Radioactive waste disposal in space

Technical, economic, legal issues and possible methods of solution

INTERNATIONAL ACADEMY OF ASTRONAUTICS
SUMMARY REPORT OF STUDY GROUP 3.21
VERSION 1.0

1 March, 2016

Contents

Acronyms

AC	-	aerodynamic capsule
NP	-	nuclear power
NPP	-	nuclear power plant
HAW	-	high-activity waste
GEO	-	geostationary orbit
SPC	-	sealed power container
AES	-	artificial Earth satellite
ASS	-	artificial Sun satellite
SC	-	spacecraft
SLS	-	space launch system
MA	-	minor actinides
IAEA	-	International Atomic Energy Agency
MSTA	-	minimum significant total activity
AITB	-	assembly, integration and test building
PM	-	payload module
LAW	-	low-activity waste
MDW	-	mass destruction weapon
DO	-	disposal orbiter
SFA	-	spent fuel assemblies
SNF	-	spent nuclear fuel
RAW	-	radioactive waste
US	-	upper stage
RTG	-	radioisotope thermoelectric generator
LV	-	launch vehicle
SLS	-	space launch system
MAW		medium-activity waste
ERS	-	emergency recovery system
TCS	-	thermal control system
CS	-	control system
PSS	-	power supply system
FA	-	fuel assembly
FU	-	fuel unit
TC	-	transporting container
TG	-	thermoelectric generator
FS	-	feasibility study
NPS	-	nuclear power source
NFC	-	nuclear fuel cycle
NPPS	-	nuclear power propulsion system
NPU	-	nuclear power unit

Introduction

In the second half of the 20-th century the conception of radioactive waste disposal in space (RAW) emerged. For the past 50-60 years the conception has been discussed more or less intensively, several variants of its implementation have been proposed.

It was stimulated by the scientific community's recognition if the enormous size of RAW problem as a result of nuclear power industrial use. Conceptually, two solutions are possible: "deferred" and "final".

At present, most states use the "deferred" method, when spent nuclear fuel (SNF) is placed in temporary (though, long enough, 50-100-200 years) storage. It is assumed that within this time these or those methods of effective and safe SNF disposal would be implemented.

The "final" solution of RAW problem assumes their radical removal from the Earth biosphere. To do this, any method, making it possible to isolate RAW for the period of hundreds of thousands and million of years, that is, long enough to reduce activity of long-lived isotopes to the safe level, may be used. As of today, this solution has been implemented in single RAW disposal projects at the construction phases in deep geologic formations (for instance, Onkalo in Finland, Yucca Mountain in the USA). RAW disposal in space is also a variant of "final" solution of the radioactive waste problem.

In general, the conception of RAW disposal in space lies in the following procedure. SNF or high-activity products of its reprocessing are provided with multibarrier protection, thus, minimizing probability of their contact with biosphere in case of possible emergency situations and ensuring the acceptable radiation level on the protection outer surface. Afterwards, RAW in the combined containment shell is transported to the launch base and located on the launch vehicle final stage as a payload. Generally, the structures of the launch vehicle final stage are optimized (with consideration of multibarrier protection) to minimize probability of injected into space RAW contact with biosphere in case of emergency situations. The project emergency situations shall consider "the worst-case" scenarios like the carrier fire, explosion or combined failure of several safety systems during ballistic reel to the Earth due to faults at the injection phase. Finally, in case of accident-free space transportation, the capsule with RAW is delivered to the disposal site and left there for indefinitely long time.

This report contains the main results of the problems and possibilities study connected with RAW disposal in space. In this report RAW disposal is considered as a task that requires a practical solution in the foreseeable future.

1 Nuclear and engineering aspects of radioactive waste disposal in space

1.1 General description of radioactive waste problem and its current state

Owing to the nuclear-power industry development in the world, a large amount of radioactive waste has been accumulated and is being accumulated. It needs to be disposed in order to provide radiation safety of population [68].

Radioactive waste generates:

- during operation and decommissioning of nuclear fuel cycle enterprises (radioactive ore production and processing, manufacture of fuel units, power generation at NPP, spent nuclear fuel reprocessing);
- during implementation of military nuclear programs, preservation and liquidation of defence sites and restoration of the areas contaminated due to activity of enterprises manufacturing nuclear materials;
- during operation and decommissioning of the navy and civil fleet vessels with nuclear power installations and their service bases;
- during use of isotopic products in the national economy and medical institutions;
- as a result of carrying out of a nuclear explosion in the interests of the national economy, during mining operations, performance of space programs and during accidents at nuclear facilities.

During use of radioactive waste in medical institutions and other research institutions RAW is generated in much less amount in comparison with nuclear power industry and military-industrial complex-several tens of cubic metres per year. But use of radioactive materials is expanding, thus, increasing the waste volume.

In 2006 IAEA counted that more than 200 thousand tons of spent nuclear fuel accumulated in the world. Annually, 10-12 thousand tons is added [1]. Increase of extremely dangerous RAW in the world makes up 25-30 t/year. Nuclear power (spent nuclear fuel) and military programs (plutonium in nuclear warheads, spent fuel of propulsion reactors in nuclear submarines, liquid waste of radiochemical industrial complexes) are the main sources of high-activity RAW. By 2000 about 2 thousand tons of plutonium [3, 88] has been accumulated in the world.

Disposal of spent nuclear fuel and high-activity waste of its reprocessing is of a considerable concern. Such waste has been generated for more than half a century, but so far there has been no considerable progress in storage facility construction for it. The present developed approaches and techniques of RAW management are primarily based on the passive protection concept by creating a number of barriers on the RAW route of penetration into biosphere (immobilization in corrosion-resistant materials, containerization, final disposal in competent geologic formations). The main problem of conventional technologies is consists in provision of reliable and long-term protection (during not less than a ten thousands of years) from entry into the environment of long-lived radionuclides making up RAW [86].

The meaning of term "radioactive waste" depends on the accepted concept of SNF management. During performance of the so-called open (once-through) nuclear fuel cycle irradiated fuel (after a certain decay cooling) is to be subject to disposal with no additional radiochemical reprocessing. In this case RAW is considered as all irradiated material including uranium, accumulated plutonium and so-called "minor actinides" - MA (neptunium, americium, curium, berkelium, etc.). Content of MA in the irradiated fuel of power reactors is relatively low and makes up $(0.7\text{-}2.5)\cdot10^{-3}$ [86]. By their neutron-physical properties MA do not belong to well fissile nuclides, such as ^{235}U and ^{239}Pu, by their chemical properties they are fairly close to fission products from the group of rare-earth elements. That is why, during chemical reprocessing of irradiated fuel it was no use to extract them. Historically, from the very beginning of nuclear reactors operation during irradiated fuel reprocessing, MA remained with the bulk of fission products, making up RAW of high specific activity.

Actually, uranium with decreased content of ^{235}U and accumulated transuranium nuclides can be reused (and are already reused) as a fuel in nuclear reactors. Nearly 95.6% of spent fuel volume, unloaded from the reactor, is the same uranium oxide that was contained in the fresh fuel. The rest part consists of high-activity fission products (3.4%) and long-lived actinides, such as plutonium (1%) [21]. In the framework of the so-called closed nuclear fuel cycle RAW include a group of fission products extracted during irradiated fuel reprocessing and not to be used in the national economy.

The minor actinides, accumulated in fuel, due to their specific nuclear and physical-chemical properties are also referred to RAW, though they may be subject to neutron fission. Thus, in within the framework of closed NFC, to the "radioactive waste" category the following products are referred to: radioactive fission products, minor actinides and a small number of uranium and plutonium in the form of waste of the irradiated fuel reprocessing.

It is considered that extraction ratio of U and Pu from irradiated fuel reaches 99.5%, that is, 0.5% remains in the waste composition. Recycling (U-Pu)-of fuel leads (and it is present during operation of European light-water reactors) to accumulation of transuranium elements (^{243}Am, curium, berkelium, californium isotopes, etc.). Their effective disposal is another problem of MA management; consideration of this problem is still in its initial stage.

Table 1.1 – Possible content of main radionuclides in irradiated fuel of light-water-reactor (LWR)-1000 [93]

Nuclide	Half-life, years	Number, kg/t U	Nuclide	Half-life, years	Number, kg/t U
Actinides			Fission products		
U-235	$7.04\cdot10^{8}$	12.3	Se-79	$6.5\cdot10^{4}$	$1.7\cdot10^{-2}$
U-236	$2.34\cdot10^{7}$	5.73	Sr-90	$2.9\cdot10^{1}$	1.1
Actinides			Fission products		
U-238	4.47×10^{9}	929	Zr-93	1.5×10^{6}	9.1×10^{-1}
Pu-238	87.74	$126\cdot10^{-3}$	Tc-99	$2.1\cdot10^{5}$	1.1
Pu-239	$2.41\cdot10^{4}$	5.53	Pd-107	$6.5\cdot10^{6}$	$2.5\cdot10^{-1}$
Pu-240	$6.57\cdot10^{3}$	2.42	Sn-126	$1.0\cdot10^{5}$	$2.2\cdot10^{-2}$
Pu-241	14.4	1.47	I-129	$1.6\cdot10^{7}$	$2.2\cdot10^{-1}$
Pu-242	$3.76\cdot10^{5}$	0.582	Cs-135	$3.0\cdot10^{6}$	$4.2\cdot10^{-1}$
Am-241[2]	$4.32\cdot10^{2}$	0.616	Cs-137	$3.0\cdot10^{1}$	1.4
Am-242	$1.50\cdot10^{2}$	$0.264\cdot10^{-3}$	Sm-151	$9.3\cdot10^{1}$	$1.5\cdot10^{-2}$
Am-243	$7.38\cdot10^{3}$	$120\cdot10^{-3}$			
Cm-242[1]	162 days	$6.10\cdot10^{-3}$			
Cm-243[1]	28.5	$0.245\cdot10^{-3}$			
Cm-244[1]	18.1	$45.7\cdot10^{-3}$			
Np-237	$2.14\cdot10^{6}$				

Notes:

1) Decay cooling 0.5 year;

2) Decay cooling 10 years.

As a result of irradiated fuel reprocessing, RAW contains the bulk of fission products and a small part of residual fission products (U, Pu and MA). As an example, table 1.2 shows the composition of elements contained in RAW after reprocessing of irradiated uranium fuel of the light-water reactor and extraction of uranium and plutonium (99.5%). [86]

Table 1.2 – Content of nuclides in actinides in spent uranium fuel of LWR-1000 reactor after its 3-year decay cooling and separation of 99.5% U and Pu [86] (normalized to 1)

Nuclide	Content	Nuclide	Content
^{238}U	0.9809	^{241}Am	$0.503 \cdot 10^{-2}$
^{237}Np	$1.095 \cdot 10^{-2}$	^{242m}Am	$1.325 \cdot 10^{-5}$
^{238}Pu	$0.188 \cdot 10^{-4}$	^{243}Am	$0.245 \cdot 10^{-2}$
^{239}Pu	$0.649 \cdot 10^{-3}$	^{242}Cm	$0.366 \cdot 10^{-5}$
^{240}Pu	$0.249 \cdot 10^{-3}$	^{243}Cm	$0.892 \cdot 10^{-5}$
^{241}Pu	$0.137 \cdot 10^{-3}$	^{244}Cm	$0.533 \cdot 10^{-3}$
^{242}Pu	$0.645 \cdot 10^{-3}$	^{245}Cm	$0.264 \cdot 10^{-4}$

The following issues shall be considered for selection isotopes for launching into space: specify the waste representing biological hazard and time intervals, the waste representing no interest to production, medical, agricultural and scientific activities, thus, they are not to be remained for a long-term storage. The RAW danger lies in the fact that despite their activity decreases with time, but it still remains high during hundreds of thousands and millions years (figure 1.1).

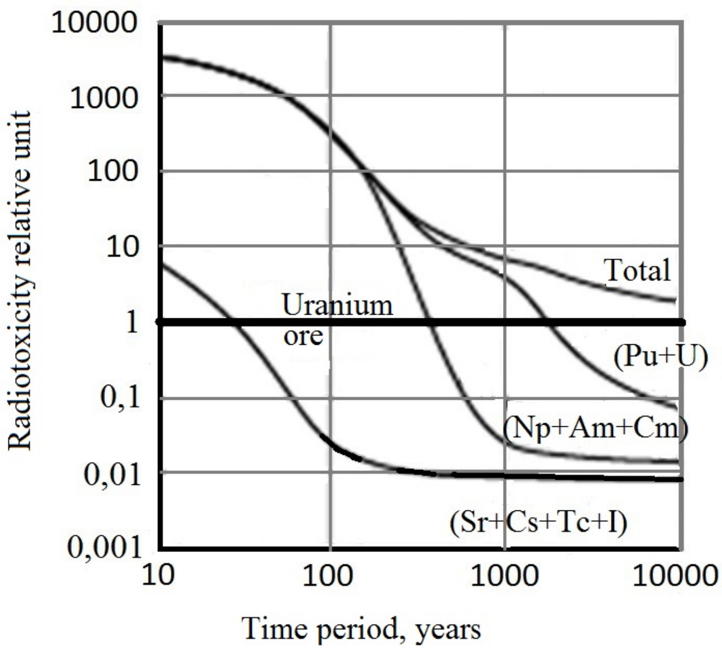


Figure 1.1 — Change of nuclide radiotoxicity during long decay cooling [86]

It is difficult and apparently impossible to guarantee high reliability of radioactive waste repository integrity maintaining with containers with radionuclides, which can penetrate in the environment despite their slow migration. The following fact can confirm the danger of such a situation: inhalation of less than 0.1 mg of plutonium is lethal. [68]

Depending on toxicity of radioactive elements they are divided in four groups according to minimum significant total activity (MSTA) [89, 90]:

Group A – isotope with particular high radiotoxicity (MSTA-1·10^3 Bq), for example: ^{229}Th, ^{232}Th, ^{232}U, ^{237}Np, ^{240}Pu, ^{243}Am, ^{245}Cm, ^{246}Cm, ^{248}Cm.

Group B – isotopes with high radiotoxicity (MSTA - 1·10^4 and 1·10^5 Bq), for example: ^{24}Na, ^{32}P, ^{56}Mn,^{90}Sr, ^{106}Ru, ^{122}Sb, ^{129}I, ^{132}I, ^{134}Cs, ^{134m}Cs, ^{136}Cs, ^{137}Cs, ^{144}Ce, ^{210}Pb, ^{210}Po, ^{206}Bi, ^{212}Bi, ^{223}Ra, ^{224}Ra, ^{226}Ra,^{227}Th, ^{230}Th, ^{234}Th, ^{230}U, ^{233}U, ^{234}U, ^{235}U, ^{238}Pu,^{239}Pu, ^{241}Am,^{242}Cm.

Group C – isotopes with medium radiotoxicity (MSTA - 1·10^6 and 1·10^7 Bq), for example: ^{14}C, ^{22}Na, ^{36}Cl, ^{38}Cl,^{54}Mn, ^{55}Fe,^{59}Fe, ^{60}Co, ^{64}Cu, ^{69}Zn,^{82}Br, ^{89}Sr, ^{91}Y, ^{90}Y, ^{91m}Y,^{94}Nb, ^{95}Nb, ^{93}Zr,^{95}Zr, ^{97}Zr, ^{96m}Tc, ^{99}Tc,^{105}Ru, ^{125}Sb, ^{131}Cs,^{132}I,^{133}I, ^{134}I, ^{141}Ce, ^{170}Tm, ^{203}Pb, ^{210}Bi,^{231}Th, ^{239}Np.

Group D – isotopes with low radiotoxicity (MSTA - 1·10^8 and 1·10^9 Bq, and ^{83m}Kr, ^{85m}Kr and ^{135m}Xe), for example: ^{3}H, ^{33}P, ^{35}S, ^{41}Ar, ^{53}Mn, ^{59}Ni, ^{71}Ge, ^{74}Kr, ^{76}Kr, ^{77} Kr, ^{97}Tc, ^{103m}Rh, ^{151}Sm.

The danger degree of radioactive element is determined by its maximum permissible amount allowed for operation without sanitary and epidemiological service permission. The main radionuclides, representing radioactive danger in SNF, are given in table 1.3.

Table1.3 – Radionuclides governing spent fuel activity and toxicity.[68]

Time interval, year	Governing radionuclides
Up to 100	Fe-55, Co-58, Ni-59, Sr-90, Ru-106, Sb-125, Cs-134,137, Ce-144, Pm-147, Eu-154,155
100-1000	Sm-151, Co-60, Cs-137,Ni-59,63
1000-10000	Pu-239,240, Am-241
104-105	Np-237, Pu-239,240, Am-243, C-14, Ni-59, Zr-93, Nb-94, Sn-126
>105	I-129, Tc-99, Pu-239

As it can be seen on figure 1.1, the irradiated fuel radiotoxicity during first 300-600 years is governed, mainly, by medium-lived fission products and later - by transuranium elements and long-lived fission products. Among long-lived fission products radionuclides shown in table 1.4 play the most significant role.

Table 1.4 – Long-lived radionuclides - fission products (including ^{90}Sr and ^{137}Cs), governing radioactive waste degree of danger [86]

Nuclide	T1/2, year	Nuclide	T1/2, year	Nuclide	T1/2, year
79Se	6.5·10^4	99Tc	2.1·10^5	129I	6.5·10^7
90Sr	29	107Pd	6.5·10^6	135Cs	2.3·10^6
93Zr	1.5·10^6	126Sn	1.0·10^5	137Cs	30

Thus, isotopes with high and particular high radiotoxicity and half-life not less than 10^3 years may be considered as potential candidates for injection into space. Their separation from the total volume of RAW is a challenging and costly task [68]. That is why, nuclear engineers shall specify this list. But it has not been done yet, as there are no published works by nuclear physics specialists on this issue.

1.2 RAW main aspects and management stages

Radioactive waste (RAW) of nuclear power industry management is one of the key issues determining acceptability and development scale of this power generation industry[86]. The selection of RAW management specific strategy is a complicated task; its solution is determined by technical, economic, environmental, legal and political criteria.

For now, IAEA has stated a set of principles [63], aimed at the radioactive waste management ensuring human health and environmental protection now and in the future with no excessive burden to the future generations:

1) **human health protection**. The radioactive waste management shall be performed to ensure acceptable level of human health protection.
2) **environmental protection**. The radioactive waste management shall be performed to ensure acceptable level of environmental protection.
3) **protection beyond national boundaries**. The radioactive waste management shall be performed to consider possible consequences for human health and environment beyond national boundaries.
4) **protection of future generations**. The radioactive waste management shall be performed to ensure predictable consequences for health of future generations. not exceeding present acceptable corresponding levels of consequences.
5) **burden to future generations**. The radioactive waste management shall be performed not to impose excessive burden to future generations.
6) **national legal frame**. The radioactive waste management shall be performed within relevant national legal frame providing for a clear allocation of responsibilities and provision of independent regulating functions.
7) **radioactive waste generation control**. The radioactive waste generation shall be maintained at the minimum practically feasible level.
8) **interdependencies of radioactive waste generation and their management**. The interdependencies of all radioactive waste generation stages and their management shall be properly considered.
9) **safety of installations**. Safety of installations for radioactive waste proper management shall be provided during their service life.

1.2.1 RAW as a part of nuclear fuel cycle

The nuclear fuel cycle (NFC) is a set of activities to provide operation of nuclear reactors. They are performed within the system of enterprises interconnected by the nuclear material flow. The enterprises include uranium mines, uranium ore processing, uranium conversion, fuel enrichment and fabrication plants, nuclear reactors, spent fuel storage facilities, spent fuel reprocessing plants and related interim storage facilities and radioactive waste repositories.

At present, there are two methods of RAW and SNF (for example, [30,68]) management depending on the type of nuclear fuel cycle.

One of them (closed NFC) is a reprocessing after a short-term (5-10 years) or longer (30-50 years) storage to isolate valuable elements (figure 1.2). The isolated uranium and plutonium return to the nuclear cycle. All activation and fission products are delivered to disposal as high-activity waste. The other (open or once-through NFC) provides for direct disposal of RAW without reprocessing after interim storage and conditioning (figure 1.3).

For civil purposes both open and closed NFC are used, for military purposes NFC functions in the closed mode only.

The initial stages of open and closed NFC are identical, they differ at the final stage connected with SNF transportation, storage, reprocessing, RAW management and their disposal.

Among advantages of closed NFC is return to power industry of expensive fissile materials - uranium and plutonium providing fuel for nuclear power industry during millennium at any increase of requirements. Moreover, volumes of highly radioactive waste intended for eternal burial are much less after SNF reprocessing, than volumes of spent fuel assemblies (SFA) without their reprocessing [68]. Globally, about 10% of nuclear fuel used at NPP is supplied for reprocessing to isolate uranium and plutonium for their further reuse.

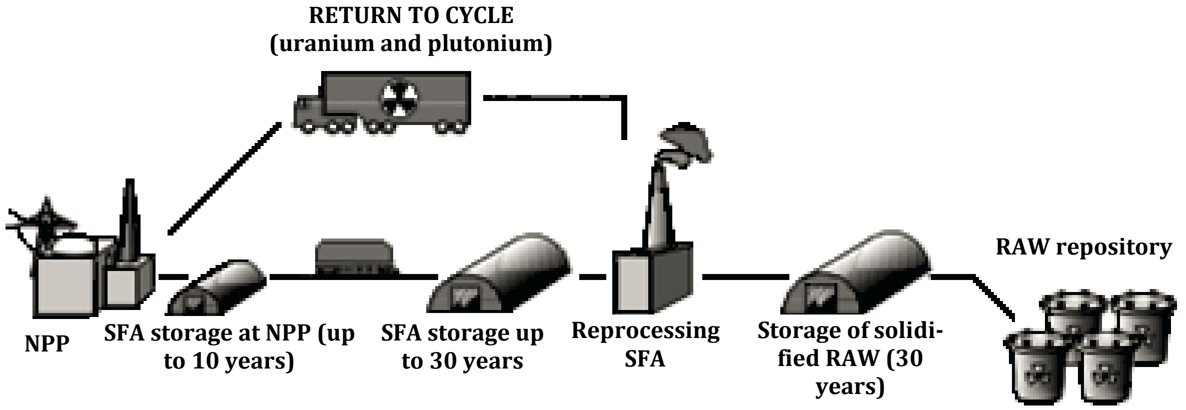


Figure 1.2 – Closed nuclear fuel cycle in nuclear power industry
(SFA – spent fuel assemblies, RAW - radioactive waste)

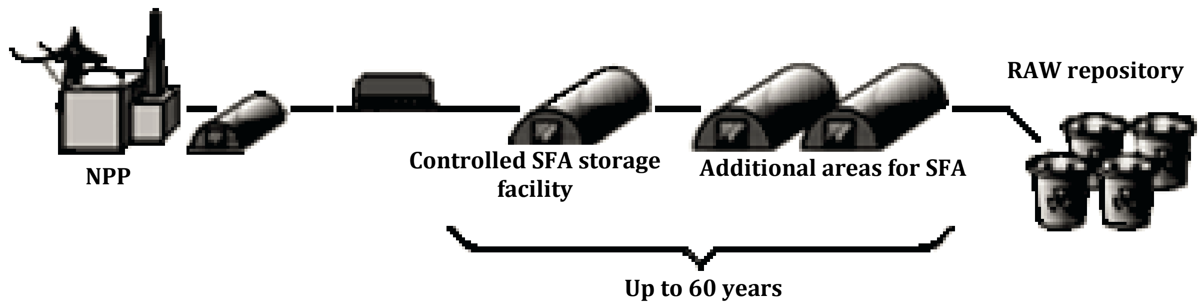


Figure 1.3 – Once-through (open) nuclear fuel cycle

At present, there are only a few plants where such reprocessing is performed in industrial scale: in Marcoule and La Hague (France), in Windscale (Great Britain), Chelyabinsk-65 (RF). The plant in Marcoule is considered to be the "cleanest" one with the particularly stringent control as its effluent enters the Rhone.

The main disadvantages of closed NFC are as follows: availability of environmentally hazardous radiochemical production and possibility of uncontrollable plutonium-239 dispersal and other fissile components of nuclear weapon. It is one of the reasons why neither of three plants, constructed in the USA for SNF reprocessing, is in operation at present.

The open NFC scheme is much shorter and simpler as compared with the closed variant. A radiochemical plant, the main source of environment contamination with radionuclides, is absent, that is there is no the most radiation-dangerous production. Radioactive substances in their solid state are permanently in the sealed package, they are not "smeared" over enormous areas as solutions and gases in case of scheduled and contingency emissions, etc. There are no problems related to construction and future decommissioning of the radiochemical plant: financial and material costs of the plant construction and operation including wage, power, heat and water supply costs, costs on a vast number of protection equipment and machinery, chemical reagents, aggressive, combustible and explosive substances (acids, alkalis, organic liquids), etc. There is no need to inject tritium under the earth, there are no problems with disposal of iodine, liquid and gaseous waste, emissions, etc. Finally, SFA "eternal" disposal does not mean complete and exclusion of nuclear materials from the cycle. It is due to the fact that the "repository" for spent fuel is an artificial compact uranium and plutonium deposit and it can be "developed" any time in case of extreme necessity: with appearance of new approaches to use of nuclear materials, new SNF reprocessing technologies, with decrease of fission radionuclides, etc. The disadvantages of the open cycle are as follows: high cost of long-term storage facilities and landfills, difficulties related to provision of FA long-term isolation from biosphere (there is a real danger of radionuclides release in case of FUs destruction during their long-term storage), necessity of permanent armed guard of repositories (possibility of fissile nuclides theft from repositories by terrorists is quite real) and constant control of the stored materials state.

It is apparent that any nuclear cycle is a costly and dangerous production. The selection of NFC optimal variant is a serious problem to the country and the whole world.

The analysis of economic aspects of NFC various variants is given a great consideration in all interested countries. It was shown [68], that at the present stage, from the economic point of view, both variants of SNF management, that is, reprocessing with further eternal storage of radioactive waste or eternal storage of SNF without reprocessing are almost equivalent. That is why, when selecting of NFC variant, environmental, energy, social and medical practicability of closed or open NFC shall come to the fore.

The main stages of RAW management are given in figure 1.4.

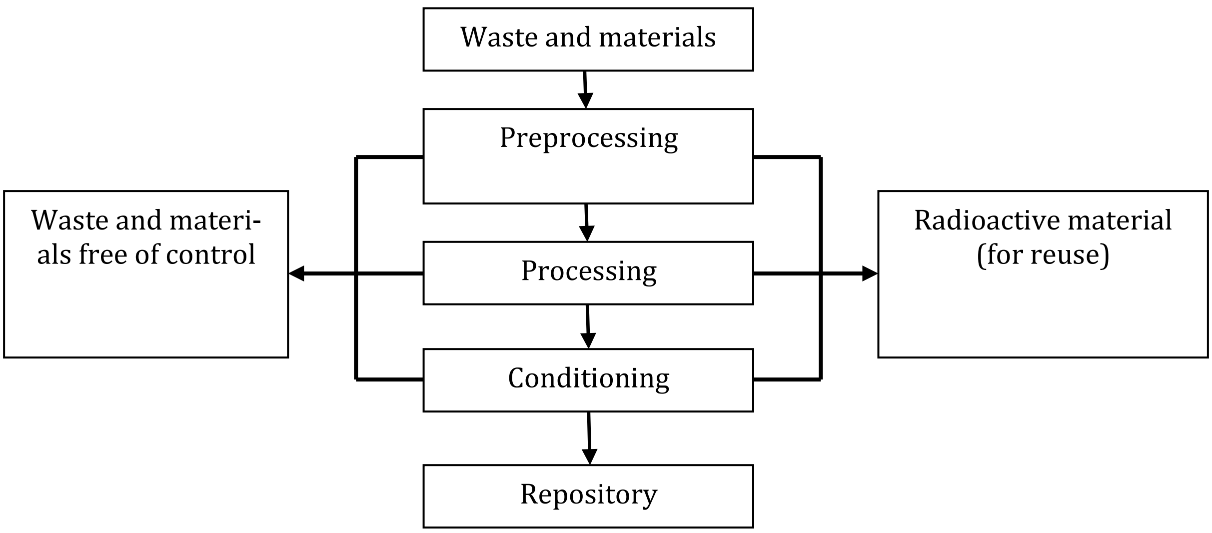


Figure 1.4 – The main stages of radioactive waste management

During storage of radioactive waste they shall be stored to:

- provide their isolation, guard and environment monitoring;

- if possible, facilitate actions at further stages (if there are any).

In some cases, storage may be performed according to technical considerations, for instance, storage of radioactive waste containing, mainly, short-lived radionuclides,; they are stored for their further decay and disposal within authorized limits or high-activity radioactive waste may be stored prior to their disposal in geologic formations in order to decrease heat emission.

Preprocessing of waste is a primary stage of waste management. It includes collection, chemical composition regulation and decontamination; it may also include the period of interim storage. This stage is very important as in many cases during preprocessing it is possible to separate waste streams.

Processing of radioactive waste includes operations aimed at safety or efficiency increase by changing characteristics of radioactive waste. Main processing concepts: volume contraction, removal of radionuclides and change of composition. Examples:

- combustible waste incineration or compaction of dry solid waste;
- evaporation, filtration or ion exchange of liquid waste streams;
- deposition or flocculation of chemical substances.

Conditioning of radioactive waste consists of such operations when radioactive waste is shaped to be acceptable for transportation, shipping, storage and disposal. These operations may include radioactive waste immobilization, their placement in containers and additional package. The standard methods of immobilization include solidification of liquid low-activity and medium-activity radioactive waste by their inclusion in cement (cementation) or bitumen (bituminization) and vitrification of liquid radioactive waste. Then immobilized waste, depending on their nature and concentration, may be packed in various containers, including ordinary 200-litre steel barrels and thick-walled containers of elaborate design. In many cases, processing and conditioning are performed together.

The very technology of waste isolation, their concentrating, pressing, containment in cement, bitumen or glass blocks is a separate branch of nuclear industry. The incineration technology that makes it possible to reduce volume of waste by 20-100 times, is even more complex and costly. Fume gases are purified using adsorption and filtration methods, ash, contaminated with radionuclides is subject to cementation, bituminization or vitrification.

These branches are developing in parallel with nuclear power industry and "take away" a considerable part of capital investments. [83]

Disposal, mainly, consists in radioactive waste placement in the disposal facility, ensuring proper safety without their further withdrawal and long-term monitoring of storage facility and maintenance. Safety is mainly achieved by concentration and containment providing for proper isolation of concentrated radioactive waste in the disposal facility.

Different countries keep to various national programs providing for either SNF reprocessing, or disposal, or "deferred solution", that is the long-term storage of spent FUs.

At present, out of 34 countries only 5 states (India, Japan, England, Russia, France) reprocess spent nuclear fuel at their enterprises. The majority of countries, including Canada, Finland, Federal Republic of Germany, Italy, Netherlands, Sweden, Switzerland, Spain, the USA and China either store SNF, or supply SNF for reprocessing to other countries. Nevertheless, in May of 2001, according to the state energy strategy of the USA, it was prescribed to "develop SNF reprocessing technologies and final management that are cleaner and more effective..." [59].

The selection of a certain fuel cycle in a specific country depends on the criteria used during evaluation of solutions of the accumulated and future waste containment (including SNF).

There are five such criteria:

1) degree of risk for human health and environment;
2) cost of SNF reprocessing, construction of storage facilities, etc.;
3) compliance with the legislation of the country when SNF is imported from abroad;
4) compliance with objectives of non-proliferation of nuclear weapon and nuclear materials;
5) community awareness.

As for radiochemical reprocessing, if SNF management is a high-tech industry, radiochemical processing is a superhigh-tech industry accessible to a few highly-developed nuclear states. SNF reprocessing costs are also high. Moreover, the modern level of reprocessing technologies makes it possible to extract from SNF only fuel components, uranium and plutonium (incomplete closed fuel cycle), the major part of SNF radioactivity remains in reprocessing high-activity waste. Disposal of this waste is quite a difficult problem.

Implementation of SNF high-level reprocessing with spent nuclear fuel separation into fractions of individual radionuclides will become possible only in the future [93].

SNF chemical reprocessing is designed in terms of safety. Comparing degrees of risk in case of internal accident and external influence at NFC enterprises, the experts consider SNF chemical recovery to be the most hazardous of all cycle stages. That is why, many experts think that the modern technology level of SNF chemical recovery does not comply with the environmental safety requirements, so it is advisable to place spent fuel units in long-term storage. Besides, SNF reprocessing is related to generation of a large amount radioactive waste (during reprocessing amount of waste increases but their specific activity decreases) [68]. That is why, nowadays open uranium fuel cycle is considered as preferable one. [88]

The level of interim storage technologies, achieved by now, provides possibility of SNF storage for not less than 50 years. It is expected that in the short term, owing to technological progress it will become possible to increase these periods up to 100 and more years. That is why, many states with operating NPP on their territories are trying to delay implementation of fuel cycle final stages by placing fuel for interim storage or decision making regarding the final stage or expecting its implementation.

On the basis of all the above, it may be stated that modern nuclear power industry operates according to the incomplete fuel cycle, which stops at the stage of SNF interim storage or high-activity waste of its reprocessing [93].

Isolation of valuable components from SNF is a hyper technology; its development was extremely costly and became possible because it was developed as the most important production of the nuclear weapon complex. This is the most valuable part of scientific and technical, intellectual wealth of nuclear states. At present, it is very difficult to start SNF reprocessing activities, train relevant personnel and scientific and industrial infrastructure from the ground up. As a result, there are many countries ready not only to give their SNF, but pay for it as they do not know what to do with it.[92]

Besides, economic efficiency is nearly always is a matter of scale. The minimum capacity of a reprocessing plant for it to become cost-effective is 1000 tons a year. The British and French enterprises have the above mentioned capacity. The planned capacity of the Russian plant RT-2 is 1500 tons per year. The annual SNF unloading from standard 1000 MW power unit is about 25 t/year. It means that a commercial plant shall service at least forty units. Such PP scales are present only in three countries - the USA, France and Japan (there is only half-power present in Russia so far, but the total power of reactors manufactured in Russia and abroad is at the required level). There are about thirty countries-members of the "nuclear power club". Their number will probably increase, probably. to fifty by the middle of the century, but the overwhelming majority will have PP of moderate scale - within ten units. That is why, only the largest nuclear states will be able to develop SNF reprocessing and maintain the relevant infrastructure. The number of such countries will never be more than ten; the rest will have to buy their services as, starting from the middle of the century nuclear fuel recycling will become one of the largest power branches.

The English plant "Thorp" in Sellafield was constructed entirely by the expense of advance payments of Japanese and European companies; then it started to reprocess their fuel. SNF storage facilities were constructed using profit from reprocessing. The plant reprocesses 900 t of SNF per year; the domestic fuel makes up only 30%. This plant was formally opened by Queen Elizabeth.

1.2.2 Transportation experience

Transportation of radioactive substances and nuclear fissile materials is an important component of the nuclear fuel cycle.

Transportation is a connecting link of manufacturing activity of enterprises (NPP, NFC enterprises, research nuclear centres, marine plants of the navy and civil fleet, etc.) managing radioactive materials. The list of transported radioactive substances is rather wide: nuclear fissile materials, radioactive substances, spent nuclear fuel and radioactive waste, fresh nuclear fuel, uranium and plutonium in various chemical compounds (various physical state and with varying degree of enrichment by fissile nuclides), isotope sources, etc. Their transportation is performed by ground, water and air transport.

The transportation process of nuclear materials is the weakest link in terms of susceptibility to unauthorized actions in comparison with stationary facilities. Protection of nuclear materials on transport vehicles, unlike stationary facilities, has no multi-structural guard system, so a conventional set of equipment and technical facilities for advance hazard detection, its evaluation, access delay and retaliatory measures cannot be implemented.

Since the nineties of the 20th century, with terrorist activity enhancement, it became apparent that it was necessary to take additional measures to protect transport vehicles, carrying nuclear materials. To achieve this, the program was developed to elaborate transportation safety automated system for nuclear materials with its phased introduction.

Annually, about 10 million of packages with radioactive substances of different type are transported in the world. Protection of radioactive substances transportation is important due to potential risk of damage to the community, environment and property during their transportation, handling operations and interim storage. The presence of such risk is caused by the possible failure of transport or loading facility, impact of breaking mechanical and heat loads on the package during transportation that may lead to dispersion of radioactive substances in the environment and personnel irradiation above allowable values due to violation of rules provided for safe handling of packages.

Performing operations related to transportation of radioactive substances and toxic substances the following factors represent danger: ionizing radiation, creating the radiation dose exceeding values specified by radiation safety standards RSS-99 for category A personnel, directly involved in handling operations and for category B personnel during transportation and interim storage of packages; radioactive pollution of surfaces of the carriage, equipment and other loads on the transport vehicle; radioactive substances that in emergency situation may enter the environment and create pollution and concentration levels of radionuclides in water and ambient air that exceed allowable values.

Radiation safety during transportation of nuclear fissile materials shall be ensured by complying with the following requirements: compliance with the specified requirements and quality assurance during development, design and manufacture of transport containers; performance of a required set of tests for containers; control of radiation characteristics of transported radionuclides; control of container technical state; compliance with loading standards and conditions of radioactive substances location in the container, control of neutron absorbers and other protection elements proper installation; radiation control of transport vehicle surface pollution; control of transport vehicle technical state and operability, its equipping with necessary fire extinguishing facilities, control of radiation situation and emergency protection facilities; compliance with safety rules during handling operations; compliance with standards and rules of packages loading onto the transport, compliance with set limitations for positional relationship of packages; performance of a set of organizational and technical measures to ensure safe transportation including the transport vehicle optimal route selection and schedule, exclusion of unauthorized access to packages.

Transportation of spent nuclear fuel from NPP to the reprocessing plant includes four stages:

1) loading of containers at NPP and preparation for transportation;
2) transportation;
3) fuel unloading at the reprocessing plant;
4) delivery of empty containers to NPP.

As a rule, containers are not services during transportation. The latest models of large railway containers are equipped with auxiliary systems of forced cooling. They are activated automatically if the temperature rises in the container.

Operations of container reception and unloading at the reprocessing plant are much similar to operations at NPP. After radiation survey to detect possible leakages of radioactive content, the container is delivered for washing to prevent contamination of pool water during next operation, that is, unloading. Unloading of containers at the reprocessing plants is performed in pools under the sheet of water.

1.2.3 Degree of risk during spent fuel transportation

During accident risk assessment leading to radioactivity release and its consequences shall be considered. In 1973, for discussion at the meeting of Atomic Energy Commission (USA), devoted to safe transportation rules of radioactive materials, there were presented probability estimation data, hazard categories and accident consequences that could happen during transportation of spent nuclear fuel. The emergency hazard category was defined depending on the transport vehicle speed at the moment of accident and fire duration (according to statistical data). The accident risk, estimated in the number of accidents per mileage is given in table 1.5 [62].

Table 1.5 – Accident risk for different categories of their severity, accident/mile [62]

Minor	Medium	Severe	Very severe	Extremely severe	Total value
$2x10^{-6}$	$3x10^{-7}$	$8x10^{-9}$	$2x10^{-11}$	$1x10^{-13}$	$2.3x10^{-6}$

Data about a number of accidents, considering their severity and related to a total number of transportations in the nuclear fuel cycle with account of transportation distances are given in table 1.6. The number of transportations is given as it was registered in 2000 [62].

Table 1.6 – The number of accidents during one year during spent nuclear fuel transportation [62]

Total number of transpor-tations per year	Total route length, miles	Accident category				
		Minor	Medium	Severe	Very severe	Extremely severe
12764	$8.53x10^6$	17	2.6	0.07	0.00017	0.0000009

It should be noted that risk calculation during spent fuel transportation is a rather difficult task. The initial data of several spheres are required to assess risk: statistics, technology, meteorology, radiation safety (biology and medicine), namely: accident statistics during transportation; failure rate of containers during accidents; degree of radioactivity release from containers; nature of radioactivity transport into environment; population distribution; dose conversion factors for radionuclides. There may be different approaches to initial data determination, affecting the final result. But most experts think that if all specified requirements to the design, technology and operation of containers are complied with, the probability of severe radiological danger during spent fuel transportation is low.

