of an insoluble form (uranium oxide). Soluble uranium compounds are eliminated much faster than insoluble ones. This especially concerns dust of uranium compounds when absorbed by the lungs.

Upon entering the bloodstream, uranium tends to bioaccumulate and may for many years remain in bone tissue (because of uranium's affinity for phosphates). Out of the quantity of uranium that is absorbed into the blood, some 67% will be filtered by the kidneys and excreted in the urine within 24 hours. Half of the uranium absorbed by the kidneys, bone tissue, and liver, is excreted in the urine within the period of between 180 and 360 days.

Uranium has been shown to cause or be conducive to genetic mutations, tumors, birth defects, cellular level toxicity, and neurological damage. Uranium can also affect growing bones, cross the placenta, and cause damage to the embryo/fetus.

In addition to its impact on the skeleton, on reproductive success, and on cancer induction and/or promotion, the neurological effects from the impact of uranium are analogous to those of a kind of radioactive lead. In all of these areas there is some indication of the potential for the heavy metal damage and the radiation-induced damage of uranium to be interacting in a synergistic manner.

Toxic damage from uranium depends on the solubility of its compounds: Uranyl and other soluble uranium compounds are more toxic. Percentage values of uranium retained from the daily intake are 1.1% for adults and 1.8% for adolescents. Significant quantities of soluble uranium compounds (uranyl nitrate, uranyl fluoride, etc.) may be absorbed through the skin, and also absorbed quickly by the blood and circulate to the body's organs and tissues. Insoluble uranium compounds (UO_2, UO_4, U_3O_8) almost never are absorbed through the skin.

In the first hours and days following intake, the highest specific content of uranium is observed in the kidneys. Uranium accumulates for a period of approximately 4 days, and 16 days later it starts to be slowly excreted from the body, with an elimination half-life of 150 to 200 days. In the longer term, over 90% of all uranium retained in the body is deposited in the bones (which is a critical organ).

The chemical toxicity of uranium and its compounds is similar to that of mercury or arsenic, or their compounds. Notably, uranyl compounds (for instance, $UO_2(NO_3)_2$) are soluble in lipids and may be absorbed through intact skin. With intake, aerosols of uranium and its compounds are the most hazardous. The maximum allowable air concentration of aerosols of water-soluble uranium compounds is 0.015 mg/m^3, and for insoluble forms of uranium it is 0.075 mg/m^3. No more than 3% of all the quantity of U-238 that has entered the human body via inhalation is detected in the lungs 18 months later.

Uranium may cause not just functional, but also organic changes – both as a result of immediate (direct) impact and indirectly via the central nervous system and endocrine glands.

Uranium's radiological effects depend on how radiation exposure has occurred and on the level of exposure (via the respiratory passages, by swallowing, by contact, or via a wound), as well as on the properties of the uranium (particle size and solubility).

Natural uranium's radiation hazard is mostly due to the emission of alpha particles, which do not penetrate the external skin layers (though there are data indicating that under certain conditions, alpha particles may penetrate through the skin as well), but are capable of affecting internal cells (as these are more susceptible to the ionizing effects of alpha radiation) when uranium is ingested or inhaled. Exposure to alpha and beta radiation from inhaled insoluble uranium particles may therefore lead to lung tissue damage and increase the probability of lung cancer. Similarly, absorption into the blood, and transport to and retention in other organs and the skeleton, is assumed to carry an additional risk of cancer in these organs, depending on the level of radiation exposure.

One important problem is assessing the dose of alpha radiation resulting from internal exposure to the natural radionuclides of the uranium and thorium series, of which most are concentrated in the skeleton. Calculations here are difficult because the radiation dose is not just due to the parent nuclides uranium and thorium, but also due to their numerous decay products – the genetically related radionuclides, whose activity changes in complex ways over time.

Uranium deposited in bone tissue causes its constant irradiation (uranium's half life of elimination from the skeleton is about 300 days). Numerous data indicate that long-term exposure may result in damage to renal function both in humans and in animals. The types of damage that have been observed are nodular changes to the surface of the kidney, lesions to the tubular epithelium, and increased levels of glucose and protein in the urine.

The hazards posed by uranium are especially pronounced for miners employed at uranium, polymetallic, and coal mines, as well as employees of uranium mills. The general population may be exposed to uranium – or its daughter products, such as radon – via inhalation of dust or intake of water and food.

Uranium content in the air is usually insignificant, but uranium exposure may occur for workers at phosphate fertilizer plants or populations residing in areas located close to nuclear weapons production or testing facilities, or residents of areas where depleted uranium munitions have been used in the course of warfare, or residents of areas located near coal-fired

power or cogeneration plants, uranium mines, uranium milling and enrichment enterprises, or nuclear fuel fabrication plants.

7.1.2. Safety measures when handling uranium

Uranium metal, especially when finely ground (as well as uranium hydride), is pyroforic – i.e., it may ignite spontaneously. When burning, it produces uranium oxide smoke, which easily penetrates the human body. This is why fine fragments of uranium metal (powder, shavings, etc.) must be stored in a fire-safe location and, if possible, in an atmosphere of protective gas or liquid (such as under oil).

If possible, water should be avoided when extinguishing a uranium fire. Dry sand, common salt, or dry powder extinguishers can be used.

Explosion risks occur especially with air dispersion of metal uranium or uranium hydride. The lower explosive limit here ranges between 45 and 120 milligrams per liter.

Uranium powder may explode when treated with halogen-containing hydrocarbons – such as during degreasing with carbon tetrachloride, which, therefore, should be avoided when degreasing metallic uranium (or dichloroethylene should be used instead).

Explosion risk is present when treating uranium with ester admixed with peroxides, and an explosion may occur in the press mould when pressing uranium powder into compact shapes in a hydraulic press. These types of work should therefore be conducted behind a protective screen.

Special caution is warranted when handling uranium to avoid producing a critical mass of the fissile isotopes U-233 and U-235. Critical state depends in complex ways on the geometry, concentrations of uranium and the moderating agent, as well as on the material of the neutron reflector. The lowest critical mass values – i.e., the smallest quantities of uranium that under certain conducive conditions may be sufficient for criticality to occur – are as follows: 591 g for U-233 solutions, and 856 g for U-235 solutions.

7.2. Plutonium (health effects and environmental impact)

Some 5,000 kilograms of plutonium has been dispersed into the Earth's atmosphere over time as a result of nuclear weapons tests worldwide. In certain regions of the planet, soils are contaminated with radioactive fallout, including plutonium, released during accidents at nuclear power plants or from the operation of nuclear fuel cycle enterprises. The total amount of plutonium accumulated in the world is sufficient to kill the planet's entire population several times without even nuclear explosions.

The Chernobyl catastrophe resulted in a plutonium contamination of a 30-kilometer area around the plant. Some estimates peg plutonium content in the soil in the United States at an average of 2×10^{-3} Ci (7.4×10^{7} Bq) (28 mg) per square kilometer.

The total radioactivity of plutonium released into the atmosphere by spent nuclear fuel reprocessing facilities constitutes a small share of the total plutonium radioactivity present in the environment (1.2×10^{-5} Ci (4.4×10^{5} Bq)). But for the areas immediately adjacent to these enterprises, the levels of contamination with plutonium released by the plants are quite significant and present a great hazard.

Plutonium is not evenly distributed on the Earth's surface: the maximum activity of Pu-239, at 2×10^{-9} Ci/m^2 (70-80 Bq/m^2), is observed within the area of 35° to 45° north – the result of atmospheric nuclear tests conducted at these latitudes. In the Southern Hemisphere and equatorial regions, plutonium-239 activity does not exceed 4×10^{-10} Ci/m^2 (10-15 Bq/m^2).

Plutonium radioactivity levels in nuclear weapons testing areas and around plutonium fabrication or radiochemical treatment facilities are higher than the values given above. Various data indicate that between 7 and 10 tons of plutonium has been dispersed around the world as a result of nuclear weapons testing, losses during production, and accidents at nuclear facilities worldwide.

7.2.1. Plutonium distribution in the human body

Plutonium is one of the chemical elements that represent the greatest hazard for all life – both in terms of the radiological damage it does to internal organs and tissues as it emits radiation and because of its chemical toxicity. Still, the chemical toxicity of plutonium as a heavy metal is incommensurate with its radiological impact.

Plutonium's specific radioactivity is 200,000 times that of U-238, which is

a natural alpha emitter. The maximum allowable content of Pu-239 in the human body is one million times as low as it is for U-238. Plutonium's toxicity is due, first and foremost, to its radiological properties. But because of their limited penetrating capacity, alpha emitters – including plutonium – are only harmful to human health with internal exposure.

The principal routes of entry of plutonium into the body are via the respiratory organs, the gastrointestinal tract, and through the skin. When plutonium enters the human body, it starts irradiating with alpha particles those tissues where it becomes lodged. Upon inhalation or ingestion, alpha-emitting microparticles of plutonium remain in the body for what is practically an indefinite period of time (plutonium elimination half-life is 50 to 200 years), depositing on the surfaces of the lungs or on the gastric mucosa, and migrating into the blood circulatory system.

Some 50% of plutonium is deposited in bone tissue and 30% in the liver, which presents a risk of development of oncological disease. The allowable content of natural uranium in the human body is measured in milligrams – whereas for plutonium, it is nanograms.

Plutonium's toxicity depends to a large degree on its route of entry into the body. The impact of plutonium that has been ingested into the gastrointestinal tract is commensurate with that of such well-known poisons as cyanide and strychnine. The lethal dose of plutonium when swallowed is 0.5 grams (and 0.1 grams for cyanide). When inhaled, plutonium's chemical toxicity is comparable to that of mercury or cadmium vapor. Plutonium has been referred to as a potent radiotoxin.

Risks of plutonium exposure from inhalation are the most pronounced for personnel of nuclear production facilities. The potential hazard posed by particles of plutonium dust when they enter the human body via the respiratory system is determined by their parameters and source. In the air, the predominant mass fraction is that of plutonium oxide (PuO_2), which is capable of dispersing. Plutonium oxides can remain in the lungs for years, whereas the more mobile compounds migrate much faster to the body's metabolic systems (the gastrointestinal tract, lymph nodes, the blood, etc.). Plutonium's entry into the blood circulation and other metabolic systems depends on the physical and chemical form of the plutonium inhaled.

