MSc Program
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International radioactive waste for long-time disposal

A Master's Thesis submitted for the degree of "Master of Science"

supervised by

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Vienna, 16.03.2018

Affidavit

I, **YANA PROSVIROVA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "INTERNATIONAL RADIOACTIVE WASTE FOR LONG-TIME DISPOSAL", 77 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

This thesis aims to reflect upon a problem of creating an International repository for long-term disposal of high-level radioactive waste. At the moment, there is no solution to the problem of long-term disposal of spent nuclear fuel and highly radioactive waste, although volumes of the latter are rapidly growing.

The author of the thesis uses her academic background to tackle the issue from political, socio-economic and technical points of view. Approximately 270 000 tons of spent nuclear fuel have been saved up and its number increases by 12 000 tons annually. The overload of on-site repositories requires prompt measures to replace storage with disposal. The option of managing those waste on the best possible terms, implying finding the safest, most technically advanced and legally proven solution was advised by IAEA in a context of building an International Deep geological repository for High-level waste (HLW) long-term storage.

The findings indicate that many countries have already accepted the technology of Deep geological storage for HLW as the most advanced nowadays, from all of the existing HLW management strategies. However, not all of those countries own technical and economic capacities for implementing domestic programmes for HLW Deep geological storage. Moreover, the insecure level of communication with public within some countries, brings mistrust towards the scientifically proven projects and triggers protest and unacceptance, that postpones an acute problem solution for later generations.

In this context, the options of reaching international cooperation via building the Deep geological repository for SNF and HLW under the aegis of the IAEA, could bring Member States a big step forward towards a long-term nuclear waste disposal.

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Abbreviations

National Agency for Radioactive Waste Management, France	**ANDRA**
French multinational group specializing in nuclear power and renewable energy	**AREVA**
American Society of Mechanical Engineers	**ASME**
Association of Southeast Asian Nations	**ASEAN**
Nuclear Safety Authority, France	**ASN**
Bundes Schweizerischer Frauenvereine	**BfS**
Belarusian Nuclear Power Plant,	**BNPP**
Boiling water reactor	**BWR**
Canadian deuterium uranium reactor (PHWR type).	**CANDU**
China General Nuclear Power Group	**CGN**
the Central Interim Storage Facility for Spent Nuclear Fuel in Sweden	**Clab**
National Atomic Energy Commission of Argentina	**CNEA**
China National Nuclear Corporation	**CNNC**
Radioactive waste retrieval company of Netherlands	**COVRA**
Comprehensive nuclear test ban treaty	**CTBT**
Électricité de France, electricity generation and distribution company	**EdF**
Emirates Nuclear Energy Corporation	**ENEC**
National Radioactive Waste Management Company of Spain	**ENRESA**
European Union	**EU**
Gas-cooled reactor	**GCR**
Gigawatt electrical	**GWe**
High-level waste	**HLW**
High-temperature gas-cooled reactor	**HTR**
International Atomic Energy Agency (IAEA)	**IAEA**
International Commission on Radiological Protection	**ICRP**
International Energy Agency (IEA)	**IEA**
Intermediate-level radioactive waste.	**ILW**
Independent Spent Fuel Storage Installations	**ISFSIs**
Italian National Institute for Environmental Protection and Research, Italy	**ISPRA**
Nuclear Fuel Safety Project (Projekt Kärnbränslesäkerhet).	**KBS**
Korea Hydro & Nuclear Power, Korea Electric Power Corporation	**KHNP**
Low-level radioactive waste.	**LLW**
Light water reactor.	**LWR**
Management and operations	**M&O**
Mixed oxide fuel.	**MOX**
Megawatt electrical	**MWe**
National Co-operative for the Disposal of Radioactive Waste, Switzerland	**NAGRA**
Nucleoeléctrica Argentina, state company	**NA-SA**
National Committee on Radiation Protection (United States)	**NCRP**

Nuclear Decommissioning Authority	**NDA**
Nuclear Energy Agency (OECD)	**NEA**
Nuclear Energy Institute	**NEI**
Nuclear Fuel Cycle	**NFC**
Non-governmental organisation	**NGO**
Nuclear Power Corporation of India	**NPCIL**
Nuclear power plant	**NPP**
Treaty on the non-proliferation of nuclear weapons	**NPT**
Nuclear Regulation Authority	**NRA**
Nuclear Regulatory Commission (United States)	**NRC**
International Network of Nuclear Reaction Data Centres	**NRDC**
Statens strålevern (Radiation Protection Authority, Norway)	**NRPA**
Nuclear Threat Initiative, NPO	**NTI**
Nuclear Waste Management Organization of Japan	**NUMO**
North Africa and the Middle East Region	**MENA**
Operation and maintenance	**O&M**
Organisation for Economic Co-operation and Development	**OECD**
Pressurized heavy water reactor	**PHWR**
Plutonium uranium reduction extraction	**PUREX**
Pressurized water reactor	**PWR**
Research and development	**R&D**
Russian abbreviation for graphite-moderated light water-cooled reactors	**RBMK**
Russian State Atomic Energy Corporation	**Rosatom**
Radioisotope power systems	**RPS**
Radioactive Waste Management	**RWM**
Strategy Action Plan for Implementation of European Regional Repository, Stage 2	**SAPIERRII**
Slovak Electric, nuclear power operator	**SE**
Swedish Nuclear Fuel and Waste Management Company	**SKB**
Spent nuclear fuel. Fuel that has been irradiated in and then permanently removed from a nuclear reactor	**SNF**
State Power Investment Corporation of China	**SPI**
Czech Radioactive Waste Repository Authority	**SÚRAO**
synthetic rock	**Synroc**
Technical Documentation	**TECDOC**
Teollisuuden Voima Oyj, Finnish nuclear power company	**TVO**
the United Nations Conference on Environment and Development	**UNCED**
United Nations Scientific Committee on the Effects of Atomic Radiation	**UNSCEAR**
United States Environmental Protection Agency	**US EPA**
Nuclear Regulatory Commission of the United States	**US NRC**
1963 Vienna Convention on Civil Liability for Nuclear Damage	**VC**
Very low-level radioactive waste	**VLLW**
Vodo-Vodyanoi Energetichesky Reaktor, a Russian-designed pressurized water reactor	**VVER:**
World Nuclear Association	**WNA**
Waste Isolation Pilot Plant (United States)	**WIPP**

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I would like to thank Dr. Kaluba Chitumbo, ETIA professor and former Director in the International Atomic Energy Agency (IAEA), Department of Safeguards, for his wise supervision and always fruitful discussions. He kindly assisted me with his insightful ideas and vast knowledge. Moreover, Dr. Chitumbo inspired me to challenge myself with a very interesting, but demanding topic for thesis.

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And foremost, I take this opportunity to thank my great family for the opportunity to grow as a person and keep developing my professional skills in any area chosen. My sister Ekaterina, my Father Oleg, my mother Margarita, my grandmother Nina and my grandfather Anatoliy – they have always seen best in me and were there to support, understand and advice.

There is no such thing as a one-sided coin, that is why I truly believe that no matter what challenges the issue of nuclear waste brings, humanity will find a better-off solution for the sake of the future generations.

As Islandic artist *Björk Guðmundsdóttir sings:* “All is full of love”,

That should be for sure our long-term agenda.

1. Introduction:

1.1.Overview of the problem

Nowadays the issue of Deep geological disposal of high-level nuclear waste (HLW) for long-term period is becoming more and more urgent. According to researches of the international organizations, dealing with issues of the nuclear waste management, the Deep geological disposal is a safest among the existing options of isolation of HLW in the long term for the environment and people.

By 2030 on the planet there could be constructed up to 60 new power units (as of February 2018, 30 countries worldwide are operating 450 NNPs for electricity generation and 60 new NNPs are under construction in 15 countries (Nei.org, 2018)). Most of all NPPs (63 NPPs, 104 power units) these days are operated on the territory of the USA (See Figure 1.1.). On the second place there is France with 58 power units.

The global nuclear energy market is estimated to grow at a CAGR of over 4% from 2015 to 2022 ((Grandviewresearch.com, 2015). The leading nuclear companies are expected to compensate elimination of old power units for new ones and provide increase in a share of a nuclear component in a world energy balance for a low-carbon ‘Sustainable Development Scenario’ to 14% of the total.

However, already by 2015 in the world about 270 000 tons of spent nuclear fuel (SNF) have been saved up. Every year world reserves of SNF increase by 12 000 tons and at the same time annually in the world 3 000 tons of SNF, or 25 % from annually acquired SNF are processed (Nuclearaustralia.org.au, 2015). If all the amount of used nuclear fuel assemblies were stacked end-to-end and side-by-side, this would cover a football field about 6,4 meters deep (Lusted, 2013).

From all the amount of the unloaded SNF about 70 000 tons have been reprocessed. That means, there are around 150 000 tons of SNF stored, from which the most part, about 140 000 tons, - situated at the reactor site or centralized in Independent Spent Fuel Storage Installations (ISFSIs), "wet" storages where SNF is kept under water. Remained SNF is kept in dry storages. More and more countries refuse to reprocess the SNF in favor of storage and/or disposal of SNF.

Most of this waste has to be stored in temporary storages. The compliance with all safety requirements increases the possibility of committing terrorist acts and raises the vulnerability towards the influence of extreme weather conditions (Fukushima Daiichi Accident, 11 March 2011).

It is becoming gradually evident, that the final disposal in geological formations is also associated with certain problems. Although this method until recently was considered as the most reliable. An example is the danger of the accidental release of radioactive materials into the biosphere that occurred in the German repository in the city of Asse (Salander, Proske and Albrecht, 1980). In this particular case, the guaranteed safety of long-term storage expired only after 40 years.

Technologies such as reprocessing and transmutation are also not a better-off solution. According to the latest data, the construction of a long-term Deep geological disposal repository is still necessary. Because, multi-stage waste treatment increases the risk of accidents, radiation exposure of employees and the public and the use of waste to manufacture nuclear weapons for the purpose of committing a terrorist act.

Transmutation is planned to be introduced in common practice within 50 years. By that time, 1 000 000 m3 of nuclear waste, waiting for transmutation will be accumulated, as well as a huge amount of conditioned and non-recyclable waste (for example, vitrified waste). Therefore, the approach of countries that already have the experience of building the Pilot repositories (like WIPP in the U.S.) or those, which are planning to launch their own in the near future (Onkalo spent nuclear fuel repository in Finland), is particularly interesting (Matthews, 1996). Thus, it is unlikely that transmutation will solve the problem of the HLW in the nearest future.

Nuclear energy has already a history of more than half of the century in operation. However, during this time, no country has developed or implemented an effective strategy for the reprocessing of all types of nuclear waste. The EU directive also does not solve the problem of radioactive waste management, due to internal issue of a wide a range of national strategies in the EU Member States.

1.2. Core objectives

The primary objective of this thesis will be to examine modern approaches to the concept of implementing a project of an International Deep geological repository for a long-term storage of HLW. Secondly, it is important to analyze the conditions for the implementation of the project for Deep geological repository for such wastes and provide a selected country review of the concepts of the nuclear fuel cycle and domestic HLW management projects. Based on the data considered, the thesis explores the potential of the project of an International repository of HLW and provides a retrospective analysis of initiatives in this area, as well as a comparative analysis of the advantages of an International repository.

This provision was summarized by the formal Director of the International Atomic Energy Agency Mohamed ElBaradei (IAEA, from 1997 to 2009) in his speech at the International Conference on Geological Repositories in December 2003 in Stockholm: “In the current climate, geological repositories have come to be viewed not as one option among many for completing the nuclear fuel cycle, but as the only sustainable solution achievable in the near term. But despite a longstanding agreement among experts that geological disposal can be safe, technologically feasible and environmentally sound, a large part of the general public remains skeptical. It is in this context that I would like to share a few of my views on the challenges we face and how the International Atomic Energy Agency hopes to help in furthering progress. Approved technologies of intermediate storage (up to 50 years) of radioactive waste are recognized by experts as half-measures, that do not meet the principles of sustainable development and carry an unreasonable burden on the final utilization of nuclear waste for future generations. "

International cooperation for building the Deep geological repository for SNF and HLW according to the IAEA has its own pros and cons but reaching the agreement on this project is crucial. Because, even in case of the cessation of the production of nuclear energy, it will be necessary to manage already generated amount of the nuclear waste.

1.3.Hypothesis.

After a comparative analysis of the main issues, that arise from long-term geological disposal and near-surface storage options, the deep geological disposal method proves itself as the most favorable one. Especially in the context of international security and terrorism threat. Some of the countries worldwide are already at one step forward then others in the development of national sites for deep geological disposal of HLW. In the current chapter we will see the up-to-date examples and argue the possibility of International site for long-term HLW disposal.

1.4.Methodology

The data for the following comparative study has been gathered from sources, provided by more than 60 years of scientific research in the area of nuclear waste management. Necessary libraries, scientific journals, legal databases of domestic and international law, online publications and interviews with specialists in HLW management developed the core informational support for this thesis.

The primary sources included international treaties and conventions, tackling the issues of radioactive materials management (Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, Vienna, 24 December 1997; Treaty on the Non-Proliferation of Nuclear Weapons, 1 July 1968) , as well as domestic legislation The Civil Code of the Russian Federation, Part II, Section IV, Chapter 34.Lease, with the Additions and Amendments of December 23, 2003) and joint reports.

Secondary sources were books and journal publications, on nuclear waste management and different practices depending on the country, containing aspects of technical, economical and legal advancement of HLW disposal. The large part of statistics was chosen from big databases of international organizations and state legal bodies: EEA, IAEA, NEI, OECD, US EPA, UN, WNA etc.

Finally, the social aspects in this thesis and up-to-date statistic data, as well as visual information sources were compiled from the websites of private and state owned nuclear operators (AREVA, ROSATOM, SKB) as well as important reflections on influence of public opinion in works of T. Schofield (The environment as ideological weapon: the offer on criminalization of terrorism with impact on the environment, 1998).

2. The role of nuclear power in the modern world

2.1. Safety and costs dilemma

In 21st Century the question of energy consumption is particularly acute. The long term non-renewability of petroleum-based resources, sets thinking towards the use of alternative energy sources for gaining the electric power, such as wind, sunlight and the geothermal energy. However not all the countries possess corresponding climatic and geographical conditions that would allow to use the renewables and the technological capacities, necessary for this purpose, aren't developed yet. Therefore, the nuclear power takes the leading positions and isn't going to hand over them yet.

By the most conservative estimates, to the middle of the 21st century consumption of energy on the planet will double, as a consequence of world economy development, growth of the population and other geopolitical and economic factors. In that case, electricity will be required not only for receiving fuel, but also through the perspective of sustainable development — for hydrogen production and also for providing people with fresh water (that requires a costly desalination procedures).

Despite recent tragic events of 2011 in Fukushima, Japan (Mahaffey, 2015) and followed up splash of mistrust towards "peaceful atom" among the public. The nuclear power continues to remain one of the most perspective directions in the energy sector. The growth of electric power consumption together with development of world economy, aggregates the demand of new power unit’s construction. Meanwhile the demand for the main resource of nuclear power — uranium grows reciprocally.

The uranium market — is quite a specific sector of World economy. More than 90% of this sector is controlled by several large uranium mining companies (A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency, 2016 (See Table 1.1.)). The direct sale of uranium is under the strict control of the international organizations and the speculation on this market is almost excluded. Because of closed-door policy on the uranium market it is extremely stable, read — very perspective object for investors.

Table 1.1. Eleven companies, that marketed 89% of the world's uranium mine production; Source: WNA (World Nuclear Association, 2017)

Company	tonnes U	%
KazAtomProm	12986	21
Cameco	10438	17
Areva	8176	13
ARMZ - Uranium One	7913	13
BHP Billiton	3233	5
CNNC & CGN	2964	4
Rio Tinto	2440	4
Navoi	2404	4
Paladin	1420	2
Other	10,455	17
Total	**62,366**	**100%**

2.2. Advantages of nuclear power

The consumption of energy grows in the world much quicker, than its production, and the industrial use of the new power supply technologies, for the objective reasons, will begin not earlier than 2030. There is a problem of shortage of fossil energy resources stands more and more sharply. Possibilities of construction of new hydroelectric power stations are very limited too. One should also keep in mind the UN agenda of target to reduce the greenhouse effect, imposing restrictions for combustion of oil, gas and coal on thermal power plants.

