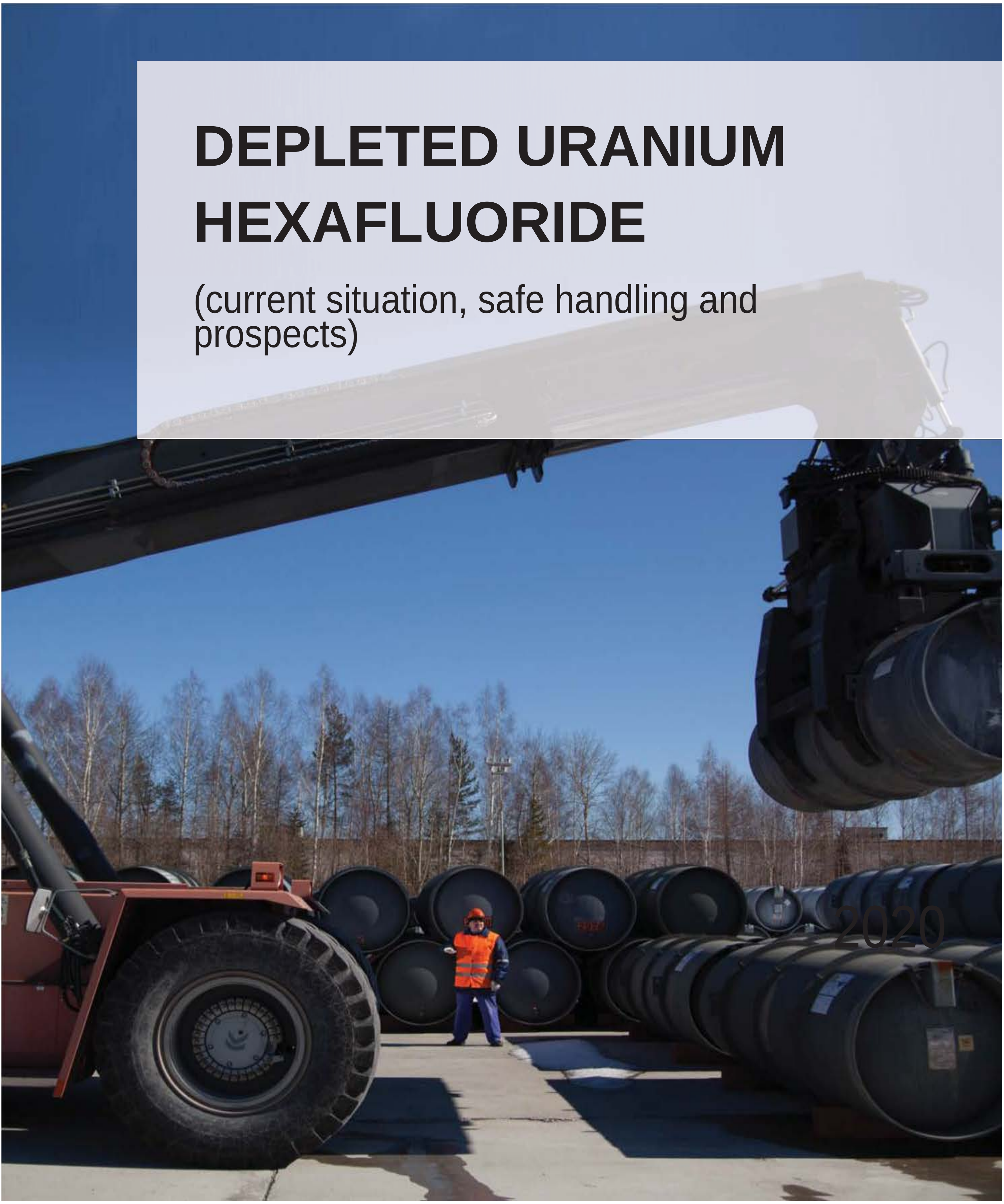
DEPLETED URANIUM HEXAFLUORIDE

(current situation, safe handling and prospects)



2020

Authors:

Alexander Nikitin, Head of Bellona Foundation

Oleg Muratov,
nuclear physicist, Head of Radiation Technology Dept., TVEL JSC

Ksenia Vakhrusheva,
Cand. Sci. Econ., Expert, BELLONA International Foundation

Editor: Elena Verevkina

Design: Alexandra Solokhina

This Report was prepared with support and participation of Environmental Board of the Public Council of Rosatom State Atomic Energy Corporation

Publishers:

Bellona Foundation

Environmental Protection NGO
'Ecopravo' Expert and Legal Center

TABLE OF CONTENTS

Abbreviations

TUO - triuranium octoxide

R&D - Research and development

EIA - environmental impact assessment

DUHF - depleted uranium hexafluoride

DTUO - depleted triuranium octoxide

EUP - enriched uranium product

SNF - spent nuclear fuel

RW - radioactive waste

NFC - nuclear fuel cycle

Foreword

Nuclear technologies, as well as the processes, phenomena and consequences that arise from their use, are of interest not only to specialists, but also to a wide range of interested public. People are primarily interested in how safe these technologies are, and what their impact on human health and the environment is. Therefore, public activity and interest of the mass media that appeared in connection with the resumption of transportation of depleted uranium hexafluoride (DUHF) from Germany to ROSATOM enterprises is quite explainable.

One of the reasons for the increased interest and concern of people was the lack of objective and timely information and knowledge about the technologies for use of the DUHF. The issue of DUHF handling became the subject of consideration at the highest level in the Nuclear Department, and in the regions where the enterprises that store and process the DUHF are located. The Environmental Board of the Public Council of ROSATOM established a working group, which invited representatives of environmental organizations like the Russian branch of Greenpeace, Bellona, RSEU, Grazhdanin, NIIPE, etc., as well as representatives of educational and scientific institutions and organizations of ROSATOM. It was decided that the experts of these organizations should prepare an informational report on the handling of DUHF. Public environmental organizations and activists of the regions where DUHF is stored and processed were also interested in preparing the report.

The authors of this report aim to share information with the interested community, whose representatives are not specialists and do not have special knowledge in the field of nuclear energy and handling of DUHF. The authors tried to explain in the most accessible form what depleted uranium hexafluoride is, and where it comes from, what properties it has, for what purpose it is imported, how it is used and stored in the nuclear industry, as well as what rules and technologies are applied when handling this substance.

In addition, the report considers prospects and phases of further use of DUHF at ROSATOM enterprises, which were defined by the ‘ROSATOM DUHF Safe Handling Program’ prepared at the end of 2019, and accepted in 2020. The main approaches to public control and issues that arose during the discussion of the concept of DUHF handling with the public are stated.

The report was prepared using materials from open sources, as well as information and documents provided by fuel company TVEL JSC and TENEX JSC.

Introduction

The information provided in the report relates to the handling of depleted uranium hexafluoride, which is formed during the enrichment of natural uranium. The term "DUHF handling" refers to all actions related to the formation, accounting, use, processing, movement and storage of DUHF.

The **first Chapter** deals with the basic concepts related to nuclear physics, radioactivity, and types of radiation, taking into account that the reader is not an expert in these areas of knowledge.

The **second Chapter** contains information about how uranium hexafluoride is produced, what chemical and physical properties it has, and why it is so important for nuclear power.

The **third Chapter** reveals the main topic of the report -- what is depleted uranium hexafluoride. Particular attention is paid to the status of the DUHF, since this issue has become a stumbling block between opponents of using foreign DUHF at Russian enterprises and those who believe that the technologies for using DUHF are absolutely acceptable in terms of security and legality.

Section 3.2 "Reprocessed uranium, its features and differences from natural uranium" has been prepared due to the fact that for various reasons it is difficult for members of the public and environmental organizations to understand the differences between DUHF formed during the enrichment of natural uranium and depleted uranium obtained during the processing of recovered (reprocessed) spent nuclear fuel.

The **fourth Chapter** offers a detailed description of all processes, which are included in the term "DUHF handling", starting from production to transportation, storage, use and processing. Cask maintenance processes and storage arrangements and transportation are described in detail. In addition, possible scenarios of emergencies and their consequences are presented. The report also presents information about the use of DUHF in the nuclear fuel cycle and industry.

The **fifth Chapter** considers economic aspects related to DUHF handling. It is difficult to estimate the cost of storage and processing of DUHF in Russia, since information about the cost of individual operations related to handling DUHF is not publicly available. Therefore, economic analysis is mainly based on data from foreign sources.

The **sixth Chapter** contains an overview of the prospects for processing and termination of DUHF stockpile. The main stages of the roadmap, which is defined in the updated Safe DUHF Handling Concept, and in the ‘ROSATOM DUHF Safe Handling Program’, are presented. The tasks are listed that need to be solved for the complete elimination of DUHF stockpile accumulated at TVEL JSC enterprises.

The **seventh Chapter** discloses information about use of DUHF abroad. The reserve of depleted uranium is now concentrated in countries that previously operated or continue to operate separation sites- - Russia, USA, France, China, and the countries where URENCO's facilities are located, Germany, the United Kingdom, the Netherlands, and a plant in the US (Eunice). Attention is drawn to the status of DUHF in the countries where its reserves are concentrated.

The **eighth Chapter** is devoted to such an important issue as public participation in the decision of issues related to the DUHF handling. The issue of public participation (including public control) is always on the agenda when it comes to nuclear energy projects, and this applies not only to the DUHF handling. The main tasks of public participation, principles and methods of its organization are also considered.

Chapter 1.

A few words about nuclear physics and radioactivity for non-specialists

Uranium fuel is used mainly for energy production in nuclear reactors of various purposes. The content of uranium in the earth's crust is 0.0003%, it occurs in the surface layer of the Earth in the form of several types of deposits (ores). Uranium ore is considered very rich if it contains 1-2% of uranium. In the main industrial fields of Russia, the content of uranium is 0.05 - 0.2%.

Uranium in natural deposits is encountered in various forms. Natural uranium contains three radioactive isotopes: The ^{238}U (99.2739%), ^{235}U (0.7205%), and ^{234}U (0.0056%). The nuclear reactors as the nuclear fuel use ^{235}U isotope enriched uranium. The mixture of natural uranium contains 0.71 - 0.73% of the ^{235}U isotope. Enriched uranium contains over 0.73% of the ^{235}U isotope. Depleted uranium contains below 0.71% of the ^{235}U isotope.

Radioactivity of uranium is the ability of its atomic core to spontaneously disintegrate with the emission of particles, which is accompanied by the release of energy. Specific radioactivity of natural uranium is 25 kBq/g. Activity of natural uranium is conditioned exactly half by ^{238}U and ^{234}U, since they are in equilibrium in natural uranium. The ^{235}U isotope specific activity in natural uranium is 21 times less than specific activity of ^{238}U.

Radioactive decay is characterized by the lifetime of a radioactive isotope, the type of particles emitted, and their energies. The main types of radioactive decay (radiation) are:

– α-decay (α-radiation) – the emission of heavy positively charged α-particles by atomic nucleus;

– β-decay (β-radiation) – emission of an electron and antineutrino, positron and neutrino by atomic nucleus, absorption of atomic electron by nucleus with neutrino emission;

– γ-radiation is a type of electromagnetic radiation, a stream of elementary particles with high energy (gamma quanta);

– spontaneous fission (neutron decay or neutron radiation) is the decay of an atomic nucleus, which usually results in the formation of a stream of neutrons (elementary particles that do not have an electric charge).

Alpha radiation is characterized by a low penetrating power and affects the body only in the immediate vicinity of the radiation source. Therefore, even a sheet of paper, rubber gloves, plastic glasses and a simple respirator will be an insurmountable obstacle for it.

Beta radiation has a greater penetrating power than alpha radiation, so plexiglass, glass, a thin layer of aluminum, a gas mask, etc. are used to protect against this type of radiation.

Often, radioactive decay is accompanied by gamma radiation, which is a stream of high-energy photons (gamma quanta). Gamma radiation spreads over long distances and penetrates through almost any surface. Heavy metals such as tungsten, lead, steel, cast iron, etc. are applied for protection.

Neutron radiation is a product of nuclear decay having the penetrating power that exceeds gamma radiation. The best protection against neutron radiation is such materials as water, polyethylene, and other polymers. Neutron radiation is usually accompanied by gamma radiation, so multilayer screens or solutions of heavy metal hydroxides are used often as protection.

The only natural isotope of uranium, which allows self-sustaining nuclear chain reaction (SCR) is ^{235}U. Therefore, this isotope is used as a nuclear fuel in transport, research, power and other types of nuclear reactors. Extracting the ^{235}U isotope from natural uranium is a sophisticated technological task.

Uranium production is conducted in a variety of ways such as quarry mining when the rock is not deep; underground tunneling, an economically feasible method with the high quality ore; and in-situ leaching method (Fig. 1), which is the most environmentally friendly and cost effective. In the uranium production by in-situ leaching, a uranium solution of uranium salts is obtained.