A significant amount of plutonium may be inhaled instantaneously. This usually happens if plant equipment suffers loss of containment integrity or due to a ventilation system failure. For instance, inhaling one gram of weapons-grade plutonium oxide (with an estimated specific alpha activity of 9×10^{-2} Ci/g (3×10^{9} Bq/g)) results in an effective lifetime dose of approximately 0.04 Sv.

The estimated absorbed doses from weapons-grade plutonium and civilian plutonium are essentially equal if they are measured per unit of activity. However, when calculated per unit of mass, a radiation dose received from civilian plutonium will exceed by an order of magnitude the dose from weapons-grade plutonium – because of the higher specific activity of civilian plutonium, on account, primarily, of Pu-238. The effective lifetime dose from civilian plutonium is thus some ten times higher than that absorbed from weapons-grade plutonium.

The largest plutonium particle that can be inhaled with ease is approximately 3 μm in diameter and has a mass of approximately 1.4×10^{-10} grams. The likelihood of developing a lethal form of cancer as a result of inhaling such a particle is approximately 10^{-6}.

Plutonium's entry into the body via inhalation may have long-term health effects (such as increased risk of fatal cancer), as well as delayed and acute effects (such as pulmonary edema). Acute effects, however, occur with exposure to rather high doses. For instance, approximately 20 mg of plutonium of optimal size (around 1 μm) must be inhaled for its chemical toxicity to cause death from pulmonary fibrosis or pulmonary edema within one month. Inhaling a large quantity of insoluble plutonium (over 2.7 μCi (10^{5} Bq)), such as during a fire or an explosion, may result in acute and severe damage caused by radiotoxic effects.

Entry into the gastrointestinal (GI) tract may occur both as a result of injection and inhalation of plutonium. Up to 50% of an insoluble plutonium compound that has entered the body via inhalation may be cleared from the lungs via the gastrointestinal tract. After its entry into the GI tract, part of the plutonium will migrate through the mucosa cells into the blood circulation system. Upon its entry into the blood circulation system, part of the absorbed material will be eliminated with the urine and feces (via the bile), with the remaining amount depositing in other organs. The blood retains an insignificant amount of the plutonium absorbed.

The share of plutonium uptake in the liver as compared to that in the skeletal system varies considerably depending on the individual case, but around 50% of the absorbed plutonium is assumed to be deposited in the skeletal bones, and 30% in the liver. The total amount of plutonium retained by the body is around 90% of the total amount absorbed.

Penetration of plutonium through the skin (both damaged and intact) may occur both under normal and accident conditions with a release of plutonium particles or plutonium solutions beyond containment barriers. In most cases, plutonium oxide can be easily removed from the surface of the skin without damaging it. Increased risks of the radionuclide's penetration into the body may occur if the skin sustains damage from aggressive acids (which are used in plutonium separation processes) or complexing agents used to decontaminate the skin. In this case, too, the highest concentration of plutonium is found in the bones and the liver, i.e., a typical distribution pattern occurs as observed for plutonium uptake via other pathways.

With contamination of an open injury, a large amount of plutonium may be concentrated locally around the wounded area. An efficient method of reducing exposure resulting from such contamination is surgically removing the contaminated tissue. Recommendations for which contamination levels necessitate a decision in favor of surgical removal are as follows: surgical removal of the wound is indicated for wounds containing over 4×10^{-9} Ci (150 Bq) of plutonium; and wounds containing less than 2×10^{-9} Ci (75 Bq) are deemed not to pose significant risk. The risks associated with surgical removal of tissues depend to a considerable degree on the age and health of the exposed individual, the location of the injury, as well as the nature and total area of the contaminated tissue.

The total dose from **external exposure to plutonium** is produced by the combined exposures to both gamma and neutron radiation. When handling plutonium, external radiation hazards for personnel result from the radioactive decay of its primary isotopes – mostly, gamma radiation from decay products of Pu-241, in particular, Am-241. Therefore, special attention is given to the ingrowth of Am-241. Gamma emissions from other plutonium decay products may become the major source of external gamma radiation exposure for personnel if Am-241 is either removed or its low-energy gamma rays are attenuated by shielding.

The rate of the neutron dose is determined by spontaneous fission neutrons emitted primarily by Pu-238 and Pu-240. With plutonium oxides and other compounds of plutonium with light elements (carbon, nitrogen, and other elements), neutrons resulting from the (α, n) reactions may contribute to the dose. Particles of plutonium accumulated, for instance, on fine filters may become dangerous sources of external exposure, which is why radiation doses from these sources must be monitored regularly and measures must be taken correspondingly.

7.2.2. Plutonium in ecosystems

The behavior of plutonium in the atmosphere varies depending on the particle size and the dispersal mechanism. Plutonium that has been released into the atmosphere is present in the environment as separate oxide molecules. Additionally, plutonium may be detected in the atmosphere as so-called hot particles – solid particles that contain plutonium molecules and have a size ranging between hundredths of a micrometer to a dozen micrometers and a radioactivity level of several dozen becquerels per particle; this exceeds by hundreds and thousands of times the radioactivity of more common radioactive aerosols.

Aerosols released in the stratosphere from nuclear weapon tests and satellite re-entry are deposited globally over a period of years. Plutonium released into the atmosphere by fabrication and reprocessing operations and accidents is typically deposited in a relatively short time close to the source. Resuspension of particulate plutonium is not a major concern as fine particles that might again become airborne adhere strongly to the surfaces of large soil particles and aggregates and are not readily entrained.

Plutonium in soil is resistant to migration and translocation irrespective of the source of the fallout. Plutonium quickly becomes fast attached to soil particles and then very slowly (0.8 cm/year) migrates in soil and with water flows. Less than 1% of plutonium is found in the biological components of ecosystems, with the largest portion of it bound in the plant life. The mean migration coefficients for the movement of plutonium in soil are approximately 10^{-7} cm^2/sec. The vertical transport rate depends on this coefficient and on the concentration of soluble plutonium species, which, however,

as estimates suggest, is less than 0.1% of the plutonium that is in the soil.

Translocation of plutonium in soil is primarily lateral. Vertical movement is promoted by certain mechanical processes such as cultivation. Wind and water erosion are the primary mechanisms for the lateral movement of plutonium in soil. Fine silt clay particles that contain plutonium concentrations are readily transported by water, or by wind when dry.

Biological systems (both plants and animal species) provide additional pathways for the translocation of plutonium from soil. The plutonium fraction transferred to plants after deposition on the leaves is approximately 10^{-5}. For expected concentrations of plutonium in soil, the fraction taken up by roots ranges from 10^{-3} to 10^{-5}. Root uptake of soluble plutonium species in the soil is thought to involve complexes of hexavalent plutonium.

Ingestion and inhalation are the principal mechanisms for the translocation of plutonium from soil to animals. Inhalation is of minimal concern because airborne concentrations of plutonium are low except in the vicinity of an accident and then only for a short time following the accident. Gastrointestinal and pelt uptake by grazing animals over a long period of time is also of minimal concern because the amount of plutonium ingested by animals is small and the fraction of ingested plutonium absorbed by animals is approximately 10^{-4}.

Combination of the described plutonium translocation processes via plant and animal systems shows that the fraction of deposited plutonium translocated to herbivores is in the 10^{-7} to 10^{-9} range.

The distribution patterns of plutonium in water systems are rather alike for both marine and fresh water systems. With microparticles of plutonium deposited in fresh water, a distributional relationship is established between the concentration of plutonium in water and the concentration in sediments or particulate matter. Distribution constants, which are in the 10^{-4} to 2×10^{-6} range, show that the plutonium resides primarily as an insoluble solid. The highest concentrations in solution are observed in systems with low pH and high sulfate concentration. Coefficients for equilibration of sedimentary and dissolved plutonium are also between 10^{-4} and 10^{-5}, suggesting that the chemical processes in salt water are similar to those in fresh water.

Translocation of plutonium in lakes and oceans occurs by chemical and mechanical processes. Both vertical and lateral transport processes are possible, depending on the conditions. Studies of plutonium uptake by marine organisms show that concentration factors relative to the plutonium concentration in sea water are 40, 300, and 3,000 for fish, crustacea, and mollusks, respectively.

Plutonium fallout in seas and oceans is gradually deposited and becomes lodged in bed sediments.

Over 99% of all plutonium released into the environment is contained in seabed sediments and surface soils.

7.3. MOX fuel

MOX fuel fabrication may involve the use of depleted uranium (uranium tailings) or natural uranium as uranium dioxide and Pu-239, civilian or weapons-grade. The degree of human exposure risk and potential environmental impact associated with MOX fuel is thus commensurate with that of the hazards that are posed by uranium and plutonium, which were described above.

The risks, hazards, and scale of potential consequences arising with plutonium contamination increase with the use of MOX fuel at nuclear power plants. Health hazards associated with MOX fuel occur first and foremost with internal exposure, with external exposure to gamma radiation from Am-241, and exposure to neutron radiation. Am-241, a decay product of Pu-241, is one of the major sources of gamma radiation. The most serious hazard in standard MOX fuel is from neutrons produced by spontaneous fission of Pu-240 and Pu-238.

Personnel involved in the manufacture of MOX fuel are exposed to additional risks associated with the technologies used in the MOX fabrication processes.

Spent (irradiated) MOX fuel is likewise an added radiological hazard compared to spent uranium dioxide fuel, primarily because of the increased content in MOX fuel of plutonium and other transuranic elements.

To ensure nuclear safety when handling MOX fuel, the same safety measures are applied as with other nuclear fissile materials: The mass of the nuclear materials and that of moderator materials is observed; the geometry (combination of mass and spacing factors) is maintained for the powders, pellets, and other products in storage; the areas where work is being conducted with nuclear fissile materials are equipped with monitoring systems, which check for increased neutron emissions (so as to prevent

a spontaneous nuclear chain reaction); and the hazard posed by decay heat (which is due, primarily, to the content of Pu-238) is likewise given due attention.

Radiolysis presents a grave hazard when working with aqueous plutonium solutions, as it produces an explosive mix of hydrogen and oxygen. This risk must also be taken into account when handling scrap, which may contain organic admixtures – i.e., measures must be implemented to remove these admixtures.