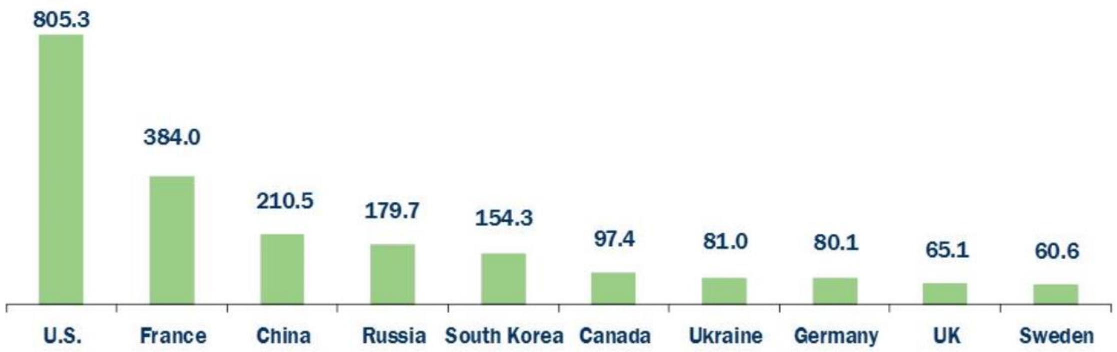

Figure 1.1. Top 10 Nuclear Generating Countries for 2016, in Billion KWh; Source: Nuclear Energy Institute (Nei.org, 2016)

An active development of nuclear power can become a solution in this case. At the moment in the world the tendency which has received the name "nuclear Renaissance" was designated, though the market emerged multiple losses in 2012 after Fukushima Daiichi nuclear accident (World-nuclear-news.org, 2018). However, the forecasts of IAEA officials claim that by 2030 on the planet there could be constructed up to 60 new power units (as of February 2018, 30 countries worldwide are operating 450 NNPs for electricity generation and 60 new NNPs are under construction in 15 countries (Nei.org, 2018)). Such factors as reliability, acceptable level of expenses in comparison with other sources of electric power generation, rather small volume of waste and availability of resources, can affect the increase in a share of nuclear power in a world energy balance.

Annually European NPPs allow to avoid emission of 700 million tons of CO_2, and in Japan — 270 million tons of CO_2. The operating NPPs of Russia annually prevent emission in the atmosphere of 210 million tons of carbon dioxide. Most of all NPPs (63 NPPs, 104 power units) are operated in the USA (See Figure 1.1.). On the second place there is France (58 power units) (See Table 1.2.).

Table 1.2. Nuclear power plants in operation world-wide; Source: IAEA (IAEA, 2016)

Country	In operation	
	Number	Electr. net output MW
Argentina	3	1.632
Armenia	1	375
Belarus	-	-
Belgium	7	5.913
Brazil	2	1.884
Bulgaria	2	1.926
Canada	19	13.524
China	36	31.402
Czech Republic	6	3.930
Finland	4	2.752

France	58	63.130
Germany	8	10.799
Hungary	4	1.889
India	22	6.225
Iran	1	915
Japan	43	40.290
Korea, Republic	25	23.133
Mexico	2	1.440
Netherlands	1	482
Pakistan	4	1.005
Romania	2	1.300
Russian Federation	36	26.557
Slovakian Republic	4	1.814
Slovenia	1	688
South Africa	2	1.860
Spain	7	7.121
Sweden	10	9.651
Switzerland	5	3.333
Taiwan, China	6	5.052
Ukraine	15	13.107
United Arab Emirates	-	-
United Kingdom	15	8.918
USA	99	98.868
Total	**450**	**391.915**

The brief overview of the advantages of nuclear power makes the following list:

• Efficient power consumption of the used fuel. 1 kilogram of uranium enriched up to 4%, at full burning out, emits the amount of energy equivalent to burning about 100 tons of high-quality coal or 60 tons of oil.

• A possibility of fuel reuse (after regeneration). The split material (uranium-235) can be used again (unlike ashes and slags of organic fuel). With development of technology of reactors on fast neutrons, in the long term the transition to the closed fuel cycle is possible and that potentially means total absence of waste.

•The nuclear power doesn't attribute towards the creation of greenhouse effect. Annually nuclear power plants in Europe allow to avoid the release of 700 million tons of CO2. Thus, an intensive development of nuclear power can be considered indirectly one of methods of Climate Change mitigation (IAEA, 2016).

2.3. Current state of nuclear power and prospects of development

According to the IAEA experts, by 2030 in the world there can be constructed up to 60 new power units with a general power up to 430 GW (See Table 1.3.), rising to a total generating capacity of 11,960 GWe by 2040. It has to compensate elimination of old power units for more and provide increase in a share of a nuclear component in a world energy balance for a low-carbon ‘Sustainable Development Scenario’ to 14% of the total.

Table 1.3. Nuclear power plants planned for construction; Source: WNA (World Nuclear Association, 2018)

Start †		Reactor	Model	Gross MWe
2018	China, CGN	Taishan 1	EPR	1750
2018	Russia, Rosenergoatom	Leningrad II-1	VVER-1200	1170
2018	Russia, Rosenergoatom	Rostov 4	VVER-1000	1100
2018	Slovakia, SE	Mochovce 3	VVER-440	471
2018	Korea, KHNP	Shin-Hanul 1	APR1400	1400
2018	Korea, KHNP	Shin-Kori 4	APR1400	1400
2018	UAE, ENEC	Barakah 1	APR1400	1400
2018	UAE, ENEC	Barakah 2	APR1400	1400
2018	China, CNNC	Sanmen 1	AP1000	1250
2018	China, CNNC	Sanmen 2	AP1000	1250

2018	China, SPI	Haiyang 1	AP1000	1250
2018	China, CGN	Yangjiang 5	ACPR-1000	1087
2018	China, China Huaneng	Shidaowan	HTR-PM	210
2018	India, Bhavini	Kalpakkam PFBR	FBR	500
2019	Argentina, CNEA	Carem25	Carem	27
2019	Finland, TVO	Olkilouto 3	EPR	1720
2019	Russia, Rosenergoatom	Pevek FNPP	KLT40S x 2	70
2019	Russia, Rosenergoatom	Novovoronezh II-2	VVER-1200	1200
2019	UAE, ENEC	Barakah 3	APR1400	1400
2019	China, CGN	Fangchenggang 3	Hualong One	1150
2019	China, CGN	Hongyanhe 5	ACPR-1000	1080
2019	China, CGN	Yangjiang 6	ACPR-1000	1087
2019	China, CNNC	Fuqing 5	Hualong One	1161
2019	China, CNNC	Tianwan 4	VVER-1000	1060
2019	China, SPI	Haiyang 2	AP1000	1250
2019	China, CGN	Taishan 2	EPR	1750
2019	France, EdF	Flamanville 3	EPR	1750
2019	Korea, KHNP	Shin-Hanul 2	APR1400	1400
2019	Slovakia, SE	Mochovce 4	VVER-440	471
2019	Belarus, BNPP	Ostrovets 1	VVER-1200	1194
2020	Russia, Rosenergoatom	Leningrad II-2	VVER-1200	1170
2020	China, CGN	Hongyanhe 6	ACPR-1000	1080

2020	China, CGN	Fangchenggang 4	Hualong One	1150
2020	China, CNNC	Tianwan 5	ACPR-1000	1080
2020	China, CNNC	Fuqing 6	Hualong One	1161
2020	UAE, ENEC	Barakah 4	APR1400	1400
2020	Belarus, BNPP	Ostrovets 2	VVER-1200	1194
2021	Argentina, NA-SA	Atucha 3	Candu 6	800
2021	China, CNNC	Tianwan 6	ACPR-1000	1080
2021	Pakistan	Karachi / KANUPP 2	ACP1000	1161
2021	USA, Southern	Vogtle 3	AP1000	1250
2021	Korea, KHNP	Shin-Kori 5	APR1400	1400
2022	India, NPCIL	Kakrapar 3	PHWR-700	700
2022	India, NPCIL	Kakrapar 4	PHWR-700	700
2022	India, NPCIL	Rajasthan 7	PHWR-700	700
2022	India, NPCIL	Rajasthan 8	PHWR-700	700
2022	Pakistan	Karachi / KANUPP 3	ACP1000	1161
2023	Brazil	Angra 3	PWR	1405
2023	USA, Southern	Vogtle 4	AP1000	1250
2023	Bangladesh	Rooppur 1	VVER-1200	1200
2023	China, CNNC	Xiapu 1	CFR600	600
2024	Japan	Ohma 1	ABWR	1383
2025	India, NPCIL	Kudankulam	VVER-1000	1050

† *Latest announced year of proposed commercial operation*

Note: units where construction is currently suspended are omitted from the above table.

In such countries as Russia, China, India, the Republic of Korea, the USA, Canada and Finland, programs of intensive development of nuclear power have already been implemented. In India by 2025, 6 new power units will be constructed, and China is going to increase the general power of the internal sector to 33% of total.

By development plans in the USA 115 reactors, that is 20,6% of world quantity will be constructed. In China for the last five years there were constructed and put into operation of 8 reactors. About 20 more reactors at the moment are under the process of construction and it is planned to construct 27 more reactors by 2020. Also, the countries, which still didn't have the NPP, have expressed the intentions to develop nuclear power: Turkey, Belarus, Poland, Vietnam, Indonesia, Morocco and others. In total in the world at the stage of construction there are 57 new reactors (Table 1), and till 2030 is planned to construct 60 more reactors.

Framework of these Master Thesis material is limited to consideration of the question concerning utilization of the spent nuclear fuel (SNF) from civilian nuclear power plants (NPPs) and highly radioactive waste (HLW) which are formed via SNF reprocessing.

In this material under the term “repositories” are considered points of final burial of SNF and HLW. Under the term of “facility”, the SNF and HLW temporary storages are considered. For the long-term storage of HLW deep within a stable geologic environment, we will be using a term “deep geological repository”.

2.4. Volumes and dynamics of accumulation of SNF

By 2015 in the world about 270 000 tons of SNF have been saved up. Annually world reserves of SNF increase by 12 000 tons. At the same time annually in the world 3 000 tons of SNF, or 25 % from annually acquired SNF are processed (Nuclearaustralia.org.au, 2015).

From all the amount of the unloaded SNF about 70 000 tons have been reprocessed. There are around 150 000 tons of SNF stored, from which the most part, about 140 000 tons, - situated at the reactor site or centralized in Independent Spent Fuel Storage Installations (ISFSIs), "wet" storages where SNF is under water. Remained SNF is kept in dry storages. More and more countries refuse to reprocess the SNF in favor of storage and/or disposal of SNF.

The storage and disposal of SNF - are an extremely expensive and technologically difficult processes. Still in the world there is no successful example of final disposal of HLW from SNF. By recognition of the of the formal Director General of the International Atomic Energy Agency Dr. Mohamed ElBaradei (IAEA, from 1997 to 2009), not the all countries possess geological structures, human, scientific and financial resources for disposal of SNF and HLW. And an active search of a solution to the problem of SNF and HLW disposal at the international correlated to the courtiers' capacities.

2.5. The existing legal framework concerning storage and disposal of HLW

The storage and disposal of HLW legal framework, for today is presented by three types of the documents: international conventions and treaties, multilateral agreements and national legislation.

The most impactful international conventions and treaties, concerning storage and disposal of SNF:

- **Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management** (Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 1997). The convention was signed on September 5, 1997. According to the Article 27 of the Convention, the "cross-border movement" of SNF and HLW to the territory of second party countries, under the condition of implementation of safety requirements, etc. is fixed by the Convention and is allowed;

- **Treaty on the Non-Proliferation of Nuclear Weapons** (NPT) (Treaty on the Non-Proliferation of Nuclear Weapons, 1970). The Treaty did come into force in 1970. According to the Article 4 of NPT, all the Parties to the Treaty undertake obligations for cooperation in development of nuclear power for peaceful purposes. Despite obvious absence in the Treaty of creation of the international repositories, nevertheless, NPT is used by IAEA for justification of the idea of internationalization of SNF storages and HLW facilities. Internationalization of national storages and repositories in the context of this article guarantees, according to IAEA, non-proliferation of nuclear materials;

- **Bamako convention** (Bamako Convention on the Ban of the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa, 1991). The convention was adopted on January 30, 1991 in Bamako, Mali and forbids any import of hazardous waste, including radioactive to Member countries of the Convention.

Multilateral agreements on storage and burial of SNF

For today in the world there are no multilateral agreements on storage or building deep geological repositories of spent nuclear fuel on the territory of other countries. Nevertheless, since 2000 IAEA takes a closer look to a proposal of an active import of SNF through introduction of a concept of the international leasing in the system i.e. return of SNF to the supplying country of fresh fuel.

However, according to the legislation of some countries (in particular the Russian Federation), the institute of leasing is inapplicable to schemes of return of SNF to the supplying country of fresh fuel (at steps in the front end of the nuclear cycle (see Figure 1.2.)). Within the context of this research under leasing we imply a type of investment activities on acquisition of property and its transfer on the basis of the contract of leasing to natural or legal entities for a certain payment, for a certain term and under certain conditions, caused by the contract, with the right of repayment of property by the lessee.

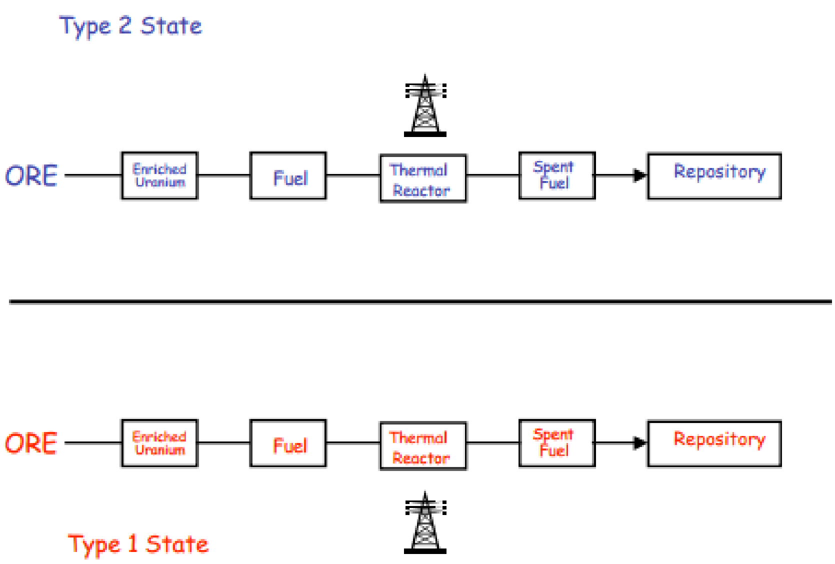

Figure 1.2. Fuel Cycle Diagram, Open Cycle, No Lease (All states use thermal reactors in open cycles and do not lease. There is no limit on the amount of spent nuclear fuel.) Source: (Reis et al., 2005)

The SNF leasing schemes are offered to be used as follows. The country A transfers new uranium fuel to the Country B for a temporary use and after the operation, country A returns this fuel already in the form of SNF. At the same time SNF remains as the property of the Country A. The fresh fuel recipient (Country B) doesn't redeem it and pays only throughout the operation period (see Figure 1.3.).