RAW transportation calls for a large scope of organizational work performance. Thus, it took 25 days to transport SNF from Hungary to RF. It took more than four years to prepare it. The number of involved companies and state organizations - 24, the personnel number - more than 100 with no account of persons providing physical protection [46]. Much time was spent on preparation of governmental agreements, acquisition procedures of certain licenses and permits are very lasting, the regulatory system is complicated.

1.2.4 Liability of the parties during RAW management

According to the hands-on experience [42], the following liability of the parties is established at different stages of RAW management.

During RAW radiochemical reprocessing, the reprocessing plant authorities are held liable for physical protection.

During container immobilization and filling, the processing plant authorities are held liable for physical protection.

At the transportation stage the cargo carrier (consignor or consignee) is liable for physical protection.

During interim storage and preparation for launch, the authorities of a lunch performing organization are liable for physical protection.

The term "physical protection" means a set of organizational measures, engineering and technical facilities and activities of security units to prevent subversive acts or theft of nuclear materials and radioactive substances.

1.3 RAW disposal methods

The reliable isolation of radioactive waste, its performance methods and techniques is one of the problems of biosphere protection from nuclides effect. RAW disposal requires long-standing and multiple-factor studies. Various variants of the problem solution are still being discussed.

During the whole history of nuclear industry the following disposal and removal methods of radioactive waste (as a rule, MAW and LAW) have been approved [84]:

1) waste disposal on the World ocean bottom;
2) disposal in stationary above-ground and near-surface storage facilities;
3) disposal in rock cavities;
4) liquid RAW injection in rocks with large open porosity (sands, gravelites, cavernous limestones, etc.).

For HAW and SNF storage, belonging to the category of special HAW, the following storage and disposal methods were used:

1) disposal on the World ocean bottom;
2) storage in near-surface or underground specially constructed storage facilities;
3) storage in at-reactor water pools or independent water storage facilities (underground water storage facility CLAB);
4) liquid HAW injection in underground rock horizons with large open porosity (in Russia this method is called the injection in deep geologic formations).

The specific features of HAW and SNF are as follows [84]:

1. Due to presence of fissile materials (uranium, plutonium, etc.), these products are able to heat up to high temperatures (hundreds of degrees). High radioactivity promotes radiolysis (decomposition under radioactive irradiation) of water and other chemical components with generation of highly explosive nitrogenous, hydrogen and other compounds. Underestimation of this factor may lead to rather complicated emergency situations with radionuclide emissions in the environment. The accident of this type took place in 1957 in Chelyabinsk-65, when waste heating up in the tank caused a high-power steam and gas explosion.

Thus, storage of HAW, SNF and splitting-up of nuclear materials (plutonium, highly enriched uranium) requires special engineering structures allowing control and regulation of the storage temperature conditions.

2. In essence, these materials form a specific technogenic deposit (any geologist would be happy to find so compact and concentrated deposit components), it may be developed if it is needed or with appearance of new technologies.
3. These materials shall be protected from unauthorized access as they may serve as a basis for production of nuclear and radiological weapon for acts of terrorism and blackmail.

During radioactive waste storage and disposal the multibarrier protection is used including artificial (engineering) and natural barriers of physical and chemical protection.

The following elements serve as engineering, physical and chemical protection: FU or vitrified mass jacket, container shell, accumulator between the glass block (for example, polyethylene that absorbs neutrons, thus, reducing heating up and the level of radiation effect on the container material); the engineering structure shell (canyon, bunker, trench, mine, well, etc.).

Rocks of different types, soil, water mass serve as natural physical and chemical protection.

In each case, depending on the waste type, volume, etc., different disposal methods are used or will be used.

Radioactive waste has a major advantage over conventional industrial waste: radioactive elements decay and self-destruct, while stable toxic elements exist eternally. As an example, figure 1.5 shows the time history of spent nuclear fuel radioactivity after radiochemical reprocessing.

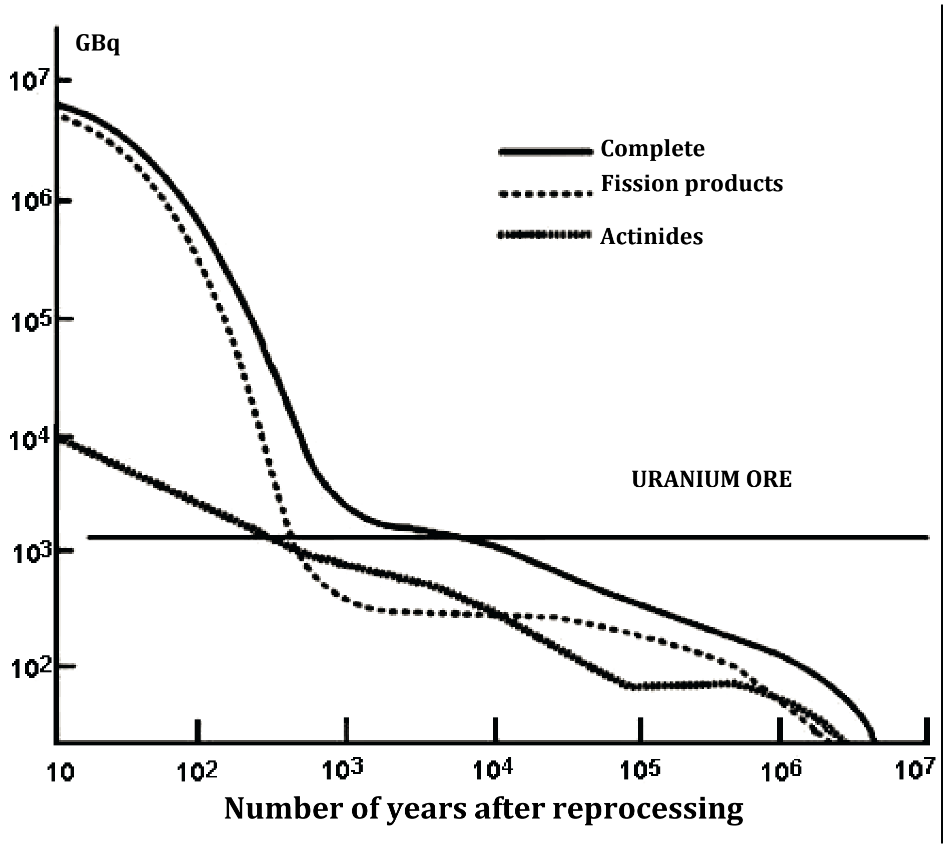


Figure 1.5 – Time history of reprocessed SNF activity/68/

It is obvious that activity of both fission products and actinides, remained in fuel, decreases with time, but not according to a simple exponential dependence (accumulation of daughter radioactive elements). In 1- thousand years the activity will fall to the radioactivity level of uranium ores, that is, the equivalence principle is complied with: the same activity that was extracted during uranium ore production will return to Earth's crust [68].

Practically all experts, dealing with RAW management problems, consider the concept of radioactive waste disposal in deep geologic formations as the most acceptable one. At that, for safety substantiation the analogue method is used with existence of uranium deposits in the Earth interior, including those, where nuclear processes were present. For example, Oklo deposit, where ~ 200 mln. years ago during 500 thousand years at the depth of ~ 3.5 km a natural nuclear reactor acted, heating surrounding rocks up to 600°C. Nevertheless, about 3 bln. years ago life germed, co-exists and develops near very dangerous substances.

In literary sources acceptable disposal depths (500-1000 m) are mostly discussed that, first of all, is determined by the construction efficiency factor of such structures. The implementation of this concept is a very responsible, costly and long-lasting task. The main problem to be solved is isolation of radioactive materials from possible RAW contact in a matrix or container with water, which is a primary conveying medium to transfer radionuclides in human environment.

The selection of HAW repository construction site is determined by many factors. For instance, in the USA according to statutory requirements and federal regulations, 117 factors shall be identified to evaluate the construction site for such structure, including:

- seismic activity and tectonic stability;
- chemical composition of waters, water exchange intensity, water flow velocity, distance to groundwater discharge area and a number of other hydrogeochemical indices;
- availability of rock types suitable for permanent structure construction with consideration of their shielding properties;
- proximity of water and mineral resources that may be involved in operation and become the reason for unintentional penetration of humans into the repository in the future;
- proximity to the system of national parks, populated areas, etc.

To prevent unintentional intrusion upon this site (territory) in the remote future, the system of permanent markers and monuments to warn future generation about disposal site location. The signs are to be place on the area surface, they shall be visible from the ground and air. Special records will be available in public libraries, computer information centres, placed in capsules, etc. and will be spread around the world to reduce probability of losing all records about this place. All these activities will be planned attracting archaeologists, linguists, etc.

The duration of selection and safety substantiation of such sites location, their further construction continues for a few tens of years, the cost of inputs may total hundreds of millions dollars only at the stage of geological engineering survey.

Even with presence of such structures there still remains the problem of HAW storage in solid state. First of all, it is connected with the intensive heating up. For instance, according to the project data of the repository construction in Yucca Mountain area, the temperature near container will be about 230 ºC and will exceed boiling temperature of water for more than 300 years. In many projects this feature is used as a factor for further compaction of filling material between containers and facility walls; for example, sodium salt cam be used as a filling material.

It should be mentioned that even well designed special engineering structures, used for storage of HAW in vitrified mass and packed in containers, shall be located at a considerable depth from the earth surface. For example, in Sellafield region (England) the storage facility is planned to be located at the depth of ~ 800 m (Tararaeva et al., 1993), or even greater depth (2000 - 4000 m) in specially drilled large-diameter wells or mines.

1.3.1 Geological disposal

At present, the search of suitable locations for deep final waste disposal is carried out in several countries; such storage facilities were expected to come into service after 2010. The international research laboratory in Swiss Grimsel deals with RAW disposal issues. High-activity and medium-activity waste containing up to 99% of radioactivity, is planned to be disposed in granite massifs.

Waste after SNF reprocessing in France will be included in the glass mass poured in steel containers with 30 cm thick walls. The calculations showed that in the course of the first 1000 years more than 99 % of the radioactivity contained in glass would decay. For this time, the carbon steel container wall corrodes for not deeper than 4 cm. 15 cm thickness will be enough to provide the container integrity according to external loads conditions. Thus, accepted dimensions ensure the package integrity. The container mass with vitrified waste is 8.4 t. They are located in mines at more than 1000 m deep horizontally and surrounded with bentonitic filling more than 1 m thick. It is expected that RAW storage safety will be ensured for more than 100 thousand years. The estimated value of this disposal is about 3 bln. dollars.[68]

It is considered that even in the most unfavourable situations migration of radionuclides through bentonite is only possible by means of diffusion and they may reach the rock walls in 100 000 years, that is only particular long-lived radionuclides will be able to break through the bentonite barrier. Permeability of the surrounding rocks (granite) shall be from 10^{-6} to 10^{-12} m/s.

In November, 2000, in Switzerland the IRIG group meeting was held, organized by PRI company. The representatives of nuclear power companies of Switzerland, the National committee of Italy on R&D in nuclear and alternative energy sources, RAW management organizations of Czech Republic, Slovenia and Netherlands participated. IRIG group recognized the need to construct the international storage facility in the future with consideration of safety, environmental and economic issues. But it was noted that as there is no imperative need in SNF and/or HAW storage facilities, the concept of the international storage facility may be developed gradually with consideration of scientific and social problems and in cooperation with IAEA without need to advance national programs. In the future, IRIG group activities shall be aimed at development of already performed by IAEA determination of political and legal conditions required for organization of regional waste storage facilities and timely preparation of discussion in the country offering the site for the storage facility. The group activity shall be based on the fact that concept of the international storage facility may be implemented, if the offer of some country would be supported by the full awareness and interest of its population.

Sweden is discussing its intentions as for direct disposal of spent fuel using KBS-3 technology as the Swedish parliament considered it safe enough. At present, in Germany discussions are held concerning search of site for RAW permanent storage with active protests by residents of Gorleben village, Wendland region. This site, till 1990, was considered perfect for RAW disposal owing to its proximity to borders of the former German Democratic Republic. Now RAW are at temporary storage in Gorleben, the decision about its final disposal has not been taken yet. The U.S. authorities selected Yucca Mountain, Nevada, but this project was intensely opposed and fiercely discussed. There is a project of high-activity RAW international storage facility construction; Australia and Russia are proposed as possible disposal sites. But authorities of Australia oppose this proposal.

Let us consider the approach to waste disposal in the USA. In the whole world this country is seen as a sample, other nuclear states closely monitor American project to regulate their policy in this sphere.

In the USA policy of nuclear waste management was formulated in 1982, during president Reagan governing, when Nuclear Waste Policy Act was adopted. These are the most important provisions of this act:

1) geologic disposal is provided for high-activity waste without reprocessing;
2) responsibility for the disposal site selection, construction and operation is placed upon Department of Energy (equivalent of Russian Ministry of Nuclear Energy);
3) Nuclear Waste Fund was established to finance all operations in disposal sphere;
4) all nuclear power complex enterprises pay a special tax to the Fund;
5) military waste disposal is paid by the Federal Government.

Another possible provision of this document says that since 1997 all responsibility for radioactive waste of commercial (civil) nuclear plants is transferred to the United Sates Federal Government. Thus, the Yucca Mountain project originated.

It was planned that the site survey would continue until 2001. The following documents were prepared and published within this research period: "Applicability appraisal" (preliminary information about applicability or inapplicability); "Environmental effect". Since 2002 to 2004 licensing process was to take place. The procedure resembles the "trial", with "members of the jury" (three experts responsible for licensing), the "accused" - Yucca Mountain, the "barrister" - Department of Energy, and the "prosecutor" - anyone, even a private person. The important moment that during licensing process experts shall testify upon oath. The law says that if someone tell lies and it is revealed, he will have to pay 10 thousand dollars as a penalty every day since the moment of lies till the day it was revealed. The money has to be paid from the personal finances and it has no statute of limitations.

The project is implemented by Department of Energy. In the works on a project 1500-2000 people participate representing 6-7 large subcontracting organizations (United States Geological Survey, National Nuclear Laboratories Los Álamos, Sandia, Livermore, etc.). It goes without saying that supervision is a must for such an important multi-billion project. The general supervision for the project is performed by a few independent organizations, such as:

1) the United States Congress;
2) Nuclear Regulatory Commission;
3) Nevada state government;
4) Nevada state district governments where works are performed;
5) Technical Inspection Commission on Nuclear Wastes, appointed by National Academy of Sciences, etc.

The quality surveillance of scientific production is performed by Science Application International - no report may be issued without QA of this organization. Moreover, due to the possible conflict of interests of Federation and state, Department of Energy shall assign means to Nevada state for their independent research and supervision of federal organizations' activities.

Many countries have expanded national programs aimed at research of different rock types properties, their ability to contain waste during hundreds of thousands years, at finding optimal disposal methods and conditions. Exchange of gathered information and international cooperation may significantly accelerate elaboration of the long-term policy and promote construction of centralized waste storage facilities in some countries.

In western Europe, under EEC supervision, the plan of radioactive waste management was developed and implemented; the plan provides for performance of works according to several unified projects and programs. For instance, "Tagir" project was developed to evaluate methods of radioactive waste management and disposal, "Mirage" project provides for study of radionuclides migration in geosphere. The third EEC program includes projects for construction of laboratory underground storage facilities and the list of tasks for these laboratories. Under EEC supervision three laboratories are to work: in Belgium - in argillaceous formations, in France - in granites, in FRG - in salt mines of Asse where the laboratory has already been established.

As a result of the preliminary evaluation and detailed study of different rock types, the following rocks were defined as the most applicable ones for disposal: salt formations (Spain, Canada, Netherlands, the USSR, the USA, FRG, Switzerland), anhydrites or unhydrous plasters (Spain, Switzerland), sedimentary rocks - shales and clays (Belgium, Great Britain, Spain, Italy, the USA, France), crystalline rocks like granites (Austria, Great Britain, Denmark, Spain, the USSR, the USA, France, Czechoslovakia), volcanic rocks (India, Canada).

In 2002 representatives of the states, interested in use of the international storage facility, united in Association of regional and underground storage (ARIUS). There are many potential advantages in this approach: cost optimization, safety and reliability enhancement, reduction of negative impact on the environment [52]. At present, ARIUS includes organizations from eight countries. The main objective of the association is to develop potential solutions of the waste problem stated in IAEA recent investigation. It is a matter of regional storage facility construction for partner countries or international storage facility that may be provided by one of the nuclear states.

The idea of regional storage facility construction formed the basis of SAPIERR project. Within its framework the possibility of waste disposal problem regional solution for small nuclear states of EU is under study. The final results of SAPIERR project were presented at the working session in Brussels at the end of 2005.

But some countries, including ARIUS members, also showed their interest to the proposal of Russia to provide a long-term storage facility for foreign spent nuclear fuel on its territory. This option is based on the possible construction of the SNF storage and, probably, disposal centre in Krasnoyarsk.

At present, both politicians and the community in different countries tend to national waste disposal schemes. It makes it possible to provide tight control of safety and environmental consequences of the project implementation. The international project will get support only if the country, constructing the international storage facility on its territory, will guarantee that standards will not be lowered.

In the 1990-ies, a few variants of radioactive waste conveyor disposal in the subsoil were developed and patented. The technology was to be as follows: a large-diameter start well is drilled up to 1 km deep, the capsule, loaded with radioactive waste concentrate, weighing up to 10 t, is lowered inside; the capsule shall self-heat and in the form of the "fire ball" melt the terrestrial rock. After the first "fire ball" has been deepened, the second, then the third, etc., capsule is lowered into the same well, thus, forming, a certain conveyor.

The project of Institute of Theoretical Physics and Institute of Physics of the Earth (Russia) provides for use of heat emission of capsules to melt down the filling material (sulphur, glass, etc.) of ultradeep well and their self-lowering in the depth by 2-3 metres per day. The melted mass will cool down, fencing RAW off from the outside world with thicker and thicker layer.

The project "Remix & Return" seems to be more realistic. According to this project, high-activity RAW, mixed with waste from uranium mines and processing plants to get the initial level of uranium ore radioactivity, then shall be placed in empty uranium mines. The advantages of this project are as follows: absence of high-activity RAW problem, return of the substance to its original location, employment of miners, provision of disposal and processing cycle for all radioactive materials.

1.3.2 Waste disposal on the ocean floor

This method has a great disadvantage, that is, containers with waste may be easily damaged and it's difficult to control them. Besides, in 1972 International Marine Pollution Convention was adopted that prohibits such disposal methods. Ukraine is a member of this Convention too;

There are projects of RAW disposal in oceans, among them - disposal under abyssal zone of the sea floor, disposal in subduction zone, when waste shall lower slowly to the earth's mantle, disposal under a natural or artificial island. These projects have their evident advantages and will make it possible to solve the unpleasant problem of RAW disposal at the international level, but despite that, for now they are frozen due to restrictive provisions of the maritime law. Another reason for that is in Europe and North America they are seriously concerned about leakage from such storage facility that may lead to environmental disaster. The real possibility of this danger was not proved but prohibitions became even more stringent after RAW had been dropped from ships. But in the future the states that failed to find other solutions of the problem would have to think about construction of RAW ocean storage facilities.

1.3.3 RAW destruction by nuclear explosion

The project of radioactive waste disposal by peaceful nuclear explosion was developed in Russia [106]. Central Institute of Physics and Technology of RF Ministry of Defense (Sergiev Posad) and Federal Nuclear Centre Arzamas-16 developed conceptual problem-solving proposals. They consist in use of underground nuclear explosions for RAW disposal.

RAW disposal is proposed to be performed on Novaya Zemlya archipelago, in old tunnels of the Central Nuclear Test Site of RF Ministry of Defense. The so-called "clean" nuclear charges, developed in Ministry of the Russian Federation for Atomic Energy and not belonging to the weapon category shall be used. According to the scientists' calculations, one nuclear explosion with 100 kg of TNT equivalent yield at 600 m deep of the permafrost may transform in vitreous mass up to 100 tons of radioactive waste. Three such explosions may solve RAW problem for Northern Fleet for good.

According to the project of Russian scientists, there is no need to construct neither plants, nor new storage facilities on Novaya Zemlya archipelago as there are enough old mine tunnels there. They shall be properly prepared and filled with spent FUs, reactors from nuclear submarines, radioactive waste of nuclear enterprises, various large-size polluted metal structures. The space between them shall be filled with different materials that are able to decrease nuclear radiation fluxes and improve fibre glass quality. The explosion itself is to do the rest. At 600-700 metres deep and at 3.5 kilometres from the tunnel opening, according to the experts, the vitreous substance is formed during the explosion, which itself becomes the most effective and reliable barrier on the path of nuclear radiations.

Central Institute of Physics and Technology of RF Ministry of Defense (Sergiev Posad) developed the business plan for its implementation. The costs on nuclear waste disposal on Novaya Zemlya archipelago by vitrification were initially measured as 36 million dollars for two years of works. In time, the price of nuclear waste disposal on Novaya Zemlya archipelago increased and made up 150-350 million dollars. It is, nevertheless, cheaper, than when the traditional approach is used. But this work also included the project international examination, transportation of spent fuel to the explosion site and performance of social programs. The Russian method of radioactive waste disposal, using the underground nuclear explosion, according to the experts of Sergiev Posad, will make it possible for Russia not only to solve its environmental problem, but also earn means for disposal of foreign NPP waste products. According to the calculations of the project authors, it may make up to 5 billion dollars per year.

RAW destruction by nuclear explosions does not take place due to political reasons, Nuclear Weapons Non-Proliferation Treaty and nuclear weapon test ban. It is impossible to prove that the nuclear explosion will be used only for peaceful purposes.

1.3.4 Transmutation

The reactor transmutation is "burning" of the most dangerous radionuclides in the field of intensive neutron irradiation. It is not necessary to introduce the elements to be destructed in the fuel: it is enough to run a pipe through the reactor for components of reprocessed FU or RAW pulp to go through it. To obtain them, special transmutation nuclear reactors are required. This process of SNF reprocessing is possible as addition of several percent of HAW in the reactor does not deteriorate its characteristics significantly.

As of today, two ways are considered to be the most realistic - either burning of undesirable nuclides in special fast reactors, provided rigidity enhancement of neutron spectrum in comparison with power reactors, or development of devices with high flux density of thermal neutrons. Technically, the first variant is easier and cost-effective as it is based on improvement of already existing fast reactors. High-flux thermal burners are attractive for use because associated transmutation is possible for a number of long-lived fission products, mainly ^{99}Tc and ^{129}I. At that, ^{99}Tc may be almost completely transformed in stable valuable platinoid ruthenium [68].

In France, in 2020, construction of experimental stations will start. In 2040, industrial plants are to start. These developments are planned to be combined with development of new reactor technologies [31]. At present, France reprocesses fuel from Japan, Switzerland, Germany, Belgium and Netherlands [82]. The strategic fuel reserve is formed on the basis of reprocessed fuel. Complete reprocessing to separate uranium isotopes is not conducted according to economic considerations. In January, 2006, the president announced that Atomic Energy Commission (AEC) started to design the 4th generation reactor to be completed in 2020. AEC relies on fast reactors, which produce less RAW and use uranium resources more efficiently, including 220 000 tons of depleted uranium and reprocessed uranium available in France.

Russia also develops fast breeder reactors. At II All-Russian scientific and technical conference "Atomic Siberia. XXI-th century" in Zheleznogorsk, the Krasnoyarsk Territory, Petr Gavrilov, a general director of FSUE "GKhK", Dr.Sci.Tech., the vice-president of Nuclear Society of Russia (NSR) presented the development strategy of his enterprise [73]. Today this strategy includes construction of the dual-purpose fast nuclear reactor by 2020. The reactor will generate heat and electric energy and also "burn" radioactive waste to stable isotopes.

The modern isotopic separation technology of nuclides with mean and heavy atomic weight provides for separation of the material in gaseous, atomic or molecular state. In this case, this operation may be considered as potentially dangerous, as radioactive material is transformed in gaseous state requiring a reliable equipment pressurisation and remote service. That is why, the safest variant would be to develop transmutation technology without this potentially dangerous operation, that is, transmutation of long-lived fission products without their preliminary isotopic separation. But this transmutation process will be characterized not only by increased consumption of neutrons on transmutation of present stable isotopes, but by other physical peculiarities [86].

In Belgium, in 2015 the construction of MYRRHA – "Multipurpose Hybrid Research Reactor for High-tech Applications" was to start. [20]. Its putting into operation is to take place in 2023 and it will become the first step on the way of radioactive waste problem solution instead of postponing it. To test concepts, forming the base of this reactor, its developers are going to put into operation its demo version called Guinevere**.** This reactor with undercritical parameters uses thorium-232 as a fuel, which is not fissionable by itself. But in presence of other neutrons from the external source (accelerator) it transforms in short-lived uranium-233, which is fissionable. The external accelerator power will be 20 MW, but the reactor power, 600 MW, will make up for consumption of the auxiliary system. The essence of a new thorium reactor design is impossibility of incidents like Chernobyl - Fukushima. Nuclear reactors on thorium fuel are safer than on uranium fuel, as thorium reactors do not have the reactivity margin. If one of the components fails, the chain reaction will stop. There will be neither iodine poisoning, nor heat carrier overheating: without external injection from the accelerator thorium will not transform in fissionable uranium-233 [20]. Thorium energy, unlike uranium energy, does not recover plutonium and transuranium elements. It is important both in terms of environmental issues and non-proliferation of nuclear weapon (separation of weapon-grade actinides from uranium fuel makes it possible for states-"outcasts" and terrorists to produce their own nuclear weapon).

As thorium energy is not possible without use of weapon-grade uranium, reactors on thorium fuel may directly use weapon-grade uranium (without its dilution with uranium-238 as in case with uranium fuel cycle).

Parks Benjamin Lindley, one of the scientists-developer calculated that 20 MW accelerator as an external source of neutrons is not actually needed: It is sufficient to mix high-activity waste with thorium in a certain proportion and not only to obtain energy, but at the same time get only short-lived isotopes instead of uranium-235 living for billions of years. Certainly, there is no need to construct an expensive accelerator, thus, exerting a positive influence on economics of a project.

In terms of RAW disposal, electronuclear plants are of unique nature: they make it possible to burn not only their own long-lived radioactive waste, but also deal with waste disposal from other NPP, including that accumulated by the nuclear industry. According to different estimates, electronuclear systems will spend only a small part of their generated energy - from 1 to 10%, on transmutation of long-lived RAW, depending on the system configuration. It will make it possible to dispose accumulated weapon-grade plutonium, minor actinides and fission products effectively [94].

Figure 1.7 shows the existing fuel cycle with a complex and costly infrastructure, 1% of extracted uranium efficiency of utilization and a new optimized cycle.

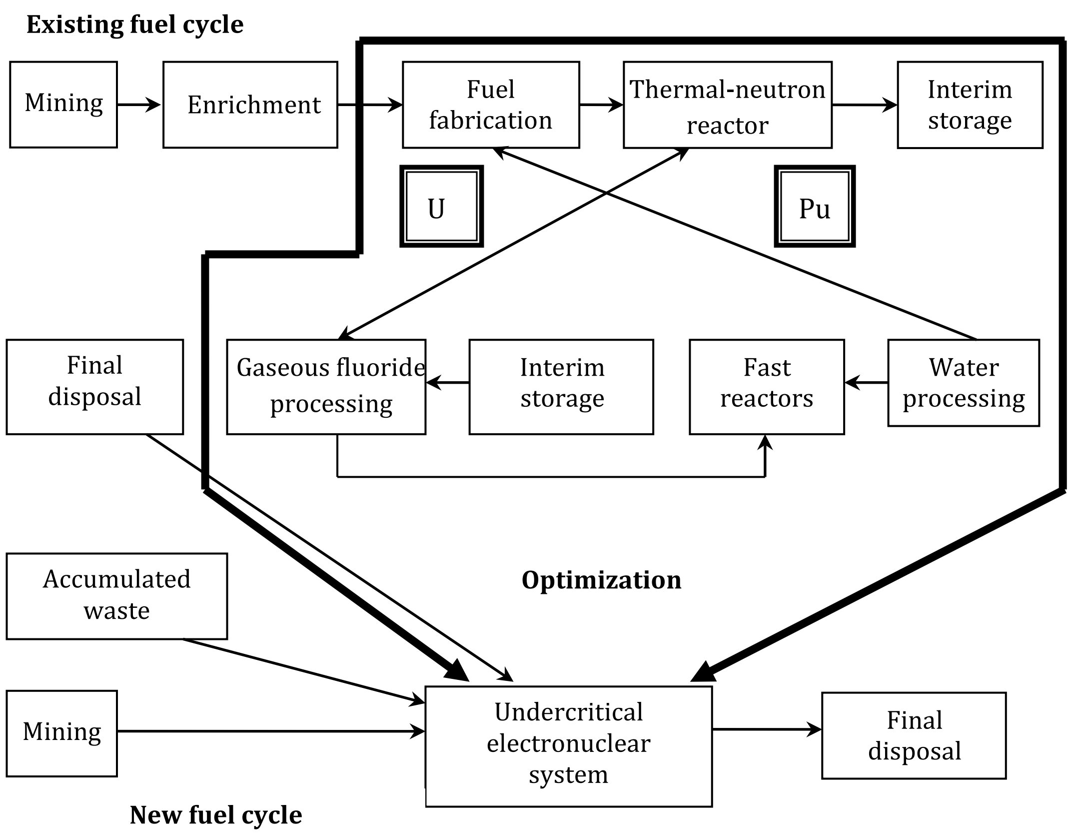


Figure 1.7 – Existing and optimized fuel cycles [94]

The optimized cycle by an order improves efficiency of mined uranium utilization and simplifies the required infrastructure significantly, as in undercritical systems there is no need in fission products disposal and recycling of actinides due to absence of limitations on fuel burn-out as there are no construction materials in the system active zone. As a result, the cost of electric energy, generated by them, is 2-3 times lower in comparison with coal-fired and gas electric power-plant, not to mention much higher ecological cleanness, complete absence of sulphur acid rains, etc. [94]. Implementation of this scheme will make it possible to reduce RAW amount considerably. Despite the fact that it is still only a strategy, the issue of technology development in this area is, beyond all doubt, is of great interest.

There are also theoretical studies devoted to use of thermonuclear reactors as "actinoid furnaces". In this combined reactor thermonuclear reaction fast neutrons disintegrate heavy elements (with energy generation) or get absorbed by long-lived isotopes with formation of short-lived ones. As a result of recent studies, conducted by Massachusetts Institute of Technology, it was demonstrated that only 2-3 thermonuclear reactors with their parameters similar to international experimental thermonuclear reactor ITER can transform the number of actinides, generated by all light-water nuclear reactors. Besides, each thermonuclear reactor will generate about 1 GW of energy.

Physicists know many ways of nuclear waste reprocessing.. And they don't like the word "waste itself. One and the same substance may be waste for one reactor type and an excellent fuel for another.

Such reactors (of different size and purpose) have existed for more than a decade, but they are few of them comparing with thermal reactors. There are also new projects of this type (in Russia, in particular, this area is given much consideration). But still it is not physics and not even engineering realization of scientists' conceptions (it is more complex comparing with a conventional reactor) that serves as a stumbling block, but accountancy.

The group of scientists, headed by Mike Kotschenreuther, from University of Texas at Austin, consider the undercritical hybrid fusion-fission plant will be the best solution. Briefly, its structure is arranged in the following way: Compact Fusion Neutron Source (CFNS) is in the centre. The "blanket" around CFNS is a nuclear reactor, where transuranium waste of traditional light-water NPP is placed as a fuel. The key element of CFNS tokamak, that is the whole transmutation complex (Fusion–Fission Transmutation System – FFTS) is a diverter. This is a part taking a flux of particles and radiation, radiating from the plasma column hanging in the magnetic trap centre.

The specialists from University of Texas developed their own variant called Super X. It surpasses its analogues five times in terms of digesting strong energy fluxes coming from the fusion reactor centre. It makes it possible to construct FFTS: a miniature plant, able by itself to cope with spent fuel of 10-15 light-water reactors of conventional NPP, according to data of the university press release.

The conception of combination thermonuclear and nuclear reactors in one facility to transform NPP spent fuel is not new. But representatives of University of Texas consider themselves to be the first ones to show how to construct this hybrid-rescuer, being feasible in terms of engineering and economy. Three scientific groups in the USA and Great Britain, working at their tokamak projects, have already interested in Super X diverter. If there are means to proceed with Kotschenreuther,'s research, the scientists' next steps shall be the extended numerical modelling, engineering project and FFTS prototype development.

Summing up ways of long-lived RAW processing, transmutation method, it may be concluded that there are no fundamental blocks on the way of nuclear energy technology disposal from long-lived high-activity RAW repositories in the future.

To achieve this, a certain progress shall be made in electronuclear and thermonuclear technologies. For this, a required generation of additional neutrons may be provided, development of high-flux blanket systems will make it possible to perform transmutation in a fast and effective manner. The key component of this process is a radiochemical reprocessing technology of transmutated materials.

Development of this technology elements with use of pilot plants for demonstration of effective transmutation of fission product long-lived radionuclides will make it possible to substantiate the following thesis: wide use of nuclear power based on the fission process of heavy nuclides by the present generation will not create any problems with radioactive waste for further generation [86].

The safest solution of RAW final disposal problem as of today IAEA sees in their disposal in repositories at 300-500 m depth in deep geologic formations, using the multibarrier protection and mandatory solidification of liquid radioactive waste.

Annex 1, on the basis of materials [31], contains the analysis of advantages and disadvantages of different methods of RAW disposal.

Annex 2, on the basis of materials [59], contains the comparative analysis of approaches used by Great Britain, Sweden, the USA, France, Germany, Japan and Canada in terms of SNF, RAW management and decommissioning of plants.

1.3.5 RAW disposal in space

RAW disposal in space seems to be an attractive idea as RAW is removed from the environment for good. The strategy of RAW injection into space has been lobbied by representatives of rocket and space industry in recent decades.

It has been already mentioned that the whole scientific and industrial industry deals with RAW management issues. There is a number of projects dealing with high-activity waste reprocessing and disposal. Significant means are spent on this; some print media assess the total annual appropriations for SNF management as 300 bln. dollars [17]. Many specialists are involved in studies. To gain their interest, the space disposal project shall have undeniable advantages in comparison with known methods of RAW disposal. Such advantages have not been revealed so far. That is why, at present, there are no supporters of RAW disposal in space conception among experts of this industry. But there are many opposing this idea. In the first place these are environmentalists; it is also obvious by comments on this issue in professional online communities. The public opinion tends to this attitude and it cannot be underestimated.

Such projects have significant disadvantages, one of the most important is a possible launch vehicle accident, as was, in particular, mentioned by Ye. P. Velikhov [78]. It is complicated by the fact that no international agreements have been come to on this problem. The analysis of these issues is presented in further sections of this report.

1.3.5.1 Isotopic composition of disposed RAW

The analysis of information [4, 6, 8, 41, 70, 81, etc.] about RAW nuclides that are proposed for disposal in space shows that the following isotopes may be considered as possible ones: ^{237}Np, ^{243}Am, ^{99}Tc, ^{129}I (table 1.7).

Table 1.7

Isotope	$T_{1/2}$, years	Specific activity, Bq/g	Content in SNF, kg/t /68,88/	Toxicity group /90/
^{99}Tc	$2.1 \cdot 10^5$	$6.286 \cdot 10^8$	1	C
^{237}Np	$2.14 \cdot 10^6$	$2.613 \cdot 10^7$	0.5	A
^{243}Am	7380	$7.391 \cdot 10^9$	0.12	A
^{129}I	$1.6 \cdot 10^7$	$6.545 \cdot 10^6$	0.2	B
^{135}Cs	$2.3 \cdot 10^6$	$4.269 \cdot 10^7$	0.4	C
^{79}Se	$6.5 \cdot 10^4$	$2.581 \cdot 10^9$	$1.7 \cdot 10^{-2}$	-
^{93}Zr	$1.53 \cdot 10^6$	$9.315 \cdot 10^7$	$9.1 \cdot 10^{-1}$	C
^{107}Pd	$6.5 \cdot 10^6$	$1.906 \cdot 10^7$	$2.5 \cdot 10^{-1}$	-
^{126}Sn	$1.0 \cdot 10^5$	$1.052 \cdot 10^9$	$2.2 \cdot 10^{-2}$	-

Isotopes ^{135}Cs, ^{79}Se, ^{93}Zr, ^{107}Pd, ^{126}Sn, despite their high activity, are neither high-toxic, nor extremely high-toxic [90], so they are not subject to disposal in space.

The elements, specified in table 1.7 are not necessarily considered as waste be the scientific and technical community. Some of them may appear useful to the society in the near future. [68, 93, etc.]. The applied usefulness of each of them is still under study, there are positive results present, some of them are given below.

Technetium-99

The technetium world production reaches a few tons per year. [68].

Technetium is a heavy, refractory and chemical-resistant metal. Metallic technetium is easy for mechanical treatment. In its free state, it is a silver-brown metal and it grows dim at humid air. At low temperatures it demonstrates superconductivity, its critical temperature is the highest of all critical temperatures of metals making up, according to different data, 11.2 or 8.2 °K.

Technetium is used for its unique properties and favourable nuclear physical characteristics of its main isotope ^{99}Tc (a long half-life, soft beta radiation).

Pertechnetate-ion in oxygen-containing media (in concentration of a few milligrams per litre) is one of the strongest corrosion inhibitors for low-carbon steel. Paints with addition of technetium prevent the ship's bottom from foaling. Its exceptional corrosion resistance and small section of neutron activation allow to use this element as a construction material in reactor construction and precision instruments industry. It may be used as a catalyst and superconducting material. High melting temperature makes it possible to use technetium in high-temperature thermal elements. Having no γ-radiation, ^{99}Tc is β⁻-standard in radiometry and dosimetry. Radionuclide ^{99}Tc may be used as a permanent source of β-particles in various radionuclide instruments. Superconductivity of technetium and its alloys makes it possible to use them as a construction material for superconducting magnets. Technetium is also used for manufacture of high-temperature thermocouples and as a catalyst for dehydrogenation processes of alcohols and hydrocarbons. ^{99}Tc is used for preparation of β-sources, applied in radiography, and for inspection of radiometric and dosimetric instruments.[68]

During a few years Scientific Research Institute for Atomic Reactors (SRIAR) in Dimitrovgrad, Russia. has been dealing with a problem of metallic technetium-99 use [74]. After irradiation of technetium-99 in reactor SM-3 and further complex chemical separation and cleaning, stable monoisotope ruthenium-100 was obtained. Using the proposed method allows to solve two problems simultaneously: to get rid of dangerous radioactive waste technetium-99 and obtain the sufficient amount of rare metal ruthenium-100. This is a very interesting metal belonging to platinoids, so their properties are much alike, but at the same time it has own specific properties. It is extremely resistant to aggressive media, very hard, superconducting at low temperatures and has high melting temperature (2250°C), multivalent (9) and forms a number of compounds having unique properties. Ruthenium is used in electrical engineering and electronics, metallurgy and medicine, chemical industry and as a selective catalyst and for equipment protection from powerful oxidizing agents. Its dioxide is used for thin corrosion-resistant coatings, some compounds are used as piezoelectric materials, other may be used as dyes. The scope of ruthenium application is expanding with demand for it growing every year. The SRIAR specialist presented theoretical justification of possible ruthenium production technology, the project needs only financing and maintenance support.

Neptunium-237

The world production of neptunium reaches hundreds of kilograms per year.

Neptunium-237 is a nuclide able for nuclear chain fission. Critical mass of Np^{237} -is 90 kg. It has a very low level of spontaneous fission - less than 0.05 fissions/s kg. High critical mass value (almost double relative to enriched uranium-235) and high cost of production make it unattractive for weapon application. ^{237}Np is the main source for ^{238}Pu production. Plutonium-238 is widely used in medical instruments and at manned space stations as isotope energy source with low gamma radiation and, thus, requiring no special protection.

Americium-243

Americium is silver-white ductile metal. It resembles rare-earth metals. Americium grows dim slowly at dry air and room temperature.