From the point of view of radiation safety, the conditions required to handle MOX fuel are different from those needed to ensure safety when handling common uranium fuel – on account, first and foremost, of the different amounts of radionuclides present in their respective compositions and responsible for the neutron and gamma radiation doses. Because of this factor, the equivalent dose rate from a fuel assembly with fresh MOX fuel is considerably higher than that from a uranium fuel assembly. The surface dose rate for a fuel assembly with fresh MOX fuel is 6.35×10^{2} μSv/h, exceeding that for a fuel assembly with uranium fuel by approximately 20 times; the dose rate in uranium fuel is produced entirely by gamma radiation, whereas in the case of MOX fuel, the shares of neutron and gamma contributions are relatively equal and are 3.31×10^{2} μSv/h and 3.04×10^{2} μSv/h, respectively.

7.4. Spent nuclear fuel

The main hazards associated with spent nuclear fuel management occur with its reprocessing. The only spent nuclear fuel reprocessing facility operating in Russia is the radiochemical plant RT-1 at Production Association Mayak. Mayak's operations have resulted in over 8×10^{8} Ci (2.9×10^{19} Bq) in liquid and solid radioactive waste accumulated at the site; 360 million tons in liquid radioactive waste has been discharged into the Techa Reservoir Cascade at Mayak, and this waste is not isolated from the surrounding environment. This is the world's largest deposit of liquid radioactive waste in the natural environment. In addition to the already accumulated waste, new radioactive waste with a total radioactivity of several dozen millions of curies is added annually from Mayak's spent nuclear fuel reprocessing operations alone.

7.5. Uranium fuel

Fabrication of uranium products, including uranium fuel, entails generation of liquid and solid radioactive waste.

Liquid radioactive waste produced during fuel fabrication includes raffinates from the solvent extraction stage, mother solutions from the precipitation stage, slurries from the filtration and hydrolysis stations, and waste water from decontamination of equipment and working areas.

Solid radioactive waste that is accumulated during fuel fabrication is metal scrap (disassembled equipment, utilities, and pipelines), furnace lining, construction materials, industrial rubber, elastrons, filter fabric, respirator masks, etc.

In expert estimates, Russia has accumulated 540 million tons of liquid and solid radioactive waste – or almost half of all the radioactive waste accumulated worldwide.

Conclusion

Developments in the field of management of nuclear fissile materials warrant constant attention of politicians, experts, and the public, since it is not just regional political issues that these events have an impact on, but global geopolitics as a whole.

This field is extremely important from the perspectives of ensuring nuclear and radiation safety, non-proliferation of nuclear materials and technologies, assessments of the state of nuclear weapons and the nuclear energy industry today and in the future, as well as solutions needed for a great many other issues. The impression one has today is that the existing international system of non-proliferation control is incapable of fully implementing the tasks it is charged with: controlling, accounting for, and preventing the proliferation of nuclear materials. This is corroborated by facts indicating the development of rogue nuclear programs by certain nations – primarily, Iran, North Korea, Israel, etc.

The number of uranium production countries is increasing. The global natural uranium market is strong – with such countries as Kazakhstan, Canada, Australia, and Russia now accounting for 70% of the world's uranium production capacity – and even the disaster at Fukushima did not affect the market significantly. State Corporation Rosatom continues to buy up uranium production assets. Atomredmetzoloto today ranks the world's second largest in terms of uranium reserves and owns 20% of the U.S. uranium reserves. The uranium holding ARMZ also owns reserves in Canada, Australia, Namibia, and Tanzania.

In November 2011, Sergei Kiriyenko stated that Rosatom's uranium production assets were enough to ensure supply of uranium to Russian nuclear power plants – including those built abroad – for the next 100 years. This, though, raises the following question: If State Corporation Rosatom has acquired such enormous uranium assets with a view to secure, for 100 years ahead, their use in thermal reactors, then why are such enormous funds being spent on the development and construction of fast reactors – designs that do not require the same quantities of uranium as thermal reactors do and are capable of operating on that stock of low-enriched uranium and plutonium that has already been accumulated?

Uranium enrichment capacity is growing, too. The world's leading nuclear nations and nuclear companies hold the largest enriched uranium market share. Russia and the United States are creating uranium banks. The American uranium bank AFS (American Assured Fuel Supply) has been set up to stock low-enriched uranium downblended from American highly enriched uranium. By 2012, the AFS was expected to take delivery of 230 tons of low-enriched uranium.

The Iranian uranium enrichment program remains a special concern for the international community. In January 2012, the IAEA officially confirmed that Iran had started production of uranium enriched to 20% at its Fordow (Fordo) enrichment facility. Experts say that when it reaches its nameplate capacity, the new plant is designed to operate up to 3,000 centrifuges.

State Corporation Rosatom expects nuclear power plants' demand in fuel fabrication services to grow by 2030 to 17,000 tons of enriched uranium, from 12,500 tons in 2011. Russia's nuclear fuel producer, TVEL Fuel Company, continues to improve its fuel assembly designs for VVER-440 and VVER-1000 reactors. In late 2010, pilot operation of third-generation VVER-440 fuel assemblies, with a higher uranium (UO_2) mass and enrichment level increased to 4.87% of U-235, started at Kola Nuclear Power Plant's Unit 4. According to TVEL, the main goal of introducing the new design is to improve economic performance of VVER-400 reactors. Rosenergoatom Concern asserts that the effect expected from employing the new design will be a 15% reduction in the number of fuel assemblies to be replaced with each refueling, with the reactor operating at 107% nominal capacity. TVEL today is the single supplier of fuel assemblies in the competition-free VVER-440 fuel market segment, and clearly, no competition

is likely anticipated in this segment in the future, since the VVER-440 reactor design is not expected to be developed further.

In the past several years, State Corporation Rosatom has been working steadily to improve VVER-1000 reactors and promote them on the international market, with fuel for reactors of all designs in the VVER-1000 series becoming, correspondingly, TVEL Fuel Company's main product. In 2011, VVER-1000 fuel was supplied to and loaded at Bushehr Nuclear Power Plant, as well as Unit 4 of Kalinin Nuclear Power Plant. The main fuel designs used for VVER-1000s are projects initiated at the end of last century and early 2000s. Today, these are fuel assemblies of the types TVS-2M and TVSA-PLUS, as well as TVSA-ALFA (TVSA-ALPHA) and TVSA-12. Additionally, the TVSA series now includes a model modified for compatible operation with TVS-2M. In 2011, a 12-assembly pilot batch was loaded for operation at Kalinin NPP's Unit 1.

TVEL has also started developing fourth-generation fuel assemblies, with pilot operation of these assemblies launched in 2012. An engineering design has also been developed for TVS-2006 fuel assemblies intended for a 24-month fuel cycle and with expected burnup of up to 70 MWd/kg in reactors of the NPP-2006 (AES-2006) project. The main solutions implemented in this model are: 7.8/0 mm diameter pellets (no central hole); possibility for a 6% to 8% power increase with heat transfer intensification; analysis of the possibility to increase enrichment above 5%; and analysis of efficiency of using uranium-erbium fuel. No orders have as yet been placed for this fuel, however, since any NPP-2006 reactors are yet to be completed.

TVEL, undoubtedly, is the monopoly producer of fuel for nuclear power plants of Russian (Soviet) designs. Still, TVEL's fuel fabrication rivals – Westinghouse, General Electric, Areva, Hitachi, and Toshiba – have lately been ramping up efforts to nudge TVEL out of the nuclear fuel markets of the former USSR and Communist Bloc states, primarily, Ukraine, the Czech Republic, and Bulgaria. This has caused TVEL to step up construction in Ukraine of a fuel fabrication facility with a production capacity of 400 tons of uranium per year.

The issue of using MOX fuel in modern reactors remains today a complicated and largely unsolved one for many countries, including Russia. Thermal reactor designs that France, Japan, and a number of other countries have at their disposal afford them the possibility to use MOX fuel in these reactors. Russia does not have this type of reactors. Any attempts to use MOX fuel in standard thermal reactors that are not suited for the purpose invite the risk of adverse consequences. The principal causes of these adverse effects are:

– the physical and technical properties of MOX fuel when using it in partial core loads in thermal reactors have an adverse effect on reactor safety. In particular, use of MOX fuel introduces inhomogeneities into the core, which cause difficulties with the calculation of the power distribution around the interfaces between the uranium and MOX assemblies;

– use of MOX fuel in reactors of the VVER type reduces the efficiency of the reactor control and protection system, which, in turn, affects safety levels;

– calculational uncertainties with regard to the operating modes of thermal reactors partially loaded with plutonium fuel have not yet been reduced to the same level as has been achieved for the traditional uranium-fueled cores. Using MOX fuel, therefore, undoubtedly leads to an increased risk of accidents;

– fallout from an accident involving a MOX-fueled core meltdown will be 2.3 to 2.5 times greater than with a core loaded with common uranium fuel.

The problem of plutonium still persists for all the countries that have amassed plutonium stockpiles as well as the global community in general, since plutonium presents a real threat to the environment and the population, and it is also the main material that can be used to manufacture nuclear weapons.

Russia's position regarding plutonium is based on the assertion that this material is a valuable commodity, and because it is an artificially produced isotope, it needs to be disposed of in an equally artificial way. Accordingly, Russia's plutonium management concept – with regard to civilian and weapons-grade plutonium alike – is tied up with the goal of closing the nuclear fuel cycle, i.e., using plutonium to produce MOX fuel and burning it as part of this fuel in reactors, thus increasing fuel efficiency and reducing the radioactivity of long-lived nuclear waste.

Attempts are being made to integrate Russia's national spent nuclear fuel management system into this same concept. But whether these attempts succeed will depend to a great extent on the type of the fuel cycle chosen, as this choice will determine the kind of infrastructure that will have to be created to manage Russia's plutonium and spent nuclear fuel stocks.

The principal provisions of the "Strategy for the Development of the Back End of the Life Cycle of Sites and Materials Involved in the Use of Atomic Energy until 2030," adopted by State Corporation Rosatom in December 2011, suggest four alternative nuclear fuel cycles for consideration. Russia is leaning toward a version of a closed fuel cycle that involves combined use of fast reactors and thermal neutron reactors. As of early 2012, however, the corporation had not reached a clear decision regarding its choice – primarily, due to economic reasons and also technological and safety issues.