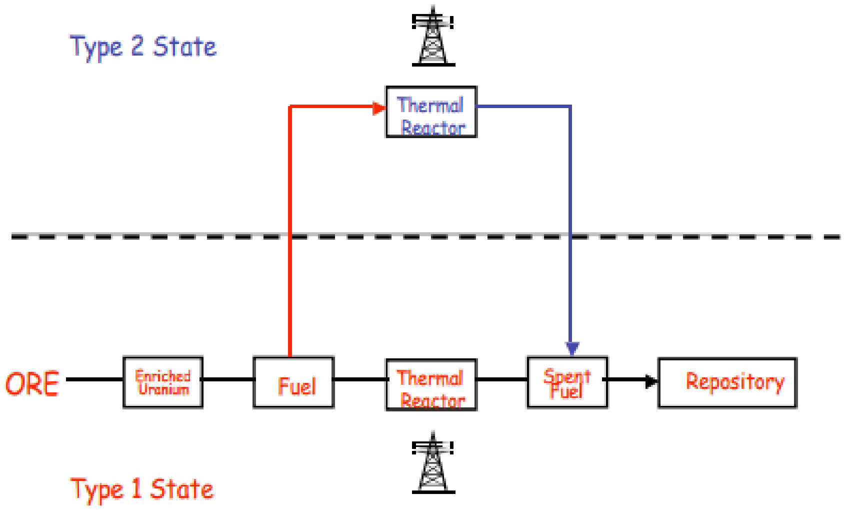

Figure 1.3. Type 1 states have thermal reactors in an open cycle, and leases fuel to Type 2 states, which only have reactors; Source: (Reis et al., 2005)

Nevertheless, in reality, some of the countries nowadays have a leasing contradicting domestic legislation e.g. could be the Russian Federation. According to the Russian legislation, a subject of leasing there can only be inconsumable things. On the basis of the Article 607 of the Civil code of the Russian Federation (The Civil Code of the Russian Federation/Lease, 2003), things which don't lose the natural properties in the course of their use are inconsumable. This condition has no relation to spent nuclear fuel as at operation uranium fuel loses the key properties in the course of "burning out" of the sharing materials and accumulation in fuel of undesirable radioactive fission products. The specified circumstances result in essential difference of SNF properties from properties of fresh fuel. Therefore, in case of return of SNF to the lessor they can't be repeatedly used for designated purpose in nuclear reactors. Proceeding from the above, SNF can't be carried to a leasing subject in Russia as it has properties, other than fresh fuel, that is isn't an inconsumable thing.

National legislation

That is why the domestic legislation should be considered as one of the pre-requisites during a buildup of multilateral treaties. In the world there is no national legislations, allowing import of SNF and HLW for a final disposal. Moreover, for example, the legislation of Saudi Arabia assumes the death penalty as a punishment for import of radioactive waste on the territory of the country.

From the point of view of administration of the USA (the letter of the Assistant to the President of the USA John Gibson of August 12, 1996), "the project on uranium fuel leasing…has many essential shortcomings which outweigh all advantages. Laws, which are still a subject of change, can promote the turn of territory of the USA into the storage of the worlds' spent fuel – prospect with which the present administration can't agree".

In this context, the legislation of the Russian Federation, according to which import of SNF for a technological temporary storage is possible, is being controversial. Because the accurate terms of technological storage have not been established yet.

Such legislative position has obviously challenging character, as import to temporary storage doesn't make economic or any other sense. Moreover, an excess transportation of SNF at first on temporary storage, and then back assumes additional expenses and increases risk of accidents or terrorist attack. Besides, according to many experts, as a result of temporary storage the situation at which the heatallocating assemblies (which contain SNF) will become unsuitable for transportation, due to high possibility of corrosion and other mechanical damages. In this case the return transportation becomes dangerous and impossible. Thus, the possibility of final disposal of non-domestic HLW (as written – for temporary storage) is confirmed by the Russian legislation, according to which storage of SNF is considered as a stage of preparation for reprocessing or final disposal.

On the contrary the recent decision of Court of Appeal of the city of Caen (France, April 12, 2005) according to which the SNF from Australia (Holland, 2002) disposal at the territory of France even for temporary storage is regarded as illegal.

Importance of the state subsidies and their volume fluctuations

On the basis of the successful researches conducted by the British government in years 1989, 1995 and 2002 consistently, following conclusion were brought up: on the free market of the electric power the enterprises in energy sector won't build nuclear power plants if there are no state subsidies and the government doesn't guarantee a substantial covering of expenses. In the majority of the countries where the monopoly in the energy sector is cancelled, similar measures are applicable (Brookes, 2014). Subsidies and guarantees can be required, most likely, in those areas which aren't controlled by the owner, namely for:

1. Covering the costs of construction. Expenses on construction of new NPPs are considerable and the risk of an over expenditure of means is very high. Therefore, the government, is expected, to establish the fixed maximum of expenses which the private investor will have to pay.
2. Operational characteristics variance. There is a serious risk that productivity will be lower than predicted. Reliability substantially is under control of the owner and isn't absolutely clear yet whether developers will be sufficiently sure of the ability to undertake risk of a lack of reliability (Wheatley, 1970).
3. Covering the expenses on operation and maintenance. The same way it substantially is under control of owners, and they should be ready to bear this risk.
4. Covering the expenses on nuclear fuel. Fuel purchase usually doesn't belong to risky activity. Reserves of uranium can be accumulated, and the risk of increase in costs of acquisition of fuel is a subject to overcome. However, the question concerning costs of elimination of the SNF (if not - to consider reprocessing option) is much more debatable, and owners of NPPs, perhaps, will try to obtain establishment of a limit for expenses of fuel utilization (Kryzia and Gawlik, 2016).
5. Covering the costs of NPPs decommission. It is quite difficult to predict expenses on decommission measures, but it is obvious that in the future they will increase. Assignments of separate funds for a decommission upon a properly developed scheme, seem like a quite convenient option, however, the experience of a decommission from operation and management of waste shows that calculations are too underestimated. Thus, the investments return of will go more slowly, than was predicted, it is necessary to increase contributions considerably (Rombough and Koen, 1975).

For this reason, private developers demand the definition of a certain maximum for the contributions. And the state is expected to provide guarantees of all-inclusive and high aids at least for the first installations under construction which will incur the first adjusting expenses on new technology. If the operating experience of several constructed installations is positive, it implies that the domestic market will agree to bear big risks though, undoubtedly, already with the support of political will to advance the nuclear power. However, it is necessary to remind that for instance, during the period of board of administrations of R. Reagan and M. Thatcher (who promised the recovery of the nuclear sector (Smart, 1975)) there was a sharp decline of nuclear power.

2.6. Main outcomes of the first chapter

The problem of radioactive waste, so-called "HLW management issue " is acute due to the large amount of the saved-up radioactive waste, insufficiency of technical means for ensuring safe handling of those waste and spent nuclear fuel, absence of reliable storages for their long-time storage or disposal and increased risk of radiation proliferation accidents. There is a threat of radiation environmental pollution, eradiation of the population and personnel of objects of economy. Especially crucial it is to solve now the problem of the utilization and burial of HLW from the nuclear power plants (NPPs), when under the terms of operation demand dismantling most of the NPPs in the world.

Among the nuclear physicists there is very a popular belief that there is already existing market of purchase and sale of SNF, out of which they are driven by means of the bribed ecologists. However, in fact, itself SNF isn't a subject to purchase and sale, i.e. in the world market there has been no precedents of purchase for the purpose of the subsequent generation of profit. Though, many countries and the companies would be ready to subsidize not only construction of the new NPPs but also to pay for somebody to hold back the SNF and guarantee the solution to solve all problems and consequences of its storage and reprocessing.

The energy sector investors have already understood that the problem of SNF still presents an absolute obstacle for the development of the atomic industry. One of the main problems in spent nuclear fuel management consists of the fact, that SNF has a mix of various substances (non-reprocessed – not the uranium burnup, but products of radioactive decay of uranium and the transuranium elements). Energetically valuable dioxides of isotopes of uranium (U-238 and U-235) and plutonium make about 97,5% of SNF. Even after the long-term storage they can be used for generating the nuclear power. Radioactive waste (HLW), unsuitable to power use, make about 2,5% of SNF. SNF constitutes big danger since its radioactivity is large (Hadermann and Mccombie, 1992).

The amount of the HLW, which are saved up by production of nuclear weapons, is much (that is not less than by 10 times) above waste of nuclear power. Even if military programs are shut down, then waste from "peaceful atom" will grow further. In this thesis we ask the question: whether it is necessary to consider HLW just as waste or as a potential power source? Depending on the answer to this question, there is a first step towards the solution of a problem - whether we want to store them (in a suitable form) or to dispose those (i.e. to make them inaccessible).

The standard answer will be now, that HLW is actual waste, except for, maybe, plutonium. Plutonium can theoretically be a power source, though the technology of obtaining energy from Pu is technologically difficult and dangerous (NASA seeks plutonium alternative to power deep-space missions, 2010). Within 50 years the scientific society was comparing the options for HLW disposal. The main idea was — HLW should be placed in such place, where they couldn't be exposed to the environment and do harm to the population. This ability of HLW to expose ionizing radiation is kept during tens and hundreds of thousands of years. The irradiated nuclear fuel which we extract from the reactor contains radioisotopes with half-life periods from several hours to million years (the half-life period is the time during which the amount of radioactive material decreases twice in its value, and in some cases, there are new radioactive materials formed). But generally, the radioactivity of waste considerably decreases over time. The tasks arising for HLW management programmes are unprecedented in the history: people never did set themselves such long-term goals.

The interesting aspect of an issue may be described like that: it is necessary not only to protect people from waste, but at the same time to protect waste from people. In times of HLW storage even modern social and economic formations can be replaced. It is impossible to exclude that in a certain situation HLW can become a target for terrorists, or used at the military conflict, etc. For this reason, the international cooperation over development of treaties and solutions for HLW management, should encourage scientific and political community to make joint efforts for exchange of experience and a responsible approach to utilization of SNF. It is clear, that any technical solution, any artificial material can't "work" during the millennia. Obvious conclusion: the environment has to isolate waste. Nowadays it has been agreed that the optimum solution is a waste disposal in deep geological formations.

In the following chapter we will consider theoretical and technical solutions of a problem of HLW management.

Metaphorically, building a nuclear powerplant these days is like building a house… without a toilet.

Nuclear Waste: Last Week Tonight with John Oliver, 20 August 2017 (HBO)

3. Technical management of radioactive waste

3.1. Classification of radioactive waste generated

The issue of radioactive waste management is one of the most important in the nuclear energy industry. The main distinctive feature of nuclear power from other sources of obtaining energy is the accumulation of considerable volumes of radioactive waste, which are formed practically at all stages of the nuclear fuel cycle.

To the material objects and substances, the activity of radionuclides or radioactive pollution of which exceed the levels established by the existing standards, belong radioactive waste, provided that use of these objects or substances isn't supposed further. Their hazardous state is caused first of all by the fact that the radionuclides, which are contained in such waste, can dissipate in the biosphere and result in negative radiative effects on the human health and the environment.

Radioactive waste can be a special type of radioactive materials in various aggregate states (gases, solutions, materials and products, biological objects). They are classified by various attributes: by aggregate state, half-life period, specific activity, structure of radiation, etc. By the aggregate state liquid radioactive waste (in form of Spent Nuclear Fuel (SNF)) have the greatest distribution, which are formed from the use of different fuels in nuclear reactors, radiochemical plants, research centers (Hannum, 2013).

Table 2.1. Classification of French radioactive waste as a function of their management; Source: French national radioactive waste management (ANDRA, Page last updated Tuesday, June 3, 2014)

		HALF-LIFE		
ACTIVITY		**Very short-lived** Half-life < 100 days	**Short-lived** Half-life ≤ 31 years	**Long-lived** Half-life > 31 years
	Very low level	**Stored to allow radioactive decay on**	**Surface disposal facility**	

<table>
<tr><td rowspan="4"></td><td>(VLL)</td><td rowspan="3">the production site then disposed of adopting conventional solutions*</td><td colspan="2">(Very low-level radioactive waste disposal facility)</td></tr>
<tr><td>Low level
(LL)</td><td rowspan="2">Surface disposal facility (Low-and intermediate-level waste disposal facility)</td><td>Shallow disposal facility (studied in accordance with the Act of 28 June 2006)</td></tr>
<tr><td>Intermediate level
(IL)</td><td></td></tr>
<tr><td>High level
(HL)</td><td></td><td colspan="2">Reversible deep geologic disposal facility (studied in accordance with the Act of 28 June 2006)</td></tr>
</table>

* Certain waste when it contains a too large amount of tritium (radioactive hydrogen) (Ccpa.net, 2006) must be stored before disposal in order to allow for the decay of this tritium (approximately 12-year half-life).

At all stages of the nuclear fuel cycle the significant amounts of solid nuclear waste are generated, in particular 300–500 m^3 of solid waste in reactors of the NPPs with a total electrical output of 1 GW per year, and from processing of the irradiated fuel of 10 m^3 more of High-level waste, 40 m^3 Intermediate level waste and 130 m^3 waste of Low-level activity are formed (See Figure 2.1.).

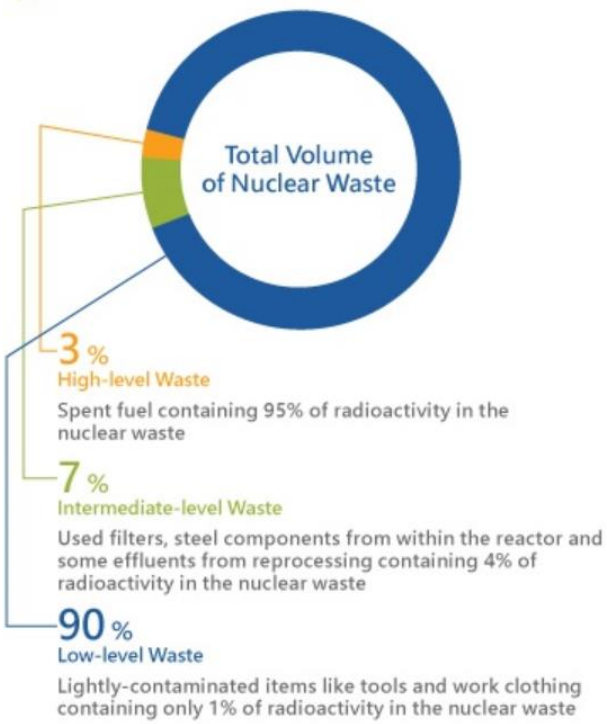

Figure 2.1. Types of Nuclear Waste by Production; Source: World Nuclear Association (WNA, 2017)

For the treatment and conditioning of radioactive waste and materials (See Table 2.1.) the relevant national standards, rules and procedures are developed, based on the recommendations of the International Commission on Radiological Protection *(*ICRP*)* and the International Atomic Energy Agency (IAEA).

The construction of the new, as well as operation and maintenance of NPPs is directly connected with the problem of radioactive waste management. Radioactive waste is the waste containing radioactive isotopes of chemical elements and constituting special biological hazard. Nowadays this problem is critical really and by the available estimates, the operation of the NPPs of the whole world lead to accumulation of 270,000 metric tons of heavy metal (MTHM) from spent fuel by 2016, and by 2030 this volume will increase up to 500 thousand metric tons (See Table 2.2.).

Table 2.2. Nuclear waste inventory by IAEA estimates for year 2016; Source: The Nuclear Energy Institute (Nei.org, 2016)

	Solid radioactive waste in storage (m^3)	**Solid radioactive waste in disposal (m^3)**	**Proportion of waste type in disposal**
VLLW	2,356,000	7,906,000	77%
LLW	3,479,000	20,451,000	85%
ILW	460,000	107,000	19%
HLW	22,000	0	0%

Note: all volumetric figures are provided as estimates based on operating and proposed final disposal solutions for different types of waste.

Thus, arises the question of possible methods of utilization of the spent nuclear fuel (SNF). The scientific community addresses this problem already for more than five decades, and there have been created, from which the most cost-effective and bringing higher level of safety have been used. Nevertheless, there are only two main ways of treatment of radioactive waste: to dispose or to reprocess.

3.2. Methods of radioactive waste management: optional and commonly accepted

The nuclear reprocessing technology has a potential to be used for production of nuclear weapons, which triggers nuclear proliferation. Meanwhile, the nuclear waste disposal, especially of the long-lived High-level radioactive waste (HLW) is interconnected with potential danger of contamination in case of unforeseen circumstances. Therefore, finding secure places for HLW disposal, is a serious issue. In this academic research we would examine various methods of HLW disposal, their advantages and disadvantages would be considered, and the most perspective solutions would be designated.