Processing of natural uranium compounds includes ore enrichment (production of ore concentrates), uranium-ore processing (production of chemical concentrates), refining (production of pure uranium compounds), sublimate (hexafluoride) and metallurgical production (production of metal and castings from it).

The first stage of uranium production is concentration. The rock (uranium ore) is crushed and mixed with water. Heavy components of the suspension are deposited.

The second stage is leaching of concentrates. Depending on the type of rock, acid or alkaline leaching is used.

At the next stage, uranium needs to be selectively extracted from the resulting solution. The content of impurities must meet the requirement of nuclear-grade, i.e. not exceed 10^{-6}-10^{-7}. This problem is solved by methods of extraction and ion exchange, which allow to extract uranium sufficiently fully even from lean solutions.

After purification, natural uranium is converted to hexafluoride (UF_6) at the separation-sublimation plants of ROSATOM, and is then enriched with the 235^U isotope, and sent to the production of fuel for nuclear power plants.

Uranium ore quarry mining

Uranium ore shaft method

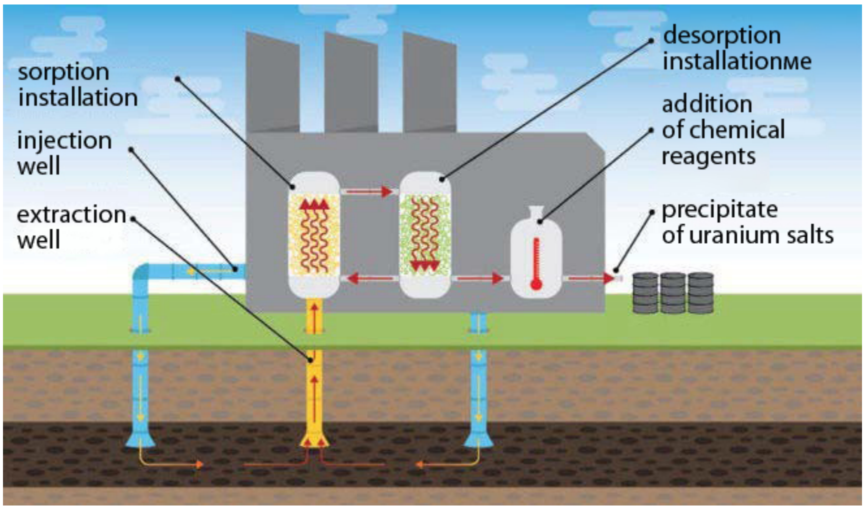


Fig. 1. In-situ leaching method

Chapter 2.

Uranium hexafluoride and its properties

Uranium hexafluoride (UF_6) plays a key role in the nuclear fuel cycle (NFC) as the main substance suitable for the separation of ^{235}U and ^{238}U isotopes by both gas diffusion and centrifuge methods, since it is the only uranium compound that converts to a gaseous state at a relatively low temperature (56.4 °C).

Uranium hexafluoride enriched with ^{235}U isotope (enriched uranium product) obtained at isotope separating plants is used further in production of fuel for nuclear reactors, while uranium hexafluoride depleted by ^{235}U isotope is sent for storage and subsequent processing.

Separation plant site

2.1. Physical properties of uranium hexafluoride

Uranium hexafluoride is compound of hexavalent uranium and fluorine (UF_6). Fluorine is present here as the only stable natural isotope, fluorine-19.

Under normal conditions (i.e. at an atmospheric pressure of 760 mm Hg, and temperature of 20 °C), uranium hexafluoride is in a solid state. During transportation and storage, uranium hexafluoride is also in a solid state and is a dense crystalline substance, which appearance depends on the production technology: from irregular particles resembling rock salt powder to a formless solid mass. Density of solid uranium hexafluoride is more than density of granite, and equals to 5.09 g/cm^3.

Uranium hexafluoride under normal conditions typically features a direct phase transition from solid to gas, bypassing the liquid (sublimation), and a reverse transition from gaseous to solid (desublimation) (Fig. 2).

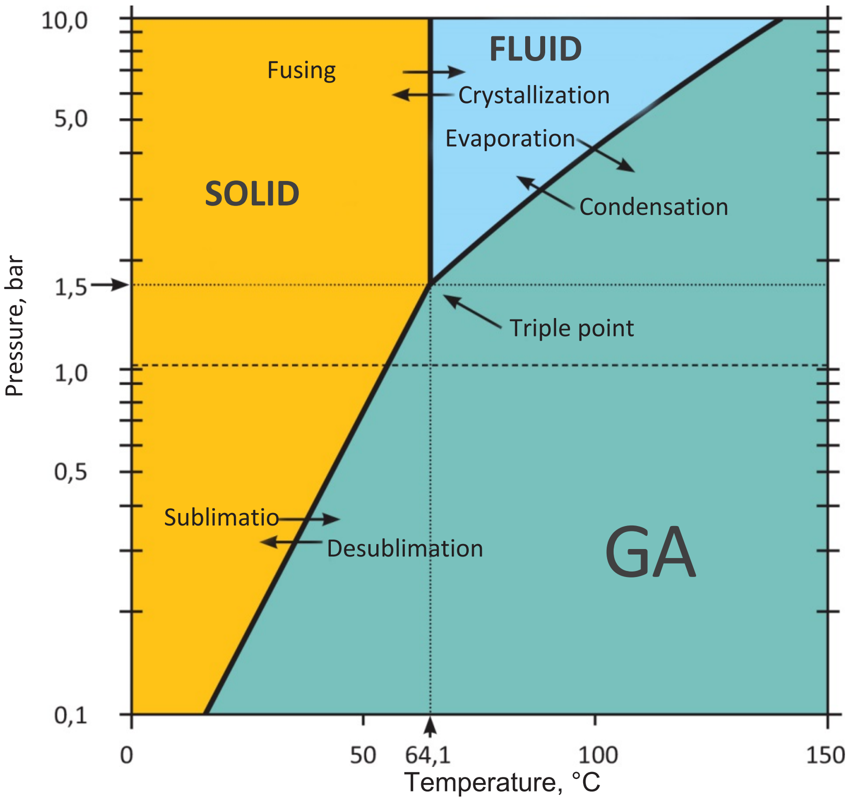


Fig. 2. Phase states of uranium hexafluoride

Gaseous uranium hexafluoride is a heavy colorless gas. At 64.1 °C and pressure above 152 kPa, the liquid and solid phases can be in equilibrium, and if there is heating or cooling at this temperature, the processes of fusing or solidification of uranium hexafluoride will occur, respectively.

2.2. Chemical properties of uranium hexafluoride

Under normal conditions, uranium hexafluoride is non-flammable and does not react chemically with oxygen, nitrogen, carbon dioxide and dry air. In gaseous and solid states, it reacts violently with water, including atmospheric moisture, generating uranyl fluoride (UO_2F_2) and hydrogen fluoride (HF), which are very hygroscopic (they absorb moisture easily). Reactions are very exothermic, and the heat release during reaction with solid uranium hexafluoride is significantly higher than with gaseous one (211.6 and 156.8 kJ/mol, respectively).

At elevated temperatures, gaseous uranium hexafluoride interacts with water vapor as follows:

$$\underset{\text{gas}}{UF_6} + \underset{\text{vapor}}{2H_2O} \rightarrow \underset{\text{solid}}{UO_2F_2} + \underset{\text{gas}}{4HF} + Q \text{ (heat).}$$

Reaction of solid uranium hexafluoride with water runs very slowly compared to gaseous state, which occurs almost instantly, since the resulting fine aerosol (uranyl fluoride, UO_2F_2) forms a protective layer that serves as a diffusion barrier that prevents water from entering the surface of the actual uranium hexafluoride. This effect leads to a significant slowdown in the reaction rate. Therefore, the rate of hydrolysis of solid uranium hexafluoride is quite low, while gaseous UF_6 interacts with water almost instantly.

Uranium hexafluoride is a strong oxidant. In liquid form, it reacts with many organic substances with an explosion, it is aggressive against certain metals, plastics, rubbers, and polymer materials. Interacting with most metals, it forms metal fluoride and low-volatile or non-volatile low-valent uranium fluoride (UF_4).

Nickel, alloyed steels, including low-alloy ones, copper, copper-nickel and some aluminum alloys are resistant to the effects of uranium hexafluoride. Teflon and other fluorine-containing plastics also withstand uranium hexafluoride.

Taking into account the listed chemical properties of uranium hexafluoride, it is necessary to exclude its interaction with moisture at all stages of its handling (technological processes, transportation, storage, etc.). Conventional hydrocarbon lubricants should not be used in vessels and containers filled with uranium hexafluoride, they should also be free of organic substances.

Since uranium hexafluoride is a chemically toxic and very caustic substance that causes severe toxication and corrodes any living organic matter with formation of chemical burns, then in accordance with GOST 12.1.007-76 Noxious substances. Classification and general safety requirements, uranium hexafluoride is referred to the I class hazard substances. When handling it, it is necessary to ensure industrial safety of production, storage and transportation as for chemical production sites. In Russia, the maximum permissible concentration (MPC) of uranium hexafluoride in the air of the working area is 0.015 mg/m^3, and, for example, in the United States, the maximum threshold level of a single exposure is equal to 0.6 mg/m^3.

Radioactivity of uranium hexafluoride with a natural content of its isotopes being delivered for enrichment is slightly lower than that of natural uranium viz., 17 kBq/g. This value of specific activity refers to a freshly prepared substance that does not contain all the daughter disintegration products of the uranium series.

After the enrichment, specific activity of uranium hexafluoride will depend on its enrichment degree (Table 1).

Table 1

Specific activity of uranium hexafluoride depending on the enrichment degree*

Kind of uranium hexafluoride	Content of ^{235}U, %	Specific activity, Bq/g
Depleted	0.1	$2.7 \cdot 10^{3}$
	0.2	$5.3 \cdot 10^{3}$
	0.45	$1.2 \cdot 10^{4}$
Natural	0.72	$1.7 \cdot 10^{4}$
Enriched	1.0	$1.9 \cdot 10^{4}$
	1.5	$2.5 \cdot 10^{4}$
	5.0	$6.7 \cdot 10^{4}$
	10.0	$1.2 \cdot 10^{5}$
	20.0	$2.5 \cdot 10^{5}$
	35.0	$5.0 \cdot 10^{5}$
	50.0	$6.2 \cdot 10^{5}$
	90.0	$1.5 \cdot 10^{6}$
	93.0	$1.8 \cdot 10^{6}$
	95.0	$2.3 \cdot 10^{6}$

* The values for specific activity include activity of ^{234} U, which is concentrated during the enrichment process, and do not include contribution of daughter products.

Activity of uranium hexafluoride at storage depends on the length of time that has elapsed since its production, since daughter nuclides accumulate in the uranium hexafluoride over time. Since all uranium isotopes have very long half-lives, and the daughter isotopes ^{238}U and ^{235}U (234^{Th} and 231^{Th}, respectively) have short half-life, the natural radioactive equilibrium is reached after 150 days. After this, specific activity of uranium hexafluoride at storage with initial natural content of isotopes increases to 40 kBq/g.

Uranium hexafluoride obtained from reprocessed uranium (uranium extracted from spent nuclear fuel, SNF) additionally contains quite large concentrations of artificial uranium isotopes, such as ^{232}U, ^{233}U, ^{236}U, whose activity is significantly higher than that of natural ones (Table 2).

Table 2

Specific activity of uranium isotopes

Isotop e	**Content in natural uranium, %**	**Specific activity, Bq/g**
^{232}U	–	$827.38 \cdot 10^9$
^{233}U	–	$356.54 \cdot 10^6$
^{234}U		$230.22 \cdot 10^6$
^{235}U		$80 \cdot 10^3$
^{236}U	–	$2.33 \cdot 10^6$
^{238}U		$12.5 \cdot 10^3$

The isotope abundance of such uranium hexafluoride depends on the reactor type, in which the source uranium was irradiated, fuel burn-out, and SNF holding time.

Chapter 3.

What is DUHF

In the process of uranium enrichment with the ^{235}U isotope, an enriched uranium product (EUP) is formed, which is used for the manufacture of fuel, and a by-product viz., depleted uranium hexafluoride (DUHF) (Fig. 3).