^{243}Am is used for radiochemical studies and accumulation of distant transuraniums up to fermium.

Isotope ^{241}Am (group of radiation danger *B*) is used in various instruments (flaw detectors, densimeter, thickness gauges, etc.) as a source of soft γ-quanta for production of energy sources with low heat power and α-radiation sources used to discharge static charges for X-ray fluorescence excitation during analysis. ^{241}Am is also used for curium-242 production.

According to the price list of 1980, one gram of Am^{241} cost 150 dollars. In thirty years it was about 4500. The conclusion is evident: demand for element-95 grows rapidly and exceeds the supply greatly [50].

Since 1990-ies, due to drastic reduction of nuclear arsenals, the conceptions emerged as for plutonium and curium disposal in space, despite the fact that many of their isotopes have long half-life and high radiotoxicity. Brief description of properties and scopes of application of these isotopes is given below.

Curium

There are 14 known curium isotopes with 238 - 250 mass numbers, the most long-lived of them is ^{247}Cm (α-radiator, half-life is $T_{1/2}=1.64\times10^7$ years).

Curium is a silver metal with density of 13.51 g/cm^3 and melting temperature of 1345°C.

The study of curium chemical properties is quite complicated because of its high radioactivity. Solutions of curium salts, due to its radioactivity, heat considerably, water decomposes to hydrogen and oxygen. The radiation is so powerful that solutions of curium salts glow in complete darkness as intensely as radium.

Curium, certain isotopes of curium, to be more precise, are produced in nuclear reactors. By subsequent capture of neutrons by nuclei of target elements accumulation of curium atoms occurs. After curium accumulates in sufficient amount, it is separated using chemical processing methods, concentrated and produce curium oxide. Production of curium in sufficient amount may solve the production problem of compact space reactors, nuclear-powered aircraft, etc.

Curium is used for production of micronuclear charges. Curium-242 in the form of oxide (density about 11.75 g/cm^3 half-life of 162 days) is used for production of compact and extremely powerful isotope energy sources (energy release is about 1169 W/cm), 1 gram of metallic curium releases about 120 W. Peculiarity, convenience and safety of heat sources on the basis of curium consist in the fact that curium is a practically pure alpha radiator. Integrated energy of alpha decay of 1 gram of curium per year is about 480 kWh! Production of high-power neutron sources for "burning" (launch) of special nuclear reactors is one of the most important scope of curium application. In recent years, engineers and manufacturers have paid much attention to the other, heavier isotope of curium - curium-244 (half-life - 18.1 years) and it is as pure as alpha radiator (energy release is about 2.83 W/gram). Curium-245 (with half-life of 3320 years) is very perspective for construction of compact nuclear reactors with ultra-high energy release, the methods of this isotope cost-effective production are under study.

As it was already mentioned, in the process of heavy nuclei fission by neutrons tremendous energy is generated; it cannot be compared with any other chemical reactions. The energy, generated due to radioactive nuclear decay, is not that popular so far, but it is more than obvious. If each fission event of ^{235}U is accompanied by release of about 200 Mev, energy of alpha particles, emitted by, ^{242}Cm, for instance, radioactive decay makes up about 6.1 Mev. It is 35 times less, but such decay occurs spontaneously at constant rate and is not subject to influence of physical or chemical factors. Use of this energy does not need complex and bulky instruments, moreover, ^{242}Cm is practically a pure alpha radiator, that is why, no heavy radiation protection is needed for operations with it. A gram of ^{242}Cm emits $1.2 \cdot 10^{13}$ α-particles each second, releasing 120 W of heat energy. That is why, ^{242}Cm is almost always .incandescent and it requires continuous heat removal for operations with it. The integrated energy of one gram of curium alpha decay per year (about 80% of total energy) comes to 480 kWH, which is a quite impressive number. To get the equivalent amount of energy from combustion reaction, about 38 kilograms of butane are to be burnt in 138 kilograms of oxygen. Even if calculations are done by weight, it is nearly 200 thousand times more, volumes are even difficult to compare: a gram of curium in the form of oxide Cm_2O_3 takes up 0.1 of cubic centimetre.

It is obvious that consumers of ^{242}Cm may be found in the spheres, where the energy source low eight and compactness are particularly valued. It may be the sphere of space research, for instance. Radioisotope sources on the basis of ^{242}Cm (in combination with thermoelectric or other energy converters) are able to develop power up to several kW. They are acceptable both for automatic and manned space stations. However, due to comparatively short half-life (162 days), the stable operation duration of this source lasts for only a few months. But it is quite enough for the terrestrial-space and moon research.

As intensive α-radiator, ^{242}Cm may be used in neutron sources (mixed with beryllium) and for generation of external beams of α-particles. The latter are used as a means of atom excitation in new methods of chemical analysis based on alpha-particle scattering and excitation of characteristic X-radiation. By means of this plant, the direct chemical analysis of the moon surface using method of alpha-particle scattering.

It is interesting to note that as a result of ^{242}Cm radioactive decay, other α-radiator – ^{238}Pu forms, which may be then separated chemically and obtained as a radiochemical pure substance. ^{238}Pu is used not only in space current generators, but also in pacemakers. Thus, time-expired curium generators may serve as an additional source to obtain isotopically pure ^{238}Pu.

In recent years, more and more scientists' attention is drawn to other heavier curium isotope with mass equal to 244. It is also an α-radiator, but with longer half-life – 18.1 years. Respectively, its energy release is less - 2.83 W per gram. So it is easier to work with: during study of chemical and physical properties radiation effects have less influence. ^{244}Cm may even be held in hands, but with gloves on and in absolutely sealed compartment. There is another important consequence: this isotope may be obtained in large quantities (kilograms).

It is considered that in radioisotope generator for space and oceanic research ^{244}Cm may be substituted for ^{238}Pu. Generators, operating on ^{244}Cm, are less durable than those, operating on plutonium, but their specific energy release is almost five times higher. However, ^{244}Cm emits about 50 times more neutrons (spontaneous fission) than ^{238}Pu. Owing to this fact, curium generators can hardly be used as pacemakers. But in other independent energy sources ^{244}Cm can substitute plutonium. Besides, curium is not as toxic as plutonium. The ultimate capacity of curium generators (determined by critical mass) is about 10 times more than of plutonium generators: 162 and 48 kW respectively.

But ^{245}Cm, a heavier and more long-lived isotope, is of the greatest interest for application. It half-life make up 3320 years. This isotope is also an α-radiator, but its perspective is determined by other property of the nucleus - its ability to be fissionable under action of neutrons like fissile isotopes of uranium and plutonium. The ability of ^{245}Cm nuclei to be fissionable by thermal neutrons is three and a half times more than any of applied fissile isotopes. It means that for chain reaction it is required much less ^{245}Cm than ^{235}U or ^{239}Pu.

The methods for obtaining ^{245}Cm in sufficient amount are being developed now, but scientists have found themselves in a vicious circle with this issue. During ^{242}Pu and ^{243}Am radiation in reactor with high density of neutron fluxes simultaneously with ^{244}Cm even heavier isotopes always form. ^{245}Cm is among them. But the useful property of ^{245}Cm, for which it is obtained, that is, its large fission cross-section on thermal neutrons, appears to be harmful in this case. Nuclei of ^{244}Cm, having captured neutrons, transform in ^{245}Cm, but under action of the same neutrons these nuclei break into fragments. Neutrons, serving as fusion instruments, become the instrument of destruction themselves. As a result, in the mixture of curium isotopes, there is only a few percent of ^{245}Cm. Given, that these isotopes shall be broken into, it becomes clear, why ^{245}Cm can not be used as a fissile material so far.

A few words shall be said about the most long-lived isotope ^{247}Cm. Its half-time is estimated as 14-16 million years. Recently, its traces have been detected in the earth's crust, in some radioactive minerals. The mass number of this isotope is expressed by formula ($4n + 3$), that is why it is logical to assume that it is a parent of a known actinouranium family (^{235}U family).

High specific heat power of ^{242}Cm (120 W/g) and ^{244}Cm (3 W/g) isotopes and relatively low intensity of γ-quantum emission make it possible to use them in compact, relatively lightweight sources of heat and electric energy. Isotope heat sources ^{242}Cm and ^{244}Cm are more competitive than heat sources where ^{238}Pu is used. Advantages of the former are: higher heat power and possibility of direct radiation from ^{238}U, and also ability to transform heat energy in electric energy (thermoide method). In cases, requiring heat sources for long operation, isotope ^{244}Cm appears to be more applicable. ^{242}Cm may serve as a source of pure ^{238}Pu.

Plutonium

Reactor plutonium, accumulated to the end of the campaign, has the following isotope composition: 60% ^{239}Pu, 25% ^{240}Pu, 10% ^{241}Pu, 3% ^{242}Pu, 2% ^{238}Pu.[93]

The great bulk of plutonium, which is at the stage of storage at radioreprocessing enterprises and in bound form in not reprocessed fuel, is a serious raw-material base for nuclear power industry based on mixed uranium-plutonium fuel.

The international cooperation program is based on the thesis that "disarmed" plutonium shall not get into international terrorists' hands and not be charged in nuclear warheads of Russia and the USA. The West, fearing of weapon-grade uranium and plutonium spreading to "terrorist regimes", agreed to finance the program of weapon-grade uranium and plutonium reprocessing. The agreement is not followed, though, because of lack of financing, disagreements over technical concept (either to burn plutonium only in thermal (the USA) or in thermal and fast reactors (Russia)) and because of environmental risk threat. That is why, so far (2003) there is no conversion plant built neither in the USA, nor in Russia.[88]

Various plutonium disposal methods are under study aimed at transforming it in the form excluding its military use, but it should be noted that no country has the acceptable disposal concept so far. Burning (transmutation) of plutonium and transplutonium elements in the nuclear reactor is the most popular variant.

The main purpose of plutonium disposal is conversion of weapon-grade plutonium, extracted from deactivated nuclear warheads in the forms not accessible for nuclear weapon production. Plutonium shall become as inaccessible as plutonium present in highly radioactive SNF, thus, implementing "the spent fuel standard" introduced by National Academy of Sciences (the USA). To do this, plutonium is mixed with gamma radiation source, for example, high-activity radioactive waste. This process, "immobilization", transforms plutonium in the product, similar to SNF, which is highly radioactive and difficult to work with. Another method, "radiation", -is a development of mixed uranium-plutonium fuel (MOX) with its further burning in power reactors. MOX - radiation and immobilization - are comparable in terms of costs on "the spent fuel standard" accomplishment.

At present, isotopes are not considered only as the component of science and technology, but also as the article of commerce, including international commerce [88].. The following radioactive chemical elements are included in commodity heading "Radioactive chemical elements, radioactive isotopes and their compounds, mixtures and waste containing these products": technetium, promethium, polonium and all elements with higher atomic number, such as astatine, radon, francium, radium, actinium, thorium, protactinium, uranium, neptunium, plutonium, americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium and lawrencium.

The following compounds are considered to be the most important:

- radium salts used as radiation source for treatment of cancer diseases and some physical experiments;
- compounds of radioactive isotopes.

Artificial radioactive isotopes and their compounds are used in industry for metal radiography, measurement of sheet metal thickness, measurement of liquid level in containers, vulcanization acceleration, initiation of polymerization or grafting of organic compounds, production of luminous paints, for clock dials, tools, etc., in medicine for diagnostics or treatment of some diseases (cobalt-60, iodine-131, gold-198, phosphorus-32, etc.); in agriculture for sterilization of agricultural products, for seed sprouting prevention; for study of fertilizers use or their absorption by plants, for genetic mutations in order to improve species and breeds (cobalt-60, caesium-137, phosphorus-32, etc.); in biology for research of functioning and development of organs of animals and plants (tritium, carbon-14, sodium-24, phosphorus-32, sulphur-35, potassium-42, calcium-45, strontium-90, iodine-131, etc.); in physical or chemical studies.

The analysis of situation with high-activity and high-toxic RAW shows that the only isotope, undoubtedly suitable for disposal in space and its possible utility value in the foreseeable future is radioisotope of iodine-129. Nevertheless, the possibility that its new properties or technologies shall be discovered in time as it was in the case with above mentioned elements, which will make a valuable raw material. It should be noted that disposal in space is not the only possible disposal method of ^{129}I, for example, in [68, 88, 94] different methods of this isotope transmutation are proposed.

At present, 430 nuclear reactors operate in the world, about ten thousand of tons of spent nuclear fuel (SNF) are unloaded [68]. Considering this and data from table 1.5 regarding ^{129}I, about 1 ton of ^{129}I will accumulate in SNF every year. Its content in the total mass of accumulated SNF may be not more than 40-60 tons [94]. As RAW composition and its activity depend on the reactor type and design, nuclear fuel type and heat carrier, used cleaning systems, the amount of accumulated ^{129}I will be defined more precisely.

Long reliable isolation of ^{129}I in the composition of solidified radioactive waste is problematic due to high migration characteristics in biosphere caused by increased volatility, complex chemical behaviour, variety of water-soluble forms and low coating efficiencies in comparison with the most spread minerals and soils [94].

Main properties of isotope ^{129}I:

Lustrous dark-grey non-metal. In gaseous state - of violet colour.
Density (under normal conditions) – 4.93 g/cm^3
Melting temperature (T_{melt}) – 113.5 ºC
Boiling temperature (T_{boil}) – 184.35 ºC
Type of decay – β^-
Half-life – $T_{1/2}=1.57\cdot10^7$ years
Radiation energy E_β = 0.150 MeV

When heated at atmospheric pressure, it is sublimated, when cooled, it crystallizes omitting the liquid state.

Due to low value of T_{melt}, for injection into space ^{129}I shall be immobilized, for example, in the form of potassium iodide – KI, representing colourless cubic crystals with melting temperature $T_{melt}(KI)$ – 686°C and density 3.115 g/cm^3 (at 20°C).

It should be noted that technological process of ^{129}I isotope separation from RAW mass has not been developed so far. In this case, this operation may be considered as potentially dangerous, as radioactive material is transformed in gaseous state requiring a reliable equipment pressurisation and remote service [68 ,86].

1.3.5.2 Sealed power container

At present, a great number of containers for radioactive materials is used for different purposes [30]:

- nuclear fuel transportation;
- for radioactive isotopes used in medicine;
- RAW transportation, storage and disposal.

Containers and/or packages, depending on their purpose, shall comply with different requirements, for example:

- transportation container shall be easy for waste to unload;
- storage container shall comply with requirements of efficiency when arranged in the storage facility;
- disposal container shall be reliable to store waste (for example, not to be corrodible) during the whole period required for decay.

In the process of the container design different transportation means shall be considered (road, railway, water or air). The most important requirements for containers to be complied with relate to safety and radiological protection, integrity maintenance in case of accident. Thus, the package shall comply with requirements of normative documents regarding resistance to fall, leakages, leaching waterproofness and fire resistance.

Transportation requirements include permissible levels of dose equivalents (from 0.5 mrem/hour to 1 rem/hour on the surface of transporting container (TC) depending on the category), permissible outside surface contamination according to Radiation Standards-97 and maximum permissible radionuclide transporting activity. They also include requirements related to container handling, use of lifting mechanisms and stacking of containers.

Selecting the type of container for design or application, it is necessary to consider that at present, there are no criteria for the final product of RAW reprocessing specified in Ukraine. That is why, issues of RAW material compatibility with the container material, the container operation life issues shall be carefully analysed in the safety analysis report.

Testing of the ability to withstand emergency conditions during transportation is the most difficult one. It includes tests for mechanical damage, thermal test and water immersion test.

In Oak Ridge laboratory (the USA) there is a test bench for fall test of containers weighing up to 100 t from 46 m height, in FRG there is a test bench for fall test of 100-t containers and fire test, in France - fire test bench at up to 1000°C during 1.5 h.

France and FRG are the most successful countries in terms of transporting containers development. In France transportation is performed in containers TN ("Transnuclear") and LK ("Lemaire"). In FRG containers are developed by GNS company. The containers made in the USA, Russia and Japan are successfully used.

For the container used for RAW disposal in space it is planned to apply the multibarrier variant of RAW package, minimizing probability of its penetration into biosphere in emergency situations.

After radiochemical reprocessing, the substance containing ^{129}I (KI), may be conditioned by vitrification before packing in the next package. Then conditioned salts will be packed in small bimetallic packages by 100-150 g batches. The packages, in their turn, will be located inside the steel container in the mesh structure acting as a damper. The container body performs many functions: provides mechanical strength of the whole structure, its tightness, possibility of mounting on LV and radiation protection.

The package is of a cylindrical shape (figure 1.2). For their manufacturing and fitting the existing technology of manufacturing and fitting of FUs for NPP with proper modifications. The container may be cylindrical and spherical. For now it is the most natural decision according to arrangement considerations of the container "integration" in the final stage structure and strength criteria.

Tantalum-tungsten alloy (internal layer, 0.5 mm thick) with melting temperature 3050°C and rhenium-molybdenum alloy (external layer, 0.5 mm thick) are used as materials for the package bimetallic shell. Free internal space of the container is filled with silicon based powder providing space fixation of packages inside containers and damping of mechanical loads. Steel is proposed to be used for manufacture of the strong container body. The main characteristics of specified materials, required for estimates, are given in table 1.8 [81, 95, 96].

Table 1.8 – Mechanical, radiation and physical characteristics of materials used for capsule and container manufacture

Material	Ta-W	Re-Mo	Steel	SiO_2
Density, g/cm^3	16	14	7.8	1
Weighted mean atomic number	74	58	26	6

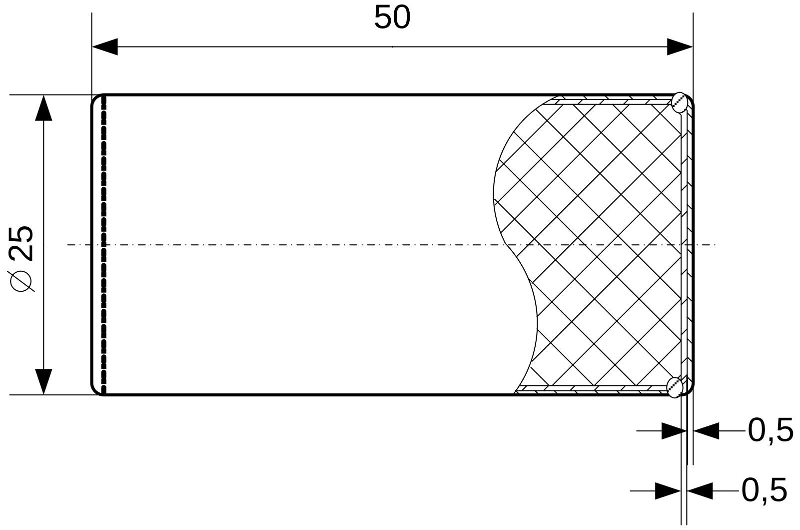


Figure 1.8 – Drawing of package for ***KI***

The technological shell of each package shall be made of heat-resisting alloy protecting package from damage under thermal and mechanical action.

Table 1.9 – Mass summary of fitted package

Package element	Weight, g
Shell	70.1
Potassium iodide KI	62
TOTAL	132.1

Package size (by outer dimensions) is 24.5 cm^3. Internal volume – 19.9 cm^3. Mean density of fitted package is 5.392 g/cm^3. Mean density of package in the volume of corresponding parallelepiped is 4.22 g/cm^3. During filling of v volume outside package with damper (plus 0.1 cm per side), average specific weight makes up (132.1 g + 8.8 g) / 2.7 · 2.7 · 5.2 cm^3=3.72 g/cm^3.

For packages the maximum radiation levels are set for surfaces (items 5.3.3 and 5.3.4 CP-053-04 and items 531 and 532 of IAEA Codes of Practice-96), and at 1 m distance from surface (as specified in item 5.3.2 of CP Rules-53-04 and items 530 and 526 of IAEA Codes of Practice-96) [57]. To provide necessary protection of personnel and population during SNF transportation, according to IAEA regulations for safe transportation, the radiation level for containers with spent nuclear fuel at all points of the container external surface shall not exceed 200 mrem/h, at 2 m distance - 10 mrem/h.

In the process of protection material selection, its mass, impact strain and fire behaviour, technological properties, cost, etc. shall be considered.

In our case, shell thickness of steel container shall be selected based on design considerations, tightness and safety requirements. As β-radiation energy of ^{129}I is low enough (0.150 MeV [97]), the radiation level on the container surface in normal conditions will be close to background radiation level.

The container design shall guarantee radiation and environmental safety during operation and in case of possible emergency situations. Considering possibility of partial or complete container depressurization, the multibarrier protection system is provided to prevent ^{129}I contact with environment. It is based on selection of radioactive material in the form of potassium iodide with melting temperature, many times exceeding T_{melt} of elementary ^{129}I (conditioning), its binding in the inert matrix (immobilization) and putting of a comparatively small amount (about 60-70 g) of this material in a sealed heat-proof two-layer metal container (primary package).

2. Rocket and engineering aspects of radioactive waste disposal in space

The subject of this section is evaluation of RAW isolation in space concept implementation using existing launch vehicles or launch vehicles to be developed in the near future. The following variants were considered for evaluation:

- existing medium launch vehicle "Zenit-3SLBF" (with about 14 t of carrying capacity into low earth orbit), equipped with upper stage "Fregat";
- heavy launch vehicle "Mayak" (with up to 70 t of carrying capacity into low earth orbit).

2.1 Safety requirements

There are precedents of radioactive materials injection into space. They are connected with necessity of spacecraft energy supply, these needs are constantly growing due to expansion of tasks to be solved and useful life increase. In the Soviet Union about 30 nuclear power plants were launched into orbit [18]. Some of them are still at 700-800 km from the Earth.

On 21 April, 1964, the launch attempt of American navigation satellite "Transit-SB" with nuclear power plant SNAP-9A on board failed. It resulted in destruction of NPU active zone in atmosphere and temporary increase of radioactive background on a large territory [110].

On 18 September, 1977, AES "Kosmos-954" 10361/1977 090A) with NPU on board was injected into earth orbit Its flight was regular till the end of October, when AES lost direction and got out of control of ground services. The team that was sent on SC board to withdraw satellite onto "disposal orbit" did not reach and its uncontrollable descent started. The situation worsened in the beginning of January, 1978, when it got depressurized. It accelerated its descent and on 24 January it entered the dense atmospheric layers. Unburnt fragments fell in the north-west of Canada, in the region of Great Slave Lake causing radioactive contamination on the territory about 100 thousand square kilometres. It caused a great scandal, which made the Soviet Union stop satellite launching with on-board NPU. During that incident it was the first time when the Soviet government recognized SC launches with "small nuclear reactors on board".

After AES "Kosmos-954" incident works aimed development of on-board systems ensuring radiation safety were intensified. SC launches with NPU recommenced in 1980 and passed more or less successfully during two years until another trouble. On AES "Kosmos-1402" (13441/1982 084A), launched on 30 August, 1982, a situation similar with "Kosmos-954" took place. The apparatus also entered the earth atmosphere and burnt over the southern part of the Atlantic ocean. But unlike "Canadian incident", introduced modifications allowed to avoid radioactive fallout, because the backup system of NPU radiation safety dissipated reactor radiation zone in atmosphere. In April, 1988, communication with AES "Kosmos-1900" (18665/1987 101A) launched on 12 December, 1987, was lost. Up to the middle of September of the next year it was descending slowly threatening with new troubles to some region of the Earth. The US National Space Surveillance Control Services were involved to trace SC orbit. Fortunately, on 30 September, 1988, just a few days prior to reentry, the protection system activated automatically on the satellite and took it away to safe "disposal orbit".

The last launch of Soviet SC with on-board NPU took place on 14 March, 1988. Though the flight passed successfully, it was resolved to abandon operation of apparatuses with NPU. The main reason for that was pressure of the USA and international organizations, demanding from the Soviet Union "to stop space pollution" [18].

In 1997 the USA launched interplanetary station Cassini into space. The station launch was intensely opposed by environmentalists and a few former employees of American space agency NASA due to 30 kg of plutonium contained in radioisotope thermoelectric generator on station board. In case of the launch error or manoeuvres near the Earth's atmosphere, that plutonium would be dispersed over a vast territory, up to 5 bln. people could suffer radiotoxic injury [9, 85].

The experience of SC operation with radioactive sources on board testifies the priority of environmental safety issues at all phases of works related to injection of extremely dangerous waste into space [5].

Use of existing and perspective injection systems will require the judicious selection of flight procedure, composition of standard and emergency rescue equipment, layout and spacecraft design and special protective measures that in combination shall exclude the possibility of direct contact of disposed RAW with the Earth biosphere at all standard or emergency situations.

But first of all, during design of the apparatus meant for RAW disposal into space, safety concept shall be considered. This apparatus shall comply with radiation safety requirements for space nuclear and isotope power sources. In recommendations of UNO Scientific and Technical Sub-Committee regarding use of space for peaceful purposes [5,13], the following is specified:

"Important safety systems shall be designed, mounted and operated in compliance with the general concept of "defence in depth" meaning, for example, presence of serially located barriers to provide containment of radioactive materials of nuclear power sources. Isotopic generators shall be protected by a system of shells withstanding heat and aerodynamic loads during return to the upper atmosphere under all possible orbital conditions, that is during entry from highly elliptical or hyperbolic orbit, if this is the case. When hitting the ground, the system of protective shells and physical form of isotopes shall guarantee absence of radioactive material emission (in soluble, volatile, aerosol form or as microparticle) in the environment.

The adopted concept of multibarrier technical protection of the Earth's biosphere from injected into space radioactive substances, may be realized in the spacecraft design in the following way: Solidified radionuclide concentrates are put in heat-resistant and hermetically sealed packages. Packages with RAW, are in turn, put in a sealed power container equipped with combined radiation protection from heavy and light metals. These operations are performed at radiochemical enterprises. The sealed power container design shall provide safety of the personnel, population and environment during its transportation with RAW and handling at the launch base, that is, have strength and radiation protection characteristics specified by the nuclear and radiation safety standards.

The sealed power container, filled with primary packages with RAW, is placed in disposal orbiter (DO), which, in its turn, is a part of the LV final stage. At present development of a sealed power container is quite a feasible task, provided tight cooperation of nuclear and space-rocket technology specialists. Depending on the type of disposed RAW, the ratio of loaded RAW mass to the loaded container mass, according to estimates [4], is within 1:5 – 1:15 range.

To comply with requirements of RAW apparatus rescue in case of any emergency situations with injection equipment [13, 5], including the launch vehicle explosion during launching and flight with subsequent burning of fuel components, a sealed power container with RAW is inserted into a special aerodynamic capsule fitted with an effective system of thermal protection and amortization to take up considerable thermal and impact dynamic loads.

To withdraw this capsule from the launch vehicle in emergency situations, a reliable emergency recovery system, developed for piloted launches, is used. The capsule shape shall ensure a steady flight in the Earth's atmosphere in all possible ranges of velocity and altitude. In case of water landing the capsule shall retain positive buoyancy. To facilitate search operations performed by the ground search and rescue service, it shall be provided with radio and light impulse beacons. It is also necessary to provide maintenance of the aerodynamic capsule with a sealed power container with RAW at launching site and in emergency landing situations.

The apparatus design may be sophisticated by thermal control on-board system introduction, if it is required to provide disposal in space of radionuclides with high level of their own heat emission.

In this report, at the stage of space launch system configuration formation, the variant of the spacecraft with radioactive waste isolation in circumsolar circular orbits with a radius of about 180 mln. kilometres between the Earth's and Mars's orbits. This variant requires the minimum additional characteristic velocity - 4.5 km/s, does not require high accuracy, launches may be conducted at any time, the flight duration is about 6 months. The preliminary estimate shows that circumsolar orbits within the specified range will be sufficiently stable to provide complete safety of the Earth.

Thus, for RAW injection into space it is necessary to develop a special space launch system of increased safety and high rate of launching with acceptable environmental and cost characteristics. During development of requirements and project studies related to such system, specialists in space-rocket and nuclear technology, ecology, economy, legal and international relations shall participate. [5].

It is obvious that solution of this task in full scope is possible only within the framework of international cooperation.

The launch base shall provide the possibility of:

- arrangement of infrastructure for handling radiation-dangerous objects;
- selection of flight path (route) ensuring that areas of stage fall in emergency situations at the launch phase are out of densely populated areas;
- personnel emergency evacuation in case of radiation accident;
- territory guarding, RAW, in the first place, from potential terrorists;

Analysing possibility of safe use of space launch systems for launching spacecraft with RAW into space, the following issues shall be considered [4,5]:

- for SLS additional "measures" enhancing reliability and safety of injection shall be provided, including backup of vital systems and units, use of on-board fire and explosion diagnostic and prevention equipment, etc.;
- during LV launching emergency outcome shall be assumed; in this case, exclusion of radionuclide contact with the Earth's biosphere in emergency launches shall be provided by on-board equipment of spacecraft with RAW. Construction of space-launch system shall provide for emergency situation counteracting, complying with the above mentioned condition at any moment during flight up to ascent into the final orbit of RAW disposal;
- LV launch routes shall be equipped with ground monitoring equipment able to well determine the point of capsule with RAW fall along the whole injection route in case of emergency launches;
- selection of launch azimuths shall be performed based on safety control along the injection route, selection of AES support (parking) orbit based on radiation safety control of orbital unit with RAW and exclusion of possibility with fragments of "space garbage". The parking orbit al-

titude shall provide time sufficient for counteracting in off-nominal situations, for example, RAW evacuation by a special (off-nominal) SC in emergency situations not allowing to execute the flight program to the final disposal orbit;
- mass launches of injection equipment shall not cause environmental disturbances, near-Earth space contamination by separable structural fragments.

The most critical requirements for the spacecraft structure, providing RAW injection into space, are requirements for strength and thermal resistance in the following cases:
- explosion of LV or stages used in the composition of space launch system (SLS) during launching and flight with subsequent burning of fuel components;
- collision of natural or man-made objects in flight orbital near-Earth phase;
- return of rescued capsule in the Earth's atmosphere at large entry angle and high velocity, up to the second cosmic velocity;
- fall of spacecraft with RAW onto rocky or frozen ground. In [4] impact velocity - up to 100 m/s and impact load - up to 100-150 g values were estimated;
- spacecraft hitting on water surface, with guaranteed buoyancy control.

2.2 Disposal orbit selection

In accordance with standards of international law (see section 4), at present, RAW injection into near-Earth and circumlunar orbits is not possible. It is valid for other planets too.

Disposal on the Sun requires excessive energy consumption: bringing of additional characteristic velocity in support near-Earth orbit about 24 km/s [6,8]. Required additional characteristic velocity for SC injection beyond solar system is 8.75 km/s, thus, reducing payload of launch vehicles by 4-5 times in comparison with the variant studied in this report.

The centuries-old disposal of radioactive waste in space is determined by selection of orbits remaining stable for the whole period of natural decay of radioactive elements. According to the specialists, heliocentric orbits between the Earth and the Mars, the Earth and the Venus appear to be sufficiently reliable "disposal" sites [6]. The orbits out of the ecliptic plane, where probability of the container collision with the natural or man-made object reduces significantly, are of interest too.

At present, the most acceptable variant of RAW disposal orbits in space in terms of environmental safety and required costs [4], is the injection in artificial Sun satellite (ASS) with radius about ~1.15 a.u. (180 mln. kilometres between orbits of the Earth and the Mars).

The first variant was selected due to the following considerations. In all orbits there is a danger of container with RAW destruction during collision with cosmic bodies. During this scenario implementation, dispersed RAW under action of the solar wind, which is a continuous plasma stream, spreading radially from the Sun at average velocity of 400 km/s, will be carried into the solar system periphery. There were no ions flying up the solar wind traced [5]. If this event occurs in the orbit between the Earth and the Venus, radiation contamination of near-Earth space an the Earth itself. The process dynamics requires separate studies.

To compare energy consumption, injection into inner relative to the Earth circumsolar orbit and in section 2.2.4 the sequence of injection into the Earth-Sun system libration points were studied.

2.2.1 Launch base selection

Let us consider variants of RAW injection into circumsolar orbit of launch vehicle on the basis of LV "Zenit-2S/2SB". Such SLV exist in the following configurations:

- with upper stage DM-SL – launch from "Baikonur" launch base or planetary rocket floating platform (by the type of launches according to "Sea Launch" program);
- with upper stage "Fregat-SB" (with droppable tanks) – launch from "Baikonur" launch base.

Use of US "Fregat-SB" as a launch vehicle is more advantageous in terms of energy in comparison with US DM-SL use. Launch from equator, that is, the launch with the maximum initial velocity at the expense of rotation of the Earth, at practically no limitations regarding regions of stage I fall and PF, also offers some energy advantage in comparison with use of the launch base in middle latitudes ("Baikonur") Thus, use of US "Fregat-SB" in SLV composition during launch from the equator would be optimal in terms of energy. At the same time, energy gain is not that important [4] to be the determining factor of the task complex solution: according to the expert evaluation, weight saving of the final payload makes up not more than 100 kgf (about 4%). Besides, this SLV configuration has not been calculated so far, possible limitations of "Fregat-SB" integration in SLS "Sea Launch" have not been studied.

Among estimated difficulties there is coordination of project risks with international organizations regulating the World Ocean use.

The project cost is another important factor of launch base selection procedure: launches from "Baikonur" is about 1.5 time cheaper than launches from the sea platform.

It is not possible to give expert evaluation regarding all problematic issues of SLV new configuration, that is why, the variant of existing configuration of SLV "Zenit-3SLBF" (with preliminarily developed variants of "Fregat-SB" energy characteristics enhancement) when performing launches from "Baikonur" launch base.

2.2.2 General sequence of object injection into the orbit of the artificial Sun satellite

To make the spacecraft leave the Earth's exobase (exobase radius is 925 000 km) and become the Sun artificial satellite, it is required to be brought to parabolic or hyperbolic geocentric velocity.

The parabolic or escape velocity value, that is, minimum initial velocity required for SC to leave the Earth's exobase, is calculated based on the following relation:

$$v_{esc} = v_{circ}\sqrt{2}\,,$$

where v_{circ} is circular velocity of geocentric orbit with radius R, calculated by the formula:

$$v_{circ} = \sqrt{\frac{\mu}{R}}\,,$$

where μ is the Earth gravitational potential.

Geocentric escape velocity v_{esc} from the Earth's exobase is called the additional velocity as "vectorial" addition to the Earth velocity V_E results in heliocentric velocity V_{esc}. The vector of heliocentric escape velocity V_{esc} completely determines heliocentric movement out of the Earth' exobase.

Depending on the value of heliocentric escape velocity V_{esc}, heliocentric orbits may be elliptical, parabolic, hyperbolic and rectilinear.

Within the framework of this project elliptical heliocentric orbits are studied. In this case, the spacecraft, having escaped the Earth's exobase, transforms in the artificial Sun satellite (ASS). The following cases are possible:

1) $V_{esc} > V_E$ and ASS orbit will be located out of the orbit of the Earth (outer orbit);
2) $V_E = V_{esc}$ and ASS orbit overlaps with the orbit of the Earth;
3) $V_{esc} < V_E$ and ASS orbit will be located inside the orbit of the Earth (inner orbit);
4) $v_{esc} = V_E$, and v_{esc} is directly opposed to V_E; then $V_{esc} = 0$ and the orbit degenerates into the radial line of fall on the Sun lasting 64 days.

The fall on the Sun is not studied in this project.

As calculations showed, the direction of the spacecraft escape out of the Earth's exobase is determined by the initial Earth orientation in space at the moment of launch, that is, by the launch data and time. Depending on the launch data and time under the same initial data both ASS outer orbit (between the orbits of the Earth and the Mars) and ASS inner orbit (between the orbits of the Earth and the Venus).

The following definition shall be introduced:

Heliocentric coordinate system ($OX_sY_sZ_s$) – right orthogonal inertial c/s. The beginning is in the centre of the Sun, axis OX_s has vernal equinox direction γ; plane X_sY_s is in agreement with ecliptic plane; axis OZ_s – adds up the system to the right.

In figure 2.1 trajectories of the Earth's and ASS motion in outer and inner heliocentric orbits during one earth year in ecliptic plane projections are shown.

Numbers stand for positions of objects at point of time T=365 days:

1 – ASS position in outer orbit;
2 – Earth's position;
3 – ASS position in inner orbit.

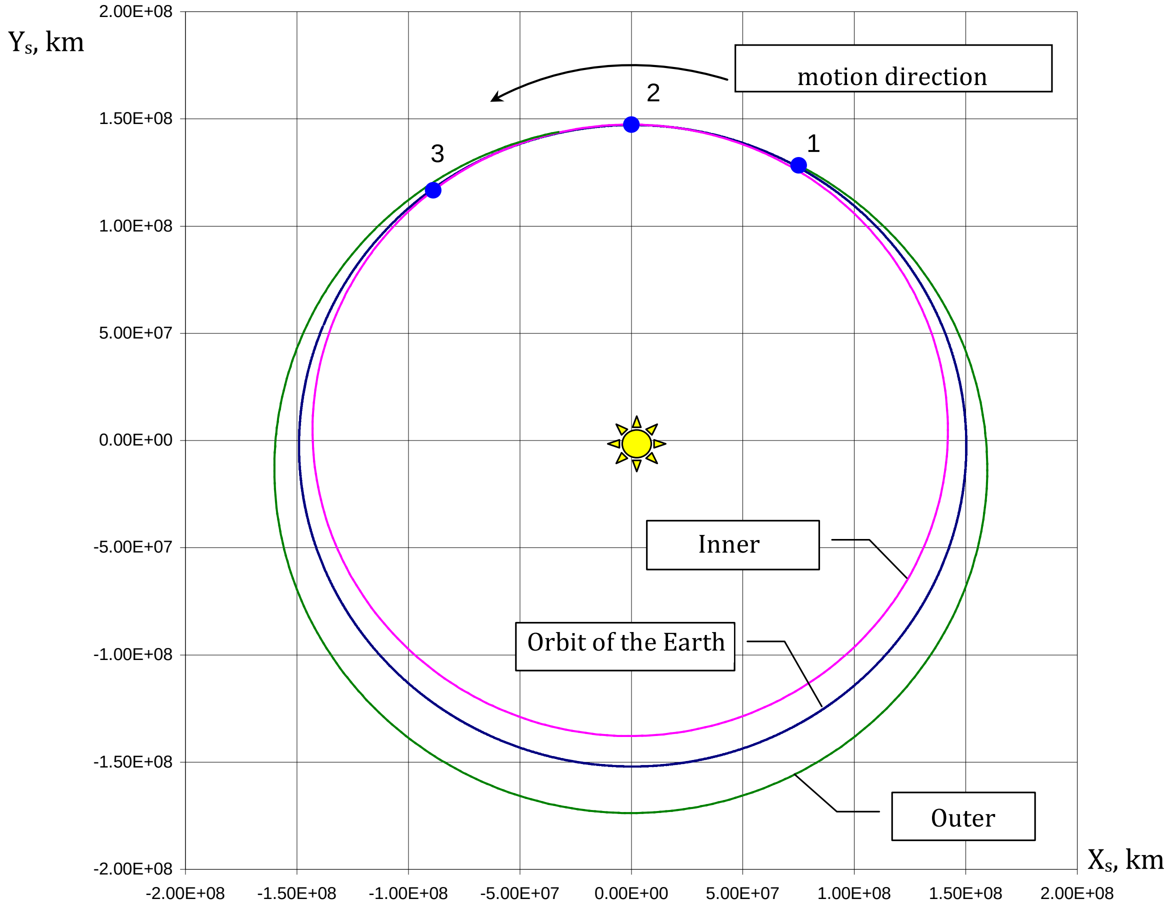


Figure 2.1 – Trajectories of the Earth's and ASS motion in outer and inner heliocentric orbits during one earth year in ecliptic plane projections

As it can be seen on the graph, ASS in the outer orbit is behind of the Earth, in the inner orbit it is ahead of the Earth. Both orbits have point 2, common with the orbit of the Earth.