Table 2.3. Options for long-term nuclear waste management, that have been considered in the past; Source: World Nuclear Agency (WNA, 2017)

Ideas	**Examples**
Long-term above ground storage	• Investigated in France, Netherlands, Switzerland, UK, and USA.

Ideas	Examples
	• Not currently planned to be implemented anywhere.
Disposal in outer space (proposed for wastes that are highly concentrated)	• Investigated by USA. • Investigations now abandoned due to cost and potential risks of launch failure.
Rock-melting (proposed for wastes that are heat-generating)	• Investigated by Russia, UK, and USA. • Not implemented anywhere. • Laboratory studies performed in the UK.
Disposal at subduction zones	• Investigated by USA. • Not implemented anywhere. • Not permitted by international agreements.
Sea disposal	• Implemented before by Belgium, France, Germany, Italy, Japan, Netherlands, Russia, South Korea, Switzerland, UK, and USA. • Not permitted anymore by international agreements.
Sub seabed disposal	• Investigated by Sweden and UK (and organisations such as the OECD Nuclear Energy Agency). • Not implemented anywhere. • Not permitted by international agreements.
Disposal in ice sheets (proposed for wastes that are heat-generating)	• Investigated by USA. • Rejected by countries that have signed the Antarctic Treaty or committed to providing solutions within national boundaries.
Deep well injection (for liquid wastes)	• Implemented in Russia for many years for LLW and ILW. • Investigations abandoned in the USA in favor of deep geological disposal of wastes in solid form.

a) Long-term above ground storage.

Storage of radioactive waste in containers on specially equipped sites, directly on Earth's surface, or at a small depth in in mostly in aboveground storage casks (See Figure 2.2). Used in present for waste with a half-life of elements of not more than 30 years. It is a fairly risky method, because when exposed to natural disasters or significant climate change, the container may be destroyed, and as a result, the environment becomes contaminated with radionuclides.

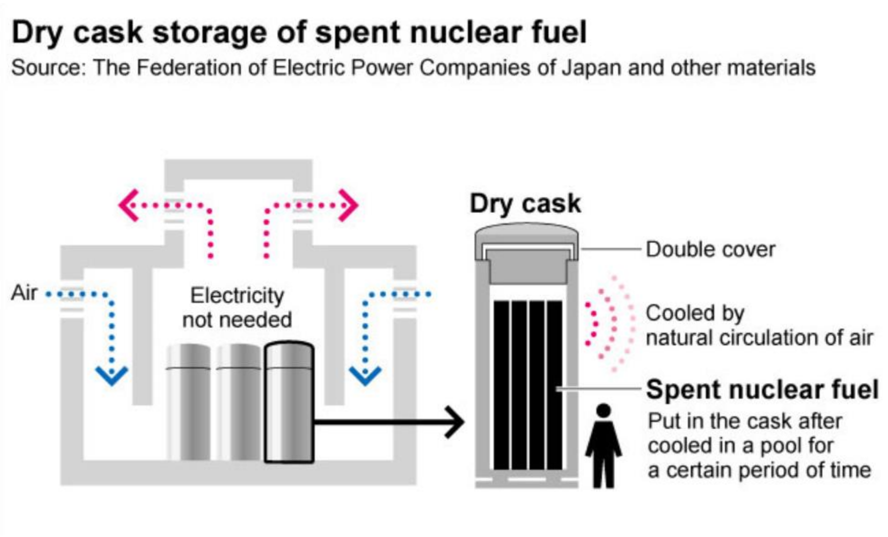

Figure 2.2 Typical Dry Cask Storage System; Source: The Asahi Shimbun: Asia & Japan Watch (The Asahi Shimbun, 2017)

b) Disposal of highly concentrated amounts of radioactive waste in outer space.

The method implies the final removal of waste from planet Earth. Nowadays, in the USA Radioisotope power systems (RPS) are launched into space (Kramer et al., 2017), which containing several kilograms of plutonium-238. On the big scale the method isn't used because of the high cost. Also, there is a high risk of radioactive waste re-entering the atmosphere, and probability of an emergency situation on the Earth due to unsuccessful launches with uncontrollable emission of radioactive materials and pollution of big territories.

c) Rock-melting and disposal of nuclear waste in subduction and burying the spent fuel rods along the conveyor belt of the Earth's tectonic plates.

It is proposed to place the radioactive waste in capsules, which will be dropped one by one into drilled wells up to 2.5 km deep, due to self-heating effect and melting the natural rock, capsules are supposed to be sinking to the center of the Earth (Levy, 1983). The method implies a high risk of an accident, since it there is a possibility of a waste detonation at great depths, which can lead to a strong earthquake and to a huge release of radionuclides into the environment.

d) Deep well injection of radioactive waste.

The following method is carried out through direct injection of liquid radioactive waste into the formation rock at great depth. In this case, the formation must have sufficient porosity and sufficient permeability to accommodate all the installed amount of waste and ensure expedite injection. Also, the formation must be surrounded by impenetrable rocks, working as an additional protective barrier (Rumynin, Konosavsky and Hoehn, 2005). Such disposal option has some negative externalities, since there is a higher risk of possible liquified radioactive waste interaction with surrounding rocks.

e) Sea and sub seabed disposal.

Packed radioactive waste from ships is lowered onto the seabed, where subsequently the packaging is destroyed and the radionuclides are dispersed in the aquatic environment. When removing into the seabed, it is proposed to place radioactive waste in containers in geological rocks below the ocean floor at great depths. This method can be carried out either by drilling wells and placing waste there, or by dumping radioactive waste containers under oceanic sediments that will be artificially created by a series of directed explosions.

These methods cannot be implemented at the present time, since international ban (London Convention 1972: Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 and 1996 Protocol), because there is a high probability of unforeseen negative impacts on the marine environment. There is also a method for disposing of radioactive waste by placing waste in the fracture sites of lithospheric plates with their subsequent infiltration into the Earth's interior**.** The most appropriate places for this option of disposal are located on the Ocean's Floor. However, as already been mentioned above, international conventions prohibit such methods of radioactive waste (RW) dumping, therefore they cannot be considered as optimal when solving the problem of RW disposal.

f) Disposal of radioactive waste into host rock and the host rock classification for deep geological repositories.

There have been also projects on placement of radioactive waste into stable blocks of crust, so-called disposal vaults. Waste should be in a solid form, put into a matrix from solid solutions of minerals. The following requirements have to be obligatory for matrixes (McCombie et al., 1994):

- the matrix has to consist of the rock that is more or less corresponding to structure of rocks in the place of disposal;
- the matrix has to concentrate in itself certain groups of elements radioactive waste (for geochemical equilibria);
- the matrix has to have the low speed of leaching.

Nowadays, there are many minerals, that are suitable for matrixes productions and the variety of those minerals increases. As mostly congruent those are considered:

- Borosilicate, aluminophosphate glasses (Aloy et al., 2012) - are the main matrix materials at the moment, that are used for neutralization of radionuclides. Their shortcoming though is an insufficient stability during placement in the Earth's crust;
- Synroc – from "synthetic rock", is considered as the best option for building the matrix, since Synroc is very resistant to leaching processes and it contains pyrochlore and cryptomelane minerals, which neutralize the radiation of some elements, namely, strontium and barium (Zhang et al., 2005). The disadvantages are the high cost of raw materials and the complex scheme of technological production. In future, it is also possible to produce double-layer matrices. The second layer is going to be of quartz, which experimentally has proved its ability to reduce the concentration of radionuclides in solution under certain conditions (Steier, Hoffmann and Schönert, 1974).

According to the international research have shown that the most suitable three types of rocks can act as host rock for radioactive waste (Renner, Hettkamp and Rummel, 2000): clay (alluvium), igneous rocks (basalt, granite, porphyrite) and rock salt. The choice of places for radioactive waste disposal has to be determined by a number of the conditions, providing the highest level of environment protection and the population from possible irradiation.

At the choice of sites for radioactive waste disposal in rocks have to be carried out according to the following safety conditions (Sugita et al., 2007):

• the disposal site must be surrounded with the sanitary protection zone, and the next settlements must be located at distance not less than 3 radiuses of a protective zone;

• the border zone (exclusion zone) is withdrawn from the sphere of human activity, located outside commercial mines and out of a zone of an active groundwater exchange;

• the disposal site has to meet all safety criteria and to provide the maximum level of safety at in emergency situations;

• the radioactive waste disposal is carried out with the higher density of solid HLW.

After the disposal, there should be performed a long-term monitoring programme of the state of the environment and the storage itself (temperature, pressure, radiation background, etc.).

The disposal of radioactive waste into host rock method has a number of advantages over other ways of neutralizing radioactive waste: first of all, radioactive waste is isolated from the environment and people. Secondly, the method ensures the disposal of waste for an indefinitely long period of time, lowering obligations on future generations. What is more, there is a sufficiently large number of suitable disposal sites on the Earth and the methods of radioactive waste treatment leaves the door opened for re-using the stored amount as a source of raw materials for the nuclear industry in the future.

Thus, the method of geological disposal of radioactive waste in host rocks is one of the most promising and economically feasible, but more detailed studies are required.

g) Deep geological disposal of radioactive waste.

There are many options for implementing this method, all of which involve the disposal of radioactive waste for the period of time longer than 100 years, without active maintenance by the staff, and therefore, there will be adjournment of responsibilities for future generations. This method is sometimes called a multi-barrier concept, since condensation of waste, its placement in containers and placement at great depths in the geological environment is a combination of barriers that prevent the people and environment from exposure to sources of radionuclides (Alexander and McKinley, 2007).

The implementation of this method is carried out by placing radioactive waste in deep tunnels and caves in solid rock formations, then surrounding radioactive waste with cement or clay (bentonite), called a buffer or a backfill material. The buffer creates an additional barrier from the release of radioactive substances into the environment. Suitable for disposal places are limited in number by certain conditions, which must be considered.
For instance, the rocks in which the storage is supposed to be, should be stable and contain a minimal amount of deep groundwaters, should be located at a depth of 250 to 1000 meters (James, 1988).

If all terms considered, the deep geological disposal will be well-thought-out as rather safe and economically profitable. The method described above is considered as the most preferable today among the scientific community. However, in a number of the countries, its economic feasibility has to pay off from conditions of the region of the alleged place of disposal and the stage of technological development of nuclear sector.

To sum up, among the existing methods of radioactive waste management there are two commonly accepted ways: near-surface and deep geological disposal.

Table 2.4. Commonly-accepted disposal options; Source: World Nuclear Agency (WNA, 2017)

Option	**Suitable waste types**	**Examples**
Near-surface disposal at ground level, or in caverns below ground level (at depths of tens of meters)	LLW and short-lived ILW	• Implemented for LLW in many countries, including Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK, and USA. • Implemented in Finland and Sweden for LLW and short-lived ILW.
Deep geological disposal (at depths between 250m and 1000m for mined	Long-lived ILW and HLW	• Most countries have investigated deep geological disposal and it is official policy in several countries. *

Option	Suitable waste types	Examples
repositories, or 2000m to 5000m for boreholes)	(including used fuel)	• Implemented in the USA for defense-related transuranic waste at W.I.P.P. • Preferred sites selected in France (Bure), Sweden (Forsmark), Finland (Onkalo), and the USA (the W.I.P.P. in New Mexico) • Geological repository site selection process commenced in the UK (Cumbria), Canada (Kincardine) and some other countries.

* The status of current international HLW management projects in the World will be discussed in the Chapter III

3.3. Radioactive waste and spent nuclear fuel management: political dimension

The following concepts of spent nuclear fuel (SNF)waste management are considered for today (LaTourrette, 2010):

- SNF reprocessing for subsequent re-use of released radioactive materials (the so-called closed fuel cycle) *
- long-term storage for the purpose of final disposal in geological formations (the so-called open fuel cycle)
- long-term storage with a space for a final decision in the long term (a choice between the first two concepts)

* Simultaneously, it should be mentioned, that SNF reprocessing does not ring the solution to the issue of radioactive waste, since as a result of reprocessing a huge amount of radioactive waste is generated, including highly active waste, which require extra disposal. The following table shows the SNF management policy distribution per country. Countries, that reprocess or have plans to reprocess SNF have in concept a closed fuel cycle.

Countries, using only SNF disposal as a way of SNF treatment, have an open fuel cycle.

Other countries that repossess SNF have or intend to build the temporary storage facilities or send their SNF to other countries for reprocessing.

Table 2.5. SNF management policies in selected countries*

The countries using only disposal of SNF as a way of utilization	**The countries which are reprocessing or having plans to process SNF**
Canada	France
Finland	Great Britain
Sweden	China
USA	Japan
	Russia
	India

* Information for the year 2000; Source: Multilateral nuclear fuel supply guarantees & spent fuel management: what are the priorities? (Goldschmidt, 2010)

Worldwide there are three SNF reprocessing complexes, also used for civilian purposes - in the UK (Sellafield), Russia (Mayak) and France (Marcoule till 1976, La Hague nowadays). At the same time, these capacities (the total capacity of 4,000 tons of SNF per year) are significantly under-utilized, primarily for economic reasons. For example, the Russian SNF reprocessing facility (Fuel Regeneration Plant-1 at the Industrial Complex "Mayak") is loaded by 35-40% (Kubuzov et al., 2016).

3.4. The concepts of HLW treatment: issues of sustainability, security, technical and non-technical risks that affect the disposal process

It is widely assumed that high-level waste requires final disposal. After the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro (3-14 June 1992), sustainable development has become one of the ideals on which the world political system is oriented. Sustainable defines such a "development, that meets the needs of the present, without depriving future generations of the opportunity to meet their needs." Regardless of the type of development, the most difficult task is to maintain a stable equilibrium between the "three pillars" - competing ecological, social and economic interests (Hansmann, Mieg and Frischknecht, 2012).

The IAEA received a task to determine whether HLW long-term storage was consistent with the interests of sustainable development, and to focus on the impact on safety of long-term storage compared to disposal. Thus, a comparison of long-term storage and geological disposal in terms of sustainable development and safety will be made below (Green and Morris, 1988).

The HLW storage is an important element of the safe management of radioactive waste, and the need for it can arise at various stages of waste management. Spent fuel and a number of other types of waste must be stored for a certain period of time in order for radioactive decay to occur, which allows to reduce the level of radiation and heat release. For some types of waste, it is an intermediate step in the whole process of handling them and continues for a relatively short period of time (Raynal, 1997).

A number of the parties which have considered the organization of long-term HLW storage, expressed concerns about the need of very long storage during the period longer than several decades. Their concerns increase if there is an obvious fact that the stage of storage can actually be discussed ages due to commercial unpredict abilities (Anthony, 1988). The parties expressing such point of view, as a rule, are concerned by the fact that the delay with decision making upon the disposal without certain plans concerning time limits of disposal and leads to adoption of uncertain administrative and financial obligations. Nevertheless, opinions differ as some groups of the population have given serious preference to further storage of radioactive waste on a surface under constant observation.