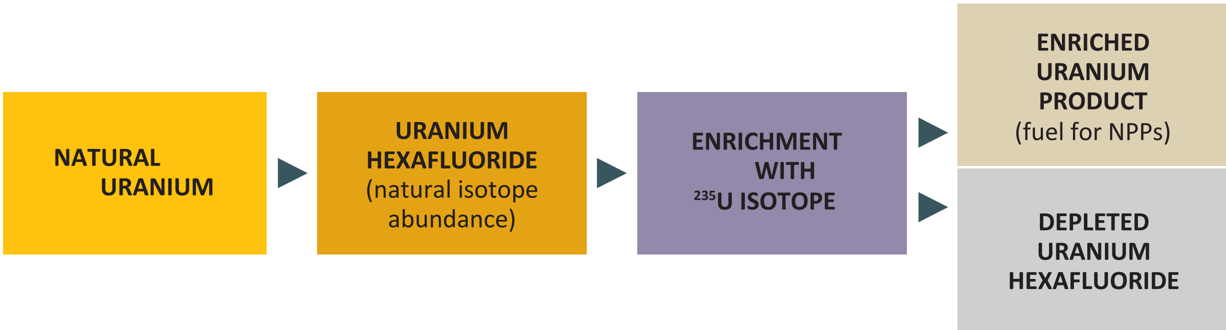


Fig. 3. Natural uranium conversion flowsheet

DUHF refers to nuclear materials, i.e. materials containing or capable of reproducing fissile nuclear substances and subject to the state accounting and control at the federal and departmental levels. DUHF differs from natural uranium hexafluoride in its isotopic composition and in that the content of the ^{235}U isotope is several times lower in it. In large part, both Russian and foreign reserves of DUHF, such a quantity of the ^{235}U is present, which makes economically sound its reuse as raw material to produce fuel for thermal reactors, although the economics of the DUHF after enrichment in each case will be determined by the ratio of prices of natural uranium on the world market and the cost of additional extraction of ^{235}U from DUHF.

DUHF features the same chemical properties as the natural uranium hexafluoride. The amount of residual ^{235}U in the DUHF depends on the enrichment technology and can range from approximately 0.07% to 0.74%. Specific activity of DUHF is defined practically by activity of ^{238}U only (12.5 kBq/g). It makes up less than a half of the activity of natural uranium, since it is impossible to separate light isotopes during the enrichment process, and the entire ^{234}U (which gives half of contribution to the activity of the natural uranium) together with ^{235}U transfers into the EUP. Moreover, even the activity of DUHF obtained after enrichment of processed uranium is comparable to that of the natural uranium, since almost all of the highly active isotopes contained in the reprocessed material (^{232}U, ^{233}U, and ^{236}U) transfers into the EUP.

From the point of safety, it is necessary to convert chemically toxic and aggressive gaseous DUHF into an oxide form (UO_2) – a solid with a melting point of 2850 °C. Uranium oxides are solid thermally and chemically stable compounds that fail to react with water and its vapors up to 300 °C, and they are insoluble in most mineral and organic acids.

During the processing of DUHF, uranium will be defluorinated and transferred from a potentially chemically hazardous substance to a safer one, which significantly minimizes the risks.

3.1. DUHF status in Russia

The main question that is constantly being discussed in the information field and among the public is this: what is the DUHF – a raw materials or radioactive waste? It is crucial to answer to this question, because if DUHF is indeed radioactive waste, then the question arises about the legality of importing the DUHF from abroad to Russia.

According to Federal Law dated November 21, 1995 No. 170-FZ "On use of nuclear energy", radioactive waste is "the materials and substances not subject to further use, and equipment, articles (including spent ionizing radiation sources), in which thecontent of radionuclides exceeds the levels established in accordance with the criteria defined by the Government of the Russian Federation" (clause 8, article 3). Federal Law No. 190-FZ dated July 11, 2011 "On handling of radioactive waste and on amendments to certain legislative acts of the Russian Federation" that regulates relations in the field of radioactive waste handling, "the concept of "radioactive waste" is used in the meaning provided under article 3 of Federal Law No. 170-FZ dated November 21, 1995 "On use of nuclear energy"..." (clause 2, article 3).

There are no other regulatory legal acts in the Russian Federation that contain criteria for classification as radioactive waste (RW).

Thus, it is necessary to find out whether depleted uranium hexafluoride is subject to further use or not.

DUHF is a radioactive material. Thanks to a high efficiency of modern Russian gas-centrifugal enrichment technology, the equivalent of natural uranium of different grades produced from DUHF at Russian separation plants has an attractive cost in comparison with the world price for natural uranium, and therefore it is used in the manufacture of fuel for nuclear power plants. Currently, Russia is implementing a program for switching to a closed NFC. The BN-800 fast neutron reactor has been put into commercial operation, where a practical demonstration of the use of depleted uranium as part of MOX fuel was commenced. A factory for production of pellet style MOX fuel for BN-800 has been built. Switching to loading of the reactor core with MOX fuel is planned in 2020. Depleted uranium with an increased content of the ^{238}U isotope compared to the natural one is a raw material for nuclear power with fast neutron reactors.

Thus, the DUHF is considered as a strategic reserve for the existing nuclear power industry, which currently has an open circuited (or open) NFC, as well as for the closed nuclear cycle, if it is implemented.

In addition, DUHF is a valuable source of fluorine, which can be used in a closed fluorine separation-sublimation cycle (see Chapter 4), as well as in other industries.

When determining the status of the DUHF, it is necessary to take into account the conclusions of the IAEA experts (ISBN 92-64-195254, 2001), according to which the DUHF is not a radioactive waste and is considered as a useful energy resource viz., an additional source of uranium and fluorine.

Attribution of DUHF to useful resources, rather than radioactive waste, is also confirmed by the expert opinion of VNIIHT, JSC, the leading Russian scientific center for chemical technologies.

The above information, as well as the description of the possibilities of using the DUHF, set out in Chapter 4, witness that depleted uranium hexafluoride is used in many areas of the Russian industry as a useful resource, which, according to the above-mentioned regulatory legal acts, excludes it from the category of radioactive waste.

DUHF is one of the largest secondary sources of uranium, since it is a raw material of nuclear-grade, which makes it attractive for the production of nuclear fuel, as well as a secondary source of fluorine for non-nuclear areas (metallurgy, chemical industry). Exactly this classification of DUHF allows for to be concluded among companies for its import as raw materials, including for the import of DUHF to Russia.

3.2. Reprocessed uranium, its features and differences from natural uranium

When discussing issues related to the DUHF handling, there is often a lack of understanding of the difference between uranium obtained from uranium ore by conversion (Fig. 3) and reprocessed uranium (reprocessed material).

Reprocessed uranium is uranium recovered during the processing of spent nuclear fuel.

Depending on the primary enrichment, the specifics of nuclear fuel in various reactors, as well as on the technology of SNF processing, reprocessed uranium may have a different content of the ^{235}U isotope viz., from tenths to several percent.

Reprocessed uranium may be returned to the fuel cycle by various ways. It can be used directly or be further enriched, as well as mixed with enriched or natural uranium.

The use of reprocessed uranium for the manufacture of nuclear fuel is difficult due to the presence in its composition of artificial even-numbered isotopes ^{232}U and ^{236}U and a higher content of ^{234}U in comparison with the natural mixture. Said isotopes may not be separated from ^{235}U during chemical processing.

To produce a nuclear fuel that meets international standards, the content of even-numbered isotopes must be limited. For instance, ^{236}U isotope is a neutron poison, and to maintain the breeding properties of the fuel it is necessary to further increase its enrichment with ^{235}U isotope.

In addition, the relatively short-lived ^{232}U with a half-life of about 69 years creates problems related to radiation safety, since its decay products (^{208}Tl) emit hard gamma quanta with an energy of 2.6 MeV, which requires additional protection of personnel when working with this material. Given that the concentration of ^{232}U in the reprocessed uranium depends on many factors, the fabrication of fuel from the reprocessed uranium is determined by the radiation safety conditions of personnel, and the standards of its content differ tenfold for different production sites. A recommended content of ^{232}U in Russia is $2 \cdot 10^{-7}$%.

The initial content of even-numbered isotopes in the reprocessed uranium depends on the burn-out of the nuclear fuel, from which it is extracted. In recent decades, there has been a steady trend towards increasing the fuel burn-out of thermal neutron reactors.

Recycling of the reprocessed uranium is a high-tech and expensive process, so not all countries use these technologies. In Russia, recycling of reprocessed material has been carried out on an industrial scale since 1977. Since 1993, TVEL JSC has been producing fuel from post-enriched reprocessed material for both domestic reactors (RBMK) and Western companies.

Hereafter, the report will not address the reprocessed uranium, since this is not directly related to the main topic.

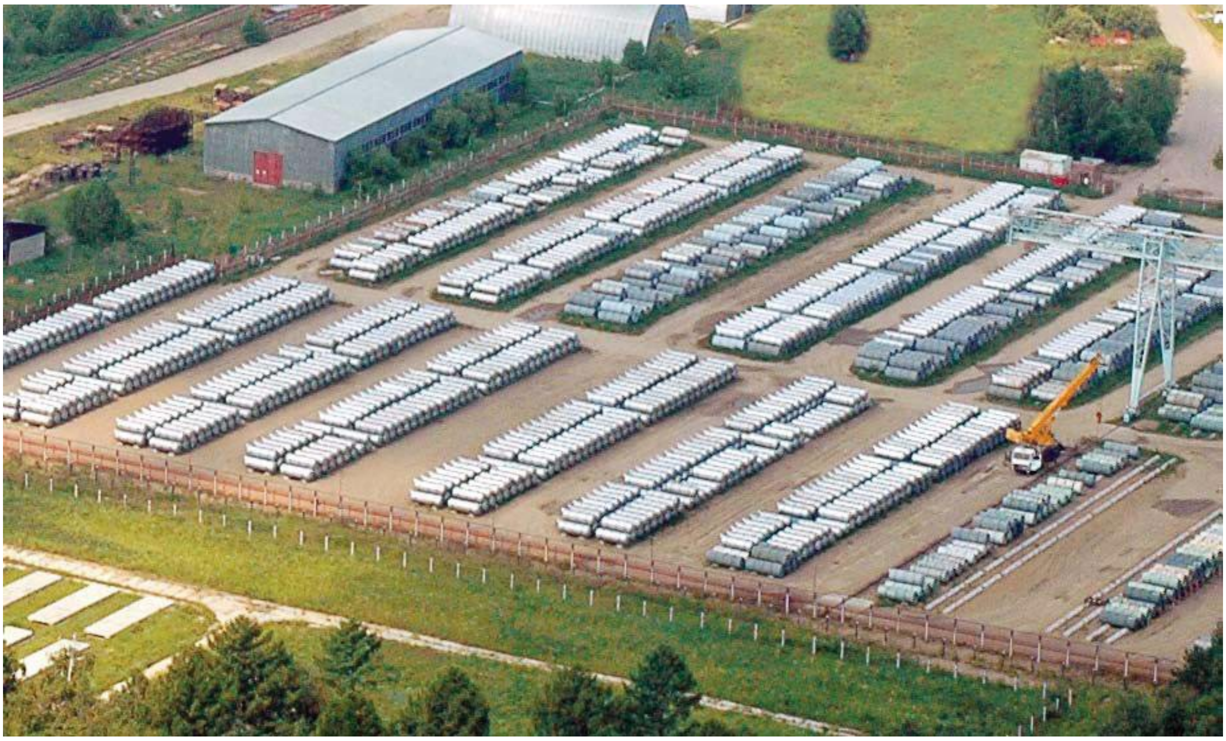
Chapter 4.

DUHF handling

All the processes of DUHF life cycle, starting from its formation and ending with long-term storage, belong to the stages of DUHF handling. The life cycle includes such stages of handling as accumulation, storage, transportation and processing.

4.1. Formation and accumulation

The problem of the formation, accumulation and service of DUHF reserves appeared simultaneously with the development of separation plants in countries that were engaged in uranium enrichment. DUHF that remains after uranium enrichment, which constitute volumes 6-8 times higher than the volume of EUP, accumulated on the industrial sites of separation plants.



DUHF storage at Angarsk electrolysis chemical integrated plant

In the very first gas diffusion units, at which uranium was enriched, the content of ^{235}U in DUHF was equal to 0.4% and more. Further improvement of technologies allowed to reduce the content of ^{235}U in DUHF to ~0.3%. Gas diffusion technology was widely used in many countries until the late 1970s and was almost the only industrial technology for uranium enrichment. Thus, the entire DUHF, which accumulated until the end of the 1970s, and most of which is now located on industrial sites, contains approximately 0.3-0.4% of ^{235}U.

Gas-centrifuge technology is a more effective technology for uranium enrichment, which reduces the content of ^{235}U in the DUHF to ~0.2% or less. In a centrifuge rotating at a high circumferential speed, heavy hexafluoride molecules with ^{238}U are concentrated at the periphery under the action of centrifugal forces, and light ones with ^{235}U are concentrated at the axis of the centrifuge rotor. The degree of separation is proportional to the square of the ratio of the rotation speed to the speed of the molecules in the gas. In addition to the efficiency of enrichment, gas-centrifuge technology is significantly less energy-intensive than diffusion technology.

At the end of the 1970s, a large-scale re-equiping of separation plants began in the world and now almost all plants have switched from diffusion to gas-centrifuge technologies.

Nowadays, Russia has the most perfect gas-centrifuge enrichment technologies that can reduce the content of ^{235}U in the DUHF to 0.1% of ^{235}U and less (foreign technologies show 0.2-0.3%). A typical concentration range for ^{235}U in the accumulated DUHF is 0.25-0.35%, and it is 0.4% and more in a significant part of accumulated DUHF produced at the separation plants of previous generations. Thus, in the USA, for example, more than one third of accumulated DUHF features concentration of ^{235}U at 0.35-0.66%.