As per the adopted long-term development scenario, the choice of the nuclear fuel cycle will be made in consecutive steps in 2015, 2020, and, for the final decision, 2030, by clearing certain milestones that will depend on obtaining a number of target results. At the moment, Russia's plutonium burning program is limited to the construction of a fast neutron BN-800 reactor at Beloyarsk NPP and a MOX fuel fabrication plant in Dimitrovgrad (scheduled for commissioning in 2014), with the plant slated for completion prior to the reactor launch.

Spent nuclear fuel management remains the main problem and the main impediment for the global nuclear power industry. The disaster at Fukushima served to show once again the urgency of addressing the issues of spent nuclear fuel storage at reactor sites and in cooling ponds. This is a complicated and costly process. Upon completing its stress tests in 2011, the French Nuclear Safety Authority (ASN) determined a list of measures required to ensure safety of spent nuclear fuel cooling ponds. The total cost of these measures is estimated at around EUR 110 billion.

The economy of nuclear fissile materials management continues to be a rather closed one even though all countries that have nuclear programs have a presence in the markets for uranium, nuclear fuel, and other nuclear materials. Russia has lately been making efforts to develop business opportunities in the field of SNF management and seeking inroads to take its SNF business to the international market. The main business areas here will be selling SNF storage solutions and equipment, as well as reprocessing technologies. It is not entirely clear what the Russian nuclear corporation's strategy is with regard to offering SNF reprocessing services for export, and with regard to storage of spent nuclear fuel of foreign origin on Russia's territory. What is clear at the moment is only that Russia intends to continue to offer services in nuclear fuel leasing and in the supply of enriched uranium, in line with a number of governmental agreements.

Thorium research is seeing continued investments into thorium fuel R&D, and the global knowledge base is growing. Some countries have accumulated a certain level of knowledge and experience today for the partial use of thorium fuel in a once-through fuel cycle of light water and heavy water reactors. The IAEA, however, is of the opinion that using thorium in a closed fuel cycle – i.e. complete with spent nuclear fuel reprocessing – will only become competitive against open uranium fuel cycles if the price of natural uranium rises to $400 per kilogram or higher.

Safety continues to be a major issue in the field of management of nuclear fissile materials. Between 1953 and 2010, some 15 criticality events took place at Rosatom's enterprises – mostly, involving installations in use at the chemical and metallurgical facilities producing plutonium, plutonium products, and products from highly enriched uranium, and, for the most part, when handling solutions and solution mixtures containing fissile materials. The causes included using nuclear hazardous equipment, errors on the part of personnel, and a lack of proper control over nuclear fissile materials during production or transportation.

Preventing a criticality accident has been and remains the chief concern when ensuring safety at nuclear fuel cycle enterprises. The incidents that have taken place demonstrate that accounting for and control of nuclear materials are fundamental to nuclear safety. Enriched uranium and plutonium represent the greatest hazard, and, on account of their state of matter, so do aqueous solutions and hydrogen-containing mixtures. Specific requirements and conditions apply for every process that is used at a nuclear fuel cycle facility with regard to safety measures and prevention of health and environmental hazards. With storage of nuclear "tailings," the spread of waste particles and wind-blown dust dispersal, as well as groundwater contamination, must be prevented. During nuclear fuel transportation, risks occur with disruptions in the geometry of the fuel rods in the casks, loss of containment, and penetration of water into a cask. At radiochemical plants, violations of safety standards and rules may lead to an explosion of hydrogen that is generated when dissolving metals and a release of radioactive aerosols and liquids

into the surrounding environment. Where radioactive solutions and solution mixtures are stored and reprocessed, the risks include localized criticality, an explosion involving gaseous products of radiolysis of liquids, autocatalytic reaction with a release of gases in liquid phase, as well as an explosion of solid radioactive waste remaining after evaporation. The risks of geological disposal of solid radioactive waste from radiochemical plants are the possibility of a spontaneous chain reaction and a release of radioactive substances into water-bearing layers and into the atmosphere.

All of the above clearly shows that handling nuclear fissile materials requires special skills and compliance with standards and rules. All nuclear fissile materials are potentially dangerous to humans and the environment.

In 2011, U.S. and Russian officials brought into force the bilateral agreement for cooperation in the field of peaceful uses of nuclear energy, or the U.S.-Russia 123 Agreement. Russia was the party primarily invested in signing this agreement. Before the 123 Agreement, Russia and the United States had already developed quite successful cooperation in the field of nuclear energy. In particular, Russia has been supplying low-enriched uranium to the United States, the two countries had an agreement in place on disposition of excess weapons-grade plutonium, the U.S. was supporting Russia's efforts to enhance physical security of nuclear installations, and Russia and the U.S. were also working together on converting research reactors from highly enriched to low-enriched uranium fuel. But the 123 Agreement served to expand significantly the two countries' nuclear cooperation, including in the field of fissile materials management. Items 3 and 4 of the Agreement's Article 7 provide for the possibility of transportation of nuclear materials from one country to the other, including via transit through third-party countries. This leaves open the issue of possible import to Russia of spent nuclear fuel that belongs to the United States.

In mid-2011, speaking at a meeting of Rosatom's Public Council, Sergei Kiriyenko stated that as long as he remained the head of the nuclear corporation, Russia would not import spent nuclear fuel from other countries. Unfortunately, the 123 Agreement *does* open the door to such a possibility, while Sergei Kiriyenko will not remain at the helm forever – and besides, not everything in Rosatom is decided by Rosatom's head.

Terms, definitions, and reference materials

1. Terms

Nuclear weapon: A device that releases nuclear energy in an explosive manner as the result of nuclear chain reactions involving fission, or fission and fusion, of atomic nuclei. Such weapons are also sometimes referred to as atomic bombs (a fission-based weapon); or boosted fission weapons (a fission-based weapon deriving a slightly higher yield from a small fusion reaction); or hydrogen bombs/ thermonuclear weapons (a weapon deriving a significant portion of its energy from fusion reactions).

Thermonuclear weapon: A nuclear weapon in which the fusion of light nuclei, such as deuterium and tritium, leads to a significantly higher explosive yield than in a regular fission weapon. Thermonuclear weapons are sometimes referred to as staged weapons, because the initial fission reaction (the first stage) creates the condition under which the thermonuclear reaction can occur (the second stage). Also archaically referred to as a hydrogen bomb.

Nuclear fuel: Fissionable material that has been enriched to a composition that will support a self-sustaining fission chain reaction when used to fuel a nuclear reactor, thereby producing energy (usually in the form of heat or useful radiation) for use in other processes.

Fuel assembly: A structured group of fuel rods (long, slender, metal tubes containing pellets of fissionable material, which provide fuel for nuclear reactors). Depending on the design, each reactor vessel may have dozens of fuel assemblies (also known as fuel bundles), each of which may contain 200 or more fuel rods.

Fissile material: A nuclide that is capable of undergoing fission after capturing low-energy thermal (slow) neutrons. Although sometimes used as a synonym for fissionable material, this term has acquired its more-restrictive interpretation with the limitation that the nuclide must be fissionable by *thermal neutrons*. With that interpretation, the three primary fissile materials are uranium-233, uranium-235, and plutonium-239.

Fissionable material: A nuclide that is capable of undergoing fission after capturing either high-energy (fast) neutrons or low-energy thermal (slow) neutrons. Although formerly used as a synonym for fissile material, fissionable materials also include those (such as uranium-238) that can be fissioned *only* with high-energy neutrons. As a result, fissile materials (such as uranium-235) are a subset of fissionable materials.

Weapons-grade nuclear material refers to the nuclear materials that are most suitable for the manufacture of nuclear weapons, e.g., uranium (U) enriched to 90% U-235 or plutonium (Pu) that is primarily composed of Pu-239 and contains less than 7% Pu-240. Crude nuclear weapons (i.e., improvised nuclear devices) could be fabricated from lower-grade materials.

Enriched uranium: Uranium with an increased concentration of the isotope U-235, relative to natural uranium. Natural uranium contains 0.7% U-235. Nuclear weapons typically require uranium enriched to very high levels – more than 20% of the isotope U-235. Nuclear power plant fuel typically uses uranium enriched to 3% to 5% U-235, material that is not sufficiently enriched to be used for nuclear weapons.

Highly enriched uranium (HEU) refers to uranium with a concentration of more than 20% (frequently, 90% or more) of the isotope U-235.

Low-enriched uranium (LEU) refers to uranium with a concentration of the isotope U-235 that is higher than that found in natural uranium but lower than 20% (usually 3 to 5%). LEU is used as fuel for many nuclear reactor designs.

Weapons-grade plutonium: Plutonium that contains almost pure (over 90%) Pu-239 and can be used in the manufacture of a nuclear weapon. Plutonium-239 is created in a reactor that is specially designed and operated to produce Pu-239 from uranium.

Reactor-grade plutonium: Plutonium produced in commercial, thermal or fast neutron, nuclear reactors.

Fast reactor: A reactor that, unlike thermal reactors, operates mainly with fast

neutrons and does not need a moderator. Fast reactors are generally designed to use plutonium fuels and can produce, through transmutation of U-238, more plutonium than they consume, i.e. they can be operated as breeder reactors with a conversion ratio greater than unity.

Thermal reactor: A reactor in which the fission chain reaction is sustained primarily by thermal neutrons. Most current reactors are thermal reactors.

Fuel cycle: A term for the full spectrum of processes associated with utilizing nuclear fission reactions for peaceful or military purposes. The "front-end" of the uranium-plutonium nuclear fuel cycle includes uranium mining and milling, conversion, enrichment, and fuel fabrication. The fuel is used in a nuclear reactor to produce neutrons that can, for example, produce thermal reactions to generate electricity or propulsion, or produce fissile materials for weapons. The "back-end" of the nuclear fuel cycle refers to spent fuel being stored in spent fuel pools, possible reprocessing of the spent fuel, and ultimately long-term storage in a geological or other repository.

Closed nuclear fuel cycle: A nuclear fuel cycle where spent nuclear fuel is recycled to extract uranium and plutonium for reuse in new nuclear fuel.

(Sources: The Nuclear Threat Initiative (NTI); the U.S. Nuclear Regulatory Commission (NRC); IAEA Safeguards Glossary, 2001 Edition; Russian State Atomic Energy Corporation Rosatom).