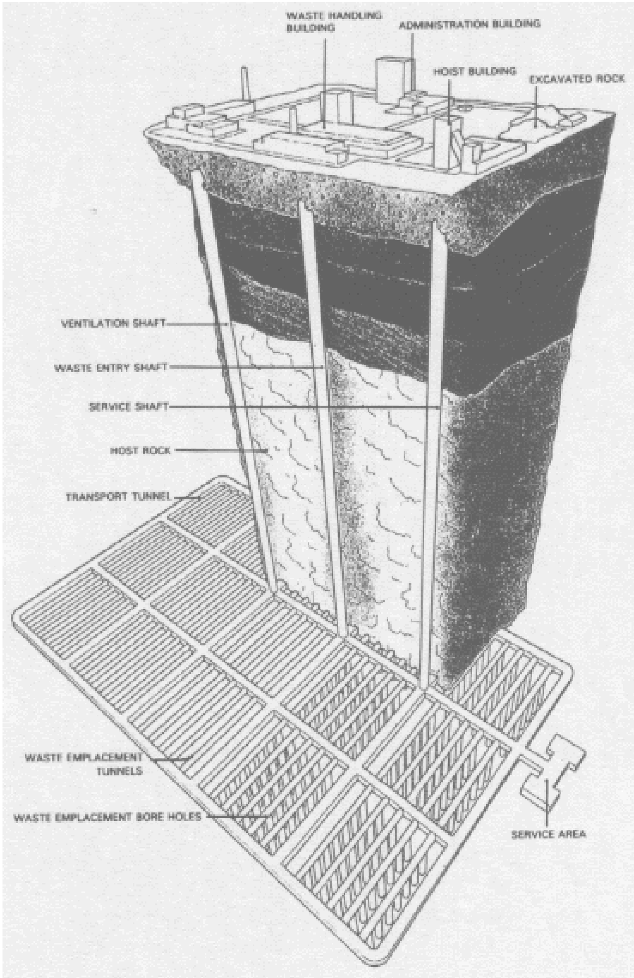

Figure 2.3. Disposal of HLW in deep geological formations on land; Source: NEA Issue Brief: An analysis of principal nuclear issues (Nuclear Energy Agency, 1989)

HLW disposal: technical risks and non-technical security issues

It has been demonstrated during decades of research at the long-term isolation test sites (See Figure 2.3.), that deep geological disposal of HLW is safe and can be relied upon, as long as an active surveillance and maintenance are carried out. In contrast to the near-surface disposal at the ground level, the deep geological disposal promises to make it possible in time to provide secure technologies for a long-time disposal without observation and maintenance measures (McKinley, 1997).

The ability to safely store HLW for several decades was vividly demonstrated by the work of existing storage facilities. Some of the storage methods, used before, have revealed defects, that were eliminated while creating new repositories. Yet, the possibility of solving any problems that may arise in-vitro can be considered an advantage of the near-surface disposal sites.

For instance, during the dry casks storage, some constructional destruction of containers and their contents may arise. Over time such breach will demand the transfer of HLW if not onto long-term storage site, then at least to another storage. The longer waste is stored before transfer to other storage, the probability that there will be such destruction that will cause threat of possible radiation exposure of personnel is higher. From this point of view even the long-term HLW storage, does not really well meets the requirements of long-term safety. Moreover, if storages of waste aren't under fixed observation, they are vulnerable to casual or deliberate intrusion. It imposes obligations on future generations for conducting active control over storages of nuclear waste (Hadermann and Mccombie, 1992).

The deep geological disposal of HLW guarantees to provide integrity and isolation of radioactive waste from a human environment for a very long time. As it was mentioned before, the design of geological storages provides such isolation without the need for active control, that makes them passively safe. The threat to security because of possible human entry into storage considerably decreases in comparison with near-surface disposal, generally due to a mine depth, in which there will be such geological disposal. Nevertheless, many experts are convinced that deep geological disposal of HLW is the best decision to address the HLW disposal issue, the practical operating experience of such storages is still absent.

Among the technical risks, there have always been non-technical security issues, while HLW were always a target of environmental terrorism acts. Environmental terrorism, as a phenomenon, became a feature of the mid-twentieth century, executed as large-scale acts of retaliation against civilians and the environment, and not at all for defending political ideas (ElBaradei, 2005). With its help, more and more often individual countries are trying to solve political issues. The problems of environmental terrorism are an important factor in the domestic political struggle, especially in developed countries.

As a potential danger for people, environmental terrorism is more risky than other varieties of it, since violent actions are applied through the natural environment, where in the future the existence of a human being will be difficult or impossible at all. Some

dangers are of a planetary nature, leading to irreversible consequences.
The situation, under which public understand terrorism with impact on the environment ("environmental terrorism"), is opposite to the radical actions of ecological movements ("ecological terrorism") is quite clear, but it is important not to confuse these concepts.

For definition of ecoterrorism, it is necessary to start with the definitions of the concepts "ecological terrorism" and "environmental terrorism". The activity of the ecological organizations and the movements for the sake of environment protection, after a certain level of aggressive acts, is defined by the concept "ecological terrorism". The concept "environmental terrorism" - "terrorism by means of impact on the environment" is widely used in work of Timothy Schofield (Schofield, 1998) "The environment as ideological weapon: the offer on criminalization of terrorism with impact on the environment" ("The environment as an ideological weapon: proposal to criminalize environmental terrorism").

The ecological acts of terrorism, in particular, interfaced to infringement of ecologically dangerous objects (the NPPs, commercial chemical and nuclear companies, etc.) or with use of ecologically dangerous means (weapons of mass destruction, nuclear materials, radioactive materials or sources of radiation or the poisonous, toxic, dangerous chemicals or biological substances) bear the danger of a planetary scale. The most common example is the Chernobyl accident on the 4th block of the NPP, as it is an implicit inadvertent act of ecological terrorism, as well as massive disposal of chemical weapons after the 2nd World War in the Baltic Sea and the dumping of by the nuclear-weapon States (NWS) of HLW in the World Ocean (Finn, 1983).

Moreover, accident on the Japanese nuclear power plant "Fukushima-1" on March 11, 2011 has caused the accumulation of radioactive strontium in the soil and plants, the concentration of radioactive isotopes in sea water exceeding the safe level and has caused a surge of oncological diseases (Yamashita et al., 2018). For the first time in the history of nuclear power at one NPP there were (by the number of damaged power units) four nuclear accidents in a row.

Environmental terrorism – is a reality of today. It important to mention some of many attempts to commission the ecologically dangerous acts of terrorism in the World. Among them: the hijacking of the nuclear submarine planned by general D. Dudaev in

Russia in 1992 (Perfil, 2018); the chemical terrorist attack conducted by sect "Aum Sinrikyo" in the Tokyo subway in 1995 (Klein, 2012); placement by the Chechen terrorists of a container with radioactive caesium-137 in the Izmaylovsky park of Moscow in 1995 (Specter, 2018); threat of occupation of the NPP by the Chechen terrorists in Balakovo in 1996 (Morozov et al., 2016); the captures of nuclear objects planned by terrorist groups of S. Raduyev in 1999 (Nti.org, 2018); the terrorist attacks planned with ricin use in Great Britain in 2003 (Bazarkina, 2015); the constant threats upcoming from the government of North Korea (Lee, 2003), etc.

As the priority directions for targeting environmental terrorism acts the following measures should be implemented: improvement and development of new international agreements (advancing ratification of International convention for the suppression of acts of nuclear terrorism, 2005) and necessary national legal acts; coordination of actions of the IOs and competent authorities of the states concerning a problem; creation of international information exchange network of all incidents, connected with ecological terrorism and also application of technical solutions for the maximum isolation of HLW at disposal sites (via deep geological disposal) and during transportation.

3.5. Advantages and obstacles of HLW deep geological disposal I: technical maintenance

There is a technical advantage of radioactive waste maintenance on near-surface facilities, than in deep geological repositories. However, it is impossible to provide organizational control for the entire period, while nuclear waste remains radioactive naturally.

Maintenance demands both identification of defects, and their correction. It is simpler to repair any device, when it is available also is on near-surface facilities, not underground; it is also simpler to reveal defects at a stage of their formation in near-surface facilities. Therefore, effective maintenance is promoted by placement of facilities on a surface. On the other hand, systems for deep geological repositories are conceived in a way, that no malfunction of a protective barrier will be able to affect human health and state of environment because of existence of other independent artificial or natural barriers (Toulhoat, 2006).

As far as an adequate protection of people and the environment (during near-surface storage) could be provided only throughout in storages maintenance period and as some of the radioactive materials which are stored will remain dangerous during many millennia, maintenance is conducted (or organizational control) will need to be exercised throughout all this time or until the concept of deep geological disposal (GIBB, 2000) is realized. The analysis of world history shows that reorganizations and revolutions happen, as a rule, through much less short periods, and that therefore hardly any existing or expected social infrastructures will be able to remain during so long period of time.

3.6. Advantages and obstacles of HLW deep geological disposal II: possibility of recovery

It is simpler to extract the nuclear material from near-surface facilities, than from deep geological disposal sites, but geological disposal can be created in several stages so the possibility of extraction will remain possible for a long time (Fullwood and Erdmann, 1983).

The advantage of near-surface facilities is simplicity of extraction of material in case of making decision on its recovery for a further re-use. The presence of an opportunity to recover nuclear waste provides future generations with freedom of choice in adoption of various options, connected with radioactive waste. For example, in future, scientist can prefer total recycling by reprocessing (WALKER, 2006). Also, for example, the decision to shut down the disposal site can be accepted later. Besides, deep geological disposal site can be constructed, and its work can be organized so that in future the disposed waste can be taken. Important achievement in this area is that already today there are control methods which can be used for an appreciable length of time, without breaking integrity of disposal techniques.

The possibility of extraction can be realized as at placement of waste in near-surface facilities, and at deep geological disposal sites. Nevertheless, the possibility of extraction exists only until there is an organizational control and necessary technical experience and where the corresponding system of the nuclear waste recovery has been organized. If all these terms considered, then the possibility of recovery will be real both at facilities storage, and at disposal sites.

3.7. Advantages and obstacles of HLW deep geological disposal III: safety issues

Placement of hazardous waste underground increases safety (security) of these materials.

Within several last decades safety of nuclear waste was a reason of the growing public concerns. Cases of illegal trade and an 9/11 tragedy in the USA have put the problem in the forefront. As it has been noted earlier the threat of "environmental terrorism" consists either from an unauthorized possession of nuclear waste, plunder of material for illegal use or committing acts of sabotage for triggering an emergency at the enterprise, for example, by emission of radioactive material in the environment (Gibb, 1999).

Naturally, it is simpler to seizure such materials in that case, when they are on a near-surface facility. In geological disposal sites, only the most resolute criminals are equipped with up-to-date means will be able to reach them.

Most of the existing storages are located in the same place, where there are other operating nuclear enterprises, so the security measures operating at the whole enterprise extend to them. If near-surface facilities, have to be used longer than NPPs operational period, then it is necessary to undertake special measures to ensure safety.

3.8. Advantages and obstacles of HLW deep geological disposal IV: capital costs

The deep geological disposal demands considerable capital expenditure, and near-surface storage – considerable operational costs (Analysis of capital and operating costs associated with high level waste solidification processes, 1978). In the context of storage and disposal, the sustainable development concept demands that expenses on the current and long-term management of storages and disposal sites, became covered at the expense of internal resources (were adopted); the internalized expenses are expenses which are incurred directly by those who get profit (Hench, 1986).

The United Nations Commission on Sustainable Development (CSD) has called the governments to internalize expenses on treatment of radioactive waste to the highest possible level (Puntenney, 2007). To provide compliance of long-term disposal with the requirements of sustainable development, for the further maintenance of the existing storages and the subsequent actions of waste disposal process. For example, CSD also mentioned that for further allocation, reprocessing or disposal of HLW, it is necessary to provide sufficient financial means. Assessment of long-term financing is carried out by methods of calculation of future expenses for costs, which are very sensitive to future rates of inflation and interest rates.

Long-term interest rates and rates of inflation can't be predicted precisely; respectively, planning of expenses on events which will be held later than through one generation (about 30 years), implies considerable levels of inaccuracy. Therefore, any assessment reports of the financial means are necessary for ensuring long-term disposal will be quite uncertain.

Very high capital expenditure, connected with long-term disposal is a telling argument, especially considering that from the beginning of siting the geological disposal and till placement in it of HLW there passes a lot of time (about 20 years and more). Many authorities have taken measures to demand from the NPPs' benefactors, which are engaged in production of nuclear energy, assignment on a constant basis for a covering of future expenses on disposal of their waste (thus, expenses have been internalized).

3.9. Advantages and risks of HLW deep geological disposal V: constructing memory for awareness of future generations

Long-term disposal storage of radioactive waste demands methods of information transfer to future generations (Riddel and Shaw, 2003). The information will be necessary for safety of long-term disposal of HLW, for example, about a measure for ensuring safety, control and inspections from administrative organs, and will demand storage of a large number of information. For certain, such sites will demand maintenance, and containers with nuclear waste, eventually, will need to be transferred to other place; therefore, necessary information will belong to inventory of nuclear waste, their characteristics and the location, technology of preliminary processing and packing and also a design of storage. All this information must be stored throughout the lifetime of the repository. To sum up, long-term storage of radioactive waste requires the transmission of information to future generations (Riddel and Shaw, 2003).

All this information needs to be stored throughout all term of existence of a disposal site, and it has to be legible and clear for the subsequent generations. Those all can become a serious problem. Usual paper systems are exposed to physical decomposition of various character over time. Systems on the basis of modern technologies (for example, the automated systems of data storage) are steadier against influence of time, but they also have shortcomings. For instance, they demand continuous updating and support that allows to provide compliance of carriers of data with a technological innovation; in process of emergence of new systems the software can quickly become unreadable. There is also a possibility that future generations won't know what is necessary for understanding of records even if such records remain in readable condition (Labeling nuclear waste for the future, 2009).

In case of nuclear materials, it is necessary to follow the security measures, which will allow to provide continuity an information transfer about that material hasn't been used in an inadequate way. The states which have signed the Nuclear Non-Proliferation Treaty (NNPT) are obliged to provide guarantees that the nuclear materials which are in their territory aren't used in the undeclared or unpacific purposes. IAEA, playing a role of the custodian and guarantor and is responsible for ensuring independent international control over observance by the governments. The system of guarantees, that is related to near-surface facilities has been worked out well.

During the monitoring phase, applicability to geological disposal will require additional activities and additional work that is not needed in the case of terrestrial storage (Okal, 2001). The safe access to materials in the disposal site should remain possible, even after the disposal site is closed. Nevertheless, it is expected that it will not be difficult to ensure the implementation of security guarantees, at the stage after the closure of geological disposal site.

After a comparative analysis of the main issues, that arise from long-term geological disposal and near-surface storage options, the deep geological disposal method proves itself as the most favorable one. Especially in the context of international security and terrorism threat. Some of the countries worldwide are already at one step forward then the others in the development of national sites for deep geological disposal of HLW. In the current chapter we will see the up-to-date examples and argue the possibility of International site for long-term HLW disposal.

4. International concepts of building deep geological repositories for HLW disposal

4.1. The international initiatives in the 70-90th

From the late 1970s to the early 1980s, the possibility of establishing international centers for SNF management was proposed through various international initiatives. But the issue of creating international repositories or disposal facilities was not as acute as it is now, given the availability at that time of plans for large-scale reprocessing of HLW. The SNF reprocessing centers were primarily tacitly accepted as international ones.

As a reference point it is possible to specify the beginning of the 90th years, when disposal of SNF (so far on a national framework level) has become more appealing, due to SNF reprocessing proved to be unprofitable, and consequently the SNF on site storages have begun to be overflowed.

In 1997 has been signed the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, according to which placement of SNF in the territory of other country on condition of compliance with safety requirements, recorded in the Convention, is possible.

In 1998 in response to a request of several State Parties expressing interest in the international HLW disposal site, IAEA has prepared the important document " Technical, Institutional and Economic Factors Important for Developing a Multinational Radioactive Waste Repository" (TECDOC-1021), where the factors needed to be considered for an implementation of such a project, were outlined.

Since then, according to the IAEA officials, a lot of research has been done, but among the most crucial practical results, the IAEA only allocates the return of SNF from research reactors that are highly enriched in uranium and return of SNF from Soviet-designed nuclear power plants to the USSR and the Russian Federation.

4.2. Overview of international and domestic initiatives of the HLW deep geological repositories siting in post-2000s.

In his speech at the 58th session of the UN General Assembly, on November 3, 2003, the formal Director General of the International Atomic Energy Agency Dr. Mohamed ElBaradei (IAEA, from 1997 to 2009) expressed the idea of an international approach to solving the problem of SNF and radioactive waste disposal, since not all countries have suitable geological conditions and sufficient financial and human resources (Un .org, 2018).

In October 2004, the IAEA technical document " Developing Multinational Radioactive Waste Repositories: Infrastructural Framework and Scenarios of Cooperation" (TECDOC-1413) was published. On February 22, 2005, the IAEA presented the report of the expert group ″Multilateral Approaches to the Nuclear Fuel Cycle″ (IAEA, 2005), according to which it is proposed to organize a series of international disposal sites: 2 in North America, 1 in South America, 2 in Central and Western Europe, one at a time - in Russia, South and South-East Asia, and also in China. According to the text of the Report he IAEA will make efforts to create international disposal sites.