To date, since the beginning of the development of the nuclear industry, more than 2 million tonnes of DUHF have been accumulated in the world, including more than 1 million tonnes in Russia. When 1 thousand tonnes of natural uranium is enriched, ~150 tonnes of EUP and ~850 tonnes of DUHF are formed, so 40-60 thousand tonnes of DUHF are added to the already accumulated amount. The vast majority of this volume is stored in special sealed steel tanks (casks) on open sites of separation plants.

DUHF storage site

In Russia, the DUHF is formed and stored at four enterprises of the separation and sublimation unit of TVEL JSC fuel company viz., Ural Electrochemical Combine, JSC (SC UEIP, Novouralsk, Sverdlovsk region), Production Association Electrochemical Plant, JSC (JSC “PA ECP”, Zelenogorsk, Krasnoyarsk territory), Siberian Chemical Plant JSC (Seversk, Tomsk region) and Angarsk Electrolysis Chemical Integrated Plant (ANGARSK ELECTROLYSIS CHEMICAL PLANT JSC, Angarsk, Irkutsk region). The total reserves of DUHF at these enterprises at the end of 2019 exceeded 1 million tonnes.

4.2. DUHF storage and cask service

DUHF in Russia is stored in thick-walled (16 mm) import casks with a capacity of 4 m^3, and domestic containers with a capacity of 2.5 m^3, made of high-strength carbon steel, undergoing overpressure tests of 28 and 10.5 kg/cm^2, respectively, and designed for extreme mechanical and corrosion effects.

Foreign casks

The design of the tanks has a significant margin of safety, which provides resistance to mechanical stress and to high temperatures. The standard service life of containers is 80 years for domestic ones, and not limited for imported ones, with a possible risk of leakage of 10^{-7}, and with the possibility of rapid re-packaging of DUHF, as well as repair of defective casks.

After manufacturing, the casks are subjected to tests for mechanical strength, tightness, heat resistance and resistance to hydrostatic pressure. For strength tests, a cask is dropped from a height of 9 m on a concrete slab with a metal pin with a diameter of 36 mm. Falling from this height is equivalent to hitting a concrete slab at a speed of 45 km/h. Heat-resistance tests are carried out by holding the cask in an open fire at 800 °C for half an hour. Impermeability tests are carried out using resistance to hydraulic pressure twice the working pressure at a temperature from minus 40 °C to plus 40 °C (the above test parameters are used for imported casks of 48Y type).

Taking into account that the DUHF transfers into a gaseous state at 56.4 °C, it is in a solid state on all sites. In addition to DUHF, some depleted uranium is stored in other chemical forms viz., in the form of oxide or metal.

Casks with DUHF are serviced at the sites in accordance with the program and instructions for servicing casks of Russian production or 48Y type casks of foreign production. The program and instructions provide for inspection, control and other actions necessary to ensure the safety of casks. During maintenance, casks are assessed for their state, defective valves and plugs are replaced, cylinders are repainted, corrosion rates are monitored, and measures are taken to minimize it. In addition, technical operation of the territory, inventory monitoring, research on improving storage technology, and security are provided.

Russian made casks

If the DUHF leaks from cylinder, the released UF_6 reacts with water vapor in the air to form uranyl fluoride (UO_2F_2) and fluorine hydride (HF). Uranyl fluoride is a solid that covers the surface of solid UF_6 and thus restricts the further flow of the reaction between UF_6 and airborne moisture to form fluorine hydride. Release of fluorine hydride into atmosphere is also slowed down when a plug is formed. When DUHF leak is detected on a valve, such valve is replaced. When the cylinder wall is corroded, integrity of the latter is restored by a patch using a welded steel joint. Casks and tanks are stored on sites in such a way that it is possible to visually inspect any packaging.

In order to improve reliability of casks, comprehensive systems for diagnostics, maintenance and repair of casks are being deployed at all separation plants. Diagnostic methods will allow identifying and assessing the risk of defects, determining the defects that have already occurred, as well as the likelihood of defects in the future. Such a comprehensive system is an integral part of the quality and environmental safety management systems implemented at enterprises, including those certified according to ISO-9000 and ISO-14000 series standards.

R&D that carried out in the area of safe DUHF storage are aimed at improving the monitoring systems, technical diagnostics and control of the condition of casks, and technologies for handling defective casks detected during storage. In addition, research is continuing to justify the possibility of extending the designated service life of Russian-made casks over 80 years.

At storage sites, radiation monitoring of casks with DUHF is constantly carried out, and the safety of its storage technology is confirmed by Rostechnadzor licenses issued to enterprises.

4.3. Transportation

According to the UN classification, all dangerous goods are divided into hazard classes depending on the types of hazard, as well as their physical, chemical and biological properties. In Russia, GOST 19433-88 "Dangerous goods. Classification and marking" is in effect, which covers dangerous goods and establishes, among other things, a schedule of indicators and criteria for referring goods as dangerous, their classification, rules for transportation and marking of cargo units.

Uranium hexafluoride is classified as a hazard class 7 according to the above documents. The ordinal number of the hazard class (from 1st to 9th) does not characterize the level or degree of danger of the cargo. To indicate the dangerous properties of goods, as well as their physical and chemical properties or belonging to a certain group of dangerous substances, classification codes are used, which themselves disclose the properties of the dangerous goods. For uranium hexafluoride, classification codes are not assigned, i.e. additional dangerous properties such as explosion hazard, asphyxiating gases, spontaneous combustion, etc. (there are 12 of them in the classifier), for uranium hexafluoride are not defined.

DUHF casks on vessel

Transportation of DUHF from Western Europe to Russia is carried out by sea through the port of Saint Petersburg (or the port of Ust-Luga) and then, by rail to the locations of processing and storage. It should be noted that, in contrast to the transportation of oil, gas, pesticides and other dangerous goods, in the entire history (more than 60 years) of DUHF transportation in Russia (and the USSR), there was not a single incident or accident on road and rail transport.

4.4. Cases and possible scenarios of cask leakage during storage and transportation

In case when a cask leaks, the main danger is leakage of uranium hexafluoride (UF_6) into the environment: it reacts with air moisture to form toxic hydrofluoric acid (HF) and uranyl fluoride (UO_2F_2). All publications describing the possible consequences of a cask leak note that estimates of the distribution of emissions to the atmosphere are difficult, but it is likely that for any UF_6 leak, distribution will be very local.

From the diagram of the state of uranium hexafluoride (see Fig. 2), it can be seen that at normal ambient temperature (and the temperature of the cask contents comes into equilibrium with the ambient temperature quite quickly) and a pressure less than atmospheric one (casks are always vacuums), UF_6 is in a solid state.

Over the past 45 years, about ten incidents with casks in solid uranium hexafluoride storage facilities are known. Most accidents were caused by corrosion around dents caused by improper handling, or corrosion around welding defects. In addition, there were staff errors that resulted in the leakage of casks.

Loading of DUHF casks on flatcar

INCIDENTS ON SITES

In the United States, in 1944, an experimental arrangement for thermo-diffusion was temporarily shut down for modification of pipelines. During the work, the weld on the cask with natural gaseous UF_6, which was heated by steam, ruptured at a length of 8 feet. About 400 pounds of UF_6 was released into the atmosphere, which reacted with steam – and formed HF and UO_2F_2. Two persons were killed during the accident, and three persons were injured from HF inhalation and uranium poisoning (they recovered later).

In 1978, a cask (cylinder) partially filled with liquid UF_6 was accidentally dropped and depressurized in a warehouse at the Portsmouth gas diffusion plant. Measures were taken to clean and collect UF_6. No one was injured during the accident. Cold weather has limited dispersion of UF_6, since the UF_6 in the cask is in a liquid state only for a few days after filling. As soon as the cask cools down, UF_6 transfers the solid phase, and will be released from the cylinder much more slowly, as illustrated by the UF_6 phase diagram (see Fig. 2).

In 1986, at a commercial uranium processing unit (Sequoyah Fuels Corp., Gore OK), a leak of UF_6 occurred with a rupture of cylinder. The accident occurred when an overloaded cylinder was heated to remove excessive UF_6. It ruptured, and released a cloud of UF_6 and reaction particles. The accident resulted in the death of one person (from HF inhalation), and 31 other employees were exposed to the gas cloud. There were no long-term effects on human health or environment.

ACCIDENTS DURING TRANSPORTATION

Over the entire history of DUHF transportation (about 70 years), only one navigation accident is known. On August 25, 1984, Mont-Louis cargo ship carrying 350 tonnes of uranium hexafluoride sank in the North sea 4.5 hours after colliding with Olau Britannia car ferry[1]. Port of destination – Riga.

The cargo consisted of 18 casks with depleted uranium hexafluoride (concentration of ^{235}U is 0.67%), nine casks with natural uranium hexafluoride (concentration ^{235}U was 0.71%) and three casks with enriched uranium hexafluoride (concentration of ^{235}U was 0.88%). Moreover, casks with depleted and enriched uranium hexafluoride contained reprocessed uranium (with approximately the same level of radioactivity).

Casks with uranium hexafluoride were placed in the bow of the ship, and the impact occurred on the starboard stern, so they were not affected by the direct impact. The ship sank at a depth of 14 m, and the casks were found in the water.

Since uranium hexafluoride has insignificant activity, the main focus of the rescue effort was on chemical contamination. Samples were collected from the water surface, from the depths, and from the hold around the casks, and each member of the "Mont-Louis" crew was subjected to a medical examination. All casks were tested for leaks on board of the rescue barge, and after they were delivered to the port of Dunkirk.

All 30 casks with uranium hexafluoride were recovered from the wreck. While in the open hold during the storm, many of them were damaged: there were dents on the walls, valve covers were torn off, and several casks had bent valves. During the rescue operation and after the casks were delivered to the port, 217 samples were collected, which were subjected to 752 different analyses, and 146 radiation dose levels were measured on the casks themselves. As a result of measurements, no signs of leakage of radioactive (in natural or reprocessed uranium) and chemical substances (fluorine or hydrofluoric acid) were detected, i.e. the accident did not have any radiological or chemical consequences.

CASK LEAKAGE SCENARIO

The Institute for Industrial Ecology of the Urals branch of the Russian Academy of Sciences has considered the main real emergency scenarios and their consequences associated with leakage of DUHF casks, which may occur during their transportation and storage on sites (method 1)[2].

The scenarios that were considered when calculating the impact parameters assumed that emissions of uranyl fluoride, hydrogen fluoride, and uranium hexafluoride would enter the atmosphere in the primary emission cloud. The calculation was made based on various conditions and the amount of damage (holes) in leaking casks. However, the relative humidity of the air was assumed to be 85%, and the temperature was 20 °C. The scenarios were reviewed, in which a leakage in cask occurred in various parts of the cask, starting from the formation of a crack in the weld of the body above the boundary between the solid DUHF and the free space inside the cask, and ending with the formation of a through hole below the boundary of the solid DUHF. In addition, scenarios of significant leaks of casks were considered viz., destruction of part of the body and damage to cask equal to 100 cm^2.

---

[1] Bernard O. Accident of "Mont-Louis" Ship and Nuclear Safety // IAEA Bulletin. Vol. 27. No. 1. 1985. pp. 31-34.

[2] Method for predicting the scale of contamination (pollution) of the environment in case of rupture of the casks filled with depleted uranium hexafluoride kept on open sites of UEHK, JSC/Institute for Industrial Ecology of the Ural branch of the Russian Academy of Sciences. Yekaterinburg, 2003.

At the same time, it was supposed that the area of spilled DUHF would be equal to approximately 1000 cm^2. The results showed that the maximum stationary emission of uranyl fluoride and hydrogen fluoride would be 2687 and 698 grams per hour, respectively.

In addition to the incidents and scenarios described above, special attention is paid to assessing the risk of man-made accidents with DUHF casks, which may be caused by unforeseen and highly unlikely factors. In particular, the probability of DUHF casks during transport and storage are struck by a heavy aircraft with fully fueled tanks (45 tonnes of kerosene) in a terrorist attack or accident, according to the VNIIHT, JSC assessment, is 10^{-8}/year. For comparison, the probability of an object falling on a person from above or a celestial body, according to scientists at the Greenwich observatory (Great Britain), is $1.5 \cdot 10^{-7}$/year.

4.5. DUHF processing and use

As part of the nuclear fuel cycle, the DUHF can be exposed to reduction to tetrafluoride, uranium oxides, or uranium metal to produce fluorine-containing compounds that serve as a secondary source of fluorine for conversion production sites. Depleted uranium in oxide and metal forms can be used in a MOX blanket or mononitride fuel for fast neutron reactors, as well as for the manufacture of special radiation-resistant concretes. These concretes are unsurpassed construction materials for the manufacture of casks and protective screens for storage and transportation of SNF and are also used as radiation-proof ballast for the geological burial of SNF.