That is why, for object injection into ASS orbit that would guarantee complete safety of the Earth in terms of collision, an additional manoeuvre shall be performed:

- for the outer orbit – in the orbit aphelion accelerating burn is required to rise the orbit perihelion;
- for the inner orbit – in the orbit perihelion deceleration burn is required to lower the orbit aphelion.

2.2.3 Sequence of RAW injection into outer relative to the Earth disposal orbit

In this section the sequence of Raw injection into circumsolar circular orbit with radius about 180 mln. km (~1.15a.u.) between orbits of the Earth and the Mars (outer relative to the Earth) is presented. Besides, results of the additional calculation of orbital motion parameters and velocity consumption for injection from the parking to the inner relative to the Earth circumsolar orbit.

The injection sequence was selected using general theory presented in section 2.2.2, in assumption to use SLV "Zenit-3SLBF" with updated upper stage "Fregat-SB" with launch from "Baikonur" launch base.

The sequence of injection includes the following stages (table 2.2):

- injection of upper stage "Fregat-SB"into the parking elliptical orbit $h_p \times h_a$ = 200 km×340 km high by continuous operation of engines of the first two SLV stages;
- formation of intermediate orbit $h_s \times h_a$ ≈230 km×3966 km by the first ignition of US cruise engine in the neighbourhood of the parking orbit perigee with fuel burnout from outboard tanks with their further dropping;
- formation of the departure geocentric orbit (elliptical heliocentric) at the end of the second ignition by means of fuel use from primary tanks;
- formation of heliocentric near-circular orbit of RAW disposal by additional ignition of US "Fregat-SB" engine or space launch vehicle in the orbit aphelion formed by the previous ignition.

The altitude of parking orbit was selected based on the acceptable time of US life time if further injection stages are not performed (off-nominal situation). The life time of this orbit as artificial Earth satellite (prior to reentry) in case of ONS will not be less than 14 days (with the maximum level of solar activity and limit deviation of aerodynamic characteristics).

The initial data used for calculation of the departure trajectory are given in table 2.1 state vector in the launch coordinate system and characteristics of the launch point.

Table 2.1 – Initial data used for calculation of the departure trajectory

Name	Value
Time from GI, s	9380.230
Launch point coordinates[1] B L	 45°56′36″ 63°39′11″
Initial height[1] H_0, m	119.5
Launch azimuth A_0	64°11′52.52″
State vector in the launch c/s X, m Y, m Z, m Vx, m/s Vy, m/s Vz, m/s	 6830295 -5174503 3654838 3760.88 -8360.59 3502.80

Note.
[1)] The launch point is set on the earth ellipsoid.

Table 2.2 – Characteristics of injection sequence into the outer relative to the Earth heliocentric orbit

Parking orbit:	
Injection time	~ 700 s
Perigee, apogee altitude	~200km×340km
Inclination	51.4 degree
Throw-weight	13500 kgf
Departure geocentric orbit (formed by two ignitions of US engine)	
Application of velocity impulses	In perigee
Engine firing duration: at first ignition (fuel consumption from droppable tanks); at second ignition (fuel consumption from primary tanks);	 ~500s ~900s

Table 2.2 (continued)

Perigee, apogee altitude: at first ignition; at second ignition	~230 km×3966 km ~460km × ∞
Inclination	51.3752 degree
Eccentricity	1.017833
Total velocity consumption (at launch from the parking orbit)	~3.3 km/s
Geocentric escape velocity v_{esc} (at the boundary of the Earth's exobase with radius 925000 km)	1.378 km/s
Time of movement to the Earth's exobase boundary (from the launch time from the parking orbit)	~6 days
Heliocentric orbit	
Perihelion, aphelion altitude of the initial orbit	~1 a.u. × 1.15 a.u.
Time of movement to aphelion (from the moment from the Earth's exobase escape)	~200 days
Velocity consumption for circular orbit formation	~1 km/s
Perihelion, aphelion altitude of the final orbit	1.15 a.u. × 1.15 a.u.
Final orbit circularization period	~457 days
Payload throw-weight	2.3 ton-force

As calculations for initial data, given in table 2.1, showed in case of launch from Baikonur launch base in 9^h UTC ASS outer orbit will; be formed with perihelion in the orbit of the Earth and aphelion about 1.15 a.u.

At launch in 21^h UTC the ASS inner orbit will be formed with aphelion in the orbit of the Earth and with perihelion about 0.87 a.u.

Calculations were performed for launch dates - 22 December, 2013, when the Earth is in the neighbourhood of its heliocentric orbit perihelion and on 22 June, 2013 - in the neighbourhood of the orbit aphelion.

Parameter calculation of US with RAW orbital motion towards the boundary of the Earth's exobase shall be performed using the following evaluation model: Earth's field 4×0 (in the potential expansion of the Earth's gravity field zonal harmonics up to the fourth order inclusive were considered), gravity disturbing action of the Sun and the Moon.

In table 2.3 parameters of transfer and final orbits (outer and inner), formed by the injection trajectory for analysed launch dates and time.

Table 2.3 – Parameters of transfer and final orbits (outer and inner), formed by the injection trajectory

Name	22/06/2013		22/12/2013	
	9^h UTC	*21^h UTC*	*9^h UTC*	*21^h UTC*
Time of escape out of the Earth's exobase, days	6.238	6.137	6.140	6.094
Geocentric escape velocity v_{esc}, km/s	1.3051	1.3871	1.3776	1.4053
Initial orbital period, days	403.92	331.67	412.38	329.91
Perihelion×aphelion of transfer orbit $R_\pi \times R_\alpha$, mln. km	151.74×168.21	128.27×152.40	146.8×177.53	132.30×147.26
Ignition time for supplement injection into the circular orbit since the launch time, days	183.339	178.608	215.652	151.942

Table 2.3 (continued)

Characteristic velocity consumption for supplement injection into the circular orbit, km/s	**0.7322**	**1.3539**	**1.3236**	**0.8361**
Final orbital period, days	435.492	290.01	472.173	303.79
Orbit inclination, degree	1.63	1.62	1.31	1.81
Semimajor axis of the final orbit, mln. km	168.21	128.27	177.53	132.30
Eccentricity	~0	~0	~0	~0
Circular velocity. km/s	28.0888	32.1654	27.3417	31.6714
Minimum distance to the Earth, mln. km	16.10	18.82	25.46	14.79

Thus, for ASS injection into the circumsolar circular orbit between orbits of the Earth and the Mars (outer relative to the Earth) additional 0.73÷1.32 km/s of characteristic velocity is required for accelerating burn in the orbit aphelion. Injection time till the complete formation of the target orbit will make up **7.2** months.

For ASS injection into the circumsolar circular orbit between orbits of the Earth and the Venus (inner relative to the Earth) additional 0.84÷1.35 km/s of characteristic velocity is required for deceleration burn in the orbit perihelion. Injection time till the complete formation of the target orbit will make up **6** months. Consequently, RAW injection into the heliocentric orbit between the Earth and the Venus (~0.85 a.e.) is not saving in terms of payload weight in comparison with heliocentric orbits ~1.15 a.u.

The launch date and time shall be selected based on the compliance with the following requirements:

1) provide optimal direction of escape out of the Earth's exobase at a given velocity;
2) exclude possibility of the critical encounter with the Moon during movement to the boundary of the Earth's exobase.

In case of unfavourable position of the Moon relative to the spacecraft motion direction to the boundary of the Earth's exobase under the action of lunar-solar perturbation, the orbit plane of the latter turned through an angle of ±30°. The Moon will not "capture" the spacecraft as the minimum distance between the spacecraft and the Moon at the maximum unfavourable conditions, such as the Moon on the route, the Moon orbit inclination 28°36′, distance from the Moon to the Earth 360 thous. km – will be not less than 130 thous. km, it 2 times exceeds the radius of the Moon's exobase

For a long-term forecast of the object motion in the circumsolar orbit it is required to develop a dedicated software.

2.2.4 RAW injection into the Earth-Sun system libration points

Variants of RAW storage in libration points of the Earth-Sun system may also be of interest.

In figure 2.2 calculated libration points of two-body system are presented.

Points L_1, L_2, L_3 are called collinear libration points, points L_4, L_5 – triangular libration points. It should be added that triangular libration points L_4, L_5 are stable, whereas collinear libration points L_1, L_2, L_3 are unstable. It means that if at the initial moment the satellite is located not in point L_4, but in its neighbourhood and having a low velocity, it will remain in this neighbourhood. In neighbourhood of any of points L_1, L_2, L_3 any arbitrarily small velocity will make the satellite leave this neighbourhood.

Triangular libration points L_4 and L_5 are also called trojan: this name originates from the Jupiter's trojan asteroids representing the most striking example of these points manifestation. It is known that the Neptune, Jupiter and Mars have trojan asteroids in the orbit of the Earth no trojan asteroids (particularly because of complexity of observations) has not been detected for a long time.

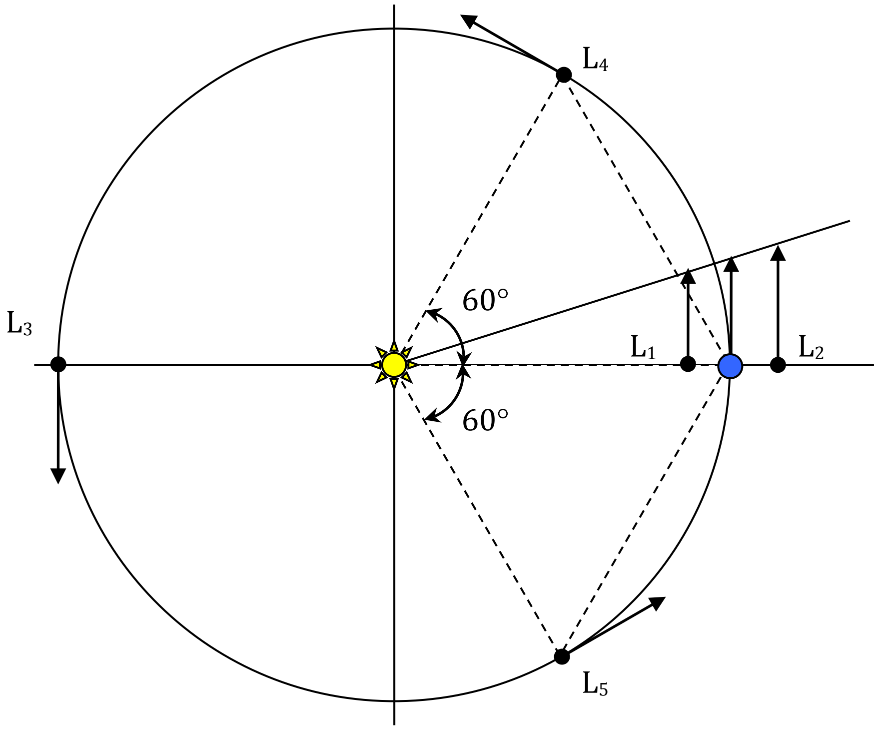


Figure 2.2 – Calculated libration points of two-body system

For ASS injection into the triangular libration point of the Earth-Sun system let us consider US with RAW launch with the intermediate near-circular orbit *Hcirc*=200 km high and ~0°inclination with parabolic velocity *v*=11.0145 km/s.

The launch date, 27/12/2013 was selected based on the Earth passing its perihelion. The launch time shall be selected so that the vector direction of escape velocity v_{esc} out of the Earth's exobase with radius *925 000* km would be close to the opposite direction of the Earth's velocity vector V_E.

Based on these data, the finer relative to the Earth heliocentric orbit of ASS with parameters $R_\pi \times R_\alpha = 135.3 \times 147.1$ mln. km orbital period *T=335* days will be formed.

In two complete circuits ASS will be ahead of the Earth at distance ~ 148 mln. km in the neighbourhood of triangular libration point L_4, that is, will take the position required for manoeuvre and overlapping ASS orbit aphelion. Accelerating burn Δv=0.882 km/s will transfer ASS into the orbit$R_\pi \times R_\alpha$=147.1×152.1 mln. km with orbital period *T=365.24* days, practically overlapping the orbit of the Earth.

ASS location after manoeuvre will be ahead of the Earth at distance ***~145÷153*** mln. km in the neighbourhood of triangular libration point L_4.

Injection time is ***1.85 year***.

Total velocity consumption for object injection into the triangular libration point makes up $\Delta V = 4.1476$ km/s.

The payload final weight (for upper stage "Fregat-SB") makes up $G_f = 2.37$ ton-force.

In figure 2.3 dependencies of distance change between ASS and the Sun, ASS and the Earth for ASS in the inner orbit $R_\pi \times R_\alpha = 135.3 \times 147.1$ mln. km with orbital period $T=335$ days in the drift area in the neighbourhood of libration point L_4 and during two complete circuits after manoeuvre.

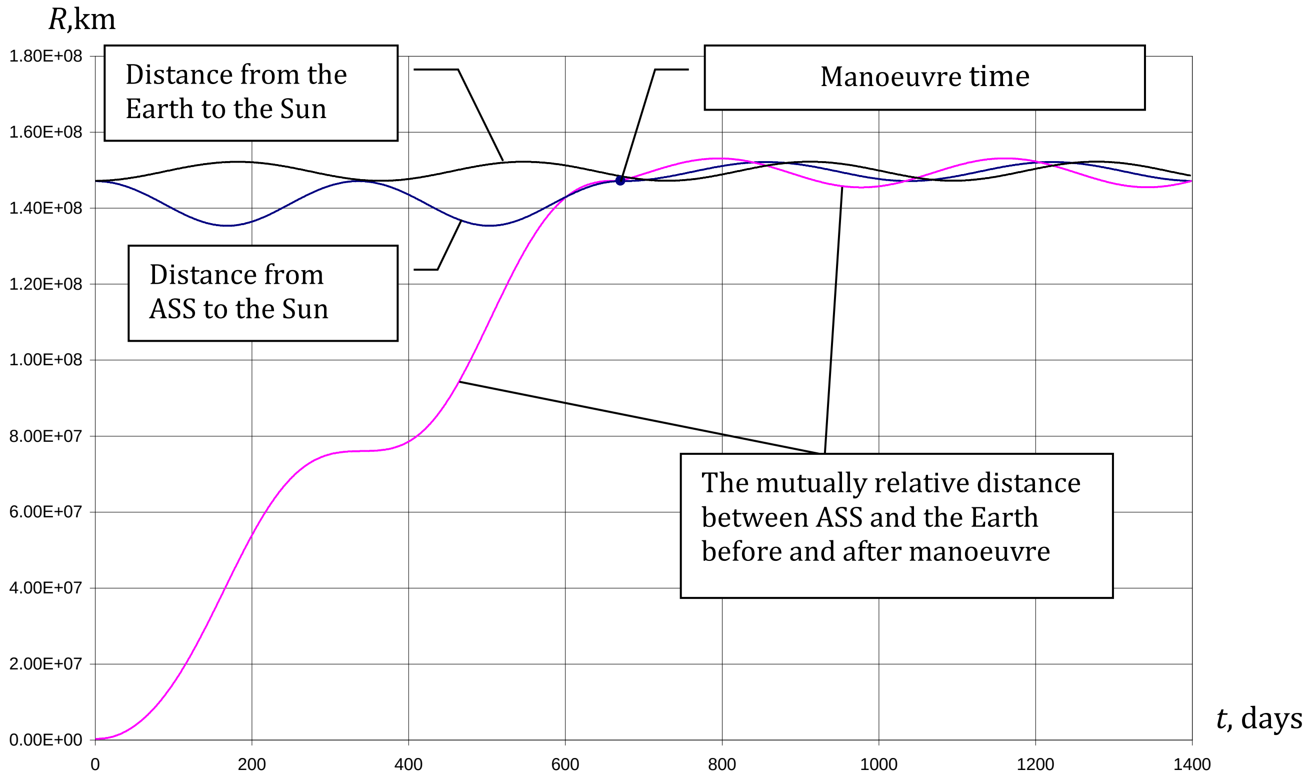


Figure 2.3 – Dependencies of distance change between ASS and the Sun, ASS and the Earth

RAW injection into libration points L_1 and L_2 of the Sun-Earth system is considered as pointless as:

1) to retain RAW in these unstable points regular correcting impulses are required;
2) this space area is of scientific interest. In the first of these points a solar patrol may be present, near the second one there may be telescopes and stations for the Earth's magnetotail observation.

Injection into point L_3 is pointless as, in the first place, the point is unstable and invisible from the Earth, thus, complicating control and observation of the object, in the second place, injection sequence into point L_3 is similar to injection sequence into libration points L_4, L_5, but with even longer drift.

The calculation of energy potentials of perspective superheavy SLV "Mayak" (5 LV units "Mayak-S") for RAW injection into the disposal orbit was performed according to the same procedure with a set of assumptions related to absence of real LV. These assumptions are as follows:

1. Injection provides for delivery into the circular circumsolar orbit ~1,15 a.u. high.
2. For injection procedure the transporting system from superheavy SLV "Mayak" fitted with two additional upper stages (US) will be required.
3. The first US is made on the basis of engine РД809К (vacuum specific impulse is 352 s). With payload total mass in the support orbit making up 70 t, US mass=48 t, transferred load mass – 22 t.
4. The second US is made on the basis of US "Fregat" as during use its LPT РДС5.92 (vacuum specific impulse is 333 s) the required fuel mass for impulse in aphelion makes up ~5.73 t, which is close to one of the US "Fregat" variants. With initial mass 22 t and final jettisonable mass of US "Fregat" ~ 1.02 t, the total mass of delivered load will make up ~15.2-15.25 t. Modifications of US "Fregat", necessary for this task performance, will increase its final mass by 100-150 kg, respectively, the actual mass of delivered SC will make up ~ 15.1 t.

Thus, into the heliocentric orbit, ~1.15 a.u. high, SLV "Zenit-3SLBF" is able to deliver 2.3 t of payload, whereas superheavy SLV "Mayak" – **15.1 t**.

In 1994 representatives of Central Research Institute of Mechanical Engineering assumed that "the detailed plan of operations (for RAW injection into space) with substantiation of its safety, experimental research results and demonstration tests may be developed during next two years" [70]. 20 years passed, but the project has not been developed yet.

The task complexity, need of attraction specialist and scientists of various fields of knowledge on the one hand and limited time and financial resources on the other hand make it possible to form the DO appearance and evaluate RAW mass that LV "Zenit-3SLBF" and perspective superheavy SLV "Mayak" are able to inject into disposal orbit. Evaluations of injected RAW mass are quite optimistic. This is due to the fact that further modifications related to need of characteristics confirmation (impact loads, aerodynamics, safety, reliability, etc.) may require to introduce new design elements; long duration of flight requires energy supply during the whole flight to provide operation of CS, v, radio communication. The DO design process in terms of its designated purpose is close to design process of spacecraft (SC) with specific requirements.

2.3 SLV "Mayak" use

The sealed power container, filled with RAW, is placed in disposal orbiter (figure 2.4), which, in its turn, is a part of the LV final stage.

DO appearance was developed considering maximum payload for LV "Mayak"

DO includes:

1. Emergency recovery system
2. Aerodynamic capsule
3. Upper stage

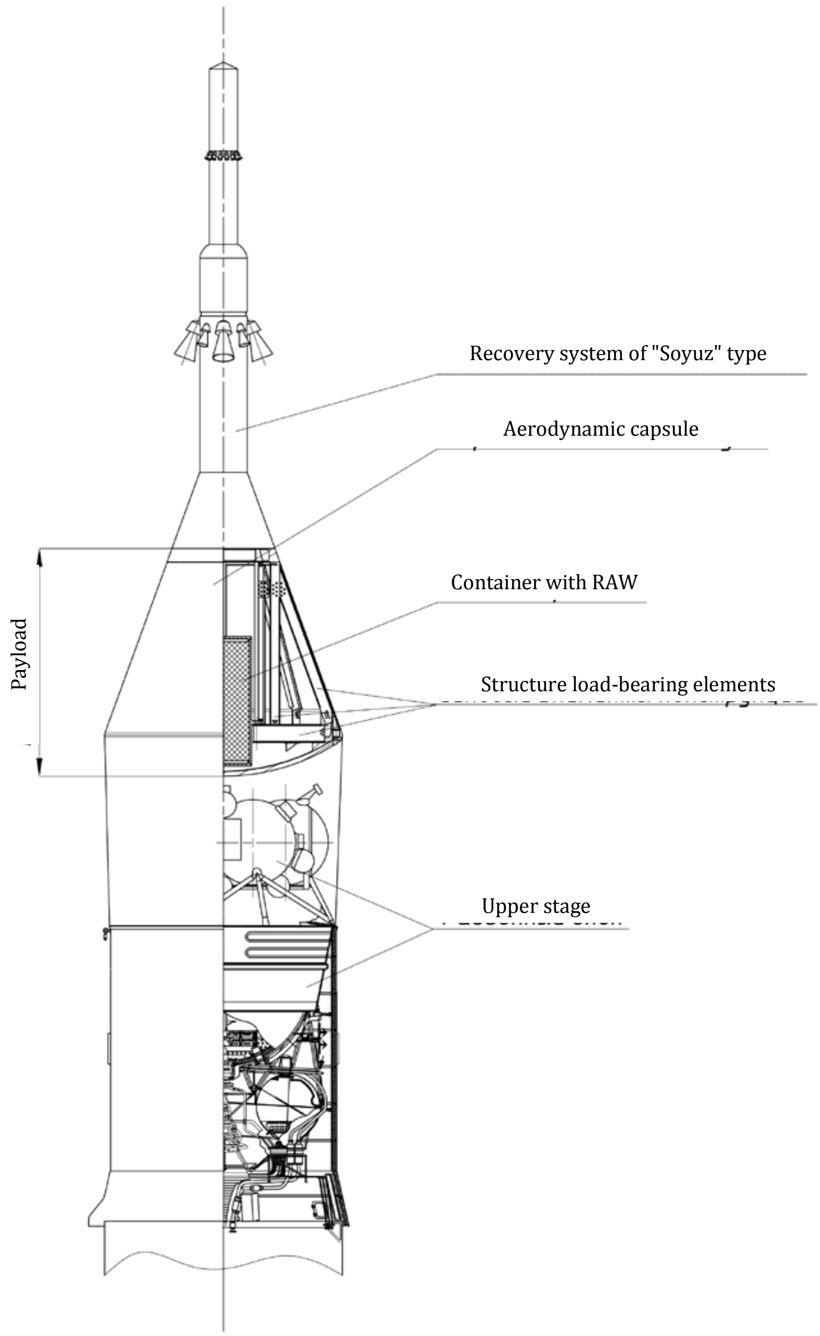


Figure 2.4 – Disposal orbiter

The aerodynamic capsule (figures 2.5, 2.6) is used for protection of container with RAW from incident flow impact during reentry in the atmosphere in case of emergency situation..

To provide a stable reentry in the atmosphere, the segment shape of aerodynamic capsule was selected. A sealed power container (figure 2.7) is fixed to the spherical bottom of the aerodynamic capsule, packages with RAW (figure 1.8) are put into the container in the quantity of 47918 pieces (38 layers by 1261 packages in each), the total mass of RAW makes up 6330 kg.

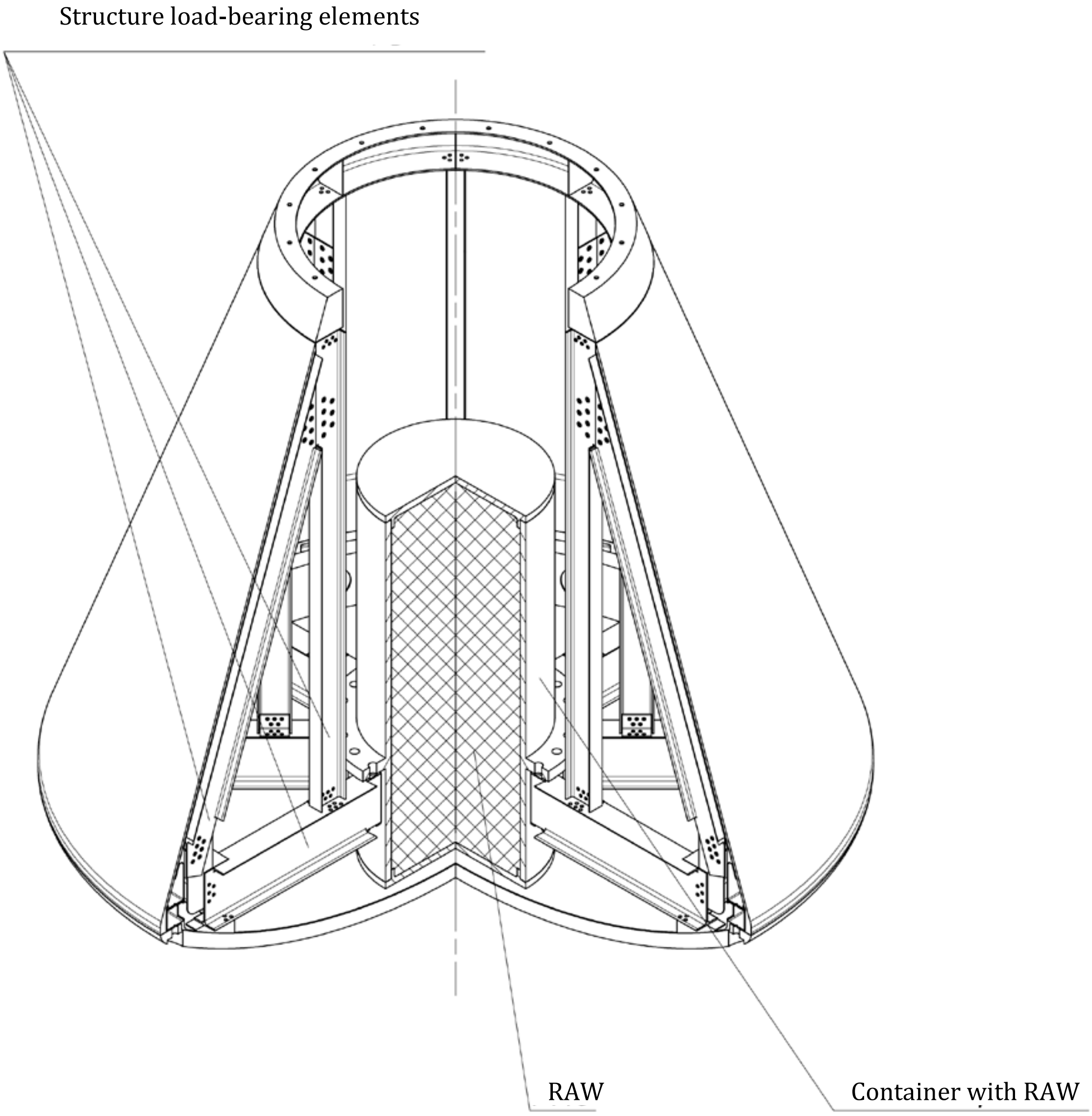


Figure 2.5 – Aerodynamic capsule (AC)

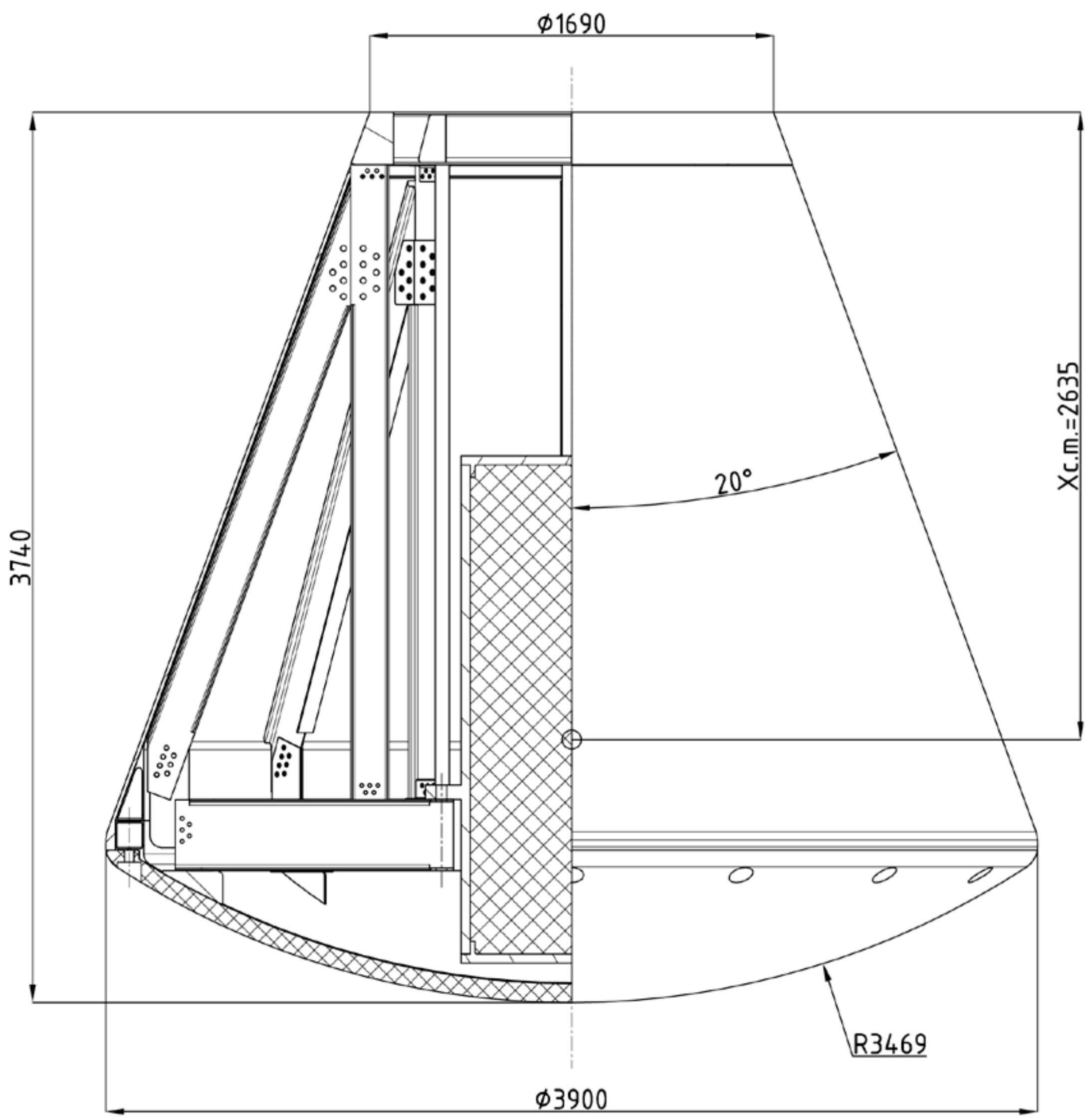


Figure 2.6 – Geometric characteristics of aerodynamic capsule

The sealed power container design shall provide safety of the personnel, population and environment during its transportation with RAW and handling at the launch base, that is, have strength and radiation protection characteristics specified by the nuclear and radiation safety standards.

The container is a welded structure - a steel cylinder with two covers (figure 2.7).

Based on design considerations and need of safe operation with the container for the personnel not using additional protection equipment against β-radiation,, the required thickness of the cylinder steel wall makes up 37.5 mm. Based on these data the structures of power container and aerodynamic capsule were developed.

It should be noted that evaluation of the container and capsule structural strength is of an expert character and requires specification at further development stages, in particular, for consideration of operating conditions in off-nominal situations.

Outline flow chart of container with RAW:

1) The container is transported from the manufacturing plant to RAW reprocessing plant.
2) A the plant packages with RAW (figure 1.8) are manufactured, put into the container, free space is filled with the powder based on silicon oxide, then the container is sealed.
3) The container, filled with RAW, is transported to the launch site in Assembly, Integration and Test Building.
4) In AITB a disposal orbiter is assembled.

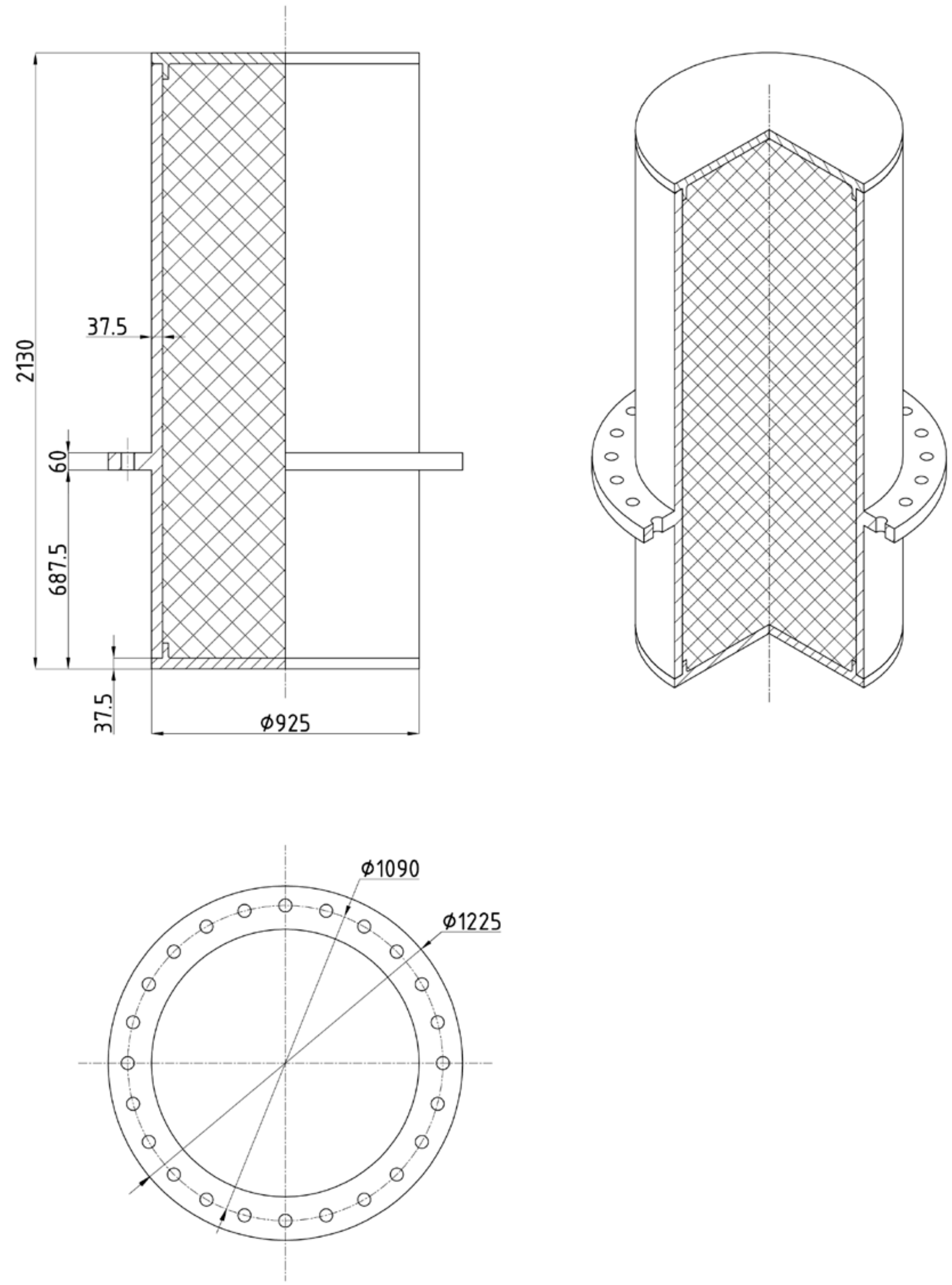
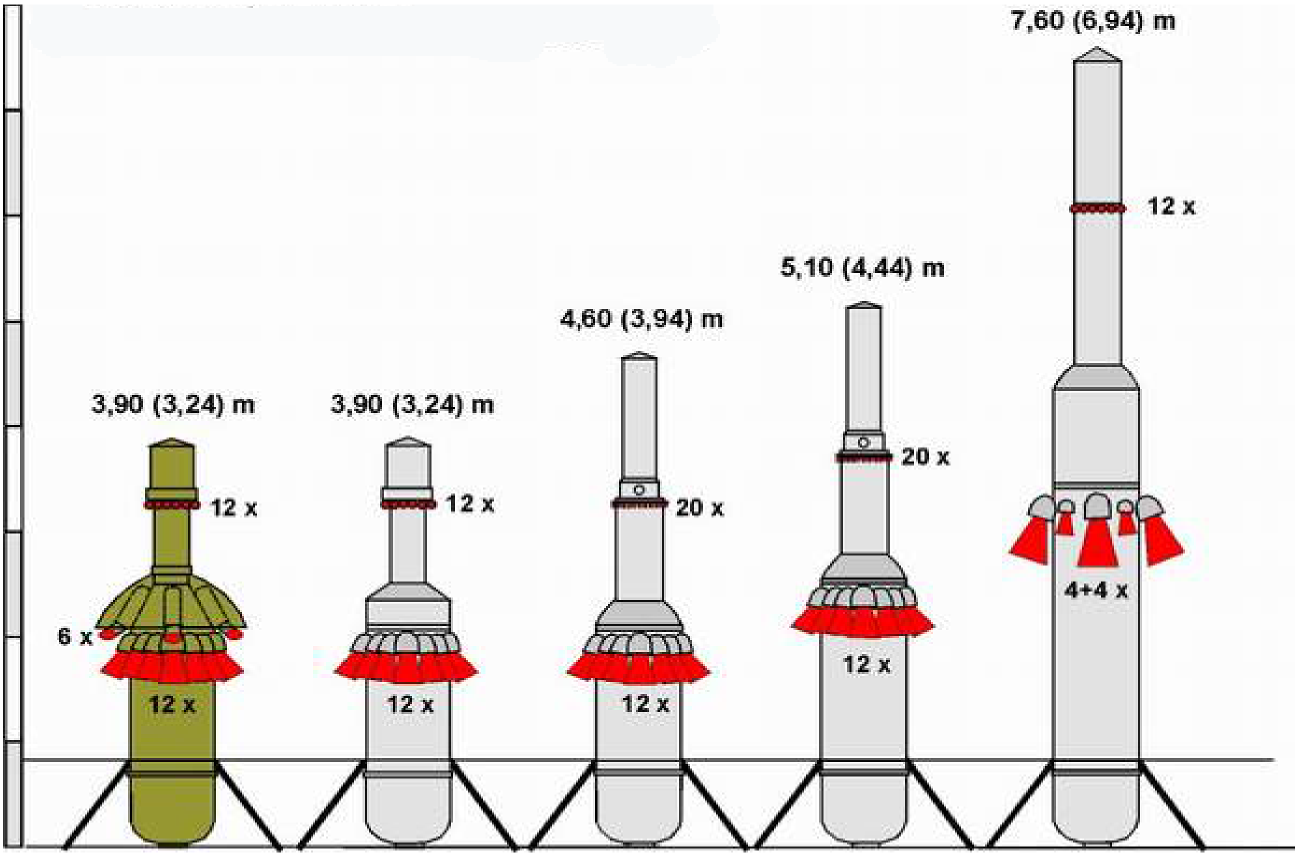


Figure 2.7 – Container with RAW

The aerodynamic capsule buoyancy, when it falls on water surface, shall be ensured structurally due to a large internal volume with average density making up 435 kg/m^3.

To facilitate search operations performed by the ground search and rescue service, it shall be provided with radio and light impulse beacons. It is also necessary to provide maintenance of the aerodynamic capsule with a sealed power container with RAW at launching site and in emergency landing situations.

To withdraw aerodynamic capsule from LV in emergency situations, a reliable emergency recovery system, developed for piloted launches, is used (figure 2.8). In case of emergency situation ERS shall provide separation of the payload unit from LV and its withdrawal into the safe zone.



Type 1	Type 1a	Type 2	Type 2a	Type 3
Soyuz 1-11	Soyuz 12-40	Soyuz 6,19,22	Soyuz T	Soyuz TM
	Progress	Kosmos ESA	Proton – K(L)	Soyuz TMA

Figure 2.8 – Emergency recovery system

2.3.1 ERS operation in emergency situations

A few emergency situations are studied (figure 2.9).

ERS operation in case of the launch abort:

1) ERS separates and withdraws aerodynamic capsule from LV at 1 km from the Earth;
2) ERS performs turning to the angle required for aerodynamic capsule separation;
3) aerodynamic capsule separates from ERS;
4) aerodynamic capsule a parachute descent.