Among the forms of organization of international repositories and disposal sites, proposed by the IAEA there are (Www-pub.iaea.org, 2018):
- nuclear fuel leasing schemes,
- the transformation of national repositories into international ones,
- creation of new international disposal sites.

It is important to mention, that the National Academy of Sciences of the USA already in 1957 recognized the concept of HLW disposal in geological formations as a promising form of localization of SNF. Scientists have proved that disposal of HLW into deep geological repositories with natural geological barriers, supplemented with engineering protection systems, is a feasible, albeit costly and technically complex project.

For the implementation of the project of the HLW deep geological repositories on the national level, those should comply with the following conditions of implementation (Five criteria for successful Deep geological repository for HLW long-term disposal):

1. Suitable geological and climatic conditions within the country (this issue is considered below in the perspective of the Pangea group studies (Pangea-group.com, 2018)).
2. A clear national strategy in the field of nuclear waste management and the necessary legislation to complete the nuclear fuel cycle (NFC).
3. Public acceptance and approval. In many countries, it was the opposition of the society that compelled the authorities to postpone the implementation of the HLW deep geological repository project (for example, in Belgium, Argentina, Spain, France (France testing viability of underground nuclear waste repository, 2014), Italy, etc.) (Jenkins-Smith et al., 2010).
4. The ability of the country to finance a large-scale project for the construction of the deep geological repository for HLW disposal.

5. Relatively large scale of the country's nuclear industry, and sufficient volume of its own HLW. These conditions ensure a reduction of costs per unit for HLW disposal and justify significant investments in geological disposal.

The fourth and fifth criteria create the prerequisites for international cooperation on joint geological disposal projects. Potential and experience of such cooperation will be also mentioned in Chapter III. Further, there will be analysis of these conditions and their role in implementing the construction project of the deep geological repository for HLW disposal.

4.3. Overview of national strategies and programs for HLW management

Objective prerequisite for a construction of deep geological repository for HLW disposal is the country’s environment, meeting the requirements of geo-ecological safety. In 2001 experts of "the Pangea Resources group" in cooperation with the national research organizations have studied various regions of the world on their geological and climatic compliance to requirements of the HLW deep geological disposal. Potential of finding large, stable and dry region was determined by following criteria: the index of aridity (indicator of the climate dryness in a certain location), tectonic stability, taking into account the world card of seismic zoning and lack of volcanism (Mccombie and Kurzeme, 2000).

The Pangea Resources group research representatively shows perspective (ideal) regions for placement of deep geological repository for HLW disposal - it is the South of South America (Argentina), the South of Africa (the Republic of South Africa, Botswana, Namibia), the Arabian Peninsula, the South of Russia and Kazakhstan, China, Mongolia and Australia. The international practice demonstrates that a suitable environment is a desirable, but not sufficient factor of success of the project of deep geological repository of HLW. In areas with less favorable environment conditions the construction of objects of geological disposal site is conducted under the toughened standards for seismic stability. For example, the construction of storages of radioactive materials in Japan is by 8 times more expensive, than in France, and 13 times more expensive, than in Great Britain. It is also necessary to remember that the research was focused on extensive areas and didn't consider the possibility of smaller platforms which also have geological disposal site construction potential.

All countries, that perform the domestic nuclear programs, the problem of nuclear waste initiates a wide political and public debate. Numerous arguments of pro and contra gradually reflect in the national strategy, addressing the issue of HLW management. A number of the countries at the legislative level has proclaimed approach of deep disposal of HLW in geological formations as the main vector of development. Among those countries are: the USA, Sweden, Finland, Japan, Russia, China, Belgium, India, Switzerland, etc. (Carter, 1981).

Great Britain and Canada consider all theoretically possible approaches addressing HLW management issue. The option of deep geological disposal in geological formations did not get public support though and its realization is postponed. At the beginning of 2004 the Advisory board has submitted 14 versions of the HLW management strategies for consideration of the Cabinet of the United Kingdom, but still no national strategy in this sphere is defined (Elliott, 2010).

In countries where the national strategy for the management of HLW is based on the disposal of waste in geological formations, the following projects are implemented (the ranking of countries is presented in terms of the start of operation of the storage facility, the financial estimates of the projects are given if the information on them is not closed):

- In 1982, in the United State the Nuclear Waste Policy Act, that was supposed to deal with the issue of establishing a for HLW, was adopted by the Congress (US EPA, 2018). Consequently, president George W. Bush signed in 2002 the resolution on the construction of the permanent disposal on the Yucca Mountain site. The storage facility was designed for disposal of over 70,000 tons of HLW. The cost of the project by 2010 was around - 57,520 million dollars (48,239 million euros) and included the disposal option for all SNF, which will would be received from operating and closing NPPs (~83,500 tons), as well as HLW from defense activities (Yucca Mountain Site Characterization Project Technical Data Catalog, 1992). The estimates above reflect the total cost of the disposal site, transportation of waste and associated programs. The Yucca Mountain nuclear waste repository is designed for 10 thousand years (See Figure 3.1.)

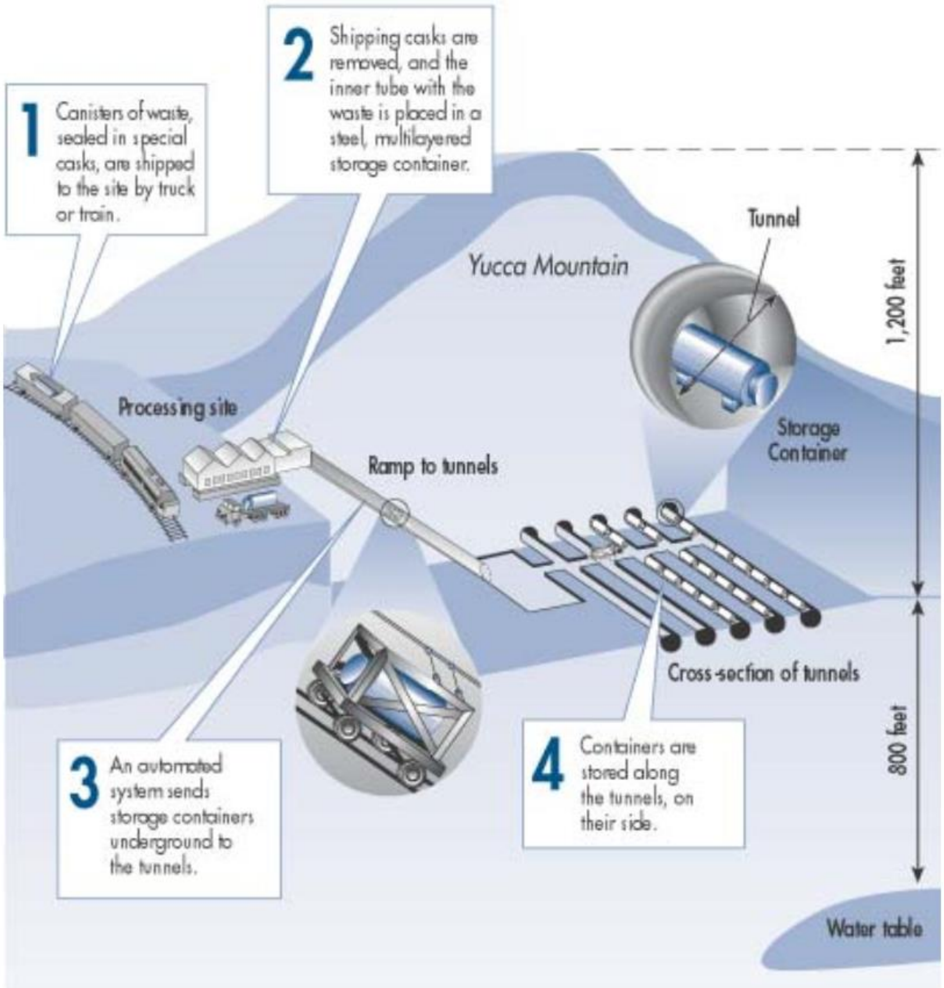

Figure 3.1.: Conceptual Design of Yucca Mountain Disposal Plan; Source: U.S. Nuclear Regulatory Comission (U.S. NRC, 2018)

- The modern strategy for completing the nuclear fuel cycle was formed in Sweden, in the late 1970s. The capacities of the Swedish Nuclear Fuel and Waste Management Company - Svensk Kärnbränslehantering AB (SKB) - include a centralized SNF storage facility – Clab (the Central Interim Storage Facility for Spent Nuclear Fuel), which was expected to be fully loaded by 2015, and was extended by today with a permit for the interim storage of a total of 8,000 tonnes, however there is still no long-term solution implemented in practice (Skb.com, 2018). In 2018, works are actively carried out in the planned encapsulation plant and the SNF Repository at Forsmark. The concept of the final disposal of SKB SNF (KBS-3) includes the encapsulation of SNF into copper canisters and their placement in bentonite clay in vertical wells. The wells are made in a crystalline rock base and connected to a tunnel system located at a depth of 500 m in (see Figure 3.2).

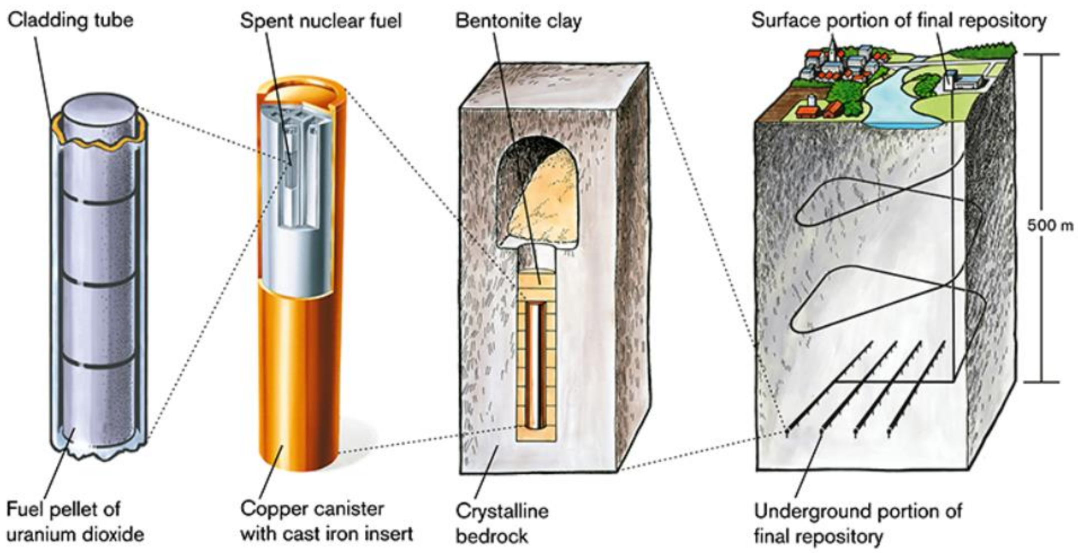

Fig. 3.2. The KBS-3 concept of spent nuclear fuel disposal by the Swedish SKB (SKB, 2010).

The projected capacity of the storage facility is 9,000 tonnes of SNF. The capital costs of the Repository are estimated at 28 billion Swedish kronor (3 billion euros). The entire national program for the management of HLW will cost to about 6,466 billion euros and includes the cost of the SNF repository and the funds for decommissioning the nuclear power plant.

- **Finland.** Studies on deep geological disposal began in 1983. In 2001, the Finnish Parliament supported the candidacy of the Olkiluoto site, municipality of Eurajoki (The Onkalo spent nuclear fuel repository) for the construction of a Deep geological repository for operation from year 2023, with a capacity of up to 4,000 tons of SNF. That will make Finland a first country n the world to advance the Deep geological disposal of HLW. The storage facility is estimated costs at 222 million euros (Posiva, 2018). The cost of the entire country's program on HLW management will be about 1,287 million euros and will include the cost of intermediate storage of spent nuclear fuel, transportation, disposal and associated programs (for example, licensing). In Finland, there is already an experience of building an underground storage facility: a unique storage facility for the disposal of intermediate- and low-level radioactive waste was built at the Loviisa nuclear power plant (Eurajoki, Outa and Routamo, 1997).

- **Germany** is aiming to complete the search for HLW long-term disposal facility by year 2031(See Figure 3.3.). According to the Nuclear Power Act of 1959, Germany adheres to the concept of geological disposal of HLW. Prior to 1998, two sites were considered: Gorleben and Konrad. The coalition government, which has been in power since 1998, has decided, starting from 2001, to start a search "from scratch" for only one site, suitable for all types of HLW. The value of the Deep geological disposal sites for 1996 was estimated: Gorleben 2,290 million euros; Conrad 1,370 million euros. Due to the revision of the sites and constant public protest, these figures are no longer valid (Spiegel Online, 2018).

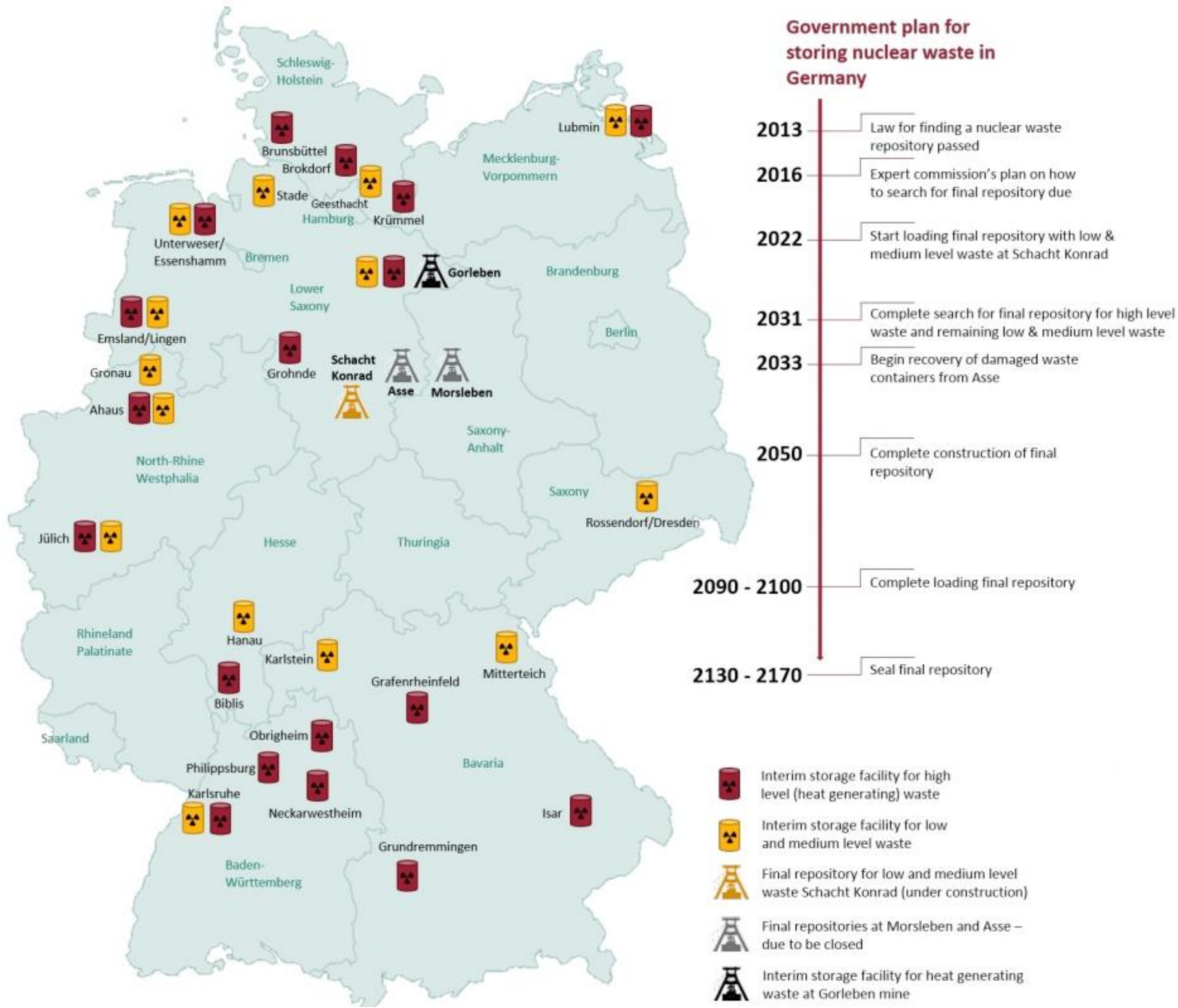

Figure 3.3. Nuclear waste storage plans in Germany; Source: Clean Energy Wire (Clew, 2018)

- According to the national strategy of Japan, vitrified HLW should be placed in Deep geological disposal sites to a depth of more than 300 m. Nowadays an open invitation is requested the volunteer regions to submit their proposals (until year 2035) to host Deep geological disposal sites (Schweitzer and Robbins, 2008). The entire national program for HLW management estimated costs are about 22,250 million euros and includes the cost of R&D, a repository with a capacity of 40,000 cans of vitrified HLW, management and taxes.