In other, non-atomic industries, fluorine-containing compounds are used in the production of ozone-safe refrigerants, and for etching printed circuit boards and chips. Depleted uranium is a promising material for doping semiconductors and magnetic material that can be used as a catalyst in the oil industry, in areas where high-density materials are required, as ballast, as well as an "accumulator" of hydrogen for its storage. Depleted uranium is also used as alloying additives in manufacture of high-strength steels. Therefore, recycling of DUHF is of commercial interest.

Finally, it is possible to organize long-term safe storage of DUHF in cases where it cannot be effectively used at the current state of the art, but there is hope for its application at the future state of the art. Thus, everywhere in the world DUHF is considered mainly as a useful resource and only as an exception can be classified as RW in those countries that do not see options or do not have the technologies for its useful application. The international practice has no unified legal status of the DUHF, which should be emphasized once again.

4.5.1. Using DUHF in nuclear fuel cycle

In 2000, the OECD nuclear energy Agency and the IAEA issued a joint report on the resources, production and demand for uranium (Uranium 1999 Resources, Production and Demand, ISBN 92-64-17198-3). As of January 01, 2000, the proven reserves of uranium worth up to $ 40/kg were 1 254 000 tonnes, and with an annual consumption of 65 000 tonnes, these reserves could last for approximately 25 years. However, due to the available storage reserves of uranium, which amount to approximately 20 thousand tonnes, as well as the use of reprocessed uranium from SNF recycling, and post-enriched uranium obtained from the DUHF, these resources may be sufficient for a longer period.

The dynamics of the increase in the difference between supply and demand in the period up to 2030 is shown in Fig. 4.

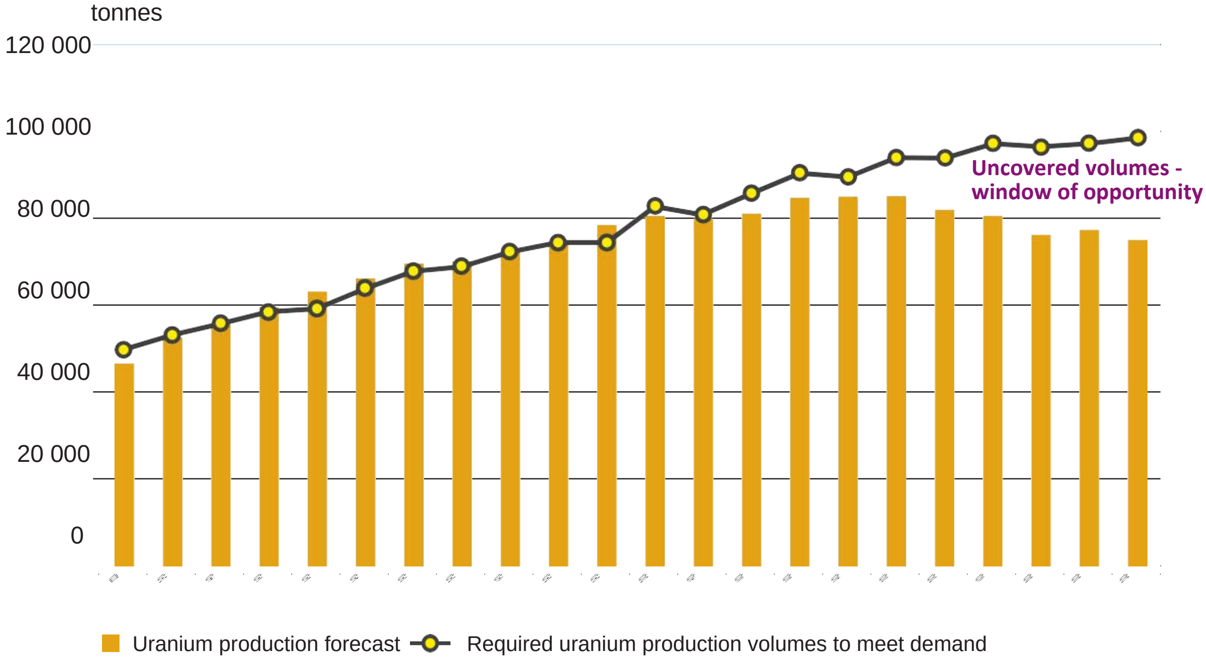


Fig. 4. Required and forecast uranium production volumes

In 2018, the volume of world uranium production was 53 500 tonnes, and the total consumption for nuclear power plants, transport nuclear power units, research reactors and special reactors was 64 457 tonnes. Given the reduction in uranium storage reserves, and the limited use of MOX fuel, the need for a secondary source of uranium, which is the DUHF, may increase.

During the post-enrichment, one part of the DUHF becomes post-enriched and suitable for use in the manufacturing nuclear fuel, and the other part becomes even more depleted, the content of ^{235}U in it will be reduced to less than 0.1%.

At all enterprises of TVEL JSC separation and sublimation unit, the rich dumps of previous years are being processed in order to additionally recover ^{235}U and use further this uranium for the production of nuclear fuel. As a result, the storages that keep accumulated "old" DUHF are systematically reduced, and the newly formed, even more depleted uranium hexafluoride is packed into new casks.

The expedience of repeated post-enrichment of the DUHF is determined by the technical and economic indicators of enrichment facilities and its economic indicators, in comparison with the production of primary uranium.

Uranium enrichment shop

The typical content of ^{235}U in the DUHF produced, for instance, at URENCO enrichment plants is 0.2-0.25%. As already noted, a significant part of the reserves of the DUHF contain an amount of ^{235}U that makes it economically sound to reuse it as a raw material for the production of nuclear fuel. Therefore, the uranium produced from the DUHF at Russian separation plants has an attractive price in comparison with the price of natural uranium.

In addition to the post-enrichment of the DUHF, other options for its use for the production of various types of fresh nuclear fuel are possible. DUHF is the source of two isotopes – ^{235}U, which is used to produce conventional uranium feed for traditional thermal reactors, and ^{238}U, which is a component for MOX or REMIX fuel. Therefore, depleted uranium extracted from the DUHF is used for mixing with plutonium to make MOX fuel. In the form of UO_2 it is
one of components of the uranium-plutonium MOX fuel in its the most common version. This component usually makes up more than 90% of the fuel matrix for any isotope abundance and fraction of plutonium. In oxide form, depleted uranium can be used as a MOX or mononitride fuel for fast neutron reactors. Depleted uranium oxides

obtained during the processing of DUHF have the status of nuclear-grade raw materials. This is a strategically important raw material viz., as the main substance of the breeding regions of fast neutron reactors operating in the uranium-plutonium cycle. The use of depleted uranium obtained during the DUHF reconversion is planned in the long term for the fuel supply of fast neutron reactors. Depleted uranium reserves will meet the needs of the "fast" energy industry for the next millennia.

For the production of natural uranium hexafluoride, hydrogen fluoride is used, which, depending on the scale of the conversion of the DUHF, is implemented in a closed-fluorine sublimate-separation cycle. The extension of projects for the processing of DUHF will fully meet the needs for fluorine, eliminate the need to operate production of anhydrous hydrogen fluoride using the technology of fluorite decomposition (CaF_2). This will ensure the independence of the nuclear industry from the purchase of imported raw materials (fluorspar) and sulfuric acid in the face of fluctuations in highly unstable prices for hydrofluoric acid.

From the point of the economy of the nuclear fuel cycle and DUHF handling, its post-enrichment or use for dilution of highly enriched uranium is primarily required with DUHF having a relatively high concentration of ^{235}U, and conversion, on the contrary, should be carried out with DUHF having a minimum concentration of ^{235}U. Therefore, a relatively rich DUHF should be preserved in this form, since its conversion to an oxide form and the subsequent reverse process requires additional material input and capacity utilization. Such approach will minimize the cost of DUHF handling.

Long-term storage of depleted uranium is accepted as the optimal strategy for further handling of depleted uranium oxides obtained as a result of processing of DUHF for the period up to approximately 2100s (i.e. until the planned transition of Russian nuclear power to operation of fast neutron reactors and clarification of the need for depleted uranium).

4.5.2. Using DUHF in industry

In addition to nuclear power, there are technical possibilities for using DUHF in other industries.

Thanks to a higher density, which exceeds the density of lead by 1.7 times, DUHF is used for biological protection against harsh ionizing radiation, where there is a need for a high density of the material. In this respect, depleted uranium is several times more efficient than lead, which is widely used for the same purposes. It is also used in the production of various materials (alloys, special concretes, cermets, etc.) for radiation protection in medical radiation therapy and in industrial radiography equipment.

A high specific mass density of uranium makes it usedful as ballast in shipbuilding, as counterweights for oil platforms, as balancing loads for aircraft, and other applications where high-density materials are required. Depleted uranium is also used as alloying additives in manufacture of high-strength steels and as a catalyst in the oil industry.

DUHF conversion is also necessary as a primary operation for most of the various uses that follow. For the needs of the nuclear industry, DUHF undergoes chemical processing, which results in obtaining of uranium oxides (U_3O_8 or UO_2), uranium metal and uranium tetrafluoride (UF_4), which is an intermediate product for the obtaining of pure uranium and its oxides. These solids have a high chemical stability, and therefore represent a practically optimal form for long-term storage of strategic depleted uranium reserves with significantly lower risks than for long-term storage of chemically active and toxic DUHF.

Depleted uranium reprocessing area

DUHF is a major secondary source of fluorine. Intermediate or final commercial products during DUHF conversion are various fluorine compounds: aqueous and anhydrous hydrogen fluoride (HF), sulfur hexafluoride (SF_6), silicon tetrafluoride (SiF_4), monosilane (SiH_4), and others. Like depleted uranium, fluorine derived during DUHF conversion has various applications in non-nuclear production units, and is widely used in chemical, electronic, and other industries. It is used to produce fluoroplastics, in particular Teflon, which is characterized by a low density, low water permeability, high thermal and chemical resistance, and high electrical insulation properties.

Fluorine-containing compounds are used in the production of various ozone-safe refrigerants, for etching printed circuit boards and chips. In large quantities, fluorine is used for the production of cryolite, which is used in aluminum production. Fluorine is widely used in the pharmaceutical industry in the synthesis of various medical products and cosmetics.

Tanks with hydrofluoric acid (DUHF processing product)

The initial raw material for the production of fluorine and fluorine compounds is fluorite. The main producer of fluorite concentrate is China, which accounts for more than 50% of world production. Russia is one of the largest importers of fluorite concentrate in the world. Taking into account the wide use of fluorine and fluoride compounds, the DUHF processing will allow involvement of a large amount of secondary source of fluorine in production. Therefore, DUHF processing is of commercial interest.

Thus, taking into account the technological capabilities and concepts of the nuclear fuel cycle of each country that has separation plants, it is necessary to develop DUHF processing technologies. In cases where they cannot be effectively used at the current state of the art, but there is a hope for their use in the future, it is necessary to ensure long-term safe storage of DUHF, eliminating the risks of natural and man-made nature. Moreover, during storage and processing of DUHF, it is necessary to ensure its availability for further use.

Despite more than half a century of experience in safe storage, DUHF still presents a potential chemical hazard. Therefore, to ensure chemical and industrial safety, as well as to reduce toxicological, chemical and environmental risks in the event of accidents, DUHF stockpiles are converted to stable forms that are more suitable for long-term storage. The preferred form of such storage is an inert, chemically resistant, non-volatile and insoluble oxide form viz., uranium nitrous oxide U_3O_8 (depleted triuranium octoxide) in the form of pressed powder, which can be stored in casks of simplified construction made of non-alloy steel for a long time.

PROPERTIES OF DTUO

The chemical and physical properties of natural and depleted triuranium octoxide (obtained by defluorination of depleted uranium hexafluoride) are completely identical, except for radioactivity.

The radioactivity of depleted triuranium octoxide (DTUO) is approximately two times lower than the natural triuranium octoxide owing to a lowered content of ^{234}U isotope.