ERS operation in case of emergency at the stage of injection into the intermediate orbit:

5) aerodynamic capsule separation is performed;
6) aerodynamic capsule performs ballistic descent in the atmosphere.

ERS operation in case of emergency during flight in the intermediate orbit:

7) separation from LV third stage takes place.
8) aerodynamic capsule performs ballistic descent in the atmosphere.

Possible ERS problems may result in catastrophic situations in the following cases:

- fire/explosion at launching site: burning in oxygen medium can lead to melting of structural materials and RAW escape into the biosphere;
- drowning in the ocean. In case of a sealed power container damage, ^{129}I diffusion will occur pretty fast. As iodine is well soluble in water, poisoning of marine flora and fauna is possible on a global scale. Due to vapours, large land areas will be contaminated in time;
- LV accident during flight and fall of Container with RAW in populated areas, on the territory with increased risk of technogenic accident (for example, chemical, power, metallurgical and other production plants).

Possible natural emergency situations at the site of RAW location (landslides, soil slides, flooding, earthquake, tsunami, etc.) in terms of safety provision require special investigations.

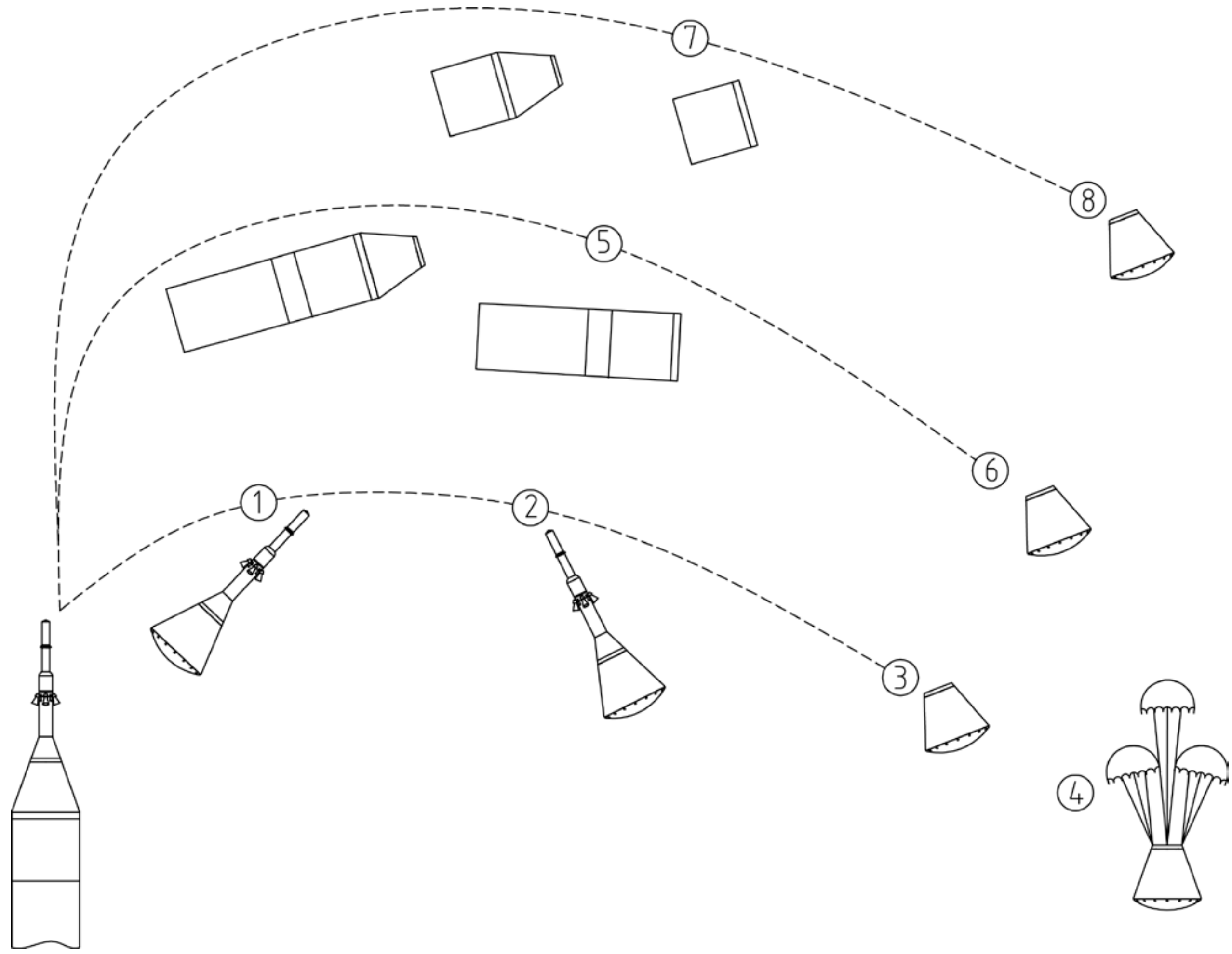


Figure 2.9 – ERS flow chart

2.3.2 Payload composition

In table 2.4 the approximate mass of structural elements and systems used for RAW injection into space based on the total mass of LV "Mayak" payload – 15.1 t. The considerable part of the payload mass with a direct injection sequence accounts for structures and systems of rescued capsule required only at those flight stages, when the container with RAW shall return to the Earth in case of off-nominal situations. This conclusion was obtained during investigation [4].

Table 2.4 – Approximate mass of structural elements and systems used for RAW injection into space and included in the payload composition injected by LV "Mayak"

No.	Name	Mass, kg	Notes
1	Aerodynamic capsule	4090	Based on design considerations: fairing (calculation of wafer-type shell with thermal protection coating) and bottom (calculation of spherical smooth bottom with thermal protection coating)

Table 2.4 (continued)

2	Control system	90	Based on statistical data
3	Parachute system	150	Based on design considerations
4	Unaccounted structural elements	200	Damping elements (crash-systems), radio beacons, light signals, ERS, TCS, docking unit for towing in off-nominal situations using a special (stand-by) SC, fastening elements, etc.
5	Container for RAW (wall thickness - 37.5 mm, see section 1.2)	3555	Geometrical parameters of the container are based on arrangement and alignment within the aerodynamic capsule composition
6	Filler	685	Provides immobility of primary packages and increases GCS shell resistance to load, for example, in case of container flooding
7	Mass of primary packages with RAW	6330	47918 packages with RAW, RAW mass 0.469x6330=2969 kg, see table 1.7
Total		**15100**	

It is obvious that for 60 tons of iodine-129 (corresponding to 78 t of potassium iodide - KI) injection into space not so many launches (78000/6330/0.469 ≈ 27) will be required. But the cost of injection is comparatively high (section 3.1). It may be reduced, for example, by exclusion of HAW deep radiochemical reprocessing.

Such situation is hypothetically possible. For instance, a certain small state gives SNF for reprocessing and, according to effective rules, has to take HAW containing uranium, plutonium and neptunium (section 1.1) back. It has a suitable disposal site, but HAW problem shall be solved.

It may also be assumed that power industry specialist have their own view of what RAW shall be injected into space. That is why, evaluation of SLS ability of suchHAW injection is of common sense.

Considering a number of assumptions regarding RAW composition, IAEA and Radiation Standards-97 requirements, calculation results given in [108], wall thickness of container with RAW shall not be less than 420 mm.

Based on all these factors, the formation of another variant of DO structure appearance was performed. Illustrations of design studies are shown in figures 2.10 - 2.13.

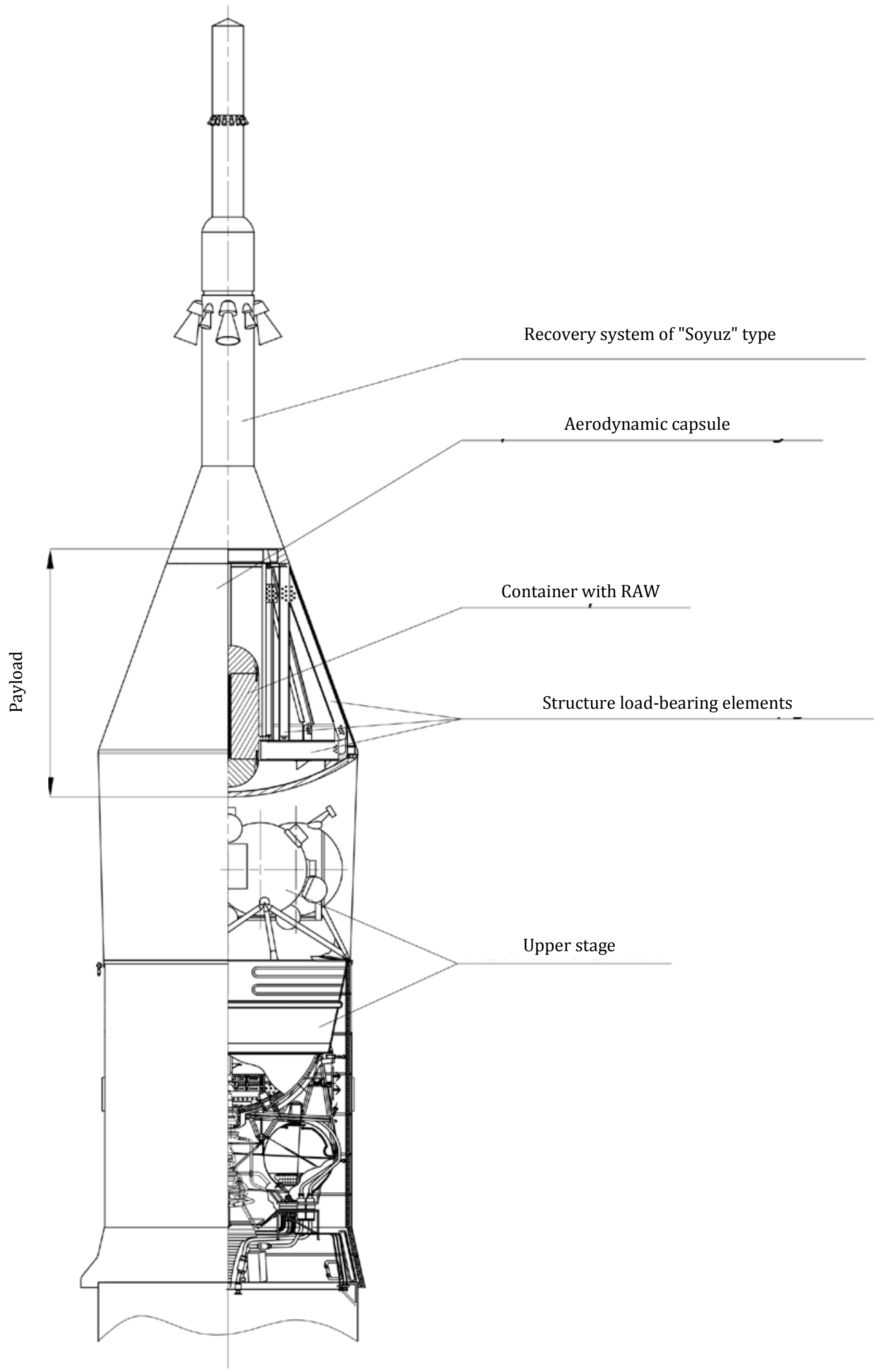


Figure 2.10 – Disposal orbiter with HAW containing uranium, plutonium and neptunium

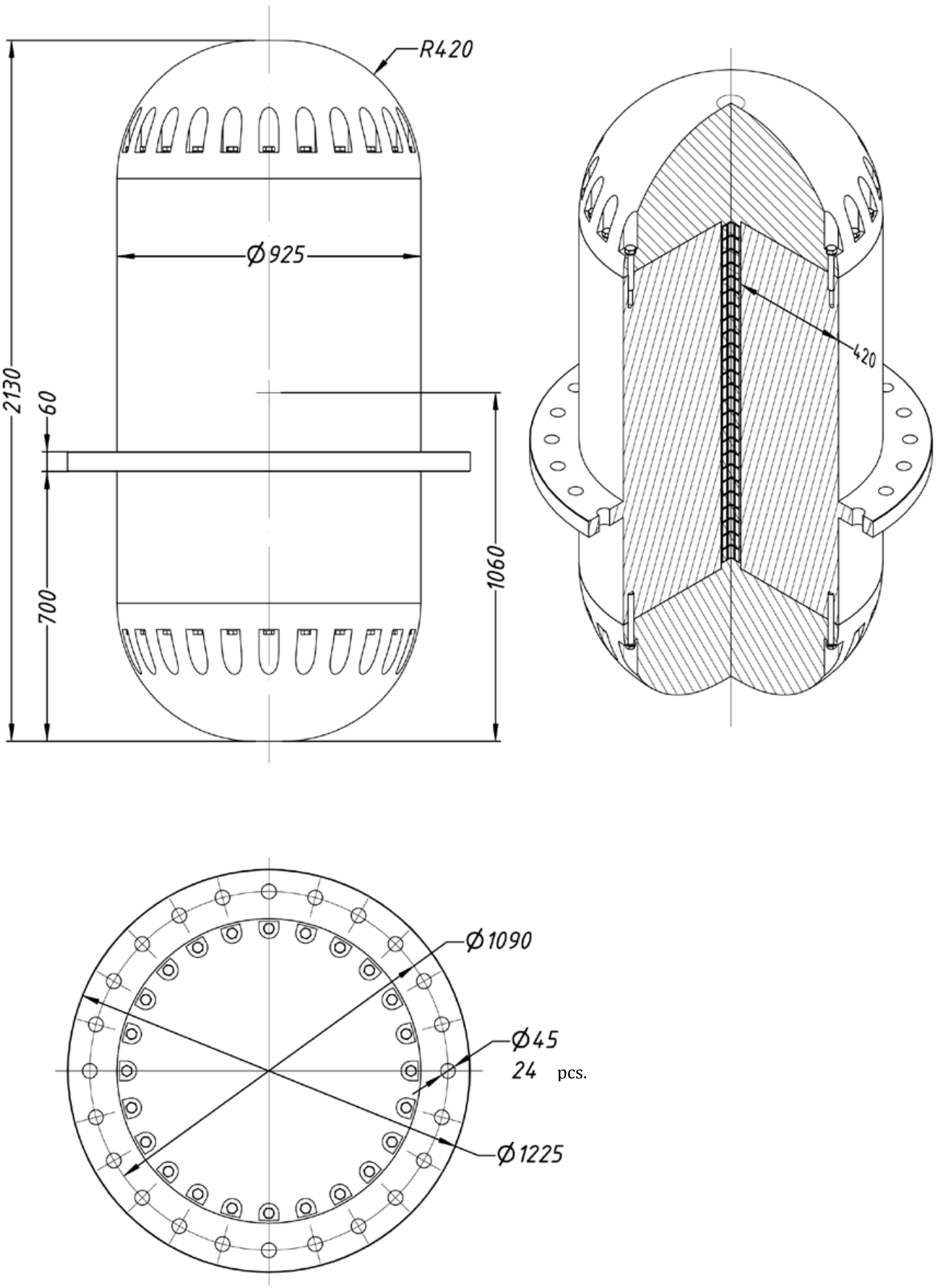


Figure 2.11 – Container with HAW containing uranium, plutonium and neptunium

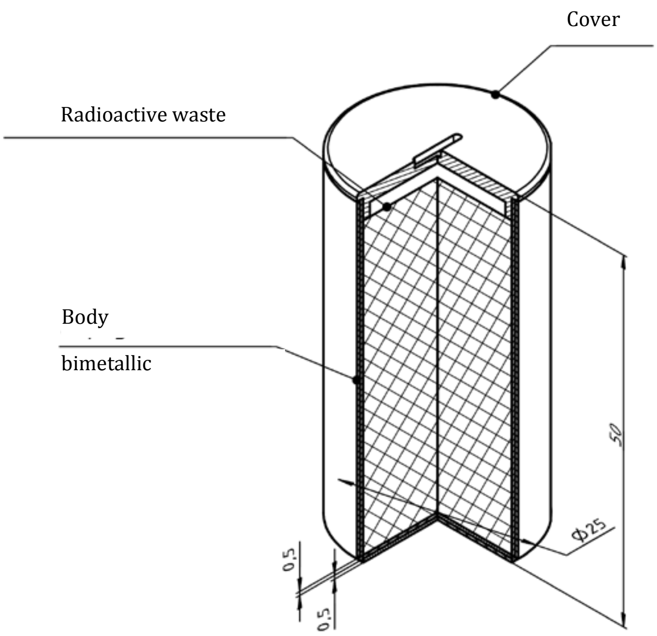


Fig .2.11a – Package with RAW (175 pcs.)

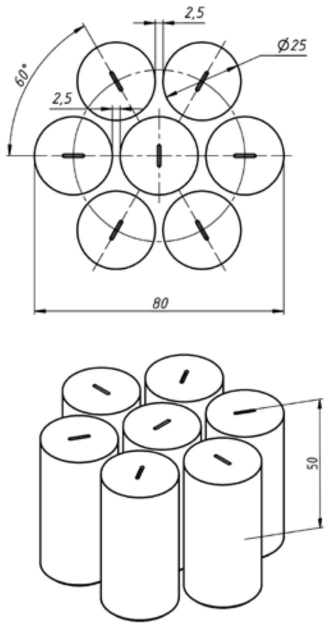


Fig. 2.11б – Row arrangement (38 rows)

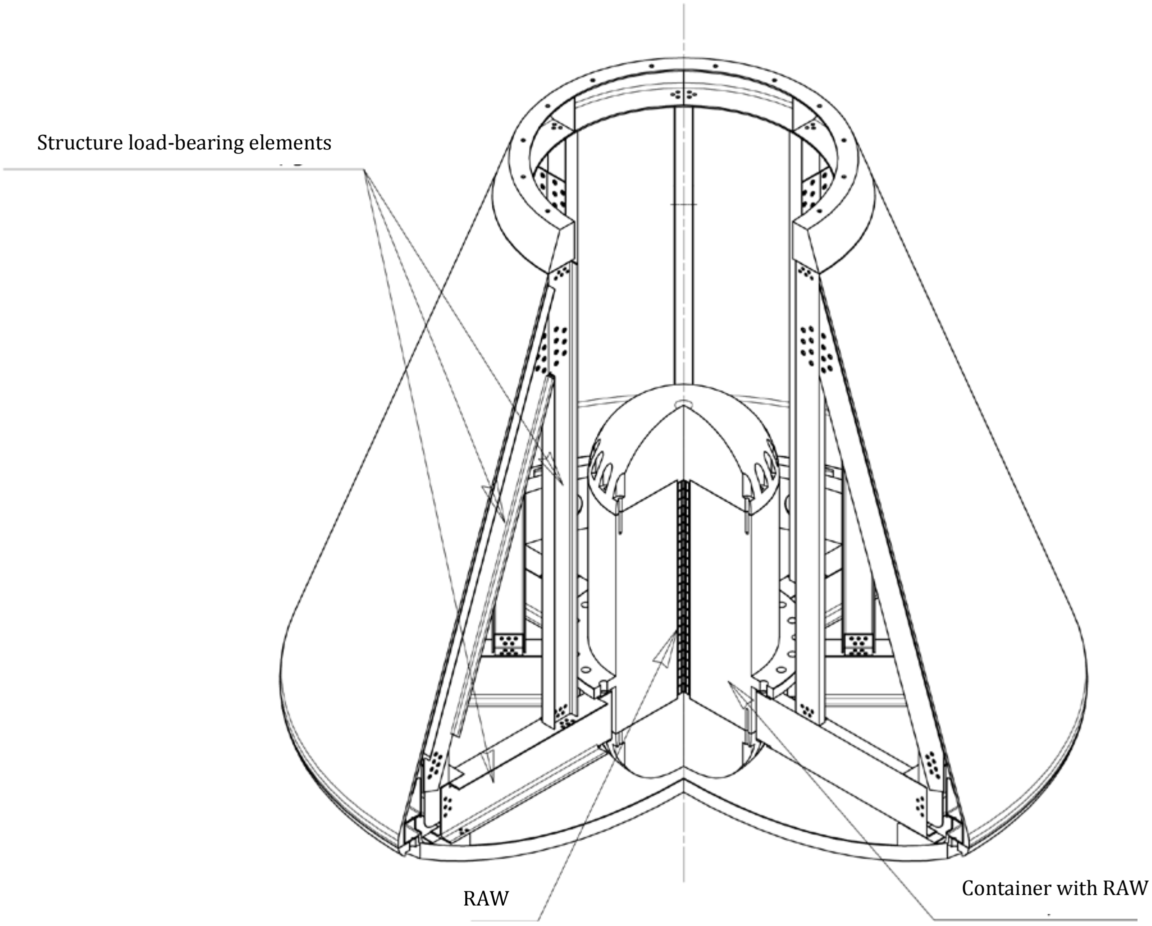


Figure 2.12 – Aerodynamic capsule with HAW containing uranium, plutonium and neptunium

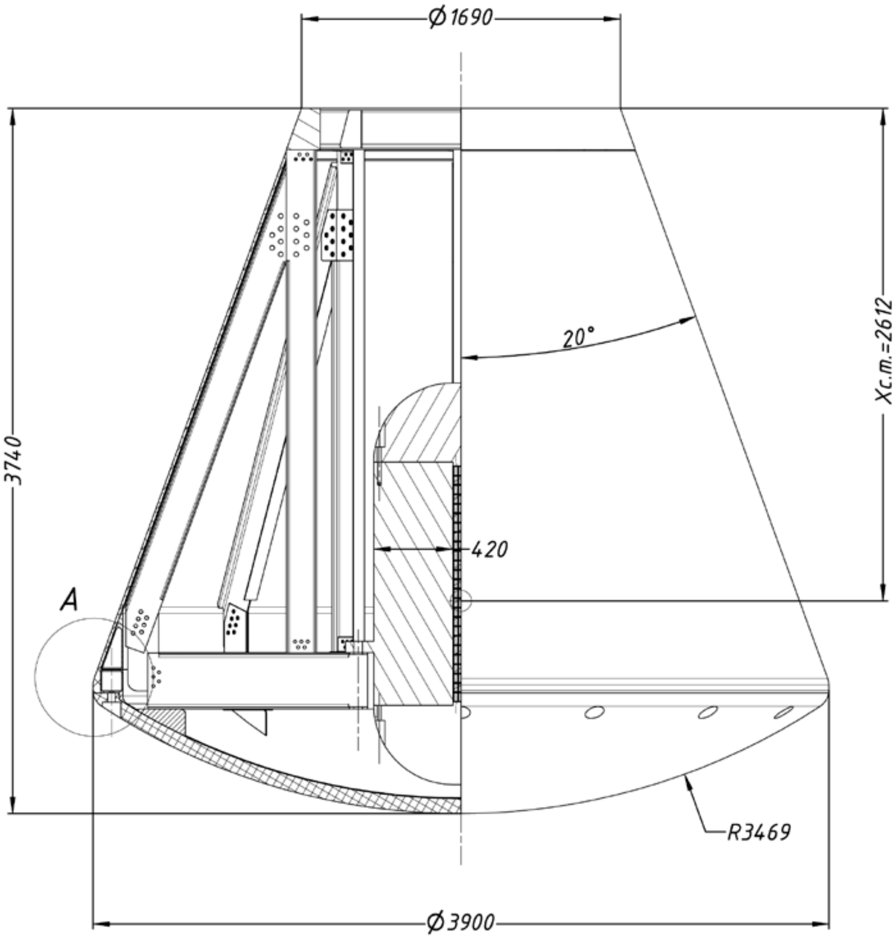


Figure 2.13 – Geometric characteristics of aerodynamic capsule with HAW containing uranium, plutonium and neptunium

Table 2.5 shows approximate mass values of structural elements and systems used for HAW, containing uranium, plutonium and neptunium, injection into space based on the total mass of SLV "Mayak" payload – 15.1 t.

Table 2.5 – Approximate mass of structural elements and systems used for HAW, containing uranium, plutonium and neptunium injection into space and included in the payload composition injected by LV "Mayak"

No.	Name	Mass, kg	Notes
1	Aerodynamic capsule	4090	Based on design considerations: fairing (calculation of smooth shell with thermal protection coating) and bottom (calculation of spherical smooth bottom with thermal protection coating)
2	Control system for rescue task solution	90	Based on statistical data

Table 2.5 (continued)

No.	Name	Mass, kg	Notes
3	Parachute system	150	Based on design considerations
4	Unaccounted structural elements	200	Including protection from neutron radiation, fastening elements, etc.
5	Container with RAW (wall thickness - 420 mm, [7])	10570	The container mass with waste is determined as the remainder of the payload total mass of injected LV (including RAW mass = 35 kg)
Total		15100	

In this case, the amount of injected into space HAW, is too small (35 kg per one launch), injection cost is too high (section 3.1) to attract a potential investor.

The comparison of HAW masses that SLV "Mayak" is able to inject into heliocentric orbits, shows that the container required mass directly depends on the composition of injected RAW. The mass, in its turn, directly influence on the amount of RAW injected into space. That is why, the list of these isotopes shall be defined by nuclear engineers. Otherwise, it is not possible to optimize DO structure.

2.4 SLV "Zenit-3SLBF" use

Based on calculations given in section 2.2 , energy parameters of "Zenit-3SLBF" allow to inject payload of about 2.3 t into the circular heliocentric orbit.

The design of aerodynamic capsule and systems included in the payload composition of injected SLV "Zenit-3SLBF" will not be radically changed in comparison with analogues for SLV "Mayak" described in section 2.3 .

The mass analysis of structural elements (table 2.4) confirms the impossibility of SLV "Zenit-3SLBF" use for RAW direct injection into space (with mass of only aerodynamic capsule equal to nearly 4 tons).

The situation may change, if the flight profile includes a "space tug" performing RAW transportation from fairly high orbits, where to RAW will be injected by separate launches. It may be a subject for special studies.

2.5 List of possible emergency situations

The depth of the project development does not allow to perform the complete safety analysis related to radiation accident threat. Such studies are to be performed in the future.

The initial events of possible emergency situations are connected with:

- external influences of technogenic origin;
- external influences of natural origin;
- socio-political situation (for example, terrorism, wars);

- failures of technical equipment at RAW delivery stages: from a radiochemical plant to the disposal orbit;

The last hyphen of this list and associated analysis shall provide for consideration of the following (incomplete) list of possible accidents that may develop into radiation ones:

- fall of container with RAW on dry land during container fitting, during transportation to GC and LC during injection into space;
- fall of container with RAW, during transportation, on LC (if LC is located on the ocean surface), during injection into space;
- fall of container with RAW and spacecraft on the ground, during air transportation;
- fall of container with RAW and transporting spacecraft on the ground with fire development at the fall site;
- fall of RAW from a loading crane on the ground, berth, structural elements during transportation;
- fire at transport vehicle (a car, railway carriage, aircraft, ship) at the location site of container with RAW;
- sinking of the ship transporting container with RAW;
- fire, tipping of the ship and fall of container with RAW in sea water.
- LV accident during flight and fall of container with RAW in populated areas, on the territory with increased risk of technogenic accident.

The given list is actually one of the initial data sections for designing of RAW disposal orbiter and its components. In nuclear power industries these are called "design" accidents. The word "design" here means that at the design phase technical solutions shall be developed for this set of emergency situations, minimizing either risk of their development into radiation accidents, or their consequences.

The accidents consequences shall be evaluated for each situation, including possible radiation related consequences (boundaries of environmental media radiation pollution, levels of possible radiation pollution, liquidation of consequences).

The general conclusion based on the materials of this report section: it is efficient to use SLV of heavy/superheavy class for RAW injection into space. SLV "Zenit" may be used in the transportation system where a "space tug" and technology of DO orbit staging are used (not mentioned in this report).

3 Cost aspects of radioactive waste disposal in space in comparison with alternative variants

The attractiveness of any new market (or its segment) to a company is defined by a few key factors:

1) profitability of the company at this market;
2) relationship of the company product marketability and the company competitive strength with its main competitors' competitive strength and product marketability;
3) existing and perspective demand for the company product or services at this market;
4) obstacles of entry into a market. [109]

Commercial attractiveness of any project is defined, in the first place, by its profitability. Selecting this or that RAW management, this aspect is of not the least importance and with safety issues out of the context - it becomes determining.

To determine the project profitability it is necessary to define estimated costs and revenues of the total cash flow.

3.1 Costs

Injection into the orbit is a substantial budget part of the space project cost. Let us evaluate it, considering the results obtained in sections 1 and 2. Considering present situation at the market of launching services, the cost of "Mayak" family heavy LV launch may be preliminarily be estimated as 120 mln. US dollars (this is the cost of LV "Energiya" launch in the beginning of 1990-ies). Injection of~78 tons of KI (~60 tons ^{129}I) will require 27 LV launches (78000 kg/2969 kg ≈ 27). It should be noted that 60 tons of ^{129}I isotope is to be extracted from already accumulated for than 50 years spent nuclear fuel; its amount in annually unloaded SNF is comparatively small and makes about 1 t.

In table 3.1 shows the estimated cost of 27 LV launches for RAW injection into the disposal orbit by the most expensive positions. The strict economic evaluation is not possible for now as many indices remain undefined. That is why costs by estimated cost items are given with consideration of cost of possible analogues.

The notes to table 3.1 contain cost items required for the project implementation as a whole but with no quantitative evaluation of these items, which is not possible for reasons beyond one's control. They, mainly, belong to the nuclear and engineering part of the project.

Table 3.1 – Estimated cost of 27 launches of heavy LV "Mayak"

No. Item	Cost item*	Cost, mln. US dollars	
		Non-recurring	Recurring
1	R&D, process preparation**	500...2000	
2	Launch base further equipping or construction**	500...2000	
3	Tests for safety and reliability confirmation*** (2 launches + ground tests)	300	
4	Transportation of a sealed power container with RAW 27 x 2.3 mln.		62
5	Launch vehicle + upper stage, 27 x (120+67) mln.		5049
6	Disposal of orbital stage without upper stage (aerodynamic capsule, sealed power container, rocket and parachute parts of emergency recovery system, control system), 27 x 25 mln.		675

Table 2.5 (continued)

No. Item	Cost item*	Cost, mln. US dollars	
		Non-recurring	Recurring
7	Launch insurance (10% of (item 5+item 6))		572
	TOTAL	**1300...4300**	**6358**

Notes.

*) *The following project costs are not included:*

non-recurring:

1) *international project expertise;*

2) *legislative and legal backing of launches for radioactive waste disposal in space;*

3) *technology development of spent nuclear fuel (SNF) head end reprocessing and separation of target isotopes from head end reprocessed SNF;*

4) *project development and construction of SNF head end reprocessing plant;*

5) *project development and construction of radiochemical plant for separation of target isotopes;*

6) *infrastructure development of RAW safe interim storage;*

recurring:

7) *SNF head end reprocessing;*

8) *separation of target isotopes from reprocessed SNF;*

9) *disposal of RAW generated during separation of target isotopes;*

10) *preparation of target isotopes for disposal in space (conditioning, immobilization, placing in primary package, sealed power container fitting);*

11) *search, evacuation and/or rescue of aerodynamic capsule in case of emergency launches and liquidation of harmful consequences;*

12) *ensuring launch base and infrastructure of RAW safe interim storage functioning;*

13) *insurance of accident risks with escape of radiation into the Earth's atmosphere;*

14) *management and marketing; demand making at the market.*

**) *Production and economic performance of LV "Energiya" ground complex development, construction cost of "Angara" LV ground complex, Bayterek.*

***) *Tests of capsule and container, RAW management methods development, emergency situations development.*

Thus, more than a half of cost items for project on the whole cannot be evaluated.

Based on data from table 3.1 let us calculate cost of 1 t of RAW disposal in space without considering expenses of undefined cost.

Cost with account of only recurring costs will make up

6358 mln. US dollars/60 t = **106 mln. US dollars/ton.**

Cost with account of recurring and non-recurring costs will make up

(6358+(1300…4300)) mln. US dollars/60 t = **127.6…177.6 mln. US dollars/ton.**

In regard to isotope ^{129}I the last figure will reduce very slowly as its amount in annually unloaded SNF is comparatively small (about 1 t) and above mentioned 60 t are to be extracted from already accumulated SNF.

Considering a set of target isotopes that require a sealed power container with wall 420 mm thick, to provide protection from their radiation, mass of such RAW at one-launch sequence of delivery in the disposal orbit makes up 35 kg (see section 2) Respectively, in this case **cost of on-disposal orbit delivery of 1 t of RAW with account of recurring costs only** for self-injection, without account of expenses of undefined cost, **will make up**

(2.3+120+67+25+0,1(120+67+25)) mln. US dollars/0.035 t = **6728.6 mln. US dollars/ton**.

3.2 Revenues

To define a potential revenue from realization of service at the market is possible based on mid-market price of analogous service. As alternative variants of RAW disposal service provision 2 approaches may be considered: disposal in geologic formations and transmutation.

Transmutation technologies require development of new physical power plants, which are being developed now. So economic calculations regarding these are premature for now.

The analysis of available information about cost of different RAW disposal methods allows to systematize it by the criterion of 1 t disposal cost (or in some cases, 1 m^3). The results are summarized in table 3.2. In the column "Source", where it is possible, bibliographical reference, the organization or person being the source of this evaluation.

As it can be seen from table 3.2, HAW disposal price by injection into space exceeds the price of all variants of RAW disposal. Comparison with HAW geologic disposal would be correct. Disposal in space is by two orders of magnitude more costly that HAW geologic disposal.

Thus, the project predictable profitability will be negative. In other words, the project will be unprofitable due to absence of demand for services as other variants of disposal are radically cheaper.

Table 3.2 – Estimated cost of different variants of RAW disposal

Disposal method	Cost of 1 ton (1 m^3) disposal, mln. US dollars	Source
1. Geologic disposal, SAPIERR project	0.10 – 1.50	[53], I. Rybalchenko, VNIPIET (All-Russian Scientific Research and Design Institute for Energy Technology), Russia, 2005
2. Geologic disposal, Great Britain*	(0.1)	[59,69], I. Jackson, Great Britain, 2008

Table 3.2 (continued)

3. Geologic disposal, Yucca Mountain (USA)	0.66 0.75	[1], U.S. Department of Energy, 2007, [38], Nuclear engineering handbook, 2009
4. Geologic disposal, Switzerland	0.12	[68], MSU, 2006
5. Geologic disposal	1	[30], NASU (National Academy of Sciences of Ukraine) NPP IPB (Institute for Nuclear Power Plant Safety Problems) 2005
6. Geologic disposal	0.06-0.07	[106], 12 RF MOD CRI (Central Research Institute), VNIIEF (All-Russian Scientific Research Institute of Experimental Physics), 1997
7. Geologic disposal of LAW	(0.002-0.006)	[10], O. Kronda, National University of Kyiv, Ukraine, 2009
8. Geologic disposal of MAW	(0.01-0.07)	[10], O. Kronda, National University of Kyiv, Ukraine, 2009
9. Geologic disposal of HAW	(0.4 - 1.4)	[10], O. Kronda, National University of Kyiv, Ukraine, 2009
10. SNF storage facility in prospect wells, Nevada (USA)	0.0284	[84], TPU (Tomsk National Research University of Resource Effective Technologies)
11. Disposal in wells	0.26-0.3	[30], NASU (National Academy of Sciences of Ukraine) NPP IPB (Institute for Nuclear Power Plant Safety Problems) 2005
12. Geologic disposal on Novaya Zemlya archipelago with use of peaceful nuclear explosions	0.36-(1.5-3.6)	[106], 12 RF MOD CRI (Central Research Institute), VNIIEF (All-Russian Scientific Research Institute of Experimental Physics), 1997
13. Formation fracturing and injection of low-activity liquid waste mixed with cement	(0.00004-0.00005)	[62], Russia
14. Disposal in space	108 - 183	[8], A. Gafarov, Russia, 2002
15. Disposal in space + launch base (2 bln. US dollars)	175 – 275**	[6,41,70], TsNIIMash (Central Engineering Research Institute), 1994; NGTU (Novosibirsk National Technical University)

Notes.

**) The planned revenue for 1 m³ of foreign RAW disposal ≈ 345 ths. US dollars.*
***) This sum includes cost of preparation of extremely hazardous and long-lived waste for space isolation, costs for search, evacuation and rescue of ballistic capsule in case of emergency launches and liquidation of harmful consequences in case of such an improbable event as scatter of ampoules.*

To determine the market attractiveness by competitiveness, it is necessary to study the project competitiveness by price and technical customer characteristics and customer satisfaction. The competitiveness by price is absent as it was shown above. The competitiveness by technical characteristics is not defined due to substantial difference in technical approaches. The competitiveness by customer satisfaction is not achieved as disposal in space does not solve RAW disposal problem as a whole, but is proposed for disposal of highly toxic, long-lived HAW of no value in the future. Besides, at present, other HAW are to be disposed in geologic formation without subjecting to deep radiochemical reprocessing. Among strategic plans of nuclear physicists there is a possibility of extraction of valuable components from RAW. To do this, economic situation, new technologies, development of new physical power plants shall be considered; they are developed not only by application engineers, but with involvement of scientists in fundamental knowledge area. Raw injection into space does not make it possible to extract valuable components from RAW in the future.

Characteristics of realized and perspective demand define possibilities of service realization and acquisition of income.

On the one hand, there is no acute necessity in development of radiochemical technologies for extraction of certain isotopes to inject them into space as the cost of such technologies is rather high. That is why, there is no demand for HAW injection into space now. On the other hand, this situation may change in the future. The demand forecast depends on how proposed alternative projects will be able to manage RAW stream in the future.

At present, nuclear power industry is developing the most dynamically in China, India and Russia. New power units are also being constructed in the USA, Canada, Japan, Iran, Finland and other countries. A number of countries have announced their intentions to develop nuclear power industry, among these - Poland, Vietnam, Byelorussia and others. Altogether, more than 60 applications for construction of power units are being considered now. More than 160 projects are under way. But three large nuclear catastrophes occurred at nuclear power units, made the developed countries seek alternative power sources, Germany, in particular, totally abandoned nuclear power industry.

The strategic orientation of nuclear power industry development lies in nuclear fuel cycle closure. Elaboration of the closed fuel cycle allows to solve two main tasks. The first one is to provide nuclear power industry with a reliable source of raw materials by involvement of uranium and then thorium-238 in a fuel cycle. The second one is solution of separation problem, volume minimization and final isolation, which are not applied now, radioactive products generated in the process of nuclear power industry functioning. Cycle closure will make it possible to ensure the most comprehensive use of natural nuclear resources (uranium, thorium) and artificial fissile materials generated during operation of nuclear reactors (plutonium, etc.) and RAW minimization.

Considering these factors, a substantial growth of demand for RAW disposal cannot be predicted. Until all possibilities of disposal on the Earth are exhausted, the variant of RAW injection into space will remain dead. Demand for RAW disposal in space may also arise due to implementation of some force-majeure circumstances (for example, a large-scale disaster related to traditional RAW storage facilities).

On the whole, demand forecast for HAW injection into space is negative. Despite this, there is a number of scientific organizations promoting such projects. The list of potential cooperation and customers of the project is given in section 6.

The attractiveness of market is also defined by absence of entry into a market obstacles. There are many legislative obstacles for HAW injection into space project, they are described in section 4. The superhigh environmental risk is also a significant obstacle for this project implementation.

Thus, the project of HAW injection into space, according to given estimates, is not competitive, unprofitable and has no perspective demand and also has a number of legislative and environmental obstacles for its implementation.

4 Legal issues of RAW disposal in space

The analysis of production and economic issues of the problem of long-lived and extremely hazardous RAW isolation in space shall be preceded by a thorough study of its international legal issues [105].

RAW injection into space due project features (space and radioactive materials) falls within jurisdiction of two international regulatory bodies: the UN and IAEA. It does not mean that international commitments related to, for instance, non-proliferation of nuclear weapon, environmental and sanitary norms and regulations are not to be complied with, features of national legislations are not to be considered. For instance, in Russia RAW injection into space is prohibited by law, thus, creating serious problems for provision of such services provision in cooperation with Russian enterprises, not mentioning the possibility of LV launching on the territory of RF, selection of LV flight path over its territory.