2. Separative work unit (SWU)

The capacity of a uranium enrichment facility to increase the percentage of U-235 is given by a unit known as the kilogram Separative Work Unit (SWU). Production level facilities typically have a capacity that ranges from a few hundred to several thousand metric tons SWU (MTSWU = 1,000 SWU). The Separative Work Unit is a complex unit that depends upon both the percentage of U-235 that is desired in the enriched stream and how much of the U-235 in the feed material ends up in the depleted uranium stream. The SWU unit can be thought of as the amount of effort that is required to achieve a given level of enrichment. The less U-235 in the feed material that is allowed to end up in the depleted uranium, the greater the number of SWUs required to achieve the desired level of enrichment.

The number of Separative Work Units provided by an enrichment facility is directly related to the amount of energy that the facility consumes. The two most important enrichment technologies in use today differ greatly in their energy needs. Modern gaseous diffusion plants typically require 2,400 to 2,500 kWh of electricity per SWU while gas centrifuge plants require just 50 to 60 kWh of electricity per SWU.

In order to provide the enriched uranium required to fuel a typical light water reactor with a capacity of 1,000 megawatts electric, it would take approximately 100,000 to 120,000 SWU a year of enrichment services.

In addition to the Separative Work Units provided by an enrichment facility, the other important parameter that must be considered is the mass of natural uranium that is needed in order to yield a desired mass of enriched uranium. As with the number of SWUs, the amount of feed material required will also depend on the level of enrichment desired and upon the amount of U-235 that ends up in the depleted uranium. The amount of natural uranium needed will decrease with decreasing levels of U-235 that end up in the depleted uranium.

The table below shows the amount of natural uranium and the number of Separative Work Units required for producing one kilogram of highly enriched uranium and one kilogram of low-enriched uranium, with U-235 content in the depleted uranium stream taken at 0.2% and 0.3%.

Requirements for producing one kilogram of low-enriched uranium and one kilogram of highly enriched uranium

U-235 percentage in the depleted stream	Low-enriched uranium (3.6% U-235)		Highly enriched uranium (90% U-235)	
	Natural uranium	SWU of enrichment	Natural uranium	SWU of enrichment
0.3%	8.2 kg	4.5 SWU	219 kg	193 SWU
0.2%	6.7 kg	5.7 SWU	176 kg	228 SWU

3. Classification of nuclear materials

Category 1 Nuclear Materials

Product	Nuclear material	Weight of nuclear material, in kg, no less than
Metal products: – metal products, metal slugs; ingots, granulate, their alloys/melts, and blends;	Pu, U-233	2 in total combined weight of Pu and U-233
	HEU	5 in U-235
– fuel rods and fuel assemblies containing metallic and intermetallic fuel; – rejects and waste reprocessed by remelt without dissolution	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	2 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with high content of nuclear materials: – carbides, oxides, chlorides, nitrides, fluorides, their alloys and blends;	Pu, U-233	6 in total combined weight of Pu and U-233
	HEU	20 in U-235
– fuel rods and fuel assemblies containing fuel fabricated from said compounds, as well as other products with concentrations (content) of nuclear materials of no less than 25 g/liter (25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	6 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf

Category 2 Nuclear Materials

Product	Nuclear material	Weight of nuclear material, in kg
Metal products: – metal products, metal slugs, ingots, granulate, their alloys and blends;	Pu, U-233	≥ 0.5 but < 2 in total combined weight of Pu and U-233
	HEU	≥ 1 but < 5 in U-235
– fuel rods and fuel assemblies containing metallic and intermetallic fuel; – rejects and waste reprocessed by remelt without dissolution	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	≥ 0.5 but < 2 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with high content of nuclear materials: – carbides, oxides, chlorides, nitrides, fluorides, their alloys and blends;	Pu, U-233	≥ 2 but < 6 in total combined weight of Pu and U-233
	HEU	≥ 6 but < 20 in U-235
– fuel rods and fuel assemblies containing fuel fabricated from said compounds, as well as other products with concentrations (content) of nuclear materials of no less than 25 g/liter (25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	≥ 2 but < 6 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with low content of nuclear materials: – products requiring complex processing;	Pu, U-233	≥ 2 but < 6 in total combined weight of Pu and U-233
	HEU	≥ 50 in U-235
– products with concentrations (content) of nuclear materials of between 1 and 25 g/liter (between 1 and 25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	≥16 in total combined weight of Pu, U-233, U-235, N p-237, Am, Cf

Category 3 Nuclear Materials

Product	Nuclear material	Weight of nuclear material, in kg
Metal products: – metal products, metal slugs, ingots, granulate, their alloys and blends;	Pu, U-233	≥ 0.2 but < 0.5 in total combined weight of Pu and U-233
	HEU	≥ 0.5 but < 1 in U-235
– fuel rods and fuel assemblies containing metallic and intermetallic fuel; – rejects and waste reprocessed by remelt without dissolution	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	≥ 0.2 but < 0.5 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with high content of nuclear materials: – carbides, oxides, chlorides, nitrides, fluorides, their alloys and blends;	Pu, U-233	≥ 0.5 but < 2 in total combined weight of Pu and U-233
	HEU	≥ 2 but < 6 in U-235
– fuel rods and fuel assemblies containing fuel fabricated from said compounds, as well as other products with concentrations (content) of nuclear materials of no less than 25 g/liter (25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	≥ 0.5 but < 2 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with low content of nuclear materials: – products requiring complex processing;	Pu, U-233	≥ 3 but < 16 in total combined weight of Pu and U-233
	HEU	≥ 8 but < 50 in U-235
– products with concentrations (content) of nuclear materials of between 1 and 25 g/liter (between 1 and 25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	≥ 3 but < 16 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf

Category 4 Nuclear Materials

Product	Nuclear material	Weight of nuclear material, in kg, no more than
Metal products: – metal products, metal slugs, ingots, granulate, their alloys and blends;	Pu, U-233	0.2 in total combined weight of Pu and U-233
	HEU	0.5 in U-235
– fuel rods and fuel assemblies containing metallic and intermetallic fuel; – rejects and waste reprocessed by remelt without dissolution	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	0.2 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with high content of nuclear materials: – carbides, oxides, chlorides, nitrides, fluorides, their alloys and blends;	Pu, U-233	0.5 in total combined weight of Pu and U-233
	HEU	2 in U-235
– fuel rods and fuel assemblies containing fuel fabricated from said compounds, as well as other products with concentrations (content) of nuclear materials of no less than 25 g/liter (25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	0.5 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
Products with low content of nuclear materials: – products requiring complex processing;	Pu, U-233	3 in total combined weight of Pu and U-233
	HEU	8 in U-235
– products with concentrations (content) of nuclear materials of between 1 and 25 g/liter (between 1 and 25 g/kg)	blend, total combined amount of Pu, U-233, HEU, and other nuclear materials	3 in total combined weight of Pu, U-233, U-235, Np-237, Am, Cf
All other products, including: a) products containing Pu, U-233, HEU with concentrations (content) of less than 1 g/liter (1 g/kg); b) any uranium compounds with less than 20% U-235 content in uranium; c) any products with absorbed dose rate of no less than 1 Gy/h = 100 rad/h at 1 m distance unshielded; d) any compounds of: plutonium with plutonium-238 content of greater than 80%; thorium; neptunium-237; americium-241; americium-243; and californium-252; e) special non-nuclear materials and any of their compounds		Total combined weight of all nuclear materials that is no less than the minimal quantities specified in this table

4. Accounting for and Control of Nuclear Materials in Russia

Minimum quantities of nuclear materials at a facility starting at which they are subject to state accounting and control

Nuclear material	Minimum amount of nuclear material	Last significant digits in the value of the weight of the nuclear material in accounting documents
Plutonium	15 g	1 g
Uranium-233	15 g	1 g
Uranium with U-235 enriched to over 10%	15 g in U-235	1 g
Uranium with U-235 enriched to no more than 10% but to a level higher than in natural uranium	15 g in U-235	0.1 kg
Neptunium-237	15 g	1 g
Total combined amount of nuclear materials specified in [the above five categories]	15 g in total combined weight of Pu, U-233, U-235, and Np-237	1 g
Americium-241	1 g	0.1 g
Americium-243	1 g	0.1 g
Californium-252	0.001 g	0.000001 g
Uranium with U-235 enriched to no more than 0.72%	500 kg	1 kg
Thorium	500 kg	1 kg
Lithium-6	1 kg	0.1 kg
Tritium	0.2 g	0.01 g
Deuterium, excluding deuterium contained in heavy water	2 g	0.1 g
Heavy water	200 kg	1 kg

5. Types of fresh nuclear fuel storage facilities and safety assurance requirements

Class 1 Nuclear Fuel Storage Facility: Fresh fuel storage facility where the possibility of ingress of water is ruled out, which is ensured by, among other means, a combination of the following measures:

- location of the storage facility above ground level;
- absence of adjacent premises from which ingress of water may occur;
- absence in the storage facility of pipelines with water, oil, hydrogen;
- location of the storage facility in a flood-proof area to ensure against flooding;
- availability of drainage.

Class 2 Nuclear Fuel Storage Facility: Fresh fuel storage facility where the possibility of ingress of water is ruled out, which is ensured by, among other means, a combination of the following measures:

- location of the storage facility above ground level;
- absence in the storage facility of pipelines with water, oil, hydrogen;
- availability of water detector alarms and drainage systems or emergency sump pumps connected with water detector alarms.

Class 3 Nuclear Fuel Storage Facility: Fresh fuel storage facility for which requirements set out for Class 1 and 2 Nuclear Fuel Storage Facilities do not apply.

The storage facility must be equipped with emergency sump pumps which engage when triggered by water detector alarms. Sump pump capacity must be sufficient to ensure the removal of water ingressing at maximum possible ingress rate to prevent water collection.

Nuclear safety during storage of fresh nuclear fuel is assured by:

- limitations on arrangement of fuel assemblies in packages (packing sets with nuclear fuel), storage canisters, racks;
- limitations on the number of fuel assemblies in packages, storage canisters, racks;
- limitations on the number of packages, storage canisters in a group;
- limitations on arrangements of groups of packages, storage canisters, racks;
- control over the arrangement of fuel assemblies, packages, storage canisters, racks.