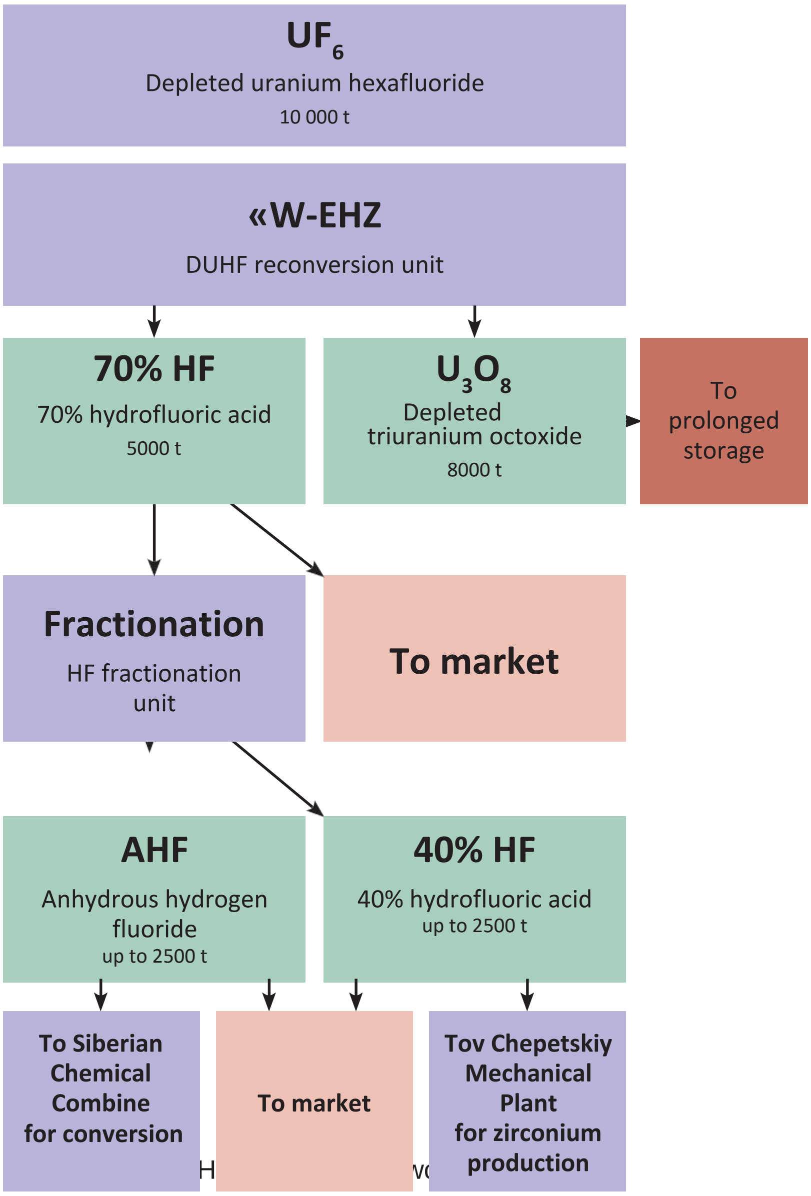
DTUO storage casks

Triuranium octoxide, or TUO (the following names are also used in literature: uranium(VI)-diuranium(V) oxide, triuranium octoxide, etc.), is an inorganic binary compound of uranium with oxygen, in which the metal has a dual atomicity: 5 (two atoms) and 6 (one atom). Gross formula of the compound – U_3O_8. Of all the uranium compounds found in nature, TUO is the most widely distributed, and is the major component of the main ore mineral of uranium – nasturan. In the free state, it is a green-black crystalline solid. Thermally and chemically stable compound.

Triuranium octoxide is thermally stable to temperatures of about 1000 °C, chemically inert and insoluble in water. TUO it is soluble only in concentrated strong acids. Diluted sulfuric and hydrochloric acids react very poorly with triuranium octoxide even when heated. As with all uranium compounds, TUO is characterized by low radioactivity. Natural triuranium octoxide is the main component of uranium concentrates, which serve as raw materials for the production of fuel for nuclear reactors that make the main portion of NPP reactor fleet in Russia and abroad at present. Depleted triuranium octoxide is considered as the raw material for fast neutron reactors.

4.5.3. DUHF processing (defluorination)

France was the first country in the world to adopt a strategy for gradual conversion of DUHF and converting it to a stable chemical form of DTUO in 1984, where the first "W1" unit with a capacity of 10 thousand tonnes of FFC per year was built for its conversion to triuranium octoxide (U_3O_8), which provides a complete defluorination of hexafluoride (Fig. 5).



The unit operates using the principle of pyrohydrolysis with water vapors. The following chemical reactions run in the unit:

$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$,
$6UO_2F2 + 6H_2O \rightarrow 2U_3O_8 + 12HF + O_2$.

Fluorine is reduced to 70% hydrofluoric acid, which is sold to the chemical industry, and U_3O_8 is compacted and packed in DV-70 casks of 3 m^3 volume. Filled casks that contain ~10 tonnes of U_3O_8 having specific activity of $2.11 \cdot 10^4$ Bq/g are placed for storage in an easily erected hangar.

Later, a second similar unit was built – "W2" with the same throughput capacity, which has processed more than 140 thousand tonnes of DUHF by now. To date, the DUHF conversion continues, and the capacity of the "W1" and "W2" units exceeds the current production of DUHF by French enrichment enterprises, which will lead to a reduction in its reserves.

A production site was commissioned in Russia, at JSC “PA ECP” in 2009 for reconversion (defluorination) of DUHF, where depleted uranium is transferred from the hexafluoride form to DTUO. The production is built under a contract with the French energy company COGEMA and is called "W-EHZ", similar to the name in France.

W-EHZ unit

Production capacity is 10 thousand tonnes of DUHF annually. As a result of the operation of "W-EHZ"at the end of 2019, the reduction in the reserves of DUHF in JSC “PA ECP” =amounted to more than 90 thousand tonnes. Reduction of DUHF at other separation sites will be commenced once additional ‘W’ production units are commissioned in JSC “PA ECP”, and on other sites.

It should be noted that in Russia, R&D efforts are active to create new technologies for converting DUHF into safer forms for storage and economically attractive commercial use. An example of work in the field of development of alternative (domestic) technologies for defluorination of DUHF to safe storage forms is a joint project of Siberian Chemical Plant JSC (Seversk) and "New Chemical Products", LLC (Saint Petersburg)[3].

4.6. Environmental aspects when establishing a framework for DUHF handling (licensing and state ecological assessment)

According to article 26 of the Federal Law dated November 21, 1995 No. 170-FZ "On use of nuclear energy", activities related to the handling of nuclear materials (DUHF) are subject to licensing. In accordance with article 3 of the mentioned law, the nuclear facility for processing (defluorination) of DUHF, DUHF storage sites, facilities for transportation of nuclear materials (in this case, DUHF) related to atomic energy utilization facility, for placement, erection, operation and decommissioning which requires a license.

The licensing procedure is established by decree of Russian Government dated March 29, 2013 No. 280 “On licensing activities in the area of utilization of atomic energy (jointly with Regulation on licensing activities in the area of utilization of atomic energy). This decree states that when an operating company receives a license, it is necessary to submit a positive conclusion of the state ecological assessment (SEA) as part of the materials justifying the license. The status of the operating company (recognition of a company as operating one) is established by an Order of Rosatom State Atomic Energy Corporation. In this case, SC UEIP (Novouralsk, Sverdlovsk region), JSC “PA ECP” (Zelenogorsk, Krasnoyarsk territory), and ANGARSK ELECTROLYSIS CHEMICAL PLANT JSC (Angarsk, Irkutsk region) are operating companies.

The object of the SEA is the license justification materials (LJM), which contain an environmental impact assessment (EIA) for the planned activity. Conducting an EIA involves organizing and conducting public discussions, which are an integral part of the EIA.

PLACEMENT OF NUCLEAR FACILITIES

Requirements for obtaining a permit for the placement of nuclear facilities for processing (defluorination) of DUHF are contained in decree of the Government of the Russian Federation dated March 14, 1997
No. 306 (rev. dated January 01, 2005) “On the rules of decision making on placement and erection of nuclear facilities, radioactive sources and storage sites”.

Paragraph 4 of the above-mentioned decree states that plants in the form of nuclear facilities located on the territory of closed administrative-territorial entities are

[3] RIA Novosti Online edition (see: https://ria.ru/20200512/1571175186.html?fbclid=IwAR2VtVGLPdmYUqkOn01ec_SmTMR5CVBUkCbIG1CDP1GxLN0vmGp7w8aFALs).

facilities of Federal significance. Paragraph 6g of the decree states that the set of documents submitted for approval for placement must include a positive opinion of the SEA of the license justification materials. In addition, paragraph 5 of the decree establishes that:"Decisions on erection of facilities of Federal significance are made by the Government of the Russian Federation. Decisions on the location of these facilities are made jointly by the Government of the Russian Federation and the state authorities of the constituent entities of the Russian Federation on whose territory the facilities are supposed to be located."

New nuclear facilities for processing (defluorination) of DUHF, which are planned to be established at SC UEIP and JSC “PA ECP”, will be integrated at already existing nuclear facilities, and their operation will be regulated by the main license, which currently regulates activity of the production plant. Under the terms of the main license, a nuclear facility is included in the General list of structures, complexes and facilities with nuclear materials intended for processing of nuclear materials.

ERECTION OF NUCLEAR FACILITIES

If at the previous stage the positive conclusion of the SEA was only necessary for placement, then they would need to develop materials for justification of licenses (LJM for erection of nuclear facility) and pass the SEA. It is possible to pass a public ecological assessment (PEA). In practice, Rostechnadzor allows combining the stages of placement and erection and issuing a combined license.

OPERATION OF NUCLEAR FACILITIES

Obtaining an operation license requires development of LJM for operation of nuclear facility and passing the SEA. For existing nuclear facilities, it will only be necessary to obtain a new license when the old license currently in force expires. An operation licenses needs to be obtained for a newly erected nuclear facility.

If the terms of the operation license are changed, the SEA is not carried out.

TRANSPORTATION OF DUHF IN RUSSIA

According to article 26 of Federal Law dated November 21, 1995 No. 170-FZ "On use of nuclear energy", handling of nuclear materials and radioactive substances, including during transportation and storage of nuclear materials, is a licensed activity.

Operating company is an organization founded in accordance with the legislation of the Russian Federation and recognized in the manner and on the conditions established by the Government of the Russian Federation, by the relevant managing authority for utilization of atomic energy, good for operation of nuclear facility, radiation source or storage site, and to carry out independently or engaging other companies activity on placing, designing, construction, operation and decommissioning of nuclear facility, radiation source or storage site, as well as activities related to the handling of nuclear materials and radioactive substances.

From this definition, it follows that the organization transporting nuclear materials may not be the operator, and therefore Rostechnadzor does not require a positive opinion of the SEA in the materials justifying the license.

Chapter 5.

DUHF handling economy

It is quite difficult to calculate the exact cost of storing and processing depleted uranium hexafluoride, since there are a small number of operating enterprises engaged in the processing of DUHF and commercial storage, with open and detailed information about cost.

It is even more difficult to estimate the cost of storage and processing of DUHF in Russia, since information about the cost of individual operations related to handling DUHF is not publicly available. Nevertheless, ROSATOM recognizes that the cost of processing DUHF at "W" type facilities (even taking into account the positive economic effect of selling fluorinated products and saving on the production of containers for DUHF) exceeds the cost of its storage. As a result, the operation of "W" production facilities in the next decade is expensive and, as declared by the fuel company TVEL JSC, has an exclusively environmental focus. At the same time, all hope is for the longterm prospect. TVEL JSC believes that it is possible to improve the design of packaging kits and to optimize storage technologies for DTUO. This will provide additional cost savings for storage of depleted uranium. If depleted uranium is used in the future as a raw material for fuel intended for fast neutron reactors, these costs may be offset by the price of this raw material. Today, the cost of ongoing work on safe handling of DUHF is included in the cost of production of separation plants of TVEL JSC.

The current methods of calculating the cost of using DUHF are mainly based on the concept of its conversion to a safer form and subsequent long-term storage. Various organizations have tried to calculate approximately the possible cost of operations for DUHF handling. Hereafter are some examples of such calculations. However, it should be borne in mind that the economic, technological and other conditions that affect the cost of a product may differ significantly in different countries, and this should be taken into account.

In the 1990s, a French company COGEMA offered its services for processing DUHF using pyrohydrolysis technology to convert uranium hexafluoride (UF_6) to uranium oxide (U_3O_8) and 70% hydrofluoric acid (HF) for the American company LES. At that time, experts estimated the cost of converting of UF_6 в U_3O_8 at $ 4.86 for 1 kg of uranium (or $ 3.29 for 1 kg of UF_6)[4].

The US Department of Energy conducted its own calculations of various options for processing DUHF and estimated the cost of long-term storage of U_3O_8 in underground mines at $ 4.57 for 1 kg of UF_6. But then the experts of the World Information Service on Energy, or WISE, considered that the storage conditions of DUHF should be compared with the requirements for the storage conditions of SNF[5]. But this is more likely to relate to the cost of storing the DUHF in unchanged form. Then, if we take the example of the SNF storage facility in Gorleben (Germany), the storage cost will be about $ 110 for 1 kg of UF_6. However, the cost of UF_6 в U_3O_8 conversion is not taken into

[4] Orekhov V.T., Vlasov A.A., Kozlova E.I., et al. Modern methods for handling of dumps of depleted UF_6, 2000 (see: https://www.osti.gov/etdeweb/servlets/purl/20299707).

[5] Nuclear fuel cost calculator, World Information Service on Energy (see: https://www.wise-uranium.org/nfcch.html).

account in these calculations.