4.1 The United Nations Organization

The UN plays a major role in the policy of legal regulation of international cooperation in the exploration and utilization of outer space for peaceful purposes [33]. The retrospective of the UN participation in legislation of space activities allows to evaluate the scale of problems solved by the UN, and role of this organization during implementation of "RAW injection into space" project.

Existing regulatory framework in space area consists of intergovernmental agreements concluded back in the 1960-1970-ies. Then it implied that all space activities will be performed only by states. Such understanding had every reason: only large countries during that period could afford costly works for production of space objects and their operation, space activities were directly connected with national-security and defence interests. For commercial purposes results of space activities were not used. But in the end of the last century commercialization process of space activities started. Having seen benefits from use of space hardware and technologies, the private business joined in exploration of outer space. The state sector also started to pay more attention to commercial aspects of use of outer space for peaceful purposes.

Space industry revenues, which in the middle of the 1990-ies made up tens billions of US dollars, became the largest world economic branch. In 1996 commercial activity total revenues for the first time exceeded state expenditure on space. In the mid 2000-s annual world space market gain made up 30-40 bln. dollars [33].

Scales of international cooperation in space area grew. With participation of the UN special regional space science and technology centres were established. The first of them was constructed in India and is meant for Asia-Pacific Region (APR) territory. With assistance of the European Space Agency preparation activities were performed for establishing of the similar centre for Central Eastern Europe. International projects of space object launching were implemented. In 1998 construction of the International Space Station started. But the international legal regulation system of space activities was developing much slower than activities.

The United Nations Organization was dealing with peaceful use of outer space after launch of the first artificial Earth satellite by the Soviet Union in 1957 [33].

At present, organizations belonging to the UN system are implementing more than 200 projects and programs related to space activities. General Assembly of the UN annually adopts resolutions on international cooperation in space, considering its political and legal, scientific and technical aspects. These documents are adopted based on reports of the Committee for Special Political Affairs and Decolonization Affairs (the Fourth Committee) of the UN. General Assembly of the United Nations Organization regularly adopts other resolutions on separate issues of cooperation in space.

The UN Secretary General is authorized with a number of powers. His area of responsibility embraces collection and dissemination of information about space activities of states including data about phenomena constituting danger to life and health of astronauts and maintenance of register of launched space objects with free access to it.

Among special UN organizations participating in development of international cooperation in the exploration and utilization of outer space for peaceful purposes the following may be called: FAO (the Food and Agricultural Organization), ITU (the International Telecommunication Union), WMO (the World Meteorological Organization), IMO (the International Maritime Organization), ICAO (the International Civil Aviation Organisation) and UNESCO (the United Nations Educational, Scientific and Cultural organization). Within their competence they participate in space activities along such directions as use of remote sensing of the Earth from outer space technologies, telecommunications, satellite meteorology and space science.

In 1958 General Assembly of the UN established the temporary Committee on the Peaceful Uses of Outer Space. In 1959 it was reorganized into a standing body - the Committee on the Peaceful Uses of Outer Space. Initially, it included 24 countries, now its number has reached 67 states. The Committee consists of two subcommittee (scientific and technical and legal) and holds annual sessions. It acts as an organization centre of international cooperation in the area it covers.

In 1958, further to this committee, under the UN Secretariat Office for Outer Space Affairs was established (since 1993 its headquarters is located in Vienna). The Office performs double function: promotes discussions arrangement and helps developing countries use of space hardware and technologies.

The Committee makes decisions on a consensus basis, to reach it often becomes a problem. At the same time principle of unanimity is required for taking in account the interests of all participants in space activities.

The legal framework of cooperation in space area is defined by five large international documents. The first one, signed in 1967, is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty). This document, as of 1 January, 2007, was signed and ratified by 98 countries. 27 states signed it, but did not ratify.

The Outer Space Treaty rules a general legal framework of use of outer space for peaceful purposes and establishes frameworks for space law development. Clauses of this document define the necessity of exploration and utilization of outer space in the interests of all mankind on the basis of equality of states. The treaty provides for freedom of research in space and prohibits appropriation of outer space by states (including the Moon and other celestial bodies), conducting space activities in accordance with international law (including the UN Charter) prohibition of injection in the orbit, placement in space and installation on celestial bodies of objects with nuclear weapon or other types of mass destruction weapon, utilization of the Moon and other celestial bodies for peaceful purposes only. At the same time the Treaty of 1967 contains such provisions as:

- international responsibility of states for national space activities;

- international responsibility of states for damage caused by space objects;
- cooperation and mutual assistance of states in exploration and utilization of space;
- preservation of jurisdiction and control in space over space objects;
- commitment of states to avoid pollution of outer space.

Clause IX of the Outer Space Treaty establishes two interrelated commitment [105]:

- conduct activities in outer space with due consideration of relevant interests of all other states;
- study and utilize outer space and celestial bodies to avoid their pollution.

In international law the term "pollution" includes both intentional and unintentional actions entailing chemical, biological, radioactive an other kinds of environmental pollution in quantities endangering its natural balance.

Another important document, signed in 1968, "The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (Rescue Agreement). It was ratified by 89 countries. 24 countries signed this document, but did not ratify it. This document is a development of clause 5 of Outer Space Treaty providing for commitment to help astronauts in case of an accident, disaster or forced landing and to return astronauts and objects launched into outer space.

In 1972 the Convention on International Liability for Damage Caused by Space Objects (Liability Convention) was signed. This document for the first time regulated liability for damage caused by the activity not prohibited by international law. Namely: deprivation of life, bodily damage or other damage of health, property destruction or damage of states, physical and legal person or intergovernmental organizations. The amount of compensation is defined in compliance with international law and principles of equity recovering situation that would exist if the damage had not been caused.

In 1976 the Convention on Registration of Objects Launched into Outer Space (Registration Convention) was concluded. Before its adoption states sent data about their space objects to the UN by their own will, following the call of resolution No. 1721 (B) adopted by General Assembly of the UN as of 20 December, 1961. After the Convention had been adopted, delivery of such information became mandatory. This innovation was aimed at simplifying the identification process of space objects. Member states committed themselves to register all space objects launched from their territory and organizations conducting such activities.

In 1984 the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (the Agreement on the Moon), signed in 1979, came into effect. It was signed and ratified by 13 countries (four countries signed it, but did not ratify). After landing of American astronauts on the Moon in 1969, Poland and Argentina proposed their draft regulations related to human activity on the Moon and other celestial bodies. In 1972 the Soviet Union also presented draft Moon treaty to the United Nations Committee on Space. The difficulties in this document adoption and narrow circle of joined in countries are related with disagreement of many states to consider the Moon as "common heritage of the mankind". Respectively, there are different opinions regarding the idea of establishing the international operating mode and distribution of potential goods among states.

Clause VII, paragraph 1, of the Agreement says that in the process of exploration of the Moon and other celestial bodies member states shall take measures against imbalance of their formed environment caused by introduction of unfavourable changes or harmful pollution or by some other way. Owing to the last supplement, all actions able to cause such consequences may be prohibited.

The regulation sources of space activities may also be considered five resolutions adopted by General Assembly of the UN in different years. Some of them served as a "starting basis" for a number of above mentioned documents [103].

Processes in exploration and utilization of outer space require improvement of old and adoption of new standards of international space law. It may be solved by adoption of the comprehensive Convention on space law. Within its framework many goals would be achieved: confirmation of previously adopted agreements on space, adding legally binding character to the principles functioning on a recommendation basis today, liquidation of gaps in legal regulation.

The Convention supporters assert that the main acting principles of space activities may also be transferred into a new document. It may be ensured by the existing in the committee consensus principle in the process of decision making and also a "batch methods", according to which the decision on a question shall be coordinated with the decision on others. The precedents of IAEA or the International Atomic Energy Agency establishment prove that signing of universal "space" convention could lead to establishment of international space organization in the future.

Development of space transport systems and launching technologies allowed to develop aerospace objects that may be used in air space and outer space. In this connection the issue about the right for these objects to pass through air space of states. It was a matter of spacecraft movement, including shuttles on their route to space or back to the Earth.

Legal regimes of air space and outer space are not the same. Air space over dry territory of the state and its territorial waters falls under this state sovereignty with the national legislation applying to it. Outer space is used in the interests of all mankind and its legal status is regulated by international law.

The Outer Space Treaty does not define outer space. There is no boundary between air space and outer space fixes by international law. In December, 1966, General Assembly of the UN requested the Committee on the Peaceful Uses of Outer Space to study variants of the outer space definition. Most committee members are inclined to set a boundary between air space and outer space at the height of the spacecraft minimal orbit passing, that is 100-120 km above sea level.

The USA support a "functional" approach. In accordance with this approach, it is not necessary to set an agreed boundary between two spaces, it is sufficient to distinguish between aviation and space activities depending on the type of a spacecraft used. However, within the functional approach framework it is extremely difficult to regulate damage liability from space activities or prohibition on deployment of nuclear weapons in space.

Attempts to define a boundary between air space and outer space using indices of air density, presence of gravity or chemical compositions of gases in a certain volume of space were not supported.

Another circle of contradictions is s question of geostationary Earth orbit (GEO) utilization. It is a question of a circular orbit above the Earth's surface at about 35 870 km high, where a satellite orbit plane is parallel to the Earth's equatorial plane. The satellite, situated in GEO, is permanently accessible to ground stations. Three satellites in GEO are enough for maintenance of the global telecommunications network. That is why, a geostationary orbit is important to television broadcasting, communication and meteorology.

GEO belongs to limited natural resources and this fact generates debates about fair distribution of satellite location zones and their operating radio frequencies. The International Telecommunication Union deals with these issues. Clause 33 of the International Telecommunication Convention, 1982, defines that frequencies and orbits of geostationary satellites belong to the resources to be used efficiently and economically to ensure fair access for different countries with consideration of special needs of developing countries and geographical position.

In December, 1976, in Bogotá, the capital of Colombia, equatorial countries (Colombia, Ecuador, Congo, Indonesia, Kenya, Uganda and Zaire) adopted declaration on their national sovereignty prevalence for the Earth's geostationary orbit. They declared that GEO depends on the Earth's gravitational field and due to this fact corresponding segments of geostationary orbit shall be considered as extension of national territories they are situated over. Most developing countries supported the "necessity to consider interests of equatorial countries regarding geostationary orbit".

The USSR and then Russia, on the contrary, asserts that a part of outer space, where orbits of geostationary satellites lie, is inseparable from outer space as a whole. That is why, it falls under relevant provisions of the Outer Space Treaty of 1967, including the provision prohibiting national appropriation of outer space by no means. Accommodation of geostationary satellites in outer space by states does not imply any proprietary rights for respective points of satellite location or separate parts of outer space. The opinion that declaration of Bogotá contradicts the Outer Space Treaty prevails, but owing to absence of a clear definition and delimitation of outer space, the problem remains unsolved up to now.

Nuclear power sources (NPS) of two types are used in space activities. First of all, these are radioisotope generators based on conversion of ionizing radiation, irradiated during radioisotope decay, into various forms of energy. Besides, nuclear reactors, obtaining heat energy at the expense of control over uranium-235 fission reaction control.

Use of nuclear materials as a power source allows to perform long-lasting space flights and complicated operations in outer space. At the same time? their use is connected with NPS danger in case of accidents and collisions in outer space at spacecraft launch and landing.

Issues of NPS use were included in the agenda of Committee on Space for the first time after Soviet satellite "Kosmos-954) with a nuclear reactor on board had fallen on the territory of Canada in 1978. The USSR covered 50% of expenses spent by Canada for search and disposal of radioactive elements. Fortunately, the satellite fell in desert sparsely populated areas. 37.1 kilograms of spent nuclear fuel were, mainly, dispersed in the atmosphere with only grams reaching the earth surface.

In 1978 the Scientific and Technical Subcommittee of the Committee on Space formed a working group on NPS use on space objects. In 1981 it presented its recommendations to the International Commission on Radiological Protection (ICRP) about standards and regulations of radiological countermeasures during all phases of spacecraft flight.

As a result of complex preparatory work, the Committee on Space formulated recommendatory "Principles Relevant to the Use of Nuclear Power Sources in Outer Space" They were approved by the resolution of General Assembly of the UN on 14 December, 1992. These principles are under development now. From time to time these or those countries bring up issues of their necessary modification and addition.

Since the end of the 1990-ies the danger of spacecraft (including those with nuclear power sources on board) collision with space debris is increasing. In the report of the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU) and the International Astronautical Federation in 1988 it was noted that in the orbits of the Earth there are more than 3.5 bln. of technogenic space bodies more than 1 mm in size and total mass exceeding 3000 tons. According to data of the International Academy of Astronautics [104] as of 1998, out of 8600 objects located in near-Earth orbits only 500 may be considered as active.

The problem of technogenic contamination of outer space is often used in international negotiations practice as a method of competition. States are trying to dictate requirements to one another as for complying with standards of space activities, launches, fires of all. They regularly repeat their attempts to dictate their own standards as obligatory for all ones.

Environmental problem of outer space have been discussed since the 1970-ies. This problem may be solved only by efforts of the world community by means of cooperation of space states. Outer space is a unique resource and its utilization shall be performed in the interest of all countries. Nine of space states will not be able to solve the problem of outer space tehnogenic contamination independently because of financial expenses.

The Inter-Agency Space Debris Coordination Committee (IADC), existing in the present form since 1993, performs functions of one of international forums on issues relating to cooperation in all aspects of space debris problem. Great Britain, Germany, Italy, France, China, Russia, Ukraine, the USA, India, Japan and the European Space Agency participate in its activities. IADC efforts are aimed at consensus achievement regarding methods of outer space contamination reduction. The guidelines of this contamination reduction were developed, different countries adhere to them on a voluntary basis.

Recently, attempts have been taken to entrust the Legal Subcommittee of the Committee on Space with preparation of declaration concerning guidelines of space debris prevention, which would be legally binding by character. But due to absence of consensus, this issue is postponed. In February, 2007, the Scientific and Technical Sub-Committee of the Committee on the Peaceful Uses of Outer Space STSC) approved by consensus "STSC Guidelines on Space Debris Prevention". But these guidelines have not attained the status of legally binding ones.

In December, 1998, on the proposal of the European Space Agency, World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) of UNESCO formed a working group dealing with outer space ethics. It was entrusted with a task to formulate ethical principles that would help politicians make decisions regarding space activities. On 22 June, 2002 the relevant report was prepared. Its recommendations held a stringent, but not legal duty of states to apply established ethical principles at each stage of outer space research and utilizations.

Undoubtedly, ethics, morals and law are three interacting, closely related categories. Human activity is based on ethical principles, often transformed into legally binding rules. Ethics serves as a basis for legislation, particularly, during development of new types of activity and during interpretation and application of existing legal norms. But unlike legal norms, ethical norms are adhered to on a voluntary basis. Otherwise, the border between these two institutions is erased, thus, breaking strongly protocols of international law act adoption. These reasons stipulate differentiation of competence of UNESCO and the UN Committee on Space.

In the future UNESCO and COMEST will continue to study ethics of space activities and inform about results of their work. But it is still difficult to predict how the guidelines, developed by them. will affect law-making; legislation of the UN Committee on Space, the UN as a whole and outer space activity practice itself of states [33].

The analysis of above mentioned information with consideration of the UN precedents, shows that RAW injection into space requires solution of the following issues on the UN level:

1) Selection of launch base for LV with RAW launching. Not every country can provide its territory for launch (for example, Russia). If launches to be performed from the territory of Kazakhstan, it would be necessary to overcome legal restraints on RAW importation existing in many countries, which territories shall be crossed during RAW transportation, the RF, in particular. If LV launch site is of extraterritorial nature, this issue coordination in the UN may last for decades, there are precedents to prove it. By virtue of the effective consensus principle, it may be assumed with confidence that a positive consolidated decision on this issue is hardly possible.

2) The launch path shall be selected to cross the territories of the least possible number of states. Besides, danger of capsule with RAW with ND will necessitate to coordinate the flying mission with a majority of Earth's countries.

3) Highly toxic radioactive materials represent one of the mass destruction weapon type; their injection into space is prohibited. To apply it, no modification of complex will be needed: only change of the flying mission, entry of capsule with waste in the atmosphere in a ballistic path and provision of capsule with high-activity waste explosion over enemy territory. The fact that system of RAW injection into space may be used like this, will provoke utterly negative attitude to such project on the part of the world community and international organizations. Ukraine, as a state that abandoned nuclear weapon and joined non-proliferation regimes, in this case, may be accused of breach of the agreement. It is obvious that this fact requires new international legislation. Broad consensus on this issue is hardly possible.

4) RAW injection into space is, by definition, is a launching of garbage into space. This process is regulated by the UN norms and necessitates to coordinate flying missions and disposal orbits at top level. Most likely, the project international expertise will be required to ensure environmental safety. It will be very difficult to obtain its approving decision due to risks relate to occurrence of off-nominal situations in DO equipment, capsule destruction in case of collision with space natural or man-made objects.

5) The project ethical aspect due to not infrequent accidents of launch vehicles (including piloted ones) and tragedies of Three Mile Island, Chernobyl and Fukushima is steadily opposed by ecologists and community. It is difficult to expect other attitude of the UN on this issue.

In accordance with the Convention on International Liability for Damage Caused by Space Objects [36], signed by Ukraine, the following provisions shall be considered during project implementation:

clause 2. The launching State incurs absolute liability for damage caused by its space object on the Earth's surface or aircraft in flight;

clause 1 defines the terms used:

a) term "damage" means deprivation of life, bodily damage or other damage of health: or property destruction or damage of states, physical and legal person or intergovernmental organizations;
b) term "launch" includes launch attempt;
c) term "launching State" means:
  – the State that organizes or performs spacecraft launch,
  – the state providing its territory or facilities for spacecraft launch;
d) term "space object" includes components of space objects, its delivery facilities and parts.

clause 5, paragraph 1 "Whenever two or more States jointly launch a space object, they shall be jointly and severally liable for any damage caused", paragraph 3 "State from whose territory or facility a space object is launched is regarded as a participant in the joint launching.

Dispersion of highly toxic RAW on the Earth's surface will inevitably cause radiation contamination of the territory (more serious variant of Chernobyl zone). Radiation injury of population will cause diseases and death of a large number of people. According to [9], reactor accident with 32.7 kg of ^{238}Pu, by NAS estimates, can cause radiotoxic injury of up to 5 bln. people and only 450 g of ^{238}Pu, provided its uniform distribution, is sufficient to cause cancer of all people living on the Earth. Taking into account possible scale of catastrophe, it could develop into the damage worth tens, if not hundreds of billions.

Clauses 3 and 4 define liability for damage caused to space objects "elsewhere other than on the surface of the Earth".

RAW dispersion on orbits actively used by spacecraft could cause radiation damage of equipment leading either to useful life reduction, or performance loss.

The UN core document regulating now injection of radioactive materials into space is "The Principles Relevant to the Use of Nuclear Power Sources in Outer Space" [13]. They prove and specify the provisions stated above, define the procedure of information exchange about radiological danger, consultations, rendering aid and impose safety requirements, the essence of which is given in section 2.

Principle 3 shall be noted (Guidelines and Criteria for Safe Use), which is formulated as follows: "In order to minimize the quantity of radioactive material in space and the risks involved, the use of nuclear power sources in outer space shall be restricted to those space missions which cannot be operated by non-nuclear energy sources in a reasonable way"

Neither the Outer Space Treaty of 1967, nor the Convention on International Liability of 1972 do not contain requirements to provide insurance coverage of liability for damage that may be caused by the state space activities. This issue belongs to the competence of states. In accordance with national legislation of the USA and Great Britain, the term of insurance coverage on damage to third parties is a necessary element of licences to get permit for private companies to space activities. Development of space insurance requires establishment of new insurance funds - transnational pools (pool stocks) of space insurance, cooperative insurance (in this case, an insurer, spacecraft owner, its manufacturer and operating party take the risk).

4.2 The International Atomic Energy Agency

The problem of RAW isolation in space, besides international space law, relates to issues of international nuclear law [105]. IAEA contributes to this problem solution, it developed a number of recommendatory standards regarding different aspects of RAW management. Among examples - the Code of Practice on the International Transboundary Movement of Radioactive Waste, approved by General Conference of the International Atomic Energy Agency in September, 1990. It prescribes that RAW movement shall be performed only after obtaining of permission by all participating states with advance notification and with the consent of consigning, receiving and transit states.

The International Atomic Energy Agency (IAEA) is the main international organization dealing with radiation safety and, according to its statute provisions, is authorized to lay down safety regulations in consultation with the United Nations Organization and other special organizations. The central offices of the Agency are situated in Vienna. The main objective of the Agency is to "accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". IAEA coordinates efforts, taken in the whole world, to improve nuclear safety, radiation safety, transportation safety, radioactive waste safety and emergency preparedness.

IAEA performs to safety functions, described in its Statute (clauses III.A.6). These are:

1. development and adoption of safety standards for health protection from radiation effect;
2. support of these standards implementation by request of the member state.

IAEA developed a comprehensive complex of safety standards for nuclear power spheres, radiation protection, radioactive waste management and radioactive waste transportation. In some cases it was done in cooperation with other international organizations. These standards are updated from time to time to ensure their urgency as guidelines in application of modern methods aimed at achievement of high-level safety.

The Agency develops standards and rules that are usually considered by governments of the countries involved in operations with radiation and radionuclides. Let us remind that radiation safety legislation is a system of laws defining the policy of the state regarding safe use of nuclear power to population and environment and management its products, including radioactive waste. This principle of operation of a law includes use of specific numerical indices that may depend on specific conditions and change in time.

Development of safety standards is supervised by the following advisory bodies: the Safety Standards Advisory Group (SRAG); the Nuclear Safety Standards Advisory Committee (NUSSAC); the Radiation Safety Standards Advisory Committee (RASSAC); the Transport Safety Standards Advisory Committee (TRASSAC); and the Waste Safety Standards Advisory Committee (WASSAC).

Though safety control is a national responsibility, international standards and approaches to safety control contribute to achievement of coordination, ensure safe use of nuclear and radiation technologies and promote international technical cooperation and commerce. The standards also support states in the process of their execution of commitments. *One of the common international commitments is that a state shall not act in manner causing damage in the other state*. Specific commitments of contracting states are described in detail in the international conventions regarding safety. Internationally coordinated IAEA safety standards provide the verification basis for the states fulfilling these commitments.

According to clause III of its Statute, IAEA is authorized to lay down safety standards for protection against ionizing radiation and control the utilization of these standards in peaceful activity of nuclear sphere. Publication related to regulating activities, through which IAEA lays down safety standards and measures, developed by ICRP and INSAG, are issued in Series of IAEA safety standards. This series covers nuclear safety, radiation safety, transportation safety and waste safety.

By 2014 IAEA is going to introduce new rules nuclear materials protection. It is a question of the amendment to the Convention on the Physical Protection of Nuclear Material approved in 2005, but not ratified yet. The present test of the Convention regulates only international transportation of nuclear material, the amendment states its use, storage and domestic transportation. For now, 59 countries adopted the amendment, but 40 more countries shall adopt for it to come into effect [37].

4.3 Other international documents

In recent years the principle of international law was formulated – the principle of holding no damage to environment [105]. It is vested in a number of environmental agreements, in section 5 of Final Act of the Conference on Security and Cooperation in Europe (1975) and in Charter of Economic Rights and Duties of States. But its full formulation is given as one of the principles of the XXI United Nations Conference on the Human Environment (Stockholm Conference) of 1972: the states will bear the greatest burden for large-scale environmental policy and action within their jurisdictions or control ensuring their activities are of no harm to environment of other states or areas out of national jurisdiction.

Issues of nuclear environmental protection are regulated by standards of the Treaty Banning Nuclear Weapon Tests in the Atmosphere in Outer Space and Under Water (1963), the Nuclear Weapons Non-Proliferation Treaty (1968), the International Convention for the Safety of Life at Sea (1974) and the Protocol to this Convention (1978) (about operation of vessels with nuclear power installations), the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (1978), the Convention on Liability for Nuclear Material Sea Transportation (1981), the Convention on Nuclear Safety (1994), other international documents.

In particular, the Geneva Convention on the High Seas (1958) states that every State shall take measures to prevent pollution of the seas from the dumping of radioactive waste and cooperate with the competent international organizations in taking measures for the prevention of pollution of the seas or air space above, resulting from any activities with radioactive materials.

The Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal was adopted on 22 March in 1989 by Plenipotentiary Conference in Basel, Switzerland, as a response to the community protest after in the 80-ies in Africa and other developing world regions imported deposits of toxic waste had been found. The main objective of the Basel Convention is to protect human health and environment against harmful effect of hazardous waste. It covers a wide range of waste that was defined as "hazardous waste" considering their origin and/or composition and properties (clause 1 and annexes I, III, IV and IX) and two types of waste classified as "other waste" (domestic waste and ash, clause 1 and annex II).

In 1995 at the third meeting of Conference of the Parties (COP) the amendment to the Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal was adopted ("Prohibitive Amendment"). Prohibitive Amendment provides for export prohibition of all hazardous waste falling under the Convention of Hazardous Waste, that are intended for final disposal, reuse, recirculation and recovery from the countries listed in annex VII of the Convention (Parties and other states being members of OECD, EU, Liechtenstein) to any other countries. As of 1 January, 2011 Prohibitive Amendment has not come into effect. At COP-9 in 2008 the unofficial discussions started to determine the way that would allow Prohibitive Amendment to come into effect considering concern and need of all countries in this context.

Antarctic Treaty (1959) . prohibits radioactive waste dumping to the south of the 60th parallel of southern latitude.

The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) was devoted to purposeful disposal of hazardous (including radioactive) waste in the ocean. The Annex to the Convention defines categories of waste prohibited for dumping (waste with high level of radiation or other radioactive substances with the same level, defined by a competent international organization as prohibitive for dumping into the sea in terms of public health service), in Annex II - dumping of which requires special precaution (all other radioactive waste). The Convention does not regulate the disposal procedure of radioactive materials transported as cargoes.

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management was adopted on 5 September, 1997 and came in to effect on 18 June, 2001. It forms the legal framework of the international disposal project, if at least one participating countries signed this document.

According to the Joint Convention, RAW shall be disposed in the country of its origin, if this disposal complies with requirements of safe waste management. However, under certain circumstances, safe and effective RAW management may be performed within the framework of agreements providing for use of objects of one of the parties to a treaty with a benefit for other participants.

Clause 27 contains additional obligations of the parties conducting international transportation of spent fuel and radioactive waste.

RAW transportation is prohibited south of 60° of southern latitude and to the countries having no technical, legal or administrative resources for safe waste management. The country of origin shall take the waste back, if their transportation cannot be completed.

The procedural code of the International Transboundary Movement of Radioactive Waste (adopted on 21 September, 1990) overlaps provisions of clause 27 of the Joint Convention and facilitates its interpretation. The European Council Directive 92[3] Euroatom about organization and control of radioactive material transportation among countries of the European Community or outside its borders (adopted on 3 February, 1992, came into effect on 1 January, 1994) extends the force of clause 27 of the Joint Convention on all EU member states.

The Convention on the Environmental Impact Assessment in a Transboundary Context (ESPOO/IAEA Convention was adopted in spring, 1991, in Finland) states all partners shall perform the environmental impact analysis of certain operations of RAW management at the early planning stage and consult with one another regarding all large projects that may have a significant negative impact on environment of several countries. All RAW storage and disposal facilities fall under force of this document.

The European Commission proposes to adopt a set of mandatory principles of radioactive waste storage [15] for the European Union states. If the Commission's recommendations are approved, these principles will come into force as the minimal standards of RAW and SNF management in all 27 EU member states.

The key elements, given in the European Commission' recommendations, are as follows:

- The governments of the European Union member states shall develop and adopt the national legislation regarding radioactive waste management.
- The European Union will not set specific dates for the states concerning construction and putting into service of nuclear waste storage facilities.
- Separate countries may join their efforts and establish joint RAW and SNF storage facilities inside the EU. Removal of nuclear waste out of the EU will be prohibited.

The Euroatom proposal as for the Council Directive on spent nuclear fuel and radioactive waste management (the so called "Nuclear package") was for the first time published on 6 November 2002 in its final version - on 30 January 2003). According to the initial draft document, every EU state had to develop and approve a clear-cut program of long-term RAW management and its disposal, having determined the time frame of this program stage. This program could include RAW and SNF transportation to the other EU state or third countries, provided transportation is in compliance with the EU legislation. The disposal in stable geologic formations (granite, salt and clay formations) was considered as the safest and the most economically sound solution in management of high-activity and long-lived waste. Besides, the schedule of storage facilities putting into operation was quite tight.

The Euroatom proposal aroused many objections, first of all, against the unreal schedule. Some countries declared against the priority of regional storage facilities, others (Great Britain, in the first place) did not approve of the geologic disposal variant as a long-term SNF and RAW problem solution. As a result, the test changed and became a non-binding resolution. But in the EU attempts to develop the waste management directive are currently in progress.

4.4 The Ukrainian legislation

The Ukrainian legislation sees management of radioactive substances as their preprocessing, processing, conditioning, transportation, storage and disposal of radioactive waste. Radioactive waste disposal is seen as the a placing of radioactive waste in the object intended for radioactive waste management without intention to use it [10].

The following Laws of Ukraine may be named in the system of legal regulation sources of environmental protection against radioactive pollution: "About Waste" as of 05/03/98, "About radioactive wastes handling" as of 30/06/95, "About Environmental Protection" as of 25/06/91, "About High Threat Locations" as of 18/01/2001.

The intensive growth of space activities requires further legal regulation, in particular, of space environment protection problems. Such regulation may be performed by introductions of additions to already effective international legal documents and by adoption of new documents concerning RAW disposal in space problems. IAEA and the UN shall participate in this process. These issues require the national regulation too.

The implementation of RAW disposal in space concept is possible only internationally and requires, first of all, solution of legal problems. In addition to unsolved legal issues, there is a number of direct statutory bars for RAW injection into space. At present, RAW injection into space is possible, provided 100% of the injection system reliability is guaranteed; the launch is performed on the territory of the country generating RAW, the launch path passes over the territories of the countries participating in the project; 100% guarantee of RAW will not fall into the sea. At that, the UN document regulating now injection of radioactive materials into space, namely "The Principles Relevant to the Use of Nuclear Power Sources in Outer Space" will be violated. The RAW isolation in space is prohibited by the national legislation of many countries including the RF. Besides, the project is sure not to be supported by the general public and politicians.

5 Comparative evaluation of RAW disposal in space implementation variants

The concept of RAW disposal in space lies in the following procedure. SNF or high-activity products of its reprocessing are provided with multibarrier protection, thus, minimizing probability of their contact with biosphere in case of possible emergency situations and ensuring the acceptable radiation level on the protection outer surface. Afterwards, RAW in the combined containment shell is transported to the launch base and located on the launch vehicle final stage as a payload. Generally, the structures of the launch vehicle final stage are optimized (with consideration of multibarrier protection) to minimize probability of injected into space RAW contact with biosphere in case of emergency situations. The project emergency situations shall consider "the worst-case" scenarios like the carrier fire, explosion or combined failure of several safety systems during ballistic reel to the Earth due to faults at the injection phase. Finally, in case of accident-free space transportation, the capsule with RAW is delivered to the disposal site and left there for indefinitely long time.

For each stage of this process there is a number of acceptable variants of minimum technical solutions (MTS). There are many variants of disposal objects, disposal sites and methods of delivery. The purpose of this analysis is to minimize the number of combinations of possible variants for their further development.

5.1 Brief characteristic of minimum technical solutions

5.1.1 Disposal object

The spent nuclear fuel can be subject to radiochemical reprocessing to extract uranium and plutonium (they return to the nuclear fuel cycle) and several tens of radioactive isotopes demanded in science, engineering and medicine. Up to now, all methods of such reprocessing implemented on an industrial scale, generate a large amount of high- and low-activity waste. For instance, after reprocessing of 1 t of RAW, approximately 1 t of high-activity waste is generated (after concentration by evaporation and vitrification) and a small amount of low-activity RAW [6] A dry (gaseous fluoride) method of SNF reprocessing allows to get less high-activity Raw, about 0.3 t per 1 t of SNF, but it has not been implemented on an industrial scale yet.[7]

When developing concept of RAW disposal in space concept, the following may be considered as disposal objects:

- not reprocessed SNF after decay cooling and conditioning (variant A1);
- high-activity waste of SNF "wet" reprocessing method (acid technology, variant A2);
- high-activity waste of SNF "dry" reprocessing method (gaseous fluoride technology, variant A3).

5.1.2 Disposal site

RAW disposal site in space shall be complied with a set of requirements:

- guaranteed exclusion of located objects penetration into near-Earth space and the Earth's biosphere;
- stability during hundreds of thousands years;

- low risk of object destruction due to meteorite hazard;

The intermediate geocentric orbits shall ensure presence of object during at least 100 years without the risk of its fall on the Earth at the expense of deceleration in the upper atmosphere.

Six variants of possible disposal site were analysed in the studies related to RAW disposal in space. These are[4]:

- high geocentric orbit (variant B1);
- lunar orbit (variant B2);
- the Moon (soft landing, variant B3);
- the Sun(variant B4);
- heliocentric orbit at 0.85/1.15 a.u. from the Sun (variant B5);
- disposal outside the solar system (variant B6).

5.1.3 Method of delivery to disposal site

At present and in the nearest decades the only real method of RAW delivery to the disposal site in space is use of launch vehicles (LV). The main problems of this method are: it is difficult to ensure safety control during injection and high cost.

Development of alternative methods of delivery, at least, into the intermediate near-earth orbit. In particular, the possible use of a cable system[8] ("space lift") to deliver RAW in the near-earth orbit and its further reloading on the rockets for transportation to the disposal site. Though the low unit cost of delivery (as compared with LV) was announced, it is difficult to forecast the term of this system prototype appearance.

Nevertheless, within the framework of this report three methods of delivery are analysed:

- use of launch vehicles, one-launch sequence of delivery, when one LV is used for RAW transportation from the Earth's surface to the disposal site (variant C1);
- use of launch vehicles, multi-launch sequence of delivery, with RAW transfer into the near-earth intermediate orbit (variant C2);
- a combined sequence with cable (Space Lift) delivery of RAW to the near-earth intermediate orbit and with transfer onto LV for transportation to the disposal site (variant C3).

5.2 Comparison technique of variants

It is obvious by described above MTS (it is not comprehensive, though) that a number of its possible combinations (54) is too large for a detailed analysis at the stage of the concept development. That is why, we need a tool to reduce their number substantially by comparing a set of quantitative indices. The proposed comparison technique of variants is exactly a tool we need.

The technique is based on the expert estimation of variants according to five key criteria with their set covering to a certain extent all problematic issues of RAW disposal in space concept. The following criteria were selected:

- operational feasibility;
- risks;

- implementation period;
- cost;
- public acceptance.

Each MTS variant of disposal site and delivery method was evaluated according to each criterion by 100-point scale. A higher point corresponds to a higher degree of the variant preference according to the corresponding criterion. Then the points by every criterion were added. It was assumed that all criteria are approximately equal in terms of the variant general estimation. Let us consider this in detail for each criterion.

5.2.1 Operational feasibility

According to this criterion, nearly all MTS scored 100 points: they have been tested to a greater or lesser extent when resolving the tasks not related to RAW disposal in space. The only exception is a combined sequence with cable (Space Lift) delivery of RAW to the near-earth intermediate orbit and with transfer onto LV for transportation to the disposal site. As there is no prototype of the system key element for now (a cable with required length and strength), this variant scored 50 points: only the "rocket" part of this delivery method was tested.

5.2.2 Risks

In this case, technical risks of this or that MTS variant were considered. Other types of risks are reflected in other criteria.

Disposal object

All three variants of the disposal object are practically the same in terms of risk assessment regarding their direct operational feasibility. The first variant is worse (not reprocessed SNF) as large amounts of disposed RAW will require a large cargo traffic from the Earth into the orbit. In its turn, it increases the probability of emergency situations in comparison with other two variants. So the first variant scored 50 points, the second and the third ones - 100 points each.

Disposal site

The risks related to disposal site were calculated as a half-sum of points scored by each variant in terms of the site safety and delivery reliability to the disposal site. Safety of B3-B6 sites was estimated as 100 points, safety of B1 and B2 sites - as 50 points. The number of points R_d for delivery reliability for each variant of disposal site was calculated by formula

$$R_d = 100 - \frac{\Delta V}{\Delta V_{min}} \cdot \ln(\frac{T}{T_{min}}) \cdot K \qquad (5.1)$$

where ΔV – required velocity increment, km/s, ΔV_{min}=1 km/s; T – required system useful life for delivery to disposal site, days, T_{min}=1 day; K – estimated number of orbital manoeuvres.

Method of delivery

The risks related to method of delivery were calculated as a half-sum of points scored by each variant in terms of the delivery safety and reliability of the delivery method. The delivery safety reflects probability of a severe accident resulting in fire, LV explosion and/or ballistic return of RAW to the Earth's surface. In case of the ground launching 50 "demerit" points are subtracted, in case of the orbital launching - 25. If LV (one-launch sequence) is used, safety was estimated as 50 points, if LV (multi-launch sequence) is used - 25 points, if a combined sequence is used - 75 points. The delivery method reliability was estimated by the average statistical value of accident-free launches percent (for multi-launch sequence - by this value squared). For a cable system, the reliability of delivery into the intermediate orbit was taken as absolute.

5.2.3 Implementation period

The number of points S_t, scored by this or that MTS variant according to this criterion was calculated by formula

$$S_t = 100 - t \qquad (5.2)$$

where t is an estimated time of preparation for the variant implementation, provided full-scale operations, years. It was accepted the same for all variants (5 years), except for the last one, where the time needed for the cable system development is estimated as equal to 50 years.

5.2.4 Cost

The MTS variant with the minimum implementation cost got 100 points, the rest were estimated inversely to the estimated increase of costs.

<u>Disposal object</u>
Variant A1 (not reprocessed SNF) has the minimum estimated cost because only conditioning costs are required. Other variants require radiochemical reprocessing costs. At the same time, if variant A1 is used, the total costs for disposal increase greatly due to a large volume of cargoes transported to the disposal site. That is why, variant A1, despite its minimum own cost, scored 50 points, whereas two other variants - 75 points each.

<u>Disposal site</u>
The number of points P_i, scored by i-th variant according to this criterion, was estimated inversely to the required velocity increment for delivery to the disposal site and was calculated by formula

$$P_i = 100 \cdot \frac{\Delta V_{min}}{\Delta V_i} \qquad (5.3)$$

where ΔV_{min} = 4 km/s (high geocentric orbit, variant B1); ΔV_i – required velocity increment for i-th variant.

<u>Method of delivery</u>
The minimum estimated cost is provided by a combined method (variant C3). It is nearly two times less than for other two variants. Respectively, this variant scored 100 points, variants C1 and C2 - 50 points each.

5.2.5 Public acceptance

This criterion is rather specific. On the one hand, estimates, related to it, are the most subjective. In case with other criteria, it is possible to use technical or economic arguments and specific figures, not always reasonable though. There have been no serious studies as the public opinion regarding RAW disposal in space yet. On the other hand, the issue of hazardous waste management is rather sensitive for ordinary citizens and politicians, reasons of experts are often underestimated. It was clearly demonstrated by the problems with repository construction in Yucca Mountain, the USA[9], storage facilities for RAW in France[10] and a number of other examples.

Forming estimates according to this criterion, experts were proposed to estimate each variant of MTS from the points of view of the scientific community and ordinary citizens. The total point was equal to a half-sum of these estimates.

Disposal object
In table I estimates for disposal object are given.

Variant	Scientific community	Ordinary citizens	Half-sum
A1	5	25	15
A2	1	25	13
A3	70	25	47.5

Table I. Expert estimates of public acceptance of variants by disposal object

Disposal site
In table II estimates for the disposal site are given.

Variant	Scientific community	Ordinary citizens	Half-sum
B1	10	10	10
B2	10	20	15
B3	10	10	10
B4	20	50	35
B5	80	90	85
B6	80	90	85

Table II. Expert estimates of public acceptance of variants by disposal site

Method of delivery
In table III estimates for delivery method are given.