- The definition of the site for Deep geological disposal in **Spain** was launched in 1986 and then promising regions were designated. However, due to public resistance, since 1997, the search for a Deep Geological site was stopped and the final decision was postponed. The entire national program on HLW management will cost about 10 billion euros and it includes the cost of programs for SNF management, high-, medium- and low-level waste, as well as the cost of decommissioning nuclear power plants. At the moment, the Spanish radioactive waste management agency ENRESA (Empresa Nacional de Residuos Radiactivos SA (ENRESA, 2018)) is implementing a plan to establish a Centralized Storage (CTS) facility in the municipality of Villar de Cañas in Cuenca for all HLW and SNF produced in Spain. The CTS facility, though, will only provide temporary storage for all SNF and HLW from Spanish NPPs.

- The research on defining a suitable site, was conducted in **Slovakia** since 1997. According to the decision of the Slovak Government (No. 5/2001) it's final goal is to build up a Deep Geological Repository in Slovakia for the final storage of HLW and SNF. Six potential sites are currently being investigated (e.g., the Tribec Mts. and in sedimentary host rocks - Seczeny Schlier) and also in the Formation (western part of the Rimavská kotlina Basin) (Oecd-nea.org, 2018) .

- In 1985, in **China**, The China National Nuclear Corporation (CNNC) initiated a 4-steps R&D programme, called "DGD programme for the Deep Geological Disposal of HLW" (Cho and Jeong, 2014). The CNNC is developing Deep Geological Repository site for SNF from CANDU reactors and HLW from used light water reactor fuel reprocessing. A probable site in the Beishan region is planned to start operating in 2040(Alexander, 2008).

- The Dutch Central Organization for Radioactive Waste, COVRA N.V. together with establishments from 6 other European countries, in the SAPIERR-II project, is developing a proposal for creating an international Deep Geological Repository for HLW. In the **Netherlands**, it is planned to complete the selection process for the Deep Geological Disposal of HLW before 2040 (Arnold et.al, 2015).

- For today in **Hungary**, the final decision, regarding the back-end of the nuclear fuel cycle has not been done yet. Thus, studies on Deep geological disposal sites have started in 1993. The possibility of participation in the international HLW Deep geological disposal sites is discussed (Kormany.hu, 2015) and according to the national program for HLW circulation, final costs for the site will amount to EUR 1,292 million, including the cost of R & D, intermediate storage, transportation of HLW, design, licensing, construction, operation and closure of Deep geological disposal sites (scheduled to operate from 2064) (Vari and Farago, 1991).

- Since the early 1980's **Switzerland** is implementing a three-phase strategy for the construction of Deep geological disposal sites. The storehouse was designed for 660 cans of high-level radioactive waste and 1200 canisters of SNF. The storage cost was estimated at 1.9 billion Swiss francs (1.39 billion US dollars). For the year 2018, NAGRA has proposed for public consultations three HLW siting regions (in Zürich Nordost, Nördlich Lägern and Jura Ost) (Nagra.ch, 2018). The cost of the entire national program for HLW management, including transportation, interim storage and disposal of spent nuclear fuel and disposal of intermediate- and low-level waste, is estimated at 7,238 million euros (Loew, 2004).

- The **Czech** State Office for Nuclear Safety (SÚJB) for management HLW and SNF, set up in 2010 the SÚRAO (RAWRA - Radioactive Waste Repository Authority). The SÚRAO is planning to make an operational Deep geological repository for HLW and SNF by 2065 (Surao.cz, 2018). Already in 1998, 8 potential sites were selected, the final decision on site selection is planned to be taken by 2025. The cost of the Deep geological disposal sites project is estimated at 1,472 million euros, including the cost of R & D, the SNF repository and associated programs (for example, for public relations) (Frantál and Malý, 2017).

4. 4. Transmutation, storage, or disposal of HLW? Case of France.

- The individual position is taken by **France**, where by the Law of 1990, except geological disposal, were defined two more versions of HLW management: intermediate storage and transmutation. The cause of this legislative solution, sets back to oil energy crises and unprecedented peaks of the prices for uranium in the 1970th (The Discovery of Atomic Transmutation: Scientific Styles and Philosophies in France and Britain, 1979).

Since then, for protection of political and economic sovereignty of France, the main reference point of the country is aimed towards the development of nuclear power and technologies of recycling. In the same Law of 1990 it is defined that in 2006 (Lefevre, 1983) the Parliament of the country has to reconsider a course of national strategy of HLW management according to the progress in nuclear research and development area. Other countries, less formally, but also adhere to diversified policy on nuclear waste management: The Czech Republic, Hungary, Spain and Japan study a possibility of realization of technologies of sorting out, transmutation and geological disposal of HLW.

The issue of radioactive waste (RW) management – is one of the most acute environmental, ethical, technological and political problems in France.

Figure 3.4 Nuclear sites in France; Source: World Nuclear Association (WNA, 2018)

Nowadays in France there are 58 nuclear reactors on 19 sites, that provide about 75% of the consumed electric power (See Figure 3.1). During his presidency Francois Hollande promised to reduce dependence of the country on the nuclear energy sources, to lower a share of nuclear power to 50% and in the year 2017 promised to close the oldest and dangerous NPP Fessenheim at the border with Germany (France 24, 2018). The national agency of radioactive waste treatment “ANDRA” conducts works on creation of point of deep placement (repository) for highly active and long-living waste (named Cigéo) in clays near the village Bure (France testing viability of underground nuclear waste repository, 2014). In total, according to the National register of radioactive waste of France, for the end of 2013, more than 1 460 000 cubic meters of radioactive waste are saved up, and this quantity will grow every year. Unlike neighboring Germany and

Belgium, France doesn't intend to reject nuclear power completely. For 2018, the issue of HLW management is still one of the most urgent environmental, ethical, technological and political problems in France.

Under the law of 1991 (LOI n ° 91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs) within 15 years in France there have to be conducted researches on three possible directions of treatment of radioactive waste: transmutation, near-surface long-term storage and deep geological disposal.

The Commission on nuclear power was responsible for a research of a possibility of transmutation, that transforms dangerous radionuclides into less dangerous in reactors. They engaged mostly in projects on transmutation to support the projects of reactors on fast neutrons, but French researches haven't implemented those projects in practice.

The French National Radioactive Waste Management Agency (ANDRA), established in 1991 (Legifrance.gouv.fr, 2018), was responsible for finding solutions on deep geological disposal option of highly radioactive waste.

The main owners of the NPPs and producers of waste - the company AREVA and EdF (Électricité de France) had to conduct researches of a possibility of long-term near-surface storage of radioactive waste. But they did not invest into it due to the leak in legislation: under the 1991 Law, the radioactive waste is owned and stay under responsibility of producers of the waste "before their final disposal". Therefore, owners of the NPPs lobbied "final disposal" at which responsibility for radioactive waste passes to the National agency ANDRA.

In that particular case, according to Yves Marignac (the director of the Parisian office of The World Information Service on Energy (WISE-Paris)), he sees injustice, as the Law already gave preference to a method of "final disposal" option and hasn't provided a comprehensive examination of the acceptability of a method of "long-term near-surface storage" of HLW (Le Parisien, 2016).

Social opinion towards the projects of organization of international deep geological repositories on the territory of the Russian Federation.

The strategic direction of development of nuclear energy in **Russia** is the closure of the nuclear fuel cycle, which should ensure the minimization of radioactive waste generation with subsequent Deep geological disposal (Shmidt, Makeeva and Liventsov, 2016). Within the framework of the Russian HLW geological disposal project, options for Zheleznogorsk and Krasnokamensk are under consideration (Melnikov, Konukhin and Gusak, 2015). The population of the Zheleznogorsk Russian Federation is extremely negative about the projects for the import of foreign radioactive materials to Russia for storage and disposal (The Economist, 2000).

The population of Russia, as the whole, is extremely negative about the projects for the import of foreign radioactive materials to Russia for storage and disposal. Below there are the results of a quantitative study of the Independent Research Center ROMIR, made for Greenpeace Russia on the attitude of Russians to importing radioactive materials from other states for storage, disposal or reprocessing (Moscow, November 2000):

Table 3.1. Distribution of answers to the question: "What is your attitude to importing radioactive materials into the territory of Russia from other states for storage, burial or processing?"; Source: The politics of environmental policy in Russia (Feldman and Blokov, 2012)

	% of the number of respondents
Definitely negative	81.5
Rather negative	12.0
Neutral	3.9
Rather positive	0.4
Definitely positive	0.4
Do not know / Blank space	1.4

It is also important to note, that in year 2000, 2.5 million signatures were collected in two and a half months period of time in support of the national environmental referendum, the main issue of which, was the import into the country of foreign radioactive materials for storage and disposal at the territory of Russia (Wiseinternational.org, 2000).

4.5. The concept of SNF management, adopted in the Russian Federation

In accordance with the policy adopted by Rosatom (Russian State Atomic Energy

Corporation), SNF is not considered as waste, on the contrary radioactive materials are viewed at as the subject to further use. This applies not only to domestic, but also to foreign SNF, which could be imported for storage and (or) reprocessing. In this case, for an SNF exporting country SNF will be the radioactive waste, and the transfer of SNF to Russia will look like a solution for disposal/reprocess of SNF. However, for Rosatom, SNF will be considered as a valuable energy source (Grachev and Pliamina, 2017).

Despite the accepted concept of a closed fuel cycle, Rosatom nevertheless considers part of the SNF as radioactive waste for long-term disposal. In accordance with Resolution of the Government of the Russian Federation No. 923 of December 29th, 2001, it is planned to build a Dry Cask Storage facility for SNF in the Krasnoyarsk Territory until 2010, including for unprocessed irradiated nuclear fuel (Nti.org, 2003). Theoretically, the Krasnoyarsk facility could be used for foreign SNF storage too, in of change in Russian legislation, which does not yet imply the import of foreign SNF for final disposal. Based on the project documents for the import of foreign spent nuclear fuel, out of the 20,000 tons of intended for import SNF, only 16,000 tons will be a subject of reprocessing (The status of nuclear waste and nuclear safety issues in Russia and the United States, 1992). The unprocessed HLW, apparently, is subject to final disposal (Techno-economic substantiation of the laws applicable to expansion of Russia's participation in the world market of irradiated nuclear fuel, Minatom, Moscow, 2000).

Given all these facts, it can be assumed that Rosatom considers any form of international cooperation in the field of spent fuel utilization from abroad - both reprocessing and final disposal (Russia to dismantle the Soviet-era nuclear waste storage ship, 2014).

The unique approach towards HLW management was developed in 2002 within a framework of the European Union EU the multi-level governance system. Despite an existence of national strategies in the sphere of closed nuclear fuel cycle technologies, in some member states (Managing nuclear safety and waste: The Role of the EU, 2006). The European Commission has established "A nuclear package" of directives in line with policy of the all-European harmonization (Post and Raccah, 2016). The purpose of directives is distribution of the unified nuclear standards and mechanisms of nuclear management in the territory of the enlarged EU. For now, all EU Member States have to develop national strategies to the address all categories of radioactive waste, with an emphasis on HLW. "The nuclear package" makes the demand to define HLW deep geological disposal facility by 2008, and to begin the storage by 2018 (Sauter, 2009). Obviously, the parameters were quite unrealistic since in practice the HLW deep geological disposal facility projects demand longer terms for realization (Eea.europa.eu, 2018).

Due to the lack of real cost estimates for the closed and open versions of the NFC, an increasing number of countries are inclined to a "deferred solution" of SNF management issues. This path was chosen by **Australia**, **Argentina**, **Belgium**, **Great Britain**, **Canada**, **Slovenia**, **France**. The "waiting period" can be delayed until the first results of the Finnish project on Deep geological repository in 2023 is implemented (see paragraph "Review of national strategies and programs for HLW management", section on Finland)

In a number of the countries (**Mexico**, **Pakistan**, **Romania**) questions of SNF treatment haven't yet gained development to the level of national strategy, for addressing the issue of HLW management (Smart, 1984). In other group of the countries geological disposal of HLW is proclaimed as the basic direction of countries' nuclear energy sector development, but no specific deadlines for the construction of HLW geological disposal sites have been defined: for example, in **Italy**, **South Korea**, **India**.

To sum up, the concept of underground disposal of HLW in geological formations has gained development in the countries, that have all pre-conditions (meaning – can follow all Five criteria, mentioned in a Paragraph "Overview of international and domestic initiatives of the HLW deep geological repositories siting in post-2000s."), necessary for implementation of the Deep geological facility project. The analysis has shown, that projects of long-term HLW disposal are characterized by strict staging, which is reached by an accurate national strategy of the country in the sphere of the HLW management. In a number of the countries the decision on building a Deep geological repository is postponed. This tendency can be broken by means of the international cooperation in the sphere of a construction of a Deep geological site for HLW storage.

4.6. Optimization of HLW long-term disposal on a global scale: concept of the international disposal site

The most conventional ethical principle, that addresses nuclear waste issue is the postulate that the country getting advantages during the use of nuclear technologies has to bear full responsibility and a burden at the back-end of the Nuclear Fuel Cycle (NFC). It was never firmly defined though, that the countries are obliged to find a solution of the problem of the nuclear waste disposal in their own territory.

As it was mentioned above, the development of deep underground facilities for HLW demands the corresponding geological conditions and huge technological and financial resources which sometimes are not available in the some developing countries, emerging the nuclear technology. The countries with a limited and/or densely populated area, with rather small volumes of nuclear programs, and respectively, relatively small amounts of generated waste and also with an unstable geological structure - can experience difficulties with implementation of the HLW Deep geological disposal projects. The set of these factors has led to development in the 50s' – late the 70s' of the 20th century of the concept of the international (or regional) HLW Deep geological repositories (Brunnengräber et al., 2015).

Let us conduct a retrospective overview of HLW long-term disposal development. The initial research in the sphere of the international Deep geological HLW disposal sites construction dates to the 70s' of the 20th century. They were made by various organizations, from a position of the most general approaches: regional centers of a nuclear fuel cycle (1975 - 1977); the Nuclear Energy Agency (NEA) as a specialized agency within the Organisation for Economic Co-operation and Development (OECD), (1987); the Synrock research group in Australia (the middle of the 1980th) (Zhang et al., 2005), etc. In the 1990s expert groups of IAEA began to be engaged in concepts of the international storages (research, conducted in 1994-95, 2001-2002). Besides, a number of initiatives was at that time developed: Marshall Islands (1995-97) (Davisson, Hamilton and Tompson, 2012); Palmyra Atoll (middle of the 1990th) (Day of two suns: US nuclear testing and the Pacific Islanders, 1990); Pangea group, Australia (1997 - 2002).

In the sphere of the HLW international deep geological storages, there are already several specialized initiatives:

- Trust of nuclear non-proliferation (Non-Proliferation Trust) since 1998.

- An initiative of Ljubljana (Slovenia), since 2001.

- Offers from Russia since 2001.

- Offers from Kazakhstan, 2001, 2002 (Brown, 2002).