6. Types of fuel assemblies produced by Russian fuel fabrication enterprises

VVER-440 fuel assembly

A VVER-440 fuel assembly consists of a bundle of fuel rods, top nozzle, bottom nozzle, and a shroud (wrapper). One bundle comprises 126 fuel rods.

TVSA

TVSA is a modified design with a rigid skeleton formed by six angle pieces and spacer grids. The main emphasis in developing these assemblies was placed on achieving increased burnup, operational reliability, and bending resistance. Developer: Afrikantov Experimental Design Bureau for Mechanical Engineering (Afrikantov OKBM).

TVSA-ALFA (ALPHA)

TVSA-ALFA is a next step in the development of the main TVSA design. TVSA-ALFA has eight spacer grids of an extended length and an optimized cell geometry, fuel rods with thinner cladding, and pellets having no central holes.

TVSA-T

TVSA-T is a modified TVSA design with eight spacer grids, developed for the Czech Republic's Temelin Nuclear Power Plant to replace fuel supplied by Westinghouse.

TVSA-U

A modified TVSA design with an increased fuel stack height.

TVSA-PLUS

A TVSA design developed for an 18-month fuel life cycle in a reactor operating at 104% nominal capacity.

RK-3

RK-3 is a third-generation shroudless fuel assembly design drawing on the operational experience of second-generation assemblies and solutions implemented for VVER-1000 assemblies of the TVSA and TVS-2 designs.

VVER-1000 fuel assembly

A VVER-1000 fuel assembly has 312 fuel rods, 18 absorber rods, 15 spacer grids, and a bottom support plate. In contrast to the rectangular designs that are common for fuel assemblies manufactured by Western producers, VVER-1000 fuel assemblies are hexagonal in shape.

UTVS

Unlike the standard VVER-1000 fuel assembly, the skeleton of a UTVS assembly is made of zirconium, rather than stainless steel. UTVS assemblies use gadolinium oxide for the burnable absorber, which is uniformly distributed in the fuel pellets inside several gadolinium-containing rods. UTVS uses a repairable demountable design, which means individual rods can be removed and replaced if damage (loss of seal) has been detected. UTVS was jointly developed by Experimental Design Organization OKB Gidropress (Podolsk, Moscow Region) and TVEL.

TVS-2

TVS-2 has a rigid skeleton formed by 12 spacer grids welded to the guide tubes. This is a next stage in the development of previous shroudless designs (TVS-M, UTVS), modified to apply improved designs for some of the components and incorporate technical solutions that had shown good operational results in the previous models. Developer: OKB Gidropress.

TVS-2 assemblies were in operation at Balakovo NPP since 2003. In 2007, all Balakovo NPP units were converted to TVS-2 fuel, as well as Reactor Unit 2 of Rostov (Volgodonsk) NPP.

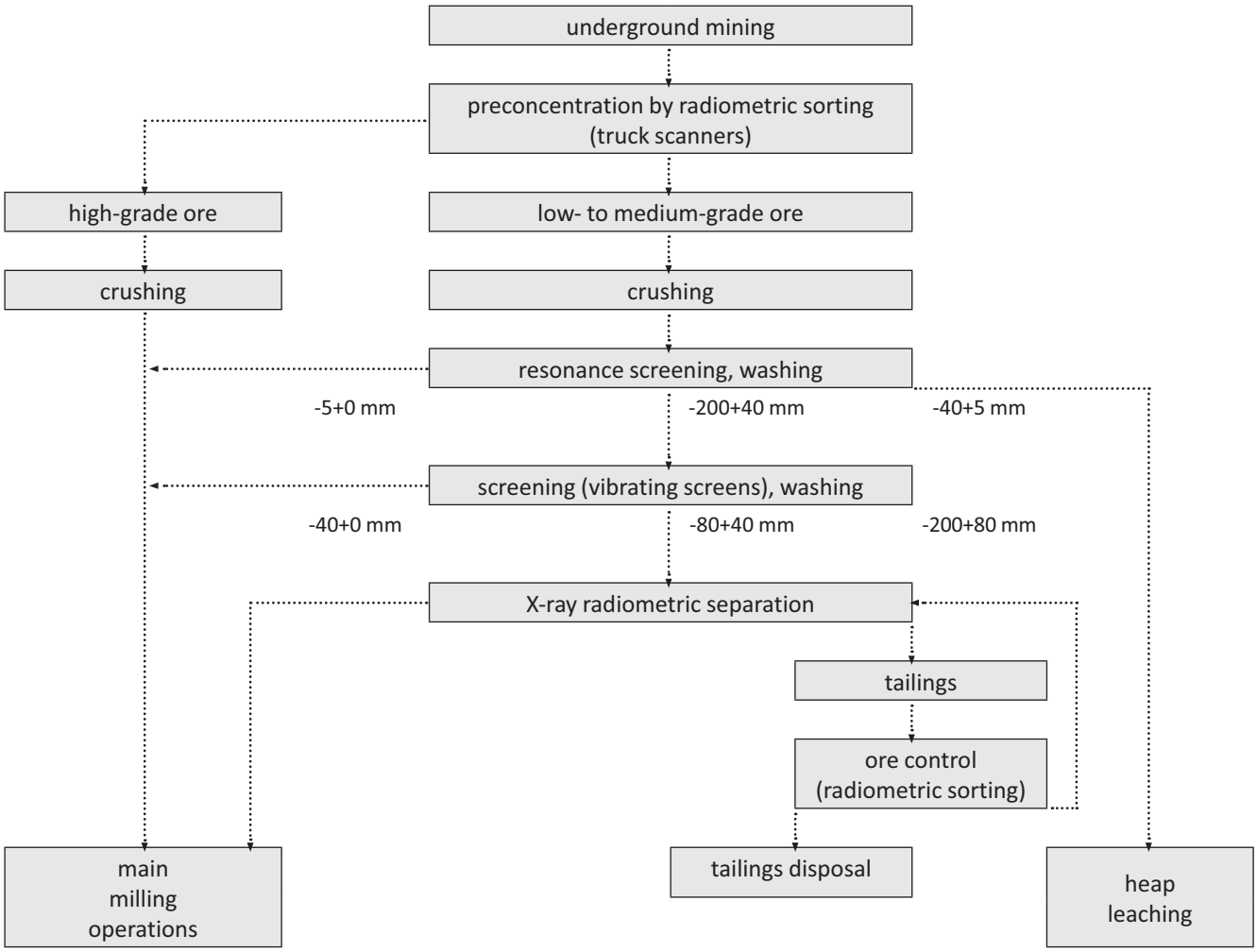
TBC-2M

TVS-2M is a modified TVS-2 design with shorter end pieces and corresponding extensions (100 mm at the bottom and 50 mm at the top) to the fuel column height, as well as an additional 13th spacer grid in the lower part of the skeleton to increase vibration resistance. The spacer grids are rigidly connected to the guide tubes to form a skeleton with a better bending resistance. The TVS-2M assemblies are intended for an 18-month fuel cycle.

TVS-2M assemblies have been in operation since 2006 (Unit 1 of Balakovo NPP). Units 1-4 of Balakovo NPP and Unit 1 of Rostov (Volgodonsk) NPP, which previously used TVS-2 fuel, are now being switched to TVS-2M. Unit 2 of Rostov NPP is operating a core composed entirely of TVS-2M assemblies. TVS-2M also serves as the prototype design for TVS-2006 fuel assemblies being developed for the NPP-2006 (AES-2006) project.

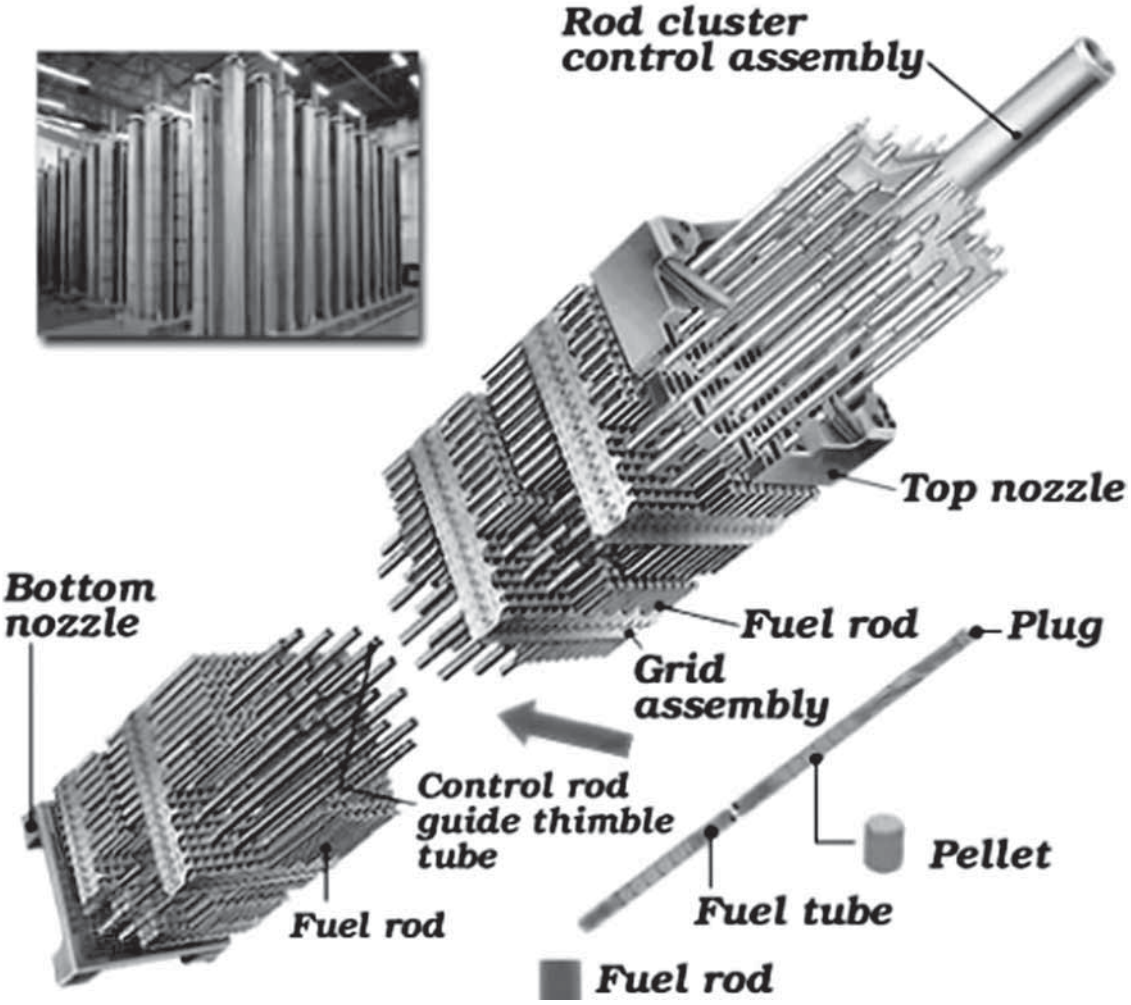
Appendix 1.1

Uranium milling process flow sheet (radiometric sorting plant, PIMCU, Krasnokamensk)