In 1999, the US Department of energy adopted a plan to process about 700 000 metric tonnes of DUHF accumulated in the process of uranium enrichment at three enterprises viz., in Paducah, Portsmouth and Oak-Ridge. According to this plan, the cost of building two plants to convert DUHF to uranium oxide, their operation for 25 years, burial of uranium oxide and decommissioning of these plants should have cost some $ 2.6 billion. In this case, the cost of processing and storing DUHF would be about $ 3.7 for 1 kg of UF_6.

In 2002, the US Department of Energy signed a contract with Uranium Disposition Services, LLC for construction of DUHF processing plants in Paducah (Kentucky), and Portsmouth (Ohio). In 2004, construction of two facilities began, and the cost of the project increased to $ 3.5 billion. As a result of processing about 700 thousand metric tonnes of DUHF accumulated in the United States, it was supposed to produce about 551 thousand tonnes of uranium oxide, which was supposed to be buried as low-radioactive waste. The cost of this operation was estimated at $ 428 million, or $ 0.8 per 1 kg of uranium oxide[6]. Thus, the cost of DUHF conversion and storage increased to $ 5 per 1 kg of UF_6, and, most probably, this is not the final cost.

In 2004, the Institute for Energy and Environmental Research upon the order of the U.S. Nuclear Regulatory Commission (NRC) analyzed the cost of disposing of the DUHF that would have been generated by operating a new uranium enrichment plant in New Mexico. LES, which proposed the project for the construction of a new plant, estimated the cost of disposal (conversion to uranium oxides and their storage) of DUHF at $ 7.44 per 1 kg of uranium. The authors of the study questioned the objectivity of LES calculations and evaluated different scenarios based on available data. According to their calculations, it turned out that the conversion of DUHF into a safe form and its further storage, depending on various technologies, will cost from $ 13 to 30 per 1 kg of uranium[7].

In 2010 and 2011, DUHF processing was launched at two plants in the United States. The US Department of Energy reviews the contract every five years and holds a tender for the operational management of the plants. The most recent contract was signed in 2016 with Mid-America Conversion Services for a period of five years and worth $ 457 million[8]. The company is responsible for maintaining production, ensuring safe storage of uranium oxide, and selling hydrofluoric acid obtained during conversion. Given that the cost of hydrofluoric acid on the market is not very high (about $ 1000 per 1 tonne), the additional profit from its sale is quite modest.

In parallel, the US Department of Energy is looking for alternative uses of uranium oxide. Thus, January 2020, it was announced that the US National Nuclear Security Administration is ready to take part of DUHF for production of metallic uranium, which is planned to be used in nuclear weapons programs. They intend to purchase about 14 thousand tonnes of DUHF[9]. In 2016, the US Department of energy entered into an agreement with GE-Hitachi Global Laser Enrichment, LLC, for the post-enrichment of DUHF using SILEX laser technology[10], but the project has not yet been launched due to the unfavorable situation on the global uranium market.

---

[6] Audit Report: Potential uses for depleted uranium oxide, 2009 (see: https://www.energy.gov/sites/prod/files/igprod/documents/IG-0810.pdf).

[7] Makhijani A., Smith B. Costs and risks of management and disposal of depleted uranium from the national enrichment facility proposed to be built in Lea County New Mexico by LES, 2004 (see: https://www.nirs.org/wp-content/uploads/les/lesdureportredactedfeb2005.pdf).

[8] Barber W. Weapons complex still weighing impact of fluor government biz sell-off / Exchange Monitor, September 27, 2019 (see: https://www.exchangemonitor.com/weapons-complex-still-weighing-impact-fluor-government-biz-sell-off).

[9] Leone D. NNSA Plans to Take Some Portsmouth DUF_6 for Weapons Programs / Exchange Monitor, January 31, 2020 (see: https://www.exchangemonitor.com/nnsa-plans-take-portsmouth-duf6-weapons-programs).

[10] Ruch A. Proposed depleted uranium facility could bring 800-1200 jobs to Paducah / KFVS12, November 10, 2006 (see: https://www.kfvs12.com/story/33683029/proposed-depleted-uranium-facility-could-bring-800-1200-jobs-to-paducah).

It is believed that DUHF enrichment would be commercially sound, if the cost of 1 kg of U_3O_8 and its conversion into UF_6 is higher than the cost of 1 SWU (unit of separation work)[11]. Until 2011, when the price of SWU grew up to US $ 160 per 1 SWU, there was no hope for commercial use of DUHF, after which the cost of the SWU began to decline significantly. But now, as the current price for uranium oxide is about $ 75 (for 1 kg of U_3O_8), the cost of conversion is about $ 22, and with the price of 1 SWU at $ 45, [12] prospects of commercial post-enrichment of DUHF are economically sound.

In addition, it is clear from the historical charts of uranium and SWU prices that over the past 20 years prices have changed significantly, risen sharply and fallen sharply, so due to instability in the market and high capital costs, it is necessary to invest in new projects for processing DUHF carefully, but at the same time, the use of existing uranium enrichment facilities, perhaps, will be justified.

Do not forget that after post-enrichment there will be twice depleted uranium hexafluoride, which will need to be converted to a stable form and sent for long-term storage. The volume of secondary DUHF, as well as the cost of its processing and storage, will not decrease very much.

[11] Joint report of the OECD Atomic Energy Agency and International Atomic Energy Agency, 2001 (see: https://www.oecd-nea.org/ndd/pubs/2001/3035-management-depleted-uranium.pdf).
[12] Data on the cost of uranium and SWU are taken from the website of UxC, LLC, a company engaged in marketing research in the nuclear industry (see: http://www.uxc.com).

Chapter 6.

Prospects of processing and elimination of DUHF stockpile

In 2015, an updated Safe DUHF Handling Concept (hereinafter the Concept-2016) was adopted. In order to further implement the Concept-2016, the ‘ROSATOM DUHF Safe Handling Program’ has been developed (hereinafter the Program-2020), which defines the horizons and outlines a roadmap for solving the task of complete elimination of DUHF stockpile accumulated at the enterprises of TVEL JSC fuel company.

As it was mentioned above (see section 4.5), for the industrial processing of DUHF and transferring it into a safe form, currently, the JSC “PA ECP” site uses the W-EHZ unit having capacity of 10 thous. tonnes per year.

At the next stage of processing of the accumulated DUHF stockpile, replication of the defluorination plants will be performed. It is planned that in 2024 another unit will be put into operation viz., W2-EHZ unit at JSC “PA ECP” site, which will allow increasing processing capacity to 20 thousand tonnes of DUHF per year, and by 2028 at the same enterprise it is planned to increase the capacity of units to 30 thousand tonnes per year (“W3-EHZ” project). In addition, the SC UEIP site will commission the W-UEHC unit having a throughput capacity of 20 thousand tonnes of DUHF per year. The SIBERIAN CHEMICAL PLANT JSC site will accomplish commissioning of the NHP-SHC unit having a planned throughput capacity up to 12 thousand tonnes of DUHF per year. DUHF flame defluorination technology, which is being developed for this facility, should be tested and implemented by 2025. If the DUHF flame defluorination technology is not implemented at the NHP-SHK facility, then it is planned to increase the capacity of W-UEHK to 30 thousand tonnes of DUHF per year.

An important decision, which is approved by Program-2020, is the decision on reducing the number of sites that house a DUHF stockpile. First of all, it is planned to eliminate stockpiles at the ANGARSK ELECTROLYSIS CHEMICAL PLANT JSC site by 2035 by moving all the DUHF stockpile to the site of the JSC “PA ECP”. Stockpiles at the SIBERIAN CHEMICAL PLANT JSC site will be eliminated before 2040.

Thus, taking into account the commissioning of the five units listed above (“W” + NHP-SHC) the time for elimination of DUHF storage by TVEL JSC fuel company will be 35 years, or by 2057.

Table 3 shows the main measures that must be implemented to solve the problem of complete elimination of DUHF stockpile at all sites[13].

[13] ‘ROSATOM DUHF Safe Handling Program’, 2019 (see: https://osatom.ru/ media/uploads/cedee0c6-ed33-41f7-823c-81924454ea3e/02_1_Doklad_po_Programme_OGFU_dlja_Obschest_EkwVQ52.pdf).

Table 3

Main measures for implementing the DUHF stockpile elimination program

Application	Deadlines	Expected result
1. Extending DUHF processing projects		
1.1. Increasing throughput capacity of W-EHZ to 20 000 tonnes of DUHF per year ("W2-EHZ" project)	2017-2023	Increasing the rate of DUHF processing, switching from accumulation to reduce of DUHF stockpile Complete assurance of the needs of TVEL JSC for anhydrous hydrogen fluoride Reducing specific cost for DUHF processing
1.2. Building DUHF defluorination facility at UEHK, JSC, capacity of 20 000 30 thous. tonnes of DUHF per year (W-UEHK Project)	2020-2026	
1.3. Increasing throughput capacity of W-EHZ to 30 000 tonnes of DUHF per year ("W3-EHZ" project)	2020-2028	
2. Reducing the number of DUHF storage sites		
2.1. Moving DUHF from ANGARSK ELECTROLYSIS CHEMICAL PLANT JSC site to PO EHC, JSC site	By 2035	Setting free ANGARSK ELECTROLYSIS CHEMICAL PLANT JSC site completely from nuclear materials
2.2. Moving DUHF from the site of Isotope separation plant (ISP) at SIBERIAN CHEMICAL PLANT JSC to the sites of PO EHC, JSC/UEHK, JSC	By 2038	Setting free the site of Isotope separation plant (ISP) at SHC completely from nuclear materials
3. Ensuring long-term safe storage of DUHF		
3.1. Operating and enhancing systems for monitoring, control and handling of transport casks (TC) for DUHF including handling of defect TCs detected at storage	Continuously	1. Ensuring a safe storage of DUHF casks during 80 years and more 2. Technologies for conversion of DUHF into safe storage forms are enhanced
3.2. Implementing current and promising R&D in the area of safe DUHF handling	Continuously	
including: – developing and testing the design of protective cask for moving DUHF with a long storage period to significant distances; – developing a technology for preparing casks with DUHF with a long storage period to be moved to significant distances	2019-2021	1. Protective cask for transportation of DUHF with a long storage period was developed, tested 2. A technology for preparing casks with DUHF with a long storage period to be moved to significant distances was developed

Chapter 7.

DUHF utilization abroad

The IAEA recognizes that the determination of nuclear fuel cycle policy is the prerogative of the state (paragraph VII of the Preamble of the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management). The joint report of the OECD Atomic Energy Agency and IAEA “Management of Depleted Uranium” (2001) defines DUHF as a useful feedstock resource. The Management of Depleted Uranium report, which focuses on the potential use of depleted uranium and its uses as an energy source and for industrial purposes, says that: "The strategy for long-term management of depleted uranium is based on considering depleted uranium as a valuable material that can have various uses, and is not considered as a waste."

It is recognized that depleted uranium is one of the most problematic products of the nuclear industry. For this reason, some countries classify DUHF as radioactive waste, while others consider it as a raw material for practical use not only in the nuclear industry, but also in many other areas. Taking into account the technological capabilities and the concept of NFC of each country that has separate production facilities, the DUHF can be considered as a useful raw resource or low-level RW, i.e. there is no unified regulatory status.

7.1. USA

In the United States, under the Atomic Energy Act, the DUHF is not directly classified. Under this Act, low-level waste includes any material that does not fall into any of the following categories: high-level waste, spent nuclear fuel, and by-products (section 2 of the Act). A by-product (accompanying product) is defined only as "tailings or waste generated during the extraction or concentration of uranium or thorium from any ore" (section 11e of the Act).

In the United States, the DUHF is classified as a by-product, but the U.S. Nuclear Regulatory Commission (NRC) can set its own category for the by-product in special cases. Therefore, the NRC through its instruction recognized DUHF as a low-level waste (Memorandum and instruction No. CLI-05-05) on the grounds that it does not fall under any category of RW. However, the mentioned NRC decision made an important reservation that the DUHF will be considered low-level waste only if its owner does not have a strategy for further use of the material. NRC regulation No. 10 CFR 40.25 provides a general license for the use of depleted uranium contained in industrial products or devices for various applications. This license allows anyone to own or use depleted uranium.

Thus, the recognition of DUHF as a low-level waste in the United States does not mean that depleted uranium should be buried after the conversion of the DUHF to a stable form. If the US Department of Energy has an attractive strategy for further use of DUHF, it will have the right to store it for as long as it wants and extract useful resources from it.

In the United States, more than 800 thousand tonnes of DUHF have been accumulated, which are located at the sites of closed gas diffusion plants in Piketon and Paducah, as well as at the operating URENCO plant in Eunice. DUHF conversion units were built in Piketon and Paducah having a throughput capacity of 18 and 13.5 thousand tonnes annually, respectively. They were put into pilot production in 2010, and their main product is triuranium octoxide (U_3O_8), and fluorine hydride (HF). In 2013, the industrial operation of the plants commenced, and their actual throughput is about 23 thousand tonnes DUHF annually.