- Association for Regional and International Underground Storage) (ARIUS), since 2001.

- The project SAPIERR – Support Action: Pilot Initiative for European Regional Repository, since 2003.

The demand of a detailed a research for potential creation of regional European HLW deep geological storage has led to emergence of the offer from the Arius and DECOM organizations (Arius-world.org, 2016), called "The supporting action: a pilot initiative for the European regional storage" (Support Action: Pilot Initiative for European Regional Repository). The purpose of "The supporting action" - to take the first steps towards definition of the main factors of feasibility of the project of the European regional HLW Deep geological repository.

The construction of an International geological storage can have a number of advantages in comparison with National geological storages: smaller number of HLW storages on a global scale; possibility of joint technical expertise; a possibility of to choose a site with the best geological characteristics; smaller number of installations on conditioning of waste and non-standard installations. In ideal case, the International HLW Deep geological repository is going to be optimally located and equipped with the most progressive technologies. International HLW Deep geological repository can become a powerful source of consolidation of efforts at the back-end of NFC and to ensure global safety of the environment.

The most part of costs of the International HLW Deep geological repository is made by the fixed expenses, that are independent from the volume of the disposed nuclear waste and include expenses on research, gaining access to underground structures, creation of infrastructure and carrying out processes of licensing and delivery of legal permissions (Poinssot, Ferry and Poulesquen, 2006). Expenses on construction of the HLW Deep geological repository for the country, that imports HLW and SNF, will be covered due to economic benefits for providing the services to the International community.

The countries, paying for waste disposal outside their borders, also will have economic benefits, as the scale of disposal will allow to reduce specific costs for the HLW management. At the same time, geological characteristics of the disposal site can create conditions, under which creation of expensive additional engineering barriers won't be required (Toulhoat, 2006).

Additionally, the international deep geological repositories would be more advantageous for tackling the nuclear non-proliferation and global safety issues. Protection against the diversion of nuclear and radioactive materials becomes an object of a direct attention from world community. There are concerns, that some countries have no adequate technical standards and the control systems behind SNF national management programs, which increases a possibility of production of "a dirty bomb" (Elcock, Klemic and Taboas, 2004).

In case of the political instability in the nuclear waste owner-state and neighboring countries are interested in movement of the HLW and SNF under more reliable protection. Due to the high terrorist attack threat these days, the international centers for Deep geological disposal of HLW, can potentially provide safer isolation of nuclear waste. Protection of nuclear materials would be carried out more transparently in the International disposal site, in the conditions of openness for the international control of IAEA, other involved states and local communities.

Operation of the International HLW Deep geological disposal facility has to lead to growth in international shipment of nuclear waste. The practical experience, which is available today, shows that the risk from transportation of radioactive materials is extremely small and doesn't play the defining role in the strategy of disposal; the same way expenses on transportation of limited quantities of HLW in a NFC aren't the constraining reason for logistics ban (Benbow, 1997).

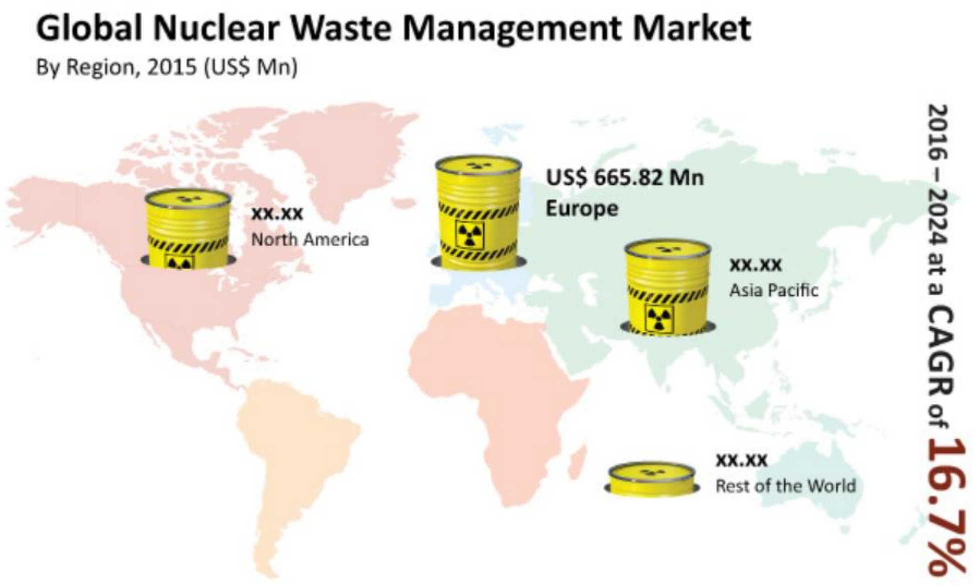

Figure. 3.5. The global market for nuclear waste management is expected to witness 16.7% Compound Annual Growth Rate between 2016 and 2024; Source: Transparency Market Research Analysis (TMR, 2016)

Under any scenario for the development of the world nuclear power industry, the capacity of the global market for services for HLW management will increase. Taking into account the delicate nature of HLW management issue, the waste treatment market and supporting services for handling HLW and SNF, will be operating for hundreds of years ahead (Williams, 1972) (See Figure. 3.5.) The concept of an international HLW repository encountered more difficulties, than forecasted at the beginning of the development the approach. The significant economic, environmental and geopolitical advantages of international Deep geological repository will help in the long term to reach a consensus among countries (potential suppliers) and recipients of HLW for disposal in geological formations.

4.7. Options for reaching International cooperation for building the Deep geological repository for SNF and HLW

The first scenario – "addition". The country operating its own disposal site at late stages of its operation allows other countries to conduct waste disposal at their site. Thus, an initiator of the similar project is the "host country", which owns sufficient financial and technical resources for implementation of the similar project and also geological conditions, favorable for an installation construction. In this case the main incentive motive for "host country" are financial benefits, e.g. is the closed cycle strategy of the Russian State Atomic Energy Corporation (Rosatom) could be considered as the most appropriate example (Air Shipment of Spent Nuclear Fuel from Romania to Russia, 2010).

The second group of scenarios could be the "cooperation" option, that assumes a participation of "partner countries" in development of the program of HLW Deep geological repository from the front-end stages. At the same time between partner countries is concluded the mutual agreement on a construction of joint site for disposal in one or several member countries, which have already created their own long-term disposal facilities. "Cooperation" scenarios can be divided into three groups.

In the first group of "Cooperation" scenarios, would be cases, when several industrialized countries conduct rather small-scale programs in the field of nuclear energy and make the decision in favor of cooperation for disposal of domestic radioactive waste in the "host country", which is capable to meet all necessary technical requirements (Finn, 1983). In this case, the main stimulating factors include the incentive to minimize the financial investment, needed to create their own final disposal sites. The ideal candidates for implementing such a scenario are countries with relatively small but long-running nuclear energy programs (Jasper, 2014), which have a rich experience in the field of nuclear technologies, for example, Belgium, Italy, the Netherlands, Switzerland, etc.

Within the second group of "cooperation" scenarios, are considered joint projects of countries with a small register of radioactive waste at different stages of industrial development and mutually supporting each other (Chellaney, 1999). At the same time, the cooperative work of this group of countries should eventually lead to the identification of one country, which eventually will have all the necessary resources to create a joint disposal site on its territory.

The third group – would be working on the creation of a joint specialized disposal site, intended for the final isolation of certain types of waste. In this case, the "host country" undertakes the responsibility to dispose HLW and SNF, imported from abroad under either a commercial agreement or an agreement on the mutual exchange of various types of radioactive waste. For example, to exchange fuel waste for transuranium waste, which are characterized by a low level of heat release (Molecke, 1992), or certain volumes of Low-, Intermediate- and High-Level Nuclear Waste.

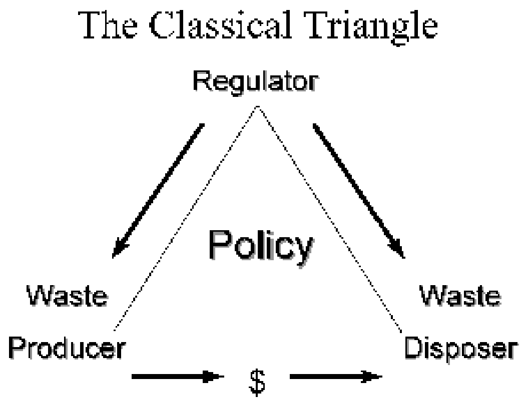

Figure 3.6. The model of the IAEA guidance on radioactive waste management infrastructure, sometimes referred to as the "classical triangle" principle; Source: the International Nuclear Society Council (INSC, 2008)

The last third type of scenarios is "cooperation under the supervision of a supranational international organization" (See Figure 3.6.). As the name of the scenario implies, an international organization would be fully responsible for the operation of such a disposal site. Thus, the "host country" is inferior to the control over the disposal site to the organization, chosen for the construction of the facility. Experts note that the implementation of the third scenario is extremely unlikely, because such a transfer of monitoring functions is a rather delicate moment in terms of political decision-making processes. The assignment of an international organization, for example, the IAEA, to the functions of the operator of a disposal site, runs counter to the traditional mission of this organization, which rather consists in carrying out supervisory functions (Banks, 2007). Otherwise, the question arises - which body of the IAEA will supervise and control the operator's activities.

Currently, it is the second scenario, which envisages the possibility of cooperation of "partner countries", is considered as the most viable option. And this strategy is being studied in the framework of international projects on the establishment of regional disposal sites in Europe (ERDO project), South-East Asia (under patronage of the Association of Southeast Asian Nations (ASEAN)), in North Africa and the Middle East (MENA project).

5. Conclusion and recommendations

Due to the fact that reprocessing of spent nuclear fuel is an expensive and technologically demanding process, still leaving an amount of radioactive waste as an output, more and more countries are inclined to refuse reprocessing of SNF. Meaning, that they begin to treat SNF as a type of High-level radioactive waste for final disposal. For many countries, the lack of opportunities for SNF disposing by their own means, as well as the nonproliferation problem (associated with the plutonium, contained in SNF), creates issues for the further large-scale development of nuclear energy.

Within the framework of the research project, IAEA specialists analyzed various aspects of the application of the multinational approach in the context of the operation of nuclear fuel cycle facilities and the creation of a joint International Deep geological disposal facility for HLW (Tsyplenkov, 1992). Financial and nuclear and radiation safety ensuring advantages, as well as the compliance with nuclear safeguards guidelines were also considered within IAEA research project. As a result, the author of this work, **recommends** the latter approach of building an **International Deep geological disposal facility** under a supervision of a comprehensive multilateral organisation as the most advantageous and respected one.

On one hand, the conclusion of joint agreements can be considered as an additional guarantee in the field of non-proliferation of nuclear weapons. On the other hand, such approach will provide considerable savings of financial and operational resources. Taking as a baseline the conclusions of expert group, and further under the auspices of IAEA, a number of research projects on a positive and negative aspects of the international cooperation, directed to creation of International Deep geological repositories, has been realized. In 40 years which have passed from the moment of carrying out the first research in this area the set of arguments in favor of creation of International Deep geological repositories has been adduced, and the put-forward concepts of creation of such installations have been formalized in Technical documentation of IAEA (Brunnengräber et al., 2015).

Nevertheless, despite the considerable interest in the concept of creation of International Deep geological repositories shown by the global community, in general, any noticeable practical results have not been achieved yet. Any state hasn't shown complete and final (with a support of all social groups involved) willingness to become potential "host country". Besides, implementation of such programs in many respects stirs the certain restrictions, imposed by the domestic legislation of the majority of the countries in the field of waste disposal, imported from abroad and also raises issues of public acceptance.

Therefore, already more than half century experts from many countries are drafting and arguing upon the safety standards for final isolation of HLW at the points of their disposal, which would guarantee reliable protection of the human health and the environment both in the present, and in the far future.

Implementation of the project of Deep geological disposal of HLW includes a set of stages, on each of which it is necessary to prove the available technical resources, sufficient enough to guarantee safety, to analyze all new scientific and technical data and to reveal the needs for obtaining additional information. The similar methodology was discussed and created in the international expert community for several decades, being constantly improved since the end of the 1990th including as the response to rapid development of computer technologies and pilot projects (Hadermann and Mccombie, 1992).

The material presented in this thesis quite clearly demonstrates, that the preparation of the rationale for the International Deep Geological Repositories for HLW management is a fundamentally creative process: there is neither a universal existing practice on how to develop it, nor a single format for its presentation. However, there is an unambiguous understanding, that the security justification materials for such projects, should clearly formulate the concept of its provision, and also collect all the necessary technical data and the results of the conducted studies.

It is also important to have a more compact version of justification of safety of repositories, intended for non-specialists and containing only the minimum volume of detailed specifications. Safety, security and reliability justification always reflects the long-term nature of O&M works, that should be expressed and made available in corresponding plan of researches, shorthand reports from round tables for discussion the issue and other public outreach materials. Important aspects in promotion of a safety standards of International Deep Geological Repositories for HLW management also are:

- Transparency (data on the safety of the disposal system are presented in an accessible manner, which makes it possible to optimize the decision-making process);
- Possibility of verification (key assumptions, especially scientific and technical data, as well as background information, which are fully documented either in the safety case itself or in accompanying materials);
- Openness for discussion and review (all uncertainties and controversial issues that may affect the safety of the disposal system are considered).

Implementation of programs of Deep geological disposal of HLW is the long process, consisting of a set of stages, success of each of which depends on a number of factors not only and not just of technical and scientific character, but also on socio-political and ethical aspects. In general, in the countries, which have achieved relative success in development of **Individual projects** of Disposal (France, Finland and Sweden), the appropriate programs have the following common positions (Riddel and Shaw, 2003).:

- the special public reach out strategy and feedback systems, on all questions that may arise, is approved;
- for many years (and sometimes decades) specialized researches in pilot plants have been conducted;
- the concept of reversible disposal of HLW, which can be realized until installation closing is offered as an alternative to a long-term final disposal;
- for search and agreement upon the sites for final disposal developers had spent decades, before the final decision.

At the same time, it should be understood that there is no ready-to-go “recipe” for the successful implementation of such projects. First of all, because the nature of stakeholder participation in the site selection process is largely determined by cultural and social aspects (like history of nuclear energy use within the counter, or level of trust to the government decisions). Therefore, an approach that is effective in one country may require development or modernization in another country.

As an experience shows, in most cases the population is opposed to the construction of Deep geological disposal facilities and by default, people are not inclined to believe that disposal is the best solution to ensure long-term safety. However, people living in close proximity to the site, as a rule, demonstrate a deeper understanding of both the technical issues associated with the disposal of radioactive waste, and the benefits that the project can bring.

It is interesting that this problem is relevant not only for the implementation of programs for the construction of deep geological disposal repositories for HLW and SNF, but also for near-surface disposal sites for ILW, LLW and even VLLW.

If for the nuclear technology engineer the construction of facilities for LLW and VLLW is not a challenge (existing developed technological solutions allow to provide a high level of nuclear and radiation safety, project management does not present special difficulties, and the radiological impact of such facilities on personnel, the population and the environment is fundamentally limited both in time , and in space), then in the representation of any common citizen, any nuclear installation, including VLLW disposal sites, is associated with something dangerous (Gibb, 1999). Nuclear wastes have always been associated with an ability to have a significant negative impact on the environment and human health.

There are quite reasonable explanations for this. First of all - historical. Nuclear technologies were originally developed for military purposes and in an environment of the complete secrecy. In addition, the issues of ensuring the safety of nuclear installations are indeed very difficult to understand, which also does not facilitate a smooth and constructive dialogue.

That is why the national operators of radioactive waste management should fully take into account the possibility of creating International Deep geological disposal sites for HLW, one of the facets of which is the exchange of multilateral experience and the time consumption of all processes. The custody of internationally recognized and respected Organization, such as IAEA, could only facilitate the process of an important check-and-balances system between public, scientist, politicians and entrepreneurs. The author sincerely hopes that this thesis will contribute to the common understanding that the Deep geological disposal of HLW is a real and reasonable technology, the alternative to which is not objectively expected to appear in the near future.

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