Appendix 2.1

Schematic view of PWR fuel assembly (Mitsubishi Nuclear Fuel)



Appendix 2.2

Schematic view of BWR fuel assembly (Nucleartourist and GE)

BWR/6 fuel assemblies & control rod module

1. Top fuel guide
2. Channel fastener
3. Upper tie plate
4. Expansion spring
5. Locking tab
6. Channel
7. Control rod
8. Fuel rod
9. Spacer
10. Core plate assembly
11. Lower tie plate
12. Fuel support piece
13. Fuel pellets
14. End plug
15. Channel spacer
16. Plenum spring

Appendix 2.3

Iran's nuclear fuel cycle facilities

Site	Location	Description
Uranium mines	Ardekan, 200 km from Isfahan	In operation. According to Iran's data, known uranium ore reserves total 1,580,000 tons with uranium content of 0.05%, or 790 tons of uranium in the ore. The deposit development project, prepared for and delivered to the Iranian side by specialists from Russia's Atomredmetzoloto, was based on assessments that the deposit held around 1.1 million tons, with 0.05% of uranium content, or 742 tons of uranium. Two shafts are reported to have been put down to date and drifts are being developed. The workforce employed to develop the deposit includes workers from China.
Ore processing plant	Ardekan	In operation. A leach plant for uranium ore processing and fabrication of triuranium octoxide was designed in 1997 by Atomredmetzoloto. The siting location was initially chosen at the Saghand uranium deposit, but then a decision was made to change the location in favor of a site near Ardekan. Projected production output was set at 50 tons of yellowcake a year.
Yellowcake production plant	Ardekan	In operation. At a negotiations meeting in 1997, representatives of the Atomic Energy Organization of Iran and Russia's Atomredmetzoloto discussed the possibility of using a technology of extracting uranium from 55% phosphoric acid at the Razi Petrochemical Complex in Shiraz. The enterprise's throughput is 100 m^3/hour at a uranium content of 0.08-0.085 kg/m^3. Given the possibility to recover up to 90% uranium using this technology, 60-70 tons of uranium could be produced annually.
Uranium conversion plant	Isfahan	In operation. This is a uranium conversion facility at the Isfahan Nuclear Technology Center. Work on the project started in 2000. Planned output: 280 tons of UF_6 as well as other products, including uranium metal. According to the IAEA's information, the enterprise started operations in August 2005.
Uranium enrichment plant	Natanz, 150 km from Isfahan	In operation. In 2004, a pilot 164-centrifuge cascade was installed in Natanz at an underground facility with a total area of 100,000 m^2, where parts were available for the assembly of between 1,000 and 5,000 additional centrifuges. In IAEA assessments, the design of the Natanz centrifuges coincided with that of first centrifuge models (SNOR, G-1) manufactured by URENCO based on design drawings that were later stolen by the founder of Pakistan's WMD program, Abdul Qadeer Khan, in the early 1970s. The capacity of these supercritical centrifuges, taking into account the possibility that improvements may have been implemented by Iranian specialists on the original design, was assessed, in various estimates, to be between 0.9 and 5 SWU per year.
Fuel fabrication plant	Isfahan	In operation.
Fuel cladding plant	Isfahan	In operation.

Appendix 3.1

Safety related characteristics of MOX as compared to UO_2

Characteristic Item	Change from UO_2	Effect
Physical-chemical:		
Melting point	Lowers by 20-40 °C	Adverse effect
Heat conductivity	Decreases	Adverse effect
Fission gas release	Increased release	Adverse effect
(Non-gaseous element release)	(possible increase)	(cesium and some others)
Nuclear:		
Fission/ absorption cross-section	Larger; strong resonance above thermal energy	Reduced control rod/ boron worth
Power peaking	Increased peak ratio	Complicated MOX rod configuration needed
Reactivity coefficient	Change of absolute value	
At low Pu enrichment:		
Doppler coefficient Void coefficient Moderator temperature coefficient	More negative More negative (BWR) More negative (PWR)	More rapid reactivity change in case of transient; reduced reactor shutdown margin
Fission yield and actinide production	Increased iodine, tritium, and actinide production	Increased hazard in accident
Decay heat	Increased (moderately)	Negative effect on residual heat control and long-term waste management
Delayed neutron fraction	Reduced fraction	Difficulty in reactor control
Prompt neutron	Shorter life time	Difficulty in reactor control

Appendix 5.1

Specific radioactivity of major fission products in VVER -1000 spent fuel, Bq/t U (×10^9 Bq/t)

Nuclide	Half-life, in years	SNF cooling period	
		1 year	10 years
Kr^{85}	10.74	542,000	303,000
Sr^{90}	28.5	3,430,000	2,750,000
Ru^{106}	1.0	1,190,000	24,600
Ag^{110m}	0.686	69,200	7.78
Sb^{125}	2.77	225,000	23,600
Cs^{134}	2.062	3,300,000	160,000
Cs^{137}	30.17	4,580,000	3,730,000
Ce^{144}	0.778	22,400,000	7,430
Pm^{147}	2.62	5,680,000	526,000
Eu^{154}	8.5	454,000	218,000

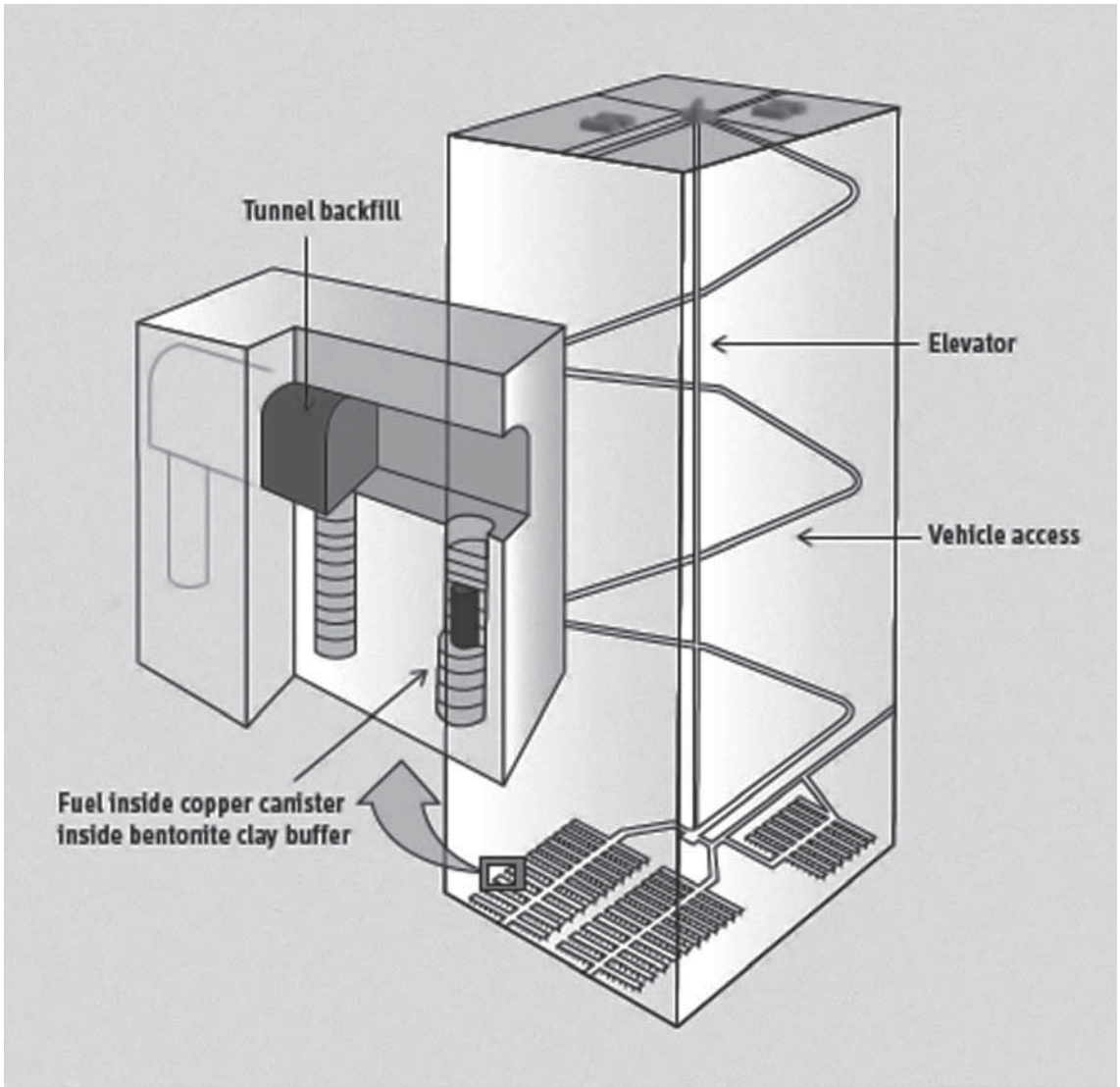
Appendix 5.2

Actinide concentrations in power reactor spent nuclear fuel, g/t U

Nuclide	VVER-440	VVER-1000	RBMK-1000
U^{235}	12,700	12,300	2,940
U^{236}	4,280	5,730	2,610
U^{238}	942,000	929,000	962,000
Pu^{238}	75.6	126	68.6
Pu^{239}	5,490	5,530	2,630
Pu^{240}	1,980	2,420	2,190
Cm^{244}	14.8	31.7	5.66
Am^{241}	517	616	293
Am^{243}	69.3	120	73.8