Variant	Scientific community	Ordinary citizens	Half-sum
C1	50	50	50
C2	50	50	50

C3	80	50	65

Table III. Expert estimates of public acceptance of variants by delivery method

5.3 Processing of results

To compare combinations of variants (in other words, variants of RAW disposal in space concept as a whole) the following sums of type were used:

$$A_i+B_j+C_k, \qquad (5.4)$$

where $i = 1...3$, $j = 1...6$, $k = 1...3$; A_i, B_j, C_k – sums of points scored by a corresponding MTS variant according to all criteria.

The results were summarized in the table, then sets of variant combinations close to the maximum and minimum by the number of points scored were separated.

First, let us present a summary table with results of estimates according to each MTS variant (table IV).

Variant	Estimation criterion					Sum of points
	III.I	III.II	III.III	III.IV	III.V	
A1	100	50	95	50	15	310
A2	100	100	95	75	13	383
A3	100	100	95	75	47.5	417.5
B1	100	72.2	95	100	10	377.2
B2	100	56	95	94.1	15	360.1
B3	100	72.9	95	66.1	10	344
B4	100	91.7	95	16.7	35	338.4
B5	100	76.9	95	89.9	85	446.8
B6	100	97	95	45.7	85	422.7
C1	100	72.5	95	50	50	367.5
C2	100	57.5	95	50	50	352.5
C3	50	85	50	100	65	350

Table IV. Quantitative estimation of MTS variants (section II) according to five criteria (subsections III.I-III.V)

Then let us give a summary table with sums of (4) type sorted descending for convenience.

Combination of MTS variants	Sum of points
A3+B5+C1	1231.8
A3+B5+C2	1216.8
A3+B5+C3	1214.3
A3+B6+C1	1207.7
A2+B5+C1	1197.3
A3+B6+C2	1192.7
A3+B6+C3	1190.2
A2+B5+C2	1182.3
A2+B5+C3	1179.8
A2+B6+C1	1173.2
A3+B1+C1	1162.2
A2+B6+C2	1158.2
A2+B6+C3	1155.7
A3+B1+C2	1147.2
A3+B2+C1	1145.1
A3+B1+C3	1144.7
A3+B2+C2	1130.1
A3+B3+C1	1129.0
A2+B1+C1	1127.7
A3+B2+C3	1127.6
A1+B5+C1	1124.3
A3+B4+C1	1123.3
A3+B3+C2	1114.0
A2+B1+C2	1112.7
A3+B3+C3	1111.5
A2+B2+C1	1110.6
A2+B1+C3	1110.2
A1+B5+C2	1109.3
A3+B4+C2	1108.3

Combination of MTS variants	Sum of points
A1+B5+C3	1106.8
A3+B4+C3	1105.8
A1+B6+C1	1100.2
A2+B2+C2	1095.6
A2+B3+C1	1094.5
A2+B2+C3	1093.1
A2+B4+C1	1088.8
A1+B6+C2	1085.2
A1+B6+C3	1082.7
A2+B3+C2	1079.5
A2+B3+C3	1077.0
A2+B4+C2	1073.8
A2+B4+C3	1071.3
A1+B1+C1	1054.7
A1+B1+C2	1039.7
A1+B2+C1	1037.6
A1+B1+C3	1037.2
A1+B2+C2	1022.6
A1+B3+C1	1021.5
A1+B2+C3	1020.1
A1+B4+C1	1015.8
A1+B3+C2	1006.5
A1+B3+C3	1004.0
A1+B4+C2	1000.8
A1+B4+C3	998.3

Table V. Quantitative estimation of MTS variants (variants of RAW disposal in space concepts)

As it can be seen from table V, difference between the maximum and minimum number of points, scored by MTS combinations, is about 23%. Let us analyse the first and the last ten combinations presented in this table.

It should be noted that because of a small difference in the number of points, scored by different variants of the delivery method (see table IV, variants C1-C3), all of them are included both in the first and the last ten of combinations. Ten combinations, scored the maximum number of points, includes two of three variants of the disposal object (A3 - SNF "dry" reprocessing waste and A2 - SNF "wet" reprocessing waste) and two of six variants of the disposal site (B5 - heliocentric orbit at 0.85/1.15 a.u. from the Sun and B6 - disposal outside the solar system). All combinations of the last ten include variant A1 of the disposal object (not reprocessed SNF) and the remaining four variants B1-B4 of the disposal site.

Not considering the obtained results as absolute (they reflect the RAW disposal in space concept of the limited number of experts), it should, nevertheless, be noted that the number of MTS variants was reasonably reduced from initial 12 to 6-7, the number of their combinations - from initial 54 to 8-12.

References

1. Katernyak L. Biosphere Purification: waste disposal in space. Nauka i Zhizn', 1994, No. 3, p.p. 22-24
2. Nuclear Waste Disposal in Space. NASA Technical Paper 1225, 1978
3. Analysis of Space Systems. Study for the Space Disposal of Nuclear Waste. Study Report on Contract NAS8-33847, 1981
4. Gafarov A. Perspectives of Extremely Hazardous Nuclear Waste Disposal in Outer Space. Bulletin on Nuclear Power, 2002, No. 11, p.p. 26-30
5. Degtyarev A. Problematic Issues of Radioactive Waste Injection into Space. Space Science and Technology, 2014, Vol.20, No.1, p.p.58-67
6. Menshikov V., Iakimets V. Spent Nuclear Fuel: Scales and Problems. In: Nuclear Encyclopedia, ed. A.Yaroshinskaya, Moscow, 1996, p.p.60-65
7. Sokolovskiy Yu. S. Gaseous Fluoride Technology in Nuclear Fuel Cycle. http://www.proatom.ru/modules.php?name=News&file=article&sid=1167
8. http://en.wikipedia.org/wiki/Space_elevator
9. http://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository
10. http://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.html

6 Possible cooperation and potential customers

The high cost of RAW disposal in space affects substantially on the possibility of its implementation. To be implemented. the project requires deeper and more convincing arguments.

The public opinion regarding RAW injection into space concept is definitely negative in the whole world. Politicians, as a rule, are not inclined to risk their careers for unpopular decisions.

At the same time, a number of scientists today do not see the reasons why not earn money on waste processing [54]. Like all other high technologies, this process is not accessible to all states. This fact allows to expect excess profits gained owing to the monopoly activity.

That is why, for this project implementation scientific organizations dealing with RAW problems may be considered as potential partners and organizations dealing with RAW disposal - as potential customers. The latter may at the same time act as the project partners. The list of potentially interested partners is given in table 6.1.

Table 6.1 – Organizations/enterprises - the project potential partners and customers

Countries	Organizations/enterprises	Type of activity
	IAEA	
	the UN	
	International Academy of Astronautics	
	International Astronautical Federation	
EEC	Euroatom	
USA	Los Alamos National Laboratory	wide-ranging research organizations of nuclear power industry
	Sandia National Laboratory	
	Livermore National Laboratory	
	Department of Energy	responsible for majority of SNF/RAW management operations for state-owned enterprises
	Nuclear Regulatory Commission	regulates commercial enterprises and fuel cycle materials, bears responsibility for licensing of commercial enterprises dealing with nuclear waste management
		independent enterprises dealing with SNF management and planned storage facility in Yucca Mountain
	Environmental Protection Agency	
	Nuclear Waste Fund	identification, development, licensing, construction, operation. decommissioning, maintenance after decommissioning and control of every waste storage facility or enterprise, including pilot or test plants, research and development, RAW disposal program management transportation, processing and packing of SNF or HAW located in a storage facility

Table 6.1 (continued)

Countries	Organizations/enterprises	Type of activity
Great Britain	Nuclear Decommissioning Authority, NDA	Nuclear Decommissioning Authority, NDA Control domestic market of radioactive waste management
	British Nuclear Fuels Limited (BNFL)	SNF commercial reprocessing;
	Health and Safety Executive (HSE)	
	England and Wales Environment Protection Agency (EA)	
	Scottish Environment Protection Agency (SEPA)	
	United Kingdom Atomic Energy Authority (UKAEA)	
	Nuclear Responsibility Fund	
	Committee on Radioactive Waste Management (CoRWM)	provides recommendations on the best variant or combination of variants of long-term HAW management in Great Britain
	"Nirex" company	bears responsibility for RAW management, provides services for waste disposal
France	Electricite de France	Finances program of decommissioning and recovery of nuclear heritage facilities
	state organization ANDRA	is authorised for management of all RAW generated by nuclear power industry, war industry and small users
		Management of storage facilities, design, arrangement and construction of new storage facilities
	Atomic Energy Department (DEN) of Atomic Energy Commission (CEA)	Manages operations performed by various commercial and state enterprises
	Corporation "Cogema"	provides services for SNF reprocessing of electric energy facilities, commercial SNF reprocessing
	group "Areva"	the only shareholder of "Cogema" corporation, has reserves for management waste of all categories that have not been disposed
	Regulatory authority of nuclear safety, joint authority of Departments of Industry, Health and Environment	control and management in the sphere of SNF and RAW
	Energy and Raw Materials Directorate General Federal Radiation Protection Agency (BfS)	bears responsibility for SNF/RAW management
Germany		bears responsibility for construction and operation of enterprises involved in nuclear waste management

Table 6.1 (continued)

Countries	Organizations/enterprises	Type of activity
	Federal Ministry of Environmental Protection (BMU)	licensing and control of nuclear enterprises
Canada	NWMO	Nuclear Waste Management Organization
	Canadian Nuclear Safety Commission	bears responsibility for regulation of atomic energy and nuclear materials use
	The government Department "Natural Resources of Canada" (NRCan)	bears responsibility for development and implementation of the government policy regarding management of uranium, nuclear
		energy and RAW. Provides LLRWMO financing and controls its policy in RAW management sphere
	LLRWMO	organization of low-activity RAW management and acts as a national agent on issues of purification and management of Canadian "historical waste"
	Atomic Energy Community	
	Department of Health and Environment Affairs	
	Environmental Assessment Department	
Sweden	Nuclear Waste Fund	
	Nuclear Power Inspectorate (SKI)	
	Swedish Radiation Protection Authority (SSI)	
	SKB company	bears responsibility for SNF and RAW management, their transportation and storage outside nuclear enterprises, planning and construction of all enterprises required for SNF and RAW management and also for research and development programs for above mentioned enterprises.
Japan	Centre of research facilities and financing of RAW management	manages Fund established for SNF reprocessing
	Nuclear Waste Management Organization	is a performer of HAW disposal procedure
	Atomic Energy Commission	plans, discusses and makes decisions on the state policy in the sphere of nuclear power use
	Nuclear Safety Commission	plans, discusses and makes decisions on policy of safe use of nuclear power
	Nuclear and Industrial Safety Agency of Ministry of Economy, Trade and Industry	
	Office of Science and Technology Policy of Ministry of Education, Culture, Sports, Science and Technology (MEXT)	

Table 6.1 (continued)

Countries	Organizations/enterprises	Type of activity
Russia	State-owned corporation "Rosatom" (the Russian Federal Atomic Energy Agency)	It is authorized with functions and authorities of the state body in the sphere of RAW management
	JSC "FSUE "Izotop"	the authorized organization of the branch for performance functions as a unified operator of isotope production of general and medical purpose and a number of adjacent branches
	FSUE "NO RosRAO"	National operator of radioactive waste management. Established on the base of specialized integrated plants "Radon"
	All-Russian Scientific Research Institute of Industrial Technology of Ministry of the Russian Federation for Atomic Energy (VNIPIP)	Developer of Russian concept of RAW and SNF underground isolation in permafrost formations
	FSUE "All-Russian Research Institute for Applied Physics and Automation of the Russian Federal Atomic Energy Agency" (VNIITFA)	Develops SNF reprocessing technologies, developer of the radioisotope thermoelectric generator
	FSUE "Production Association "Mayak"of the Russian Federal Atomic Energy Agency (PA Mayak)	Develops SNF reprocessing technologies, SNF chemical reprocessing plant, produces isotopes
	State Enterprise "Siberian Integrated Chemical Plant"	Develops SNF reprocessing technologies, produces isotopes
	FSUE "Special Transportation Base" of the Russian Federal Atomic Energy Agency	Deals with RAW transportation
	FSUE of Nuclear Navy of RF Ministry of Transport ("Atomflot")	
	FSUE Production plant "Zvyozdochka"	
	Krasnoyarsk Integrated Mining and Chemical Plant	Develops SNF reprocessing technologies
	FSUE "Scientific Production Association V.G. Khlopin Radium Institute"	Develops SNF reprocessing technologies
	JSC "Academician A.A. Bochvar All-Russian Research Institute for Inorganic Materials" (VNIINM)	Develops SNF reprocessing technologies
	FSUE "All-Russian Scientific Research and Design Institute for Energy Technology" (VNIPIET)	Designs RAW storage facilities, standards
	JSC "Sverdlovsk Research Institute of Chemical Machinery"	
	FSUE Russian Research Centre "Kurchatov Institute"	The leading scientific centre of Ministry of the Russian Federation for Atomic Energy
	Atomic Reactor Research Institute (NIIAR)	Develops SNF reprocessing technologies, transmutation technologies, produces isotopes

Table 6.1 (continued)

Countries	Organizations/enterprises	Type of activity
	RAS Institute of Atomic Energy Safe Development (IBRAE)	
	Russian Aviation and Space Agency	
	Russian Academy Of Sciences	
	Institute of Chemical Physics (RAS)	
	Central Institute of Physics and Technology of RF Ministry of Defense, Sergiev Posad	
	Federal Nuclear Centre (VNIIEF)	
	FSUE All-Russian Scientific Research Institute of Chemical Technology (VNIIHT)	
	Central Research Institute of Mechanical Engineering	performed studies of RAW injection into space in the 1990-ies
	SLS "S.P Korolev Rocket and Space Corporation Energia	in 1996 feasibility study of RAW disposal in space was developed
	SRC FSUE "Keldysh Centre"	Developer of space NPPS, performed studies of RAW injection into space in the 1970-ies
	FSUE "Krasnaya Zvezda"	Developer of space NPU and TG
	N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET)	Developer of space NPU
	SRC A.I. Leipunsky Institute of Physics and Power Engineering	Developer of space NPU
	JSC "MDO "Iskra"	Developer of engines, CS, ERS devices and assemblies
	Tomsk Polytechnic University	Prepares specialists for RAW management
Ukraine	Ministry of Fuel and Energy	
	Ministry of Emergency Situations	
	National Space Agency of Ukraine	
	RI AUS	Developer of parachute systems
	NASU	
	NASU Institute of Nuclear Research	
	NSC KIPT	

These partners are not enough for the project implementation as the specific nature of project requires to attract organizations dealing with research and development of measures to be in compliance with social and economic and environmental requirements. If these works are not performed it may result in reduction of technogenic systems reliability and increase of probability of RAW emissions in the biosphere. In this case, it may be considered as unmanageable, non-localizable and non-neutralizable global technogenic catastrophe with negative effects for humans and biosphere [101].

The consequences will inevitably lead to enormous social costs for compensation for all kinds of damage, losses due to destruction or transformation of interindustrial complexes based on utilization of natural resources in the zones of emergency pollution. It will discredit not only the concept of RAW disposal in space for a long time, but also the very existence of structures related to project implementation, public reaction initiation aimed at curtailment of economic activity in RAW injection into space and use of radioactive substances as a whole.

7 Project SWOT analysis

The analysis of strengths, weaknesses, opportunities and threats for a project (SWOT analysis) is one of the required components taken into consideration by the Performer and the Customer at the project preliminary stages. It allows to make decision regarding practicability of the project development, identify operations requiring special attention, select the right implementation strategy, make amendments to the existing implementation plans.

Table 7.1 – SWOT-analysis of "RAW injection into space" project

Item No.	Project Weaknesses
1.	The project has not been worked out in terms of long-term effects. All consequences of project implementation are not predictable. For example, RAW escape outside biosphere may disrupt the energy and material balance in the biosphere. Extraction of radioactive substances and, finally, different types of energy, spent in the whole chain of RAW generation, from the energy balance of the Earth natural system of planetary level and their disposal in space may lead to reversible or irreversible changes of its state. In terms of possibility of human activity organization (including RAW disposal) space is finite and limited by sized, negligible as compared with space as a whole. Therefore, the analysed case does not belong to "arrangement of the finite in the infinite" category, but to "arrangement of the finite in the finite" category. RAW in space has all chances not to be dispersed in infinity, but concentrated in the finite space, thus, disrupting existing balances of matter and energy. It is necessary to find out the possible consequences of RAW contact with plasma in near-Earth space and analyse if disposed into space RAW remain localized without spreading farther. RAW transfer in space belongs to the type of "RAW disposal" using the method "open dump". Consequently, this transfer does not solve "RAW problem", but only postpones it. At the start of space activities used satellites in the orbit of the Earth were not considered as space debris. That is, in the future the space dump of RAW may become a problem to the mankind. There are concerns that "turning of space in a "radioactive dump" may impede further development of astronautics". In time, RAW in space may become a real threat to astronauts and spacecraft. RAW in space may penetrate in the zone of potentially possible contacts with humans, where radiation effect and its consequences for a living organisms may appear different as compared with natural conditions on the Earth. RAW storage on the Earth provides future extraction of valuable components and reprocessing of others by transmutation methods.
2.	High cost and unprofitability of the project. The cost of 1 t of RAW disposal is not less than 100 times more expensive as compared with the geologic disposal. There is no state able to finance the whole set of actions related to RAW disposal in space independently.
3.	Superhigh risks of processes of RAW removal from the Earth's surface. In case of fire at launching site, the outer shell of the container will melt in the oxygen medium with subsequent HAW escape into the atmosphere. The structure of capsule and container with RAW, as SC element, is not intended for long-term storage. That is why, being disposed in the sea, diffusion of 129I will occur rather quickly. It is obvious that capsule destruction in case of fall will accelerate this process. As iodine is well soluble in water, poisoning of marine flora and fauna is possible on a global scale. Due to vapours, large land areas will be contaminated in time. New forms of insurance funds are required. High cost of insurance policy of the payload launch services.

Table 7.1 (continued)

Item No.	Project Weaknesses
4.	Absence of a number of key technologies and infrastructure required for the project implementation, extremely high cost of their development absence of infrastructure, RAW safe interim storage and transfer at subordinate enterprises; need of a special regime introduction at LC (radiation situation control, radiation monitoring, division in zones, access control, personnel, equipment and structures decontamination, radiation monitoring and control of environment condition, control and measurement instruments and equipment for radiation monitoring); a large volume of experimental development requiring significant costs for further international certification (capsule and container testing, development of RAW management methods, development of emergency situations); verification of the project safety requirements will demand to perform numerous tests for development of nominal and emergency situations. It includes not only ground tests, but also LV launches; absence of radiochemical technology of isotope ^{129}I extraction. High cost of design and organization of radiochemical plant for extraction of HAW isotopes (^{129}I); high cost of design and organization of immobilization, RAW conditioning and container fitting; SNF reprocessing is related to generation of a large amount of radioactive waste. Separation of high-activity long-lived RAW to be transported into space from the general mass of RAW is a potentially dangerous operation as it will require to transform into gaseous state, when reliable equipment pressurisation and remote service will become necessary.

Item No.	Project Strengths
1.	The project provides for RAW removal from the Earth's biosphere for good. The biosphere is not able to assimilate all RAW generated by the mankind. The "eternal" isolation inside biosphere from the biosphere is not possible, so RAW impact on the environment cannot be excluded. In case of "eternal" controlled RAW disposal on the Earth principles are broken regarding their protection against harmful effects and putting on them an excessive economic burden. RAW disposal in space solves these problems (not entirely though)

Item No.	External threats to project implementation
1.	Legislation obstacles of project implementation, lack of proper regulation in international legislation of a number of provisions that are important to the project. The situation becomes complicated due to the consensus principle effective in the UN and IAEA. RAW isolation in space is prohibited by the law in a number of countries, including Russia; There is a complicated regulatory approval system related to RAW transportation (licenses, political agreements, environmental standards, public relations, etc.); RAW, injected into space, may be used as MDW and it contradict international legislation. Settlement of this issue has to do with substantial organizational and financial costs or impossible in principle; Compensation for damage to the affected party and in compliance with international law is put on project participants. Ukraine does not have such finances.

Table 7.1 (continued)

Item No.	External threats to project implementation
2.	There is no demand for RAW injection into space services and it is does not seem to arise. Theoretically, not so much radioactive waste is generated in the world [54]. The specialist have already calculated: if the world volume of spent nuclear fuel from power generation during a year is reprocessed, only 1000 cubic metres of high-activity waste in vitrified state generate. And if it is not that much, it is better to collect and dispose nuclear waste in one very reliable place, thus, ensuring safety of waste and environment.
3.	The negative attitude to the project on the part of specialists, the community and politicians Specialist of nuclear power industry and nuclear engineers do not show any interest to this project, but the negative attitude to RAW injection into space is present. Many experts think that the modern technology level of SNF chemical recovery does not comply with the environmental safety requirements, so it is advisable to place spent fuel units in long-term storage; The project will not appeal to the general public and political leaders due to extreme danger for the mankind and ethical considerations.
4.	Threats on part of terrorist organizations for whom the project is a very attractive target
5.	Threats on part of acts of nature - extreme weather conditions, earthquakes. Realization of these threats at many stages of the project implementation may lead to global catastrophic consequences
Item No.	**External opportunities for project implementation**
1.	There are organizations interested in the project implementation and they are ready to become partners.
2.	The project implementation is possible, provided all other disposal methods are no longer present or in case of a large-scale accident at conventional RAW storage facilities.

As it can be seen from table 7.1, the list of problems to be solved prior to design work, is quite wide and is as follows:

1) legislative and legal;

2) commercial unattractiveness of the project;

3) no motivation for the Customer;

4) environmental risks;

5) high commercial risks;

6) new insurance funds are required;

7) no necessary radiochemical technologies;

8) lack of convincing arguments in favour of project safety for public and specialists;

when the previous issues for the project implementation have been solved, it will require a wide information support for interaction with the public.

8 Problematic issues

So far, RAW injection into space is not a project able to convince the society in its necessity and, what is more important, in safety of this method of RAW disposal. That is why, problematic issues shall be settled, project weaknesses be managed or the decision about complete or temporary abandonment of project implementation.

This task cannot be solved without involvement of specialists familiar with RAW problems in the project analysis (physicists, chemists, power engineers, nuclear engineers, etc.), ecologists, specialists in international law, military theorists, etc.

For a start, with their assistance the possibility to solve macro-problems shall be theoretically defined and further strategy to be worked out. The macro-problems are described in section 7. Then, on positive solution, it is necessary to find the Customer interested in the project implementation and having necessary financial resources or able to attract them on acceptable terms. The perfect option would be to form the pool of such customers. And in cooperation with them the program of problematic issues solution shall be formed. In present situation, it is assumed that the following lines shall be included in the cycle of studies related to the concept of radioactive waste disposal in space:

1. study of composition, chemical and physical properties of specific RAW to be injected into space;
2. development of requirements for documents and licensing of RAW management;
3. performance of research in long-term effect of the outer space on RAW - study of solar wind interaction with dispersed RAW, effect of the outer space conditions on RAW degree of spreading, study of possibility of dispersed RAW penetration in atmospheres of planets, including the Earth;
4. study of interaction of man-made space objects with dispersed RAW;
5. theoretical study of possible RAW escape into the solar system periphery;
6. study of required organizational and technical measures related to RAW concentration in the locations not intended for its collection and storage (launch bases);
7. clarification of issue on localization of RAW, disposed in space, and its non-spreading. The danger level of concentration of extremely hazardous RAW in separate areas of outer space in case of DO destruction.
8. selection of container, issues of RAW material compatibility with the container material, issues of the container useful life;
9. technology development of the radiochemical extraction of I-129 from SNF;
10. selection of I-129 immobilization method and technology;
11. study of possibility for counteracting in off-nominal situations in case penetration of extremely hazardous RAW in the Earth's biosphere;
12. development of SLS and DO able to ensure safe injection;
13. development of joint for DO and rescue technology for counteracting in off-nominal situations in the near-Earth orbit impeding the flight program to the disposal orbit;
14. study the possibility of SLV "Zenit-3SLBF" use for RAW injection with a "space tug";

15. performance of a range of works to ensure compliance with safety requirements. Development of a range of activities to liquidate consequences of emergency situations at each project stage. Development of activities for project protection against terrorist attacks and extreme acts of nature;
16. study of parameters of aerodynamic, heat and impact loads affecting the capsule and container with RAW in different off-nominal situations;
17. performance of experiments verifying the ability of the aerodynamic capsule to withstand impact loads;
18. modelling of situations related to fire at launch, storage, transportation for safety evaluation;
19. works aimed at international law adaptation, acknowledgement of the project peaceful character at the world level. Development and implementation of a range of activities to provide peaceful utilization of infrastructure and instrumentation within the project framework. Promotion of international cooperation, ensuring support of the public and politicians.

Prior to RAW disposal in space concept implementation, it is necessary to have a clear vision of future scenarios and calculate possible consequences of this action in the maximum number of variants. Only with having firm confidence in practicability, possibility and safety of this project implementation, it makes sense to promote it at the market.

Thus, the project of RAW injection into space is not commercially attractive at present. To prove its feasibility and safety, large-scale and expensive scientific research shall be conducted.

Conclusions

1 The technology of a part of RAW disposal in space (less than 1% of spent nuclear fuel mass) may serve as a supplement, not a substitution of existing technologies of RAW disposal in deep geologic formations.

2 Selection of isotopes for space disposal is objectively a complicated scientific problem that has not been addressed by specialists of the nuclear industry yet. This task does not have an unambiguous solution.

3 The circular heliocentric orbit with radius about 1.15 a.u. may be considered as a disposal orbit. (outer relative to the Earth orbit). Masses of payload delivered by one and the same vehicle into this orbit, into equivalent orbit with radius of 0.85 a.u. and orbits corresponding to stable libration points of the Sun-Earth system are close (with difference less than 5%).

4 Duration of RAW injection into the disposal orbit is 7.2 months. (1.15 a.u.), 6 months. (~0.85 a.u.), 1.85 year (libration points). Therefore, to provide DO monitoring and control at all flight sections, its design shall comply with standards accepted for SC, with consideration of special requirements for aerodynamic capsule.

5 The mass expenses required for implementation of safe RAW delivery into the disposal orbit (aerodynamic capsule, emergency recovery system and supporting systems) are about 5 tons. The vehicle ability to deliver into the disposal orbit the payload of higher mass defines the limit mass of a sealed power container with RAW. For perspective heavy vehicle "Mayak" the mass of a sealed power container with RAW will make up about 10 t (with total mass of the payload delivered into the disposal orbit - about 15 t). For vehicle "Zenit-3SLBF" the total mass of the payload delivered into the disposal orbit is about 2300 kg.

6 Technically it is impossible to ensure 100% safe RAW delivery into the disposal orbit. The scenario, when high-activity, high-diffusion and highly toxic RAW penetrate in the biosphere cannot be excluded altogether (for example, in case of non-project accident or terrorist actions). The possible damage cost may exceed the equivalent value for NPP accidents.

7 The isotope composition of not injected into space RAW affects greatly the requirements for a sealed power container. Depending on radiation characteristics of isotopes, the shell thickness of a sealed power container shall be from 37 to 420 mm of steel. Respectively the weight of RAW delivered into the disposal orbit by one launch of perspective heavy vehicle "Mayak" may vary from 2969 kg to 35 kg.

8 Optimistically estimated cost of 1 t of RAW disposal in space (delivery into the disposal orbit of 2969 kg of RAW per one launch, costs for RAW radiochemical reprocessing, conditioning and immobilization are not considered) at least two orders higher than the cost of the most expensive variant of underground disposal of 1 t of RAW in deep geologic formations.

9 The present international legislation and contractual framework (at the level of the UN, IAEA, multilateral treaties and agreements, national laws) regarding utilization of outer space and RAW management leaves unsettled the issue of a country or a group of countries competence to perform space launches of launch vehicles with concentrated radioactive waste on board and location of this RAW in this or that zone of outer space. A number of provisions of these documents contain express prohibitions or limitations for performance of certain actions required for implementation of RAW space disposal.

Sources

1 Radioactive Waste and Nuclear Power Industry - Together Forever. Washington ProFile, 2007.

2 Yu.G. Cherkashin, RAW Disposal Near the Sun's Surface, "Atomnaya Strategiya", No. 13, September, 2004.

3 Yu. V. Dublyanskiy. Radioactive Waste Disposal: Problems and Concepts in the USA and Russia. http://modernproblems.org.ru/ecology/31-radioact.pdf

4 V. E. Minenko, V. Yu. Koloskov, Systems of Radioactive Waste Disposal in Space, collection of articles "Kosmos, Vremya, Energiya. Collection of articles issued to D. D. Ivanenko 100th birthday" - M.:"Belka", 2004.- 415p.

5 M. Zh. Muhamedzhanov, S. V. Chekalin. Perspectives of space isolation of extremely hazardous nuclear waste. Novoe v zhizni, nauke, tehnike. Subscription popular science series "Kosmonavtika, Astronomiya, Kosmos i Ekologiya: (Collection of articles), 7/1991.

6 Yu. Mozzhorin, Radioactive Waste - into Space?

7 Report on ESA research contract. Subject WP3000. Criteria of the Earth's Biosphere and Environment Safety Evaluation, Requirements to "Earth-Orbit" Launch and Container with Waste. Yuzhnoye SDO, 2006.

8 A. A. Gafarov "Perspectives of Extremely Hazardous Nuclear Waste Disposal in Outer Space", Bulletin on Nuclear Power, 2002, No. 11, p.p. 26-30

9 V. Volkov, I. Ostretsov. "Into Space without Plutonium". 2012.

10 O. Yu. Kronda. Legal Problems of Radioactive Waste Disposal, KNU, MSU, http://lomonosov-msu.ru/archive/Lomonosov_2009/

11 Radioactive Waste. Collection of Facts, Washington ProFile, 2007. http://nuclearno.ru/

12 L. Popov Hybrid Reactor Will Destruct the Most Hazardous Nuclear Waste, 2009 http://www.membrana.ru/

13 "Principles Relevant to the Use of Nuclear Power Sources in Outer Space, Resolution of the General Assembly 47/68, 1993.

14 Where To Nuclear Waste Go, http://trial-news.ru/2980-kuda-devayutsya-yadernye-otxody.html

15 Main Recommendations of the European Commission Regarding RAW and SNF', http://www.atominfo.ru/news3/c0705.htm

16 General Electric Called on the US Congress to Support Fuel Cycle Closure, http://www.atominfo.ru/news/air6943.htm

17 M. Kormilitsyn, SNF is a Market Worth 300 Billion Euro, http://www.atominfo.ru/news/air5967.htm

18 A. B. Zheleznyakov Into Space - with Nuclear Plant. 2005.

19 SNF Recycling - Old Technologies and New Options, www.anl.gov

20 A. Berezin. Radioactive Waste Will Make Thorium Reactors Cheaper, Annals of Nuclear Energy.

21 Mathew Wald. What Is To Be Done With Nuclear Waste?, V Mire Nauki, No. 10. October, 2009.

22 Hannum U, Marsh D., Stanford D. How To Use Nuclear Waste // V Mire Nauki, No. 3, 2006.

23 Hippel F. Nuclear Fuel Disposal // VMN, No. 8, 2008

24 The Energy Strategy of Russia Up To 2030, 2009.

25 AtomInfo.Ru

26 IAEA website, http://www-pub.iaea.org/MTCD/publications/

27 http://www.izvestia.ru/news/519450

28 http://www.ibrae.ac.ru/

29 http://www.strf.ru/

30 A. A. Klyuchnikov, E. M. Pazuhin, Yu. M. Shigera, V. Yu. Shigera. NPP Radioactive Waste and Methods of Their Management, edited by Yu. M. Shigers, Chernobyl, NASU NPP IPB. 2005
31 Wolfgang Neumann. Disposal of Nuclear Waste in the European Union: Growth of Volumes and No Solution, Voronezh. 2011 – 68 p.
32 GOST R 51824-2001. Non-Retrievable Shielding Containers for Radioactive Waste Made of Concrete-Based Structural Materials. General Performance Requirements. Committee of the Russian Federation for Standardization, Metrology and Certification.
33 A. Krutskih. Space in Political Plane, Journal "Mezhdunarodnye Processy", Volume 10, No. 1(28). January-April, 2012.
34 Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposa of 1989 // Current International Law / Compl. by Yu. M. Kolosov and E. S. Krivchikova V. 3, p.p. 700-721
35 Principles Relevant to the Use of Nuclear Power Sources in Outer Space. Resolution of the General Assembly 47/68 as of 14 December, 1992.
36 Convention on International Liability for Damage Caused by Space Objects (the Convention on Liability), the UN, Resolution 2777 (XXVI), 1972
37 Vestnik Atomproma, No. 8, October, 2012.
38 Nuclear engineering handbook / editor, Kenneth D. Kok., CRC Press, Taylor & Francis Group, 2009.
39 I. N. Bekman. Nuclear Physics, Course of Lectures, Manual, Moscow, 2010.
40 Strana Rosatom, No. 12(57) May 2012., www.strana-rosatom.ru
41 A. A. Manulin, Problem of Radioactive Waste Disposal in Space, R. E. Alekseev Nizhniy Novgorod State Technical University, Alekseeva, Institute of Nuclear Energy and Technical Physics, Nizhniy Novgorod, Russia.
42 Improvement of Russian regulatory basis in the sphere of safety control during decommissioning and disposal of radioisotope thermoelectric generators, Joint Project of Radiation Safety Agency of Norway and Federal Environmental, Engineering & Nuclear Supervision Agency (Rostekhnadzor), The Final Project Report, 2008.
43 Brian Dodd, Safety and security of radioactive sources: conflicts, commonalities and control.
44 Management of High-Activity Radioactive Waste, Safety Manual, Series on Safety Manuals No. WS-G-2.6, IAEA, Vienna, 2005.
45 I. Sokolovskiy S. G. Testov, Issues of Supervision and Licensing Related to Development of Radioactive Waste Management System in Northwestern Region of the Russian Federation, RF Ministry of Defense, Voprosy Utilizatsyi APL, No. 1 (15), 2008.
46 J. Dewes (Washington Savannah River Company), Sh. Tozher, I. Vidoski (Research Institute of Atomic Energy KFKI of National Academy of Sciences of Hungary), M. V. Baryshnikov, Candidate of Science, (RPC "Sosny", Russia), Lessons of Hungarian Transportation, Bezopasnost' Yadernyh Tehnologij i Okruzhaushchej Sredy, No. 1, 2011, special edition.
47 Valeriy Beigul, Candidate of Science, Centre for Development of RAW and SNF Underground Isolation Technologies of VNIPI. Does Russia Need International SNF Storage Facility? "Barjer Bezopasnosti", No. 3-4, 2005.
48 P. P. Poluektov, Academician of Russian Academy of Natural Sciences (FSUE "Academician A.A. Bochvar All-Russian Research Institute for Inorganic Materials" Peaceful Atom by Peaceful Efforts, International Storage Facilities May Become the First Embodiment of Multidisciplinary Approach, "Barjer Bezopasnosti, No. 3-4, 2005.
49 Management of Spent Nuclear Fuel and Radioactive Waste in Nuclear Power Industry: Manual / N. N. Davidenko, K. V. Kutsenko, G. V. Tihomirov, A. A. Lavruhin. – M.: MEPhI, 2007. – 136 p.

50 Loisha V. A. We Suffered a Victory. Stories About 25th Object. – Tomsk: "D'print" Press, 2011. – 266 p.
51 M. E. Budu, B. A. Kanashov, S. V. Komarov, A. V. Smirnov (LLC RPC "Sosny", Russia), E. N. Lazarev (JSC "Volga-Dnepr", Russia), Ken Allen (INL, USA). Safety Control of SNF Air Transportation. Book of Reports of VII International Nuclear Forum "ATOMTRANS-2012", St. Petersburg, 17-21 September, 2012.
52 Niel Chapman, Charles Maccombie (ARIUS, Switzerland). What Is Required For Development of International Storage Facility in Russia? "Barjer Bezopasnosti, No. 3-4, 2005
53 I. Rybalchenko, How To Save Billions, "Barjer Bezopasnosti, No. 3-4, 2005
54 M. I. Ozhovan, Doctor of Physical and Mathematical Sciences, (Sheffield University, Great Britain), "Madness of the Brave" or Profitable Import, "Barjer Bezopasnosti, No. 3-4, 2005
55 V. V. Lebedev (SUE MosSPA "Radon"), Vitrification: Efficiency and Effectiveness, "Barjer Bezopasnosti, No. 3-4, 2005
56 P. P. Neveikin, Yu. V. Myshkin, S. M. Lashchyonov, SUE MosSPA "Radon". About the Status of Radioactive Waste Storage Facility. VI International Exhibition and Conference "AtomEco-2012", Moscow, Radisson Slavyanskaya Business Centre, 17 October, 2012.
57 Federal Environmental Industrial and Nuclear Supervision service of Russia. Safety Manual. Safety Control During Transportation of Radioactive Materials (Reference material to Regulations on Safe Transport of Radioactive Materials, NP-053-04), RB-039-07, Moscow, 2007.
58 IAEA Series of Safety Standards. Radioactive Waste Disposal. Specific Safety Requirements, No. SSR-5, Vienna, 2011.
59 Problems of Nuclear Heritage and Their Solution. - Edited by E. V. Evstratov, A. M. Agapov, N. P. Laverov, L. A. Bolshov, I. I. Linge. - 376 p. V. 1.
60 Financial aspects of decommissioning: Report by an expert group IAEAJTECDOCJ1476, International Atomic Energy Agency, November 2005.
61 Bolshov L. A., Abalkina I. L., Eroma A. A., Kazakov S. V., Linge I. I., Malyshev A. B., Agapov A. M. Analysis of Foreign Experience in Financing of Operations of Long-Term Management of SNF, RAW and Decommissioning of Nuclear and Radiation-Dangerous Objects. M.:Preprint IBRAE RAS, 2006.
62 Nuclear Technology: Manual for Institutions of Higher Education/Shvedov V.P., Sedov V. M., Rybalchenko I. L., Vlasov I. N.; Edited by I. D. Morohov. - M.: Atomizdat, 1979. - 336 p.
63 The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, IAEA, Vienna, 2011.
64 Draft Report of the Working Group on Use of Nuclear Power Sources in Outer Space, General Assembly of the UN, the Committee on the Peaceful Uses of Outer Space, the Scientific and Technical Sub-Committee, 49th Session, Vienna, 6-17 February, 2012.
65 Practical Training Session of Use of Nuclear Power Sources in Outer Space: discussion of issues on Use of Nuclear Power Sources in Outer Space, General Assembly of the UN, the Committee on the Peaceful Uses of Outer Space, the Scientific and Technical Sub-Committee, 49th Session, Vienna, 6-17 February, 2012.
66 Principles Relevant to the Use of Nuclear Power Sources in Outer Space, General Assembly of the UN, 23 February, 1993.
67 The Committee on the Peaceful Uses of Outer Space: Guidelines on Space Debris Prevention, the UN, Inter-Agency Space Debris Coordination Committee, Space Debris Working Group, www.iadconline.org
68 I.N. Bekman. Radiochemistry, Course of Lectures. Moscow M.V. Lomonosov State University, Moscow, 2006.