In addition, International Isotopes Inc. (INIS), on October 02, 2012, received a license for construction and operation of a DUHF conversion plant with throughput of 3.7 thousand tonnes of DUHF annually. Launching a plant, which should perform DUHF defluorination with production of uranium oxides (UO_2 and U_3O_8) up to 1400 tonnes of boron trifluoride (BF_3) and/orsilicon tetrafluoride (SiF_4), and 450 tonnes of anhydrous hydrogen fluoride (HF) was planned at the beginning of 2014. However, in 2013, INIS announced the suspension of the project.

The United States does not consider its reserves of DUHF as a future energy resource and has a policy of recycling it into a more stable, environmentally safe form for disposal until a potential consumer of this material is identified.

7.2. France

In France, the legal status of DUHF is also not defined. In 1974, France was the first to use depleted uranium extracted from the DUHF to make MOX fuel.

The question of classifying DUHF as a useful resource or waste arose in 1998 in terms of the possibility of its long-term storage. In July 1998, the administrative tribunal of the province of Limoges recognized the DUHF as radioactive waste at the current state of the art and revoked the license of COGEMA for its perennial storing. However, in November 1998, the Bordeaux court of appeals ruled that the DUHF was not a waste, but "a raw material of direct application that can be effectively used for a variety of purposes". Since the time of the judicial precedent, DUHF in France has been regarded as a useful resource.

France carries out post-enrichment of DUHF in minor volumes. DUHF is enriched with a sufficiently high concentration of ^{235}U (0.3-0.4%). Post-enrichment of reprocessed uranium for a French company EDF is carried out by URENCO.

7.3. URENCO countries

In the United Kingdom, Germany and the Netherlands, the status of the DUHF is not directly defined in national legislation, but the prevailing view is that the DUHF is a useful resource. Moreover, Germany, which has a policy of abandoning nuclear power, operates a processing plant in Gronau and, accordingly, continues to accumulate DUHF.

In the UK, more than 130 thousand tonnes of DUHF have been accumulated at the Capenhurst site, where there are two storage facilities, one of which houses the main volume of DUHF formed during the operation of the gas diffusion plant in 1950-1980. Currently, the site operates an enrichment plant of URENCO, and, accordingly, accumulation continues. The site also conducted research on plasma processing of DUHF to obtain metal uranium and elemental fluorine, and as a result of experimental work, some of it was converted to metal uranium, oxides and uranium tetrafluoride.

Storage of DUHF at separation plant in Gronau (Germany)

In 2019, the Capenhurst site began operating a DUHF conversion facility with a capacity of 7 thousand tonnes of uranium to produce depleted uranium oxide and ~5 thousand tonnes of hydrogen fluoride. The plant plans to process DUHF from all three European sites of the URENCO enrichment company, including Almelo (the Netherlands) and Gronau (Germany). Potential applications of depleted uranium have not been identified, but their disposal is not being considered.

7.4. Other countries

In Japan, the storage of DUHF continues, and its processing is planned only in the future for the use of depleted uranium as fuel in fast neutron reactors. The status of DUHF in Japan, as well as in other countries, is not defined. After the accident at the Fukushima-1 nuclear power plant, no work is being carried out concerning the methods for DUHF conversion.

There are no plans to process DUHF today in China, where it continues to be stored as a future energy raw material.

Enriched uranium from DUHF is also used in Belgium, Finland and Sweden. This secondary source of enriched uranium provides up to several percent of the demand in the European market.

Thus, currently only four countries (France, Russia, the United States, and the United Kingdom) are converting DUHF on an industrial scale, converting it to a stable oxide form and reducing its reserves.

Chapter 8.

How to organize public participation in solving issues of safe DUHF handling

In order to achieve public acceptance in addressing the issues of safe DUHF handling, it is necessary to create conditions for public participation in the processes related to the tasks facing Rosatom State Corporation organizations.

Public participation can take various forms, such as public expertise, discussions, hearings, and public monitoring and control. The main task of public participation is to ensure that organizations of the ROSATOM that implement projects for DUHF handling comply with the law and ensure maximum safety of all processes.

In order to arrange public participation on the principles of openness and transparency, a working group was established within the Environmental Board of the Public Council of ROSATOM. Interested activists representing environmental and other public organizations, as well as the media and representatives of regional and local legislative bodies are invited to participate in the working group. The plan of the working group provides for various forms of public participation, such as monitoring, visits to enterprises during technical and press tours, as well as expertise, public discussions and hearings.

An important result of public participation is to achieve openness, establish feedback between ROSATOM organizations and the public, ensure mutual understanding and take into account the opinions, suggestions and recommendations of the parties.

At the end of 2019 – beginning of 2020, the 'ROSATOM DUHF Safe Handling Program' was prepared During the discussion and adoption of the Program, proposals and a number of issues were formulated by the environmental community.

The main questions concerned the subject of DUHF handling. About 40 questions were asked, most of them answered in the previous chapters of the report. Some questions related to economy, statistics on the occurrence of certain events (emergencies, accidents), or forecasts and scenarios for the future that are not directly related to the processes of DUHF handling (for example, forecasts for the development of fast reactors and the transition to a closed fuel cycle, including abroad). A small part of the questions remained unanswered due to restrictions on the distribution of commercial or official secrets.

Interaction experience that feature the community and the State Corporation within the established working group showed that there is quite a lot of tasks that need to be addressed for the entire period, while the Program-2020 will be implemented.

First of all, these are issues of timely public awareness and creation of conditions for monitoring what is happening in the field of DUHF handling. The information disseminated should primarily concern security, as well as implementation of measures provided by the Concept-2016 and Program-2020. Channels through which information will be provided should be established. This work is expediently and feasibly to be focused in the format of the Environmental Board working group, while emphasizing once again that all interested representatives of the public from the regions can participate in activities of the working group. There are almost no other real channels currently available.

The second important issue of public participation is familiarity with the enterprises (production facilities) where the storage and processing of DUHF is carried out. As the experience of organizing technical tours to ROSATOM enterprises shows, members of the public have the opportunity not only to hear how projects are implemented, but also to see them, having received explanations from direct participants in the process of DUHF handling.

Technical tour at “Electrochemical Plant” Production Association”

Public expertise allows members of the public with special knowledge to analyze and evaluate technical regulations, planned projects, adopted documents and other materials that relate to the issues of DUHF handling. Based on the plans of the ROSATOM to increase the capacity for DUHF processing, the interested public will have the opportunity to organize an expert review, as well as public discussions in the process of preparing documents for the state ecological assessment. These issues are considered in the details under section 4.6 hereof.

Sitting of the Public Council of ROSATOM

The main task of the Environmental Board working group of the Public Council of ROSATOM is to increase the level of confidence of community in projects in the field of handling of DUHF, and to ensure interaction of industry enterprises with civil society institutions on all the issues listed above.

CONCLUSION

The authors of the report hope that they have thoroughly explained in an accessible form and in full what constitutes a complex and problematic material called DUHF, as well as described the entire process of handling it in order to help the interested public get answers to some important questions.

SAFETY

DUHF is a nuclear material, a byproduct of the uranium enrichment process. Under normal conditions of storage (transportation), DUHF does not pose a radiation hazard and its activity is less than that of natural uranium. At the same time, depleted uranium hexafluoride becomes a chemically dangerous toxic substance under certain special conditions. Radiation and chemical effects in various scenarios (other than hypothetical) are described in section 4.4. It should be borne in mind that as a result of accidents, there are almost no serious consequences (loss of life or extensive contamination of territories).

In the text of the report, the probability of a hypothetical accident (the fall of a heavy aircraft on a storage area or on a train with DUHF load) is estimated at 10^{-8}/year. In comparison, the probability of a person being hit by a celestial body falling to earth (which, according to scientists at the Greenwich observatory, is $1.5 \cdot 10^{-7}$/year) or the probability of death as a result of a road accident in Russia (which in 2019 was 10^{-3}/year) is greater.

These examples make it possible to compare risks and understand that the fears spread by alarmists have no real basis.

CATEGORY OF DUHF (RADIOACTIVE WASTE OR USEFUL RESOURCE)

The most heated discussions in the public field revolved around the issue of whether DUHF is radioactive waste or a useful resource.

If DUHF is a radioactive waste, then the project of TENEX JSC to import DUHF from Germany should be regarded as violating Russian legislation, since foreign radioactive waste is not permitted to be imported to Russia.

Chapters 3, 4 and 6 show information about the use of DUHF at Russian sites, and about plans for DUHF handling for the near future. Arguments and concrete data show that DUHF is a useful resource nuclear and other industries. In addition, as shown in the DUHF processing diagram (see section 4.5.3), as a result of technological operations, ultimately only DTUO remains in storage, which in the future is planned for use as raw materials for fast neutron nuclear reactors. It is worthy of note that DTUO features properties, which almost fail to impose potential radiation or other hazards (see section 4.5.2).

Thus, according to Russian laws that define and explain the concept of "radioactive waste", DUHF cannot be classified as RW, and the legislation of the Russian Federation that prohibits the import of RW to the territory of Russia, as well as the moral standards that some ecological activists assert, are not violated.

The only task facing enterprises engaged in transportation, storage and processing of DUHF is to ensure the safety of these processes.

ECONOMY

In the current conditions of the uranium market, the use of DUHF as a resource for obtaining uranium and fluorine-containing products may be economically justified, since the cost of separation production is quite low. If the demand for uranium, and with it the price of uranium on the world market, decreases, the economic efficiency of post-enrichment of the DUHF will be different. The sale of fluorine-containing products, which are a useful component of production, is unlikely to ensure the profitability of processing of DUHF. In order to assess the commercial effectiveness of the use of DUHF in fast neutron reactors, it will be necessary to determine how successfully this initiative will develop. At the moment, it is premature to draw any clear conclusions.

PROSPECTS

Currently, the world has accumulated more than 2 million tonnes of DUHF. Half of the total accumulated global volume is located in Russia. The better part of rich dumps of the past years is planned to be post enriched. The other part, taking into account the chemical and toxicological hazards of DUHF, will be converted into stable chemically resistant forms, safe for long-term storage and convenient for further use in various industries, including nuclear.

Acceptance and implementation of programs for switching DUHF to a stable safe from in the nearest 30-40 years has a great significance. This is accounted for in the Program-2020 in the form of a road map, and the period is defined by 2057, by which is planned to perform a complete elimination of the accumulated DUHF stockpile.

BIBLIOGRAPHY

Andreev B.M., Arefiev D.G., Baranov V.Yu., et al. Isotopes: properties, production, use /ed. by V.Yu. Baranov Vol. 2. M.: Fizmatlit, 2005. 727 p.

Borisevich V.D. Physical fundamentals of isotope separation in a gas centrifuge: textbook for higher education/Borisevich V.D., Borman V.D., G.A. Sulaberidze, et al.; ed. by Borman V.D.
M.: MPEI Publishing House, 2011. 275 p.

Bykov A.A. Overview of world practices for handling depleted uranium hexafluoride // Nuclear club. 2016. No. 1-2. pp. 16-21.

Vnukov V.S. Ensuring nuclear safety at plants that produce nuclear fuel for NPP. M., 2009. – 172 p.

Depleted Uranium Hexafluoride Safe Handling Concept. Approved December 27, 2006 by S.V. Kirienko, Head of the Federal agency for atomic energy

Kopyrin A.A., Karelin A.I., Karelin V.A. Technology for the production and radiochemical processing of nuclear fuel. M.: Atomenergoizdat Publishing House CJSC, 2006. 576 p.

Kudrina N. Do not poor-mouth // Atomic expert. 2019. No. 8 (77). pp. 8-11.

Orekhov V.T., Rybakov A.G., Shatalov V.V. Use of depleted uranium hexafluoride in organic synthesis. M.: Energoatomizdat, 2007. 112 p.

Pavlov A.V., Platov M.A. Uranium enrichment: the spread of gas-centrifuge technology in the world // Nuclear club. 2000. No. 2 (3). pp. 8-14.

‘ROSATOM Depleted Uranium Hexafluoride Safe
Handling Program’. Approved February 26, 2010 by A.E. Likhachev, General Director of

ROSATOM Uranium project HOME WISE (https://www.wise-uranium.org/edumu.html).

Federal norms and rules in the field of atomic energy use, NP-053-16 “Safety regulations for transportation of radioactive materials” (order of Rostechnadzor dated September 15, 2016 No. 388).

Shulga I. Legacy of enrichment / Atomic expert. 2018. No. 2 (63). pp. 40-

47. Bulletin International Atomic Energy Agency (IAEA) // Spring. 1985. P.

28-31.

Management of Depleted Uranium / A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency: Paris, OECD Publications Service. 65 p.

Nuclear fuel cycle science and engineering / Ed. by I. Crossland. Cambrige Woodhead Publishing Ltd, 2012. 648 p.

bellona.org