Appendix 5.3

Swedish deep geological SNF repository concept (source: IPFM, adapted from SKB)



Appendix 5.4

Characteristics of VVER spent nuclear fuel

Characteristic	VVER-1000	VVER-440
1. Average burnup, GWd/t	50	28
2. Fuel enrichment, U-235:		
Initial, wt% U-235	3.3-4.4	3.6
Residual, wt% U-235	1.3	0.75
3. Specific activity, Bq/t	3×10^{16}	$2.0\text{-}2.5\times10^{16}$
4. Content by weight:		
Uranium	947	960
Fission products, kg/t	42	~ 30
Pu (incl. 60-70% Pu-239), kg/t	9.9	8.5-9.5
Np, kg/t	0.7	0.3-0.5
Am (241, 243), kg/t	0.2	0.15
Cm (242, 244), kg/t	0.06	0.04
Pd, kg/t	0.8-1.5	0.3-1.4
Tc, kg/t	0.9-1	0.8-0.9
5. Decay heat (3 years cooling period), kW/t	< 1.7 kW/SFA < 4.2 kW/t	2.8

Appendix 5.5

SNF accumulation at nuclear reactors in operation and under construction in Russia

Reactor type	Power reactors	U-235 enrichment, %	SNF accumulation, in spent fuel assemblies (SFAs)
	VVER		
VVER-440 (6 units)	Novovoronezh NPP (Units 3-4), Kola NPP (Units 1-4)	1.6-4.4	55.5-87.0 t/yr (~ 450-700 SFAs/yr)
VVER-1000 (10 units)	Novovoronezh NPP (Unit 5), Kalinin NPP (Units 1-3), Balakovo NPP (Units 1-4), Rostov NPP (Units 1-2), Kalinin NPP (Unit 4, construction), Rostov NPP (Units 3-4, construction)	1.3-4.4	190 t/yr (~ 380 SFAs/yr)
VVER-1200 (NPP-2006)	Novovoronezh NPP-2 (construction), Leningrad NPP-2 (construction), Baltic NPP (construction)	2.4-3.9	
	RBMK		
RMBK-1000 (11 units)	Leningrad NPP (Units 1-4), Kursk NPP (Units 1-4, Unit 5: construction*), Smolensk NPP (Units 1-3)	1.3-4.4	390-450 t/yr (~ 3,500-4,000 SFAs/yr)
	BN		
BN-600	Beloyarsk NPP (Unit 3)		6.2 t/yr (~ 120 SFAs/yr)
BN-800	Beloyarsk NPP-2 (construction)		
	EGP		
EGP-6	Bilibino NPP (Units 1-4)	3.0-3.6	in storage SNF > 164 t/yr (~ 4,600 SFAs/yr)
	AMB		
AMB-100, 200	Beloyarsk NPP (Units 1-2), under decommissioning	1.5-21.0	190 t (NPP), 76 t (PA Mayak)
	Propulsion reactors		
	Pressurized water reactors		
VM, OK-650, KN-3	Nuclear-powered submarines, heavy nuclear-powered guided-missile cruisers	21-45	~ 15-20 t/yr (2002-2009)
OK-900, KLT-40			~ 0.5 t/yr

* According to a statement made by Rosatom head Sergei Kiriyenko in March 2012, construction of Kursk NPP's Reactor Unit 5 will not be completed.

Appendix 5.6

General properties of spent nuclear fuel shipping casks

Purpose, spent nuclear fuel source	Shipping cask type	Capacity, in number of spent fuel assemblies	Weight, in tons	Dimensions, in millimeters	Notation
Research reactors	TUK-19	4	5	910×2,170	Transportation
	TUK-128	20	9	1,120×2,250	Transportation
	SKODA VPVR/M	36	11		Transportation
VVER-440	TUK-6	30	90	2,200×4,145	Transportation
	TUK-140	36/48	105	3,160×5,880	Transportation
VVER-1000	TUK-13	12	120		Transportation
	TUK-141	20	125	2,770×6,130	Transportation, storage
RBMK	TUK-109	144	127	3,140×6,200	MBK*, transportation, storage
AMB	TUK-84	17	86	1,400×15,170	Transportation, storage
BN-600	TUK-136	-	5	500×2,970	Transportation
Nuclear propulsion reactors	TUK-18	35/49	40		Transportation
	TUK-108	15/49	40	1,850×4,600	MBK*, transportation, storage
	TUK-120	41/49	40	1,850×4,600	Storage

* Metal-concrete cask (for *metallobetonny konteiner*).

Design requirements:

The following conditions must be met with regard to packaging in order to assure nuclear safety and prevent criticality: The total mass of fissile materials must not exceed 80% of critical mass, and the effective neutron multiplication factor must not exceed 0.95 both under normal and accident conditions. A range of requirements are set for the package design and content of the packages as well. Additionally, the finished products (transport casks, upon fabrication) are subjected to quite rigorous field testing to assess: integrity of containment (immersion in water); strength (filling with water, excessive pressure, free drop test from a 9-meter height onto a solid surface), and capacity to withstand open fire conditions (up to 800 °C).

Appendix 5.7

Classification of ships as per the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code)

Class	Class description
Class INF 1	Ships which are certified to carry INF cargo with an aggregate activity less than 1.1×10^{5} Ci (4×10^{15} Bq)
Class INF 2	Ships which are certified to carry irradiated nuclear fuel or high-level radioactive wastes with an aggregate activity less than 5.4×10^{7} Ci (2×10^{18} Bq), and ships which are certified to carry plutonium with an aggregate activity less than 5.4×10^{6} Ci (2×10^{17} Bq)
Class INF 3	Ships which are certified to carry irradiated nuclear fuel or high-level radioactive wastes and ships which are certified to carry plutonium with no restriction of the maximum aggregate activity of the materials

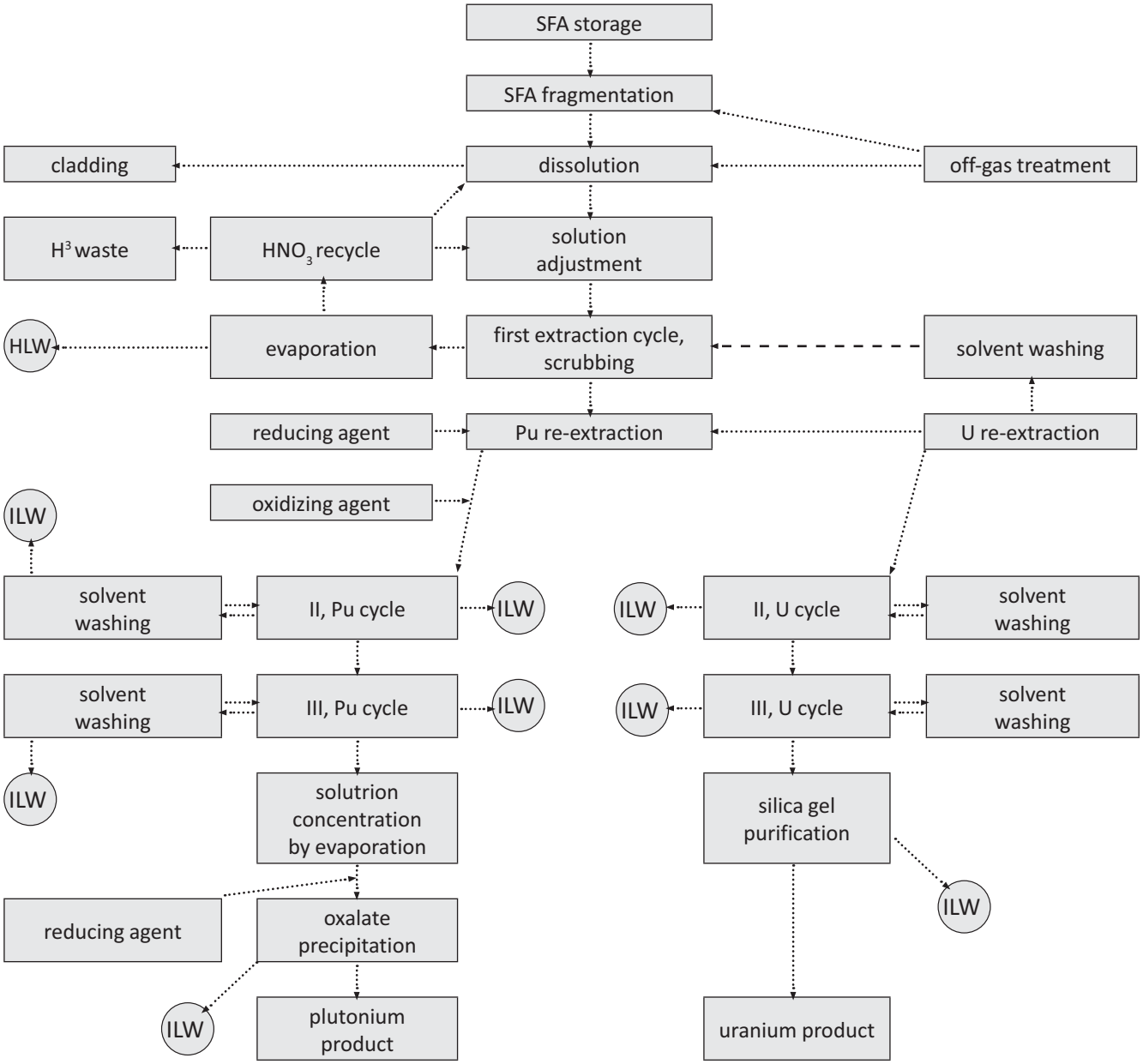
Appendix 5.8

Characteristics of the general cargo ship Rossita

RS Class notation (as per the Register of Ships of the Russian Maritime Register of Shipping):	**KM★Arc4|2|Aut 1-C INF3**
Displacement	3,731 t (2 cargo holds)
Speed	12 knots
Crew	23
Length OA	84 m
Breadth OA	14 m
Draught	4.15 m
Carrying capacity	16 TUK-18 shipping casks

Appendix 5.9

Power reactor spent nuclear fuel reprocessing with aqueous solvent extraction method



Note. ILW: intermediate-level waste; HLW: high-level waste.

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