69 Jackson Ian. Extracted from «Nukenomics – The commercialization of Britain's nuclear industry»?//Nuclear Engineering International. 2008. April. P. 24-26.
70 L. Katernyak, TsNIIMash Biosphere Purification: waste disposal in space, Nauka i Zhizn' 1994 No. 3.
71 A. Aleksandrov, Unified Connecting Link, Atom – pressa, No. 5 (893) February 2010
72 V. Filatova, Radioactive Waste Wiil Be Managed By Law, Atom – pressa, No. 5 (893) February 2010
73 II All-Russian scientific and technical conference "Atomic Siberia. XXI-th century", 27-29 January, Zheleznogorsk, the Krasnoyarsk Territory, Atom – pressa, No. 5 (893) February 2010.
74 V. M. Radchenko, Alchemists from NIAR, Atom – pressa, No. 5 (893) February 2010
75 Commercialization of Space, http://www.promved.ru/
76 I. Artemiev, A. Yablokov, V. Slivyak, M. Katys. Import of Spent Nuclear Waste, Radio Svoboda, 21 February, 2001
77 Personal website of Elena Valilieva, an expert ecologist, http://evasiljeva.ucoz.ru/
78 Evgeniy Velihov: There are no new real projects of nuclear waste liquidation yet, ITAR-TASS , http://daily.sec.ru/publication.cfm?pid=9944 , 06 May, 2004.
79 Principal Sanitary Radiation Safety Rules (OSPORB 99/2010).
80 Radioactive Waste, Wikipedia - open encyclopaedia, http://ru.jazz.openfun.org/wiki/
81 E. P. Velihov, N. F. Glazovskiy, N. N. Klyuev. Safe Danger. Journal "Vokrug Sveta" No. 7 (2754), July, 2003.
82 Nuclear engineering handbook / editor, Kenneth D. Kok., CRC Press, Taylor & Francis Group, 2009.
83 Nuclear Power - What Next? (Collected works). – M.:Znanie, 1989. – 48 p.
84 http://portal.tpu.ru/files/personal
85 G. Raguzina Radiactive Waste Are Proposed To Be Delivered To The Sun, http://www.bellona.ru/subjects/NW-and-SNF, 2007.
86 Shmelyov A. N., Apse V. A., Kulikov G. G. Basic Physics of Long-Lived Radioactive Waste Neutralization. Potenial of Innovative Technologies: Manual. M.: MEPhI, 2008. 120 p.
87 Frans Berkhout. International Commercial Activity in Spent Fuel Reprocessing. Reprocessing Economics, Energy and Security, No. 2, 1997, edition IEER (The Institute for Energy and Environmental Research).
88 I. N. Bekman. Nuclear Industry. Moscow M.V. Lomonosov State University, Course of Lectures, Moscow, 2005.
89 Radiation Safety Standards (NRB-69), M., 2 edition, 1972; Principal Sanitary Radioactive Substances and Other Ionizing Sources Management Rules (OSP-72), M., 1972.
90 adiation Safety Standards NRB-99 / 2009. Sanitary Regulations and Standards, SanPin 2.6.1.2523-09, Moscow, 2009.
91 V. Shvetsov. Transmutation of Spent Nuclear Fuel and Radioactive Waste As One of Variants of Nuclear Branch Strategic Development, Joint Institute of Nuclear Research (JINR) weekly "Dubna", N 6, 2003.
92 What is SNF, http://daz.su/
93 Bryleva V. A. Voyteskaya E. F. Nareiko L. M., NPP Spent Nuclear Fuel, " "JINR-Sosny", Byelorussia NAS, Newletter No. 7-8 (13-14), 2010, http://www.sosny.bas-net.by
94 S. A. Bznuni, V. S. Barashenkov, V. M. Zhamkochyan, A. N. Sosnin, A. Polyanski, A. G. Hudaverdyan Perspective Eletronuclear Syatems, Fizika Elementarnyh Chastits i Atomnogo Yadra, V. 34, issue 4, 2003.

95 J. Coopersmith "Real Chance for Russian-American Cooperation", journal "Energiya" No. 6, 1992, p.p. 54-56.
96 N. Ivanov "RAW Space Isolation as Conversion Direction", journal "Energiya" No. 4, 1994, p. 11.
97 Nemets O. F. Gofman Yu. V. Nuclear Physics Handbook, Naukova dumka, Kiev, 1975.
98 aternyak L. (Centre for Development of Space Technologies, Central Research Institute of Mechanical Engineering). Will Conversion Spare the Earth from RAW? // ZM. 1995. N 7.
99 Frolov D. May Nuclear Waste Be Disposed in Space? ZM. 1994. N 12.
100 Yaskin S. A. Legal Issues of Radioactive Waste Disposal in Space // Bul. Centre for Defense Information of NPI. 1994. No. 2
101 R. S. Moiseev. Disposal of Radioactive Waste in Geologic Formations at the Far East: Evaluation Problems. Kamchatka Institute of Ecology and Natural Resources Management of Far Eastern District of RAS, http://geo.web.ru/db/section_page.html/s=121113000&ext_sec=190400000
102 Foke R. Energy and Life Evolution on Earth. M.: Mir, 1992. 216 p.
103 The UN documents: Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space (1963), Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting (1982), Principles Relating to Remote Sensing of the Earth from Outer Space (1986), Principles Relevant to the Use of Nuclear Power Sources in Outer Space (1992), Declaration of International Cooperation in the Exploration and Utilization of Outer Space for Peaceful Purposes (1996).
104 Doc. UN No. A/AC.105/C.1/L.217.
105 Jojrysh A. I., Yaskin S. A. Does Law Permit to Dispose Radioactive Waste in Space? Zemlya i Vselennaya, No. 5/93
106 Litovkin V. Secret Nuclear Explosion // Izvestiya. 1997. 6 May.
107 Degtyaryov A. V., Kushnaryov A. P., Slyunyaev N. N. et al, Criteria of the Earth's Biosphere and Environment Safty Evaluation, Requirements to "Earth-Orbit" Launch and Container with Waste, Yuzhnoye SDO, 2006.
108 "Innovation Management", manual, Yu. P. Anisimov, E. V. Solntseva, Voronezh, 2007. p.179-191.
109 http://www.cosmoworld.ru/spaceencyclopedia/publications/index /zhelez_04.htm

Annex 1

Advantages and disadvantages of different methods of RAW disposal [31]

Advantages	Disadvantages
DIRECT DISPOSAL	
does not require construction of large chemical plants for radionuclide reprocessing, which activity, in its turn, is accompanied by escape of radionuclides in water and atmosphere. Absence of such plants excludes emergency situations. radioactive effluent is absent; nuclear fuel remains in the fuel matrix, thus, greatly reducing the probability of fission products escape, which is very important with presence of long-lived radionuclides; number of transportations is much lower.	All long-lived radionuclides remain in the waste. For this reason, prior to the final geologic disposal, it is difficult to guarantee safety, at least, during one million of years.
REPROCESSING	
In waste intended for a long-term geologic disposal the amount of uranium and plutonium radionuclides will reduce greatly.	The personnel of nuclear facilities and population are subject to stronger radiation effect as compared with the direct waste disposal; The spent fuel and radionuclides, generated in the reactor, can be stored in their liquid state for a long time. In case of accident, radionuclides will be emitted into the atmosphere in an enormous amount. The consequences may be more catastrophic than after Chernobyl accident; A great amount of contaminated effluent generates requiring high financial costs for the interim storage and their further disposal;
	The waste volume increase in whole; A great number of fuel unit processing and transportations increase the risk of accidents and occurrences. Partial extraction of uranium and plutonium from waste just gives appearance of the long-term disposal safety. But proofs of this safety are still required as a part of long-lived radionuclides remain in waste; The probability of extracted plutonium utilization for atomic bomb making with purpose of terrorist actions; Use of MOX fuel may cause to the most serious accidents at nuclear plants.
SEPARATION AND TRANSMUTATION	
if separation of radionuclides complies with requirements for the final disposal and with a sufficiently high degree of transmutation, it will become a proof of safe long-term disposal for a few thousands of years; some separated radionuclide classes may be reused; chance to get rid of high-activity waste representing the greatest danger when disposed	all disadvantages related to reprocessing; studies and development require a huge investment (tens billions of euro); introduction of the Concept of separation and transmutation will take a few decades but still will not manage reprocessing of all high-activity nuclear waste. Moreover, the nuclear waste, generated during these processes, shall be disposed too.

FINAL DISPOSAL	
possibility of a long-term forecasting of the radioactive waste state; thanks to barrier systems, waste will be isolated from humans and environment. It will require no maintenance and control; geologic barriers will provide safety of storage facilities even in case, when information about them is lost. The only condition required is to select a suitable disposal site; probability of production accidents and release of radiation reduce due to geologic strata; low external influence (for example, earthquake, weather conditions, terrorism); In case of correct long-term forecasts, future generations will not have to perform this waste reprocessing one more time and bear the costs (the principle is that the contaminator pays); presence of geologic barriers practically excludes use of radioactive waste for terrorist actions.	there are no guarantee that barriers will function for a long time (one million years) and in a reliable manner; the sphere of activity for future generations will be limited due to necessity of careful waste management and the final disposal site.
CONTROLLED LONG-TERM GEOLOGIC DISPOSAL	
The stage-by-stage disposal procedure increases probability of safe final disposal of waste at the initial stage (a few hundreds of years). The probability of external influence is low. Future generation will be able to solve issues on the further waste processing.	The technical characteristics of open mines may be disturbed (for example, stability of geotechnical barriers). Even with consideration of control at the experimental stage during a hundred of years, it is impossible to predict or ensure correct continuous functioning of barriers (especially geologic ones) for a required period (1 million of years). It is difficult to predict the mankind development during 100 years, as long as mines are open.
LONG-TERM INTERIM STORAGE	
The developed later more reliable methods of waste reprocessing may be implemented without any problems. The sphere of activity for future generations will not be limited.	It would be incorrect to state if more reliable methods of waste reprocessing are going to be developed and how much time it is going to required to develop them. It is more difficult to foresee the society development than geologic changes. In case of external influence on storage facilities, environmental release of potentially hazardous radioactive waste may occur. During a long time it is necessary to monitor waste and perform repair and shift works. As a result, the risk of incidents and radiation effect on humans will increase. Easy access to waste for their use for terrorist purposes. The problem of radioactive waste final processing and this process financing is put upon future generations.

Annex 2

The comparative analysis of approaches used by Great Britain, Sweden, the USA, France, Germany, Japan and Canada in terms of SNF, RAW management and decommissioning of plants [59]

What documents contain information about the national policy in the sphere of SNF, RAW management and decommissioning?	
Great Britain	1. Radioactive Substances Act (1993). 2. Atomic Energy Act (2004).
Sweden	1. Nuclear Activity Act (1984): licensing requirements for construction and operation of nuclear plants and for management of nuclear materials or their use including radioactive waste. 2. Radiation Protection Act (1988): licensing requirements for radiation protection and radiological operation. 3. Financing of Anticipated Costs For Spent Nuclear Fuel Management Act (1992): main financial aspects, determination of responsibility for management of SNF and RAW and their disposal.
USA	Nuclear Waste Policy Act (1982)
France	1. Waste Disposal and Materials Recycling Act No. 755633 (1975). 2. Radioactive Waste Management Research Act No. 9111391 (1991).
Germany	1. Atomic Energy Act (1959): general national standards of nuclear plants safety. 2. Acts based on Atomic Energy Act, including: – advance payments for construction of plants dealing with RAW disposal (Decree On Advance Payments For Waste Disposal, 1982 and 1990; EndlagerVlV); - provisions on sufficient defrayal (Decree On Financial Protection In Compliance With Atomic Energy Act, 1977 and 1990, AtDeckV), etc. 3. Act On Gradual Discontinuance Use of Atomic Energy For Commercial Power Generation Within Thoroughly Coordinated Process (2002): limitation of NPP life cycle to 32 years, increase of RAW amount limits. 4. General administration provisions and directives, including the Directive on nuclear decommissioning according to section 7 of Atomic Energy Act (AtG).
Japan	1. Atomic Energy Act (1955). 2. Act On Regulation Of Raw Stock For Nuclear Materials, Nuclear Fuel Materials and Reactor Operation (Reactor Operation Regulatory Act) According to amendment to this Act (2005), the regulatory procedure for nuclear facility commissioning was defined, the regulatory approval system was reintroduced. 3. Act On Final Disposal Of Specific RAW (2000): final disposal of HAW obtained as a result of SNF processing. Including: the final disposal plan, establishment of organization got task solution, activities aimed at ensuring availability of financial resources. 4. Act On Payments and Fund Management Intended For Processing Of SNF Generated During Atomic Energy Generation (2005). 5. Act On Saving and Reserve Fund Management Intended For Processing Of SNF Generated During Atomic Energy Generation (2005). 6. Power Generation Utility Act (1964).
Canada	1. Resolution On Atomic Energy Use Regulation (1946). 2. Resolution On Nuclear Energy (1985, 2000). 3. Resolution On Nuclear Safety Regulation (1997): key provisions of law for ensuring power industry safety and RAW management in Canada.

	4. Resolution On Nuclear Fuel Waste (2002): according to it, nuclear industry plants were obliged to found a non-profit organization dealing with nuclear waste management, development of general approaches to long-term management of nuclear fuel waste with its recommendations to be submitted to Federal Minister of Natural Resources by 15 November, 2005. 5. Resolution On Nuclear Liability (1985).
What is the current national practice of SNF management (storage, reprocessing, disposal)?	
Great Britain	The policy of the British government in SNF management and its reprocessing (and if "yes", then when) or search for alternative variants of management consists in the fact that this issue is solved by SNF owners with consideration of commercial interests.
Sweden	The present policy of SNF management was adopted in the end of the 1970-ies and was oriented at direct disposal of waste without reprocessing
USA	In the 1960-ies -beginning of the 1970-ies, there were plans to construct a few plants for SNF reprocessing. They abandoned the idea of SNF reprocessing in the 1970-ies. Nevertheless, in May of 2001, according to the state energy strategy of the USA, it was prescribed to "develop SNF reprocessing technologies and final management that are cleaner and more effective...".
France	France chose the variant of SNF reprocessing. The system includes SNF reprocessing plant with capacity of 1700 t/year. Plutonium is reprocessed into MOX fuel (the "equal stream" principle"). Mox fuel (mixed (uranium and plutonium) oxide): the variant could provide for plutonium reprocessing to be reused in the future in reactors on fast neutrons GEN4. The present strategy of "Electricity de France" energy company regarding NFC consists in SNF reprocessing. The strategy of Atomic Energy Commission consists in SNF reprocessing of research reactors whenever it is possible. Every SNF owner in France owns it to reprocessing. After reprocessing, the owner "Electricity de France", Atomic Energy Commission, "Areva" group) remains responsible for long-term RAW management. Distribution of waste generated as a result of reprocessing operations, is performed based on UR-principle (by radioactivity) and controlled by French administrative bodies.
Germany	Until 1994 Atomic Energy Act included requirement for reuse of fissile materials from SNF. This requirement was changed by resolution of 1994, according to which, organizations dealing with NPP operation, obtained the right of choice between SNF reuse by reprocessing and its direct disposal. Since 1 June, 2005, SNF delivery for reprocessing was prohibited in accordance with Amendment to the Atomic Energy Act as of 22 April, 2002. At present, only spent fuel assemblies may be subject to direct disposal in Germany.
Japan	The key policy of Japan consists in SNF reprocessing and effective use of recovered uranium, plutonium and other elements ensuring safety and nuclear non-proliferation. The national policy declares as its purpose to reprocess all SNF inside the country and maintaining of self-sustained nuclear fuel cycle.
Canada	At present, all SNF in Canada are kept in "wet" or "dry" interim storage facilities. Canada has no SNF disposal program. All SNF are kept in interim storage facilities waiting for the state resolution regarding the approach to long-term management of spent fuel shall be selected. Organization, dealing with nuclear waste management, owned by Canadian NPP, is responsible for development and implementation of long-term decisions regarding SNF in Canada. The nuclear industry of the country utilizes natural uranium. Due to large resources

	of natural uranium, there is no need in SNF reprocessing in Canada.
Does SNF belong to RAW according to the national legislation?	
Great Britain	The state considers that SNF shall not be categorized as waste. The issue of SNF reprocessing stays open, it may be used in the future.
Sweden	
USA	No.
France	No.
Germany	
Japan	No (see above)
Canada	Within the framework of current legislation and accepted system of approaches, SNF is considered as a kind of radioactive waste. Legislative and regulatory policy of Canada regarding RAW attributes SNF to AW implicitly. As a result, SNF is considered with other RAW forms by legislation and strategy of RAW management.
Is SNF intended for disposal according to national legislation?	
Great Britain	No.
Sweden	The policy of SNF management consists in spent fuel management and its disposal shall take place in geologic formations on the territory of Sweden.
USA	It is planned to construct a deep geologic storage facility for SNF and HAW generated in the commercial sector and state enterprises (Department of Energy deals supervises licensing and construction).
France	No. Officially, SNF is not intended for disposal.
Germany	SNF reprocessing shall be ceased and replaced by direct disposal of spent fuel assemblies.
Japan	No (see above)
Canada	Canada has no SNF program of nuclear fuel waste disposal. At present, all SNF are kept in interim storage facilities waiting for the state resolution regarding approach to long-term SNF management.
Are there special saving funds accumulating means for management of SNF, RAW and decommissioning?	
Great Britain	In November, 2001, the government declared that it would take direct financial responsibility for all commitments of British Nuclear Fuels Limited (BNFL) used to have, except for those covered by commercial contracts of SNF reprocessing and storage in Sellafield. These are also commitments related to nuclear reactors of "Magnox Electric" company (completely owned by BNFL). The Nuclear Decommissioning Authority (NDA) is financed both by the sate and by commercial profits obtained from power generation at NPP, operated by "Magnox" company, from SNF reprocessing and storage, from fuel processing. The Authority is not responsible for decommissioning and purification of "British Energy" facilities controlled by the private sector. After restructuring in 2003, "British Energy" is obliged under the contract to remit to the Nuclear Responsibility Fund annual defined instalment plus a part of its free cash flow (depending on electric power prices).
Sweden	Yes, the Nuclear Waste Fund. In the 1970-ies, nuclear enterprises established their own internal funds for future costs for waste management. Afterwards, these funds

	were converted in the financial system controlled by the state and established in 1981 after adoption of Financing of Anticipated Costs For Spent Nuclear Fuel Act Financing Act) by the Parliament.
USA	Yes, the Nuclear Waste Fund representing a special account opened in Treasury Department for SNF.
France	There is no special fund for long-term RAW management in France. This obligation is put upon owners of licenses within the frames of their own financial allocations.
	But the French government requested "Electricity de France" company, Atomic Energy Commission and "Areva" group to establish specialized funds. In the future the government does not propose to establish a special fund for RAW management as a draft law, but requests only to operating organisations to identify and back necessary assets. Their sum shall be equal to allocations given for reimbursement of costs. The financial profit shall allow to give sufficient means for financing of dismounting and RAW management at the end of operation stage. These assets cannot be used for other purposes and charged by any creditor. Assets shall be properly registered.
Germany	Private operating organisations have to provide financial support to cover costs for final closure of enterprises and decommissioning (for SNF or RAW liquidation) and also for decommissioning and dismounting of nuclear and radiation dangerous facilities). According to the commercial law, establishment of reserves is based on the commitment as a result of the public right to liquidate the radioactive part of the enterprise waste, which is directly regulated by the Atomic Energy Act. Financial resources of private enterprise belonging to energy utilities, NPP, in particular, are formed as reserve funds, allocations for them are performed during their operation. Special reserve funds are formed for SNF disposal. As for the enterprises, financed by the public, financial means for their decommissioning and dismounting of nuclear facilities shall be included in the current budget.
Japan	Act On Final Disposal Of Specific RAW (2000) provides for establishment of the organisation for performance of HAW disposal operations and saving of financial resources for disposal. Previously, power generating enterprises saved means in two types of internal reserves intended for SNF reprocessing and for decommissioning of nuclear facilities based on the Ministry order issued according to Power Generation Utility Act. According to Act of 2005 about management of the Fund established for SNF reprocessing, internal reserves of power generating enterprises shall be transferred to the organisation assigned
	by the Minister of Economy, Trade and Industry. According to Act On Final Disposal Of Specific RAW (2000), operating organisations of energy facilities pay means for HAW disposal to the Organisation of nuclear waste management, which is a performer of works. Centre of research facilities and financing of RAW management governs the fund.
Canada	In 2002, according to Resolution On Nuclear Fuel Waste, their owners had to establish special funds to provide overall financing of long-term operations related to waste management. Special funds were established as trust funds. For other waste management the mechanism of financial guarantees is used according to Regulating resolution on nuclear safety. Guarantees are present in different

	forms: monetary funds, letters of credit, bonds, insurance, etc. The assets are managed within the framework of financial guarantees shall be performed by clearly defined and secured in legislation agreements acceptable to Canadian Nuclear Safety Commission. These agreements shall be concluded to guarantee separation from other assets the means or securities given by an applicant/licensee as a guaranteed financing of approved plan of nuclear facilities decommissioning. It may require to include provisions restricting access to the means granted by the fund or from securities or their use. Canadian Nuclear Safety Commission shall receive confirmation regarding the fact that the Commission or its agents are able to use adequate volumes of financing on request, if the licensee is absent and cannot carry out his commitments on decommissioning of nuclear facilities. The means of trust funds, established in compliance with the Resolution On Nuclear Fuel Waste, are considered as a part of the overall financial guarantee of the licensee to Canadian Nuclear Safety Commission.
What are legislative fundamentals of establishment and operation of saving funds for management of SNF, RAW and decommissioning?	
Great Britain	-
Sweden	Financing of Anticipated Costs For Spent Nuclear Fuel Management Act (1992): main financial aspects, determination of responsibility for management of SNF and RAW and their disposal.
USA	Nuclear Waste Policy Act (1982)
France	Financial commitments and liability of the waste generator (right of ownership for waste cannot be passed to the licensed enterprise of waste disposal). The waste generator is responsible for it, especially in terms of finances, without limitation of time. Unlike some other countries, France did not introduce the system when a state agency takes upon the responsibility for RAW management with absence of disposal facilities after the generator had paid financial compensation in full.
Germany	Decree On Financial Protection In Compliance With Atomic Energy Act (AtDeckV) and Decree on Advance Payments For Waste Disposal (EndlagerVlV)
Japan	Power Generation Utility Act (1964). Act On Final Disposal Of Specific RAW (2000). Act of about management of the Fund established for SNF reprocessing (2005).
Canada	SNF: according to Resolution On Nuclear Fuel Waste (2002).
Are saving funds for management of SNF, RAW and decommissioning centralized or decentralized?	
Great Britain	The Nuclear Responsibility Fund is a special fund of "British Energy".
Sweden	The Nuclear Waste Fund is centralized.
USA	The centralized fund for SNF and high-activity waste
France	The reserve funds are decentralized.
Germany	Centralized since 2005. According to Act of 2005 about management of the Fund established for SNF reprocessing, internal reserves of power generating enterprises shall be transferred to the organisation assigned by the Minister of Economy, Trade and Industry.
Japan	The funds are decentralized.
Canada	

How is the issue of financing problems of the previous activity, accumulated before establishment of relevant funds for SNF, RAW management and decommissioning settled?	
Great Britain	To take strategic responsibility for nuclear heritage, in April, 2005, the Nuclear Decommissioning Authority (NDA) was established as a non-departmental organisation. The Authority is responsible for the facilities operated, previously, by the British Nuclear Fuels Limited (BNFL) and the United Kingdom Atomic Energy Authority (UKAEA), including Sellafield and Dounreay. The NDA is responsible for placement of contracts for commercial operations and waste management operations not intended for this facility. In October, 2006, the government announced about expansion of NDA's role as the only domestic organisation responsible for implementation of HAW geologic disposal. SNF: financial resources for safe SNF management, its reprocessing and RAW management are considered by the licensee as a part of ordinary operational costs. RAW: generators and owners of RAW are responsible for expenses for waste management and disposal. When decommissioning nuclear facilities, each operating organisation develops and implements the strategy and plans for their facilities. The operations shall be performed as soon as it is feasible with consideration of all relevant factors. The Health and Safety Executive is authorized to order a licensee to start operations of facility decommissioning. According to accounting control standards of Great Britain, the owner of the nuclear asset shall provide means for facility decommissioning since the moment of this facility commissioning. In case of nuclear facilities, this moment is the moment of active material installation requiring its further decommissioning.
Sweden	Since 1989 energy facilities have paid a special fee in compliance with special Studsvik Act (1988). This collection provides for covering expenses for nuclear waste of former pilot plants management and for decommissioning of these plants. According to the calculations, 1.5 bln. kronas will be needed to cover such expenses up to 2030.
	The special fee is equal for all four energy facilities and now makes up 0.0015 kronas per kilowatt-hour and recalculated every year by SKI proposal. These assets are governed jointly with the Nuclear Waste Fund.
USA	For SNF of civilian objects, generated before adoption of the Nuclear Waste Policy Act, one-time fee for 1 kg of heavy metal in SNF (equivalent to 0.001 dollar for 1 kW of generated electric energy) was introduced. Having paid this fee, the person, giving SNF or HAW to the federal government, will not have any financial commitments for long-term storage and its final disposal in the future.

France	There is no special financial regulation regarding responsibility of waste generators. The French system proceeds from the unlimited in time possibility of appealing to generators whenever it is necessary (joint works, new legal commitments). Operations for purification and dismounting of civilian objects of Atomic Energy Commission are financed from the special fund established in 2001 and maintained by earnings of Commission industry, industrial sponsoring organisations and partners. Corporation "Cogema" provides services for SNF reprocessing of electric energy facilities, reserving their rights of ownership for their waste and is a holder a very small amount of waste itself. "Areva" group, the only shareholder of "Cogema" corporation, has reserves for management waste of all categories that have not been disposed yet. They account for all waste subject to management, including those left from the previous activity of enterprises and dismounting. The cost of such operations as waste packing, its disposal and cost of waste recovery generated as a result of the previous activity, is also included. The sum of reserve funds of "Areva" group made up 3859 mln. euro in 2003. At present, SNF is reprocessed, the relevant costs for HAW reprocessing and disposal are taken into account in financial allocations. HAW is vitrified, thus, allowing to optimize storage and future disposal.
Germany	The sum of advance payment for necessary expenses incurred since 1 January, 1977 will be collected. General expenses shall be determined for the period preceding coming into effect of Decree On Financial Protection In Compliance With Atomic Energy Act
	the sum equal to two-thirds of expenses after the decree coming into effect will also be collected. The sum of one third of these expenses shall be collected from the first payment of expenses incurred after the decree coming into force. Decommissioning of enterprises of federal ownership is financed from the current budget.
Japan	
Canada	The leading government department "Natural Resources of Canada" (NRCan controls compliance with Resolution On Nuclear Fuel Waste and is fully responsible for management of "historical waste", that is, that waste that was managed in the past using methods no longer acceptable. The present owner cannot be responsible for them, so the federal government took the responsibility upon itself. Atomic Energy of Canada Limited (AECL) is a part of the organisation dealing with low-activity RAW (LLRWMO), which, in its turn, is a national agent on issues of purification and management of Canadian "historical waste". The government department NRCan provides LLRWMO financing and controls its policy in RAW management sphere

What are the sources of formation of means of saving funds for management of SNF, RAW and decommissioning?	
Great Britain	Except for payments by "British Energy", the Nuclear Responsibility Fund receives its "portion" by virtue of previous payments performed by "British Energy" since 1996. If it is not enough, deficit will be covered by the government.
Sweden	Allocations from each kilowatt-hour. In 1982-1996 the average sum of these allocations made up 0.019 kronas for 1 kW h, then it gradually reduced. At present, allocations make up 0.008 kronas for 1 kW h (2005) and are based on the assumption that every reactor will generate energy during 25 years. If operation period exceeds the normative period, the fee for future expenses is collected for additional SNF and nuclear waste generation.
USA	Nuclear Waste Fund: 0.001 dollar fee for 1 kW h of electric energy generated and sold by atomic energy enterprises; allocations of the Congress for nuclear materials being under the state supervision, one-time fee and investment income
France	SNF and RAW generators
Germany	Individual enterprises bear responsibility for fund saving intended for RAW disposal and decommissioning of nuclear facilities. Required costs are distributed among companies generating waste as follows: 75.5% – a share of enterprises licensed according to § 7 of Atomic Energy Act for SNF reprocessing with capacity of max. 50 t a year or a share of those who applied for a license; 4% – a share of enterprises, licensed according to § 7 of Atomic Energy Act for SNF reprocessing with capacity of up to 50 t a year; 17.5% – a share of enterprises, licensed according to § 7 of Atomic Energy Act for SNF fission at reactor electric power not exceeding 200 MW; 3% – a share of enterprises, licensed according to § 7, 6, 9 of Atomic Energy Act or according to § 3 of Radiation Protection Act . If waste generators, listed in the first two items, are absent during one calendar year, their corresponding share is additionally distributed among other waste generators. Advance payments for storage facility financing are calculated by volumes of RAW according to Decree On Advance Payments For Waste Disposal (EndlagerVlV).
Japan	
Canada	SNF: according to Resolution On Nuclear Fuel Waste, their owners had to establish special funds to provide overall financing of long-term operations related to waste management. The mechanism implementation is in establishment of trust funds according to this Resolution.

What are the main types of expenditure of saving fund means for SNF, RAW and decommissioning?	
Great Britain	
Sweden	The fund covers all expenses related to ensuring safe SNF management and its disposal, decommissioning of nuclear enterprises and liquidation of waste generated as a result of decommissioning of nuclear facilities. Besides, the Fund finances research and developments of Swedish company SKB
USA	Nuclear Waste Fund: identification, development, licensing, construction, operation. decommissioning, maintenance after decommissioning and control of every waste storage facility or enterprise, including pilot or test plants, research and development, RAW disposal program management, transportation, processing and packing of SNF or HAW arranged in the storage facility.
France	ANDRA company is responsible for management of storage facilities, design, arrangement and construction of new storage facilities.
Germany	
Japan	The reserve fund, intended for purposes of SNF reprocessing, covers all expenses for reprocessing minus cost of recovered uranium and plutonium. By the end of May, 2005, the sum of fund made up 3 100 000 yens (for 10 enterprises). The reserve fund for decommissioning of atomic power generation facilities covers expenses for decommissioning and liquidation of commercial nuclear enterprises and expenses for waste reprocessing and disposal. By the end of May, 2005, the sum of fund made up 1 100 000 yens (for 10 enterprises). Reserves for HAW disposal. According to Act On Final Disposal Of Specific RAW (2000), operating organisations of energy facilities pay means for HAW disposal to the Organisation of nuclear waste management. The deposit sum for vitrification made up 33 964 000 yens in 2004. The sum of means for storage facility construction in the middle of the 2030-ies and disposal of about 40 000 vitrified containers with HAW is estimated as about 3 trln. yens.
Is there a specialized organisation to perform operations of management of SNF, RAW and decommissioning?	
Great Britain	Great Britain elaborates policy of long-term management of long-lived RAW. This waste is stored at the facilities until "Defra" and authorized organisations are busy with policy elaboration.
Sweden	Swedish company SKB of nuclear fuel and nuclear waste management is responsible for management of SNF and RAE, transportation and storage outside nuclear enterprises, planning and construction of all enterprises required for management of SNF and RAE and also for programs of research and developments for support of the above mentioned activities.

USA	Department of Energy is responsible for majority of SNF/RAW management operations for state-owned enterprises. The Department has a complete system of SNF/RAW management operations for state-owned enterprises. The Nuclear Regulatory Commission regulates commercial enterprises and materials of nuclear fuel cycle. Owners and operators of NPP and other types of enterprises perform management of generated SNF/RAW prior to disposal. The facilities of waste disposal will be under supervision of federal or state authorities. The Nuclear Regulatory Commission also bears responsibility for licensing of commercial enterprises of nuclear waste management, independent enterprises of SNF management and planned storage facility in Yucca Mountain.
France	State organisation ANDRA is authorised for management of all RAW generated by nuclear power industry, war industry and small users. The waste generators, delivering containers with waste, shall comply with specification of ANDRA company.
Germany	The Federal Radiation Protection Agency (BfS) bears responsibility for construction and operation of enterprises managing nuclear waste. Atomic generation enterprises within their responsibility manage decommissioning and dismounting processes (except for RAW disposal), but under mandatory control of competent bodies
Japan	Atomic industry enterprises established Organization, dealing with nuclear waste management, which is a performer of HAW disposal, approved by the state based on Act On Final Disposal Of Specific RAW, May, 2000. The main duties of the organisation are waste disposal and collection of payments to the fund.
Canada	According to Resolution On Nuclear Fuel Waste (2002) of atomic industry, a non-profit organization dealing with nuclear waste management (NWMO) was established for performance of managerial, financial and operational activities to implement long-term management of nuclear fuel waste.
Are there mandatory requirements for SNF and RAW transfer to the specialized organisation?	
Great Britain	The Committee on Radioactive Waste Management (CoRWM), established in 2003 and sponsored by the government shall present recommendations regarding the best variant or a combination of variants of ling-term HAW management in Great Britain. Company "Nirex" was established by the atomic industry in 1982 to provide services for waste disposal. Since 1 April, 2005 the company was transferred to joint ownership of Defra/DTI. On 30 November, 2006, the government ratified the transfer of "Nirex" company to the Nuclear Decommissioning Authority (NDA). The present government policy is as follows: vitrified HAW shall be stored at least 50 years to reduce radioactivity, thus, simplifying their expensive management.

Sweden	SNF management practice: after SNF removal from the reactor core, fuel is stored at NPP facilities for about a year, then it is transported to the central interim storage facility of SNF (Clab), where it is to remain for at least 30 years, then it will be packed and disposed in the final isolation storage facility. RAW management practice: disposal of low-activity waste is performed in shallow repositories at the facility. Short-lived LAW are delivered to final disposal near NPP "Forsmarks". In the future SKB will construct a storage facility for short-lived LAW (most of them will be generated during decommissioning). The storage facility is to be put into service in 2040.
USA	The storage facility will start functioning during 30 years out of the licensed life of any reactor to provide disposal of SNF and HAW, generated as a result of commercial reactors functioning. SNF may be stored in a cooling pond or independent plant for spent fuel storage at the facility or outside the facility before the enterprise is licenses for permanent disposal.
France	SNF shall be stored at basic nuclear plants. The waste generator bears responsibility for waste up to its disposal at a proper site.
Germany	In Germany there are no plans regarding long-term interim storage of spent fuel assemblies. Interim storage is limited to 40 years
Japan	SNF, generated by nuclear reactors, is delivered to reprocessing after its holding at the facility. Until now, most part of SNF has been reprocessed at foreign enterprises. The Japanese Fuel Group (JNFL) is constructing fuel reprocessing plant in Rokkasho-Mura. SNF storage in the enterprise storage facility started in 1999.
Canada	Canada has no program of nuclear fuel waste disposal, there are neither waste disposal enterprises.
Are there SNF and HAW disposal facilities?	
Great Britain	No. At present, HAW disposal is absent. "Nirex" company is engaged in development of storage facilities for medium-activity waste, they are not going to appear earlier than the second decade of the XXI century.
Sweden	No. Construction of SNF disposal facility is planned. The start of waste arrangement is expected in 2018.
USA	High-activity waste is stored at 126 facilities. It is planned to construct storage facilities for SNF and HAW in Yucca Mountain (license application - 2007, start of waste reception - 2017). The storage facility of waste isolation pilot plant (WIPP), intended for transuranium waste of defence industry is the first underground storage facility in the world (it has been operated since 1999).
France	For a certain type of waste (long-lived medium-activity and high-activity waste) there is still no final decision as for its disposal. Possible solutions are being discussed during development of the National Plan of RAW and Recoverable Materials Management. ANDRA conducts research regarding geologic disposal of high-activity long-lived RAW (with a mandatory substantiation of disposal reversibility.
Germany	No. The government sees it as a purpose to construct storage facility in deep geo-

	logic formations for disposal of all types of waste including SNF by 2030.
Japan	SNF: at present, Japan does not have a specialized facility for SNF final disposal, it is not being constructed and is not at the stage of license application (there is no need due to SNF reprocessing policy). HAW: by the middle of the 2030-ies a storage for disposal of about 40000 vitrified containers with HAW is planned to be constructed. The estimated cost is about 3 trln. yens.
Canada	At present, there are no waste disposal enterprises in Canada, all RAW are stored.
What controlling and management authorities are there in the sphere of SNF and RAW management?	
Great Britain	Health and Safety Executive (HSE), England and Wales Environment Protection Agency (EA), Scottish Environment Protection Agency (SEPA), Nuclear Decommissioning Authority (NDA).
Sweden	Nuclear Power Inspectorate (SKI). Swedish Radiation Protection Authority (SSI).
USA	Department of Energy of the US, Nuclear Regulatory Commission of the US, Environmental Protection Agency of the US.
France	Regulatory authority of nuclear safety, joint authority of Departments of Industry, Health and Environment is the authoritative organisation. It develops and submits to the government proposals as policy in the sphere of nuclear safety. The Energy and Raw Materials Directorate General is responsible for SNF/RAW management.
Germany	Federal Ministry of Environmental Protection (BMU) licensing and control of nuclear enterprises. Federal Radiation Protection Agency (BfS)
Japan	The Atomic Energy Commission (plans, discusses and plans, discusses and makes decisions on the state policy in the sphere of nuclear power). The Nuclear Safety Commission (plans, discusses and plans, discusses and makes decisions on the state policy in the sphere of nuclear power). Nuclear and Industrial Safety Agency of Ministry of Economy, Trade and Industry. Office of Science and Technology Policy of Ministry of Education, Culture, Sports, Science and Technology (MEXT).
Canada	Atomic Energy Community. Company "Natural Resources of Canada" (responsible for development and implementation of the government policy in management of uranium, atomic energy and RAW). Canadian Nuclear Safety Commission bears responsibility for regulation of atomic energy and nuclear materials use. A number of other federal departments are authorized and responsible for safe management of SNF/RAW, including Department of Health and Environment, Department of Environmental Evaluation.
Are there cost estimates for future periods?	
Great Britain	The estimated value of all operations related to decommissioning of atomic facilities and their purification, for which NDA is responsible now. makes up about 50 bln. pounds and it will take 50-100 years to complete all works.

Sweden	The estimated cost of future costs for the period from 2005 to 2050 makes up about 53 bln. kronas. The sum of future and already performed works for projects in the sphere of nuclear waste management is about 68 bln. kronas.
USA	The total cost of the system life cycle of RAW management at civilian enterprises includes costs for a controlled geologic storage facility, waste transportation to Yucca Mountain storage facility and other associated costs. The total estimated cost for the period of 2001-2019 for completion of the above mentioned system is estimates as 49.3 bln. dollars (in prices for 2000), except for 8.23 bln. of already incurred costs in 1983-2000.
France	
Germany	Individual enterprises bear responsibility for fund saving intended for RAW disposal and decommissioning of nuclear facilities. As of 2003, 35 bln. euro (about 55% - for waste and 45% - for decommissioning).
Japan	
Canada	SNF: within the framework of adaptive stage-by-stage waste management (approach to risk management proposed by Nuclear Waste Management Organisation NWMO) expenses are estimated as 24.4 bln. dollars. (2002). According to Resolution On Nuclear Fuel Waste, their owners began to make payments to trust funds for financial support of the selected approach and long-term nuclear waste management.

Annex 3

Studied variants of disposal in space [8]

Characteristic	Required velocity increment, km/s	Required system useful life, days	Standard location site	Expected number of orbital manoeuvres	Advantages	Disadvantages
Near-Earth high-altitude orbit	4.00	<1	Circular orbit 55000 km	2	Can be easily rescued, easily returned, the least required velocity increment	Uncertain orbit stability, public non-acceptance, temporary isolation
Lunar orbit	4.25	6	Circular orbit 21700 km	5	Can be rescued; can be returned; low required ΔV	Uncertain orbit stability, complicated flight program
Lunar surface (soft landing)	6.05	6	Surface on the back side of the Moon	5	Can be rescued; can be returned; permanent isolation on the celestial body; no problem of orbit stability	Potential possibility of the Moon's surface contamination, public non-acceptance and scientists; complicated flight program
Solar orbit	4.45	180	Orbit 0.85 a.u. with 1° inclination	2	Permanent isolation; very high orbit stability >10^7 years)	Considerable system useful life, rescue is hindered
Removal from solar system	8.75	<1	-	1	Permanent isolation; potentially high public acceptance, easy to perform	High required ΔV; rescue is hindered, return to the Earth is not possible
Fall on the Sun	24.00	<1	-	1	Permanent isolation; easy to perform	Very high required ΔV; a small part of waste returns to the Earth