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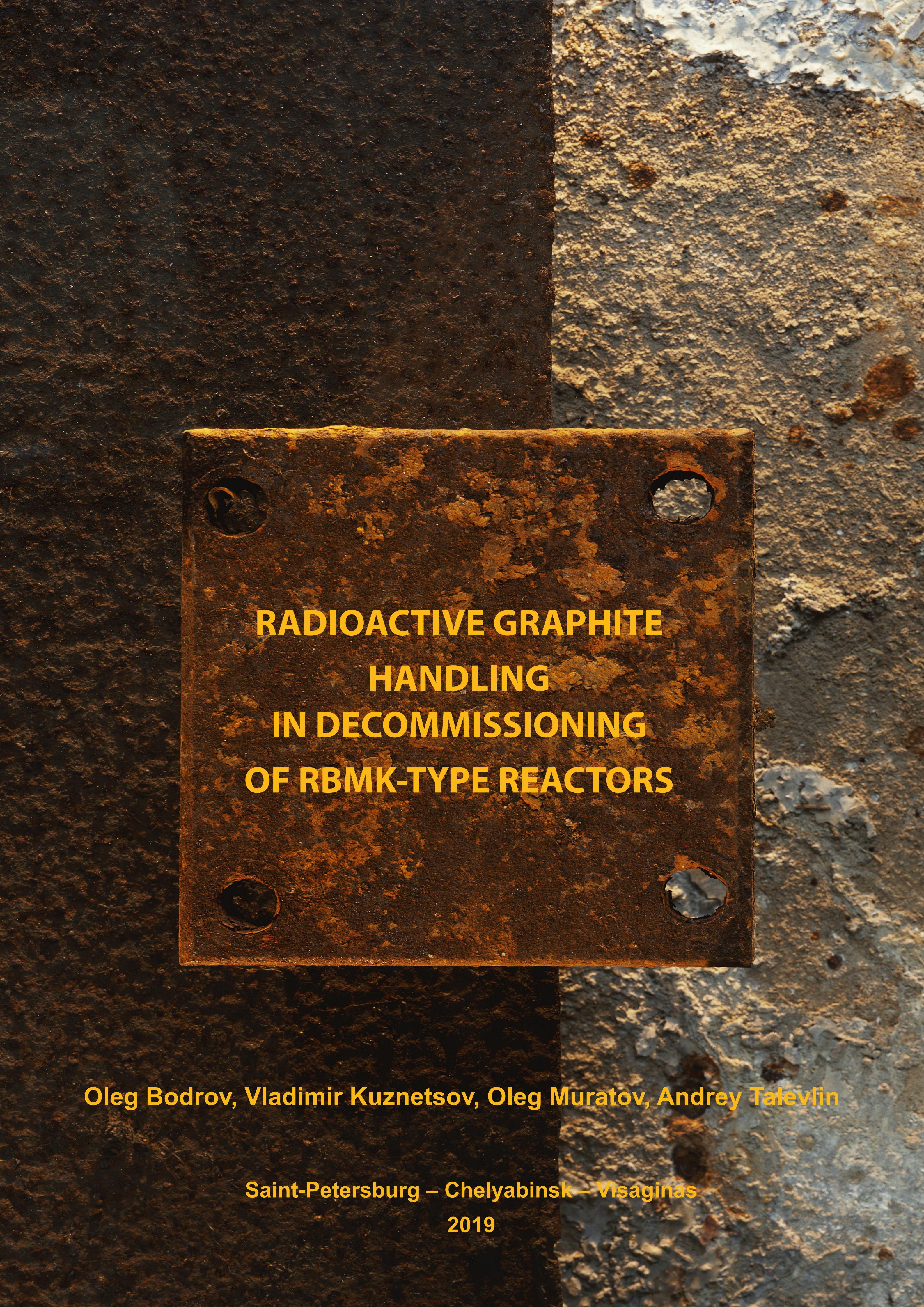

RADIOACTIVE GRAPHITE HANDLING IN DECOMMISSIONING OF RBMK-TYPE REACTORS

Oleg Bodrov, Vladimir Kuznetsov, Oleg Muratov, Andrey Talevlin

Saint-Petersburg – Chelyabinsk – Visaginas
2019

RADIOACTIVE GRAPHITE HANDLING IN DECOMMISSIONING OF RBMK-TYPE REACTORS

Current challenges and possible solutions for radioactive graphite handling in decommissioning of RBMK-type reactors

Oleg Bodrov, Vladimir Kuznetsov, Oleg Muratov, Andrey Talevlin

The report may be of interest to representatives of the nuclear business, state authorities, local governments, and the public in the regions where nuclear power plants with uranium-graphite reactors are located.

The publication was prepared by independent experts from Russia and Lithuania who have worked for many years in the field of decommissioning nuclear power plants, handling spent nuclear fuel and radioactive waste.

The authors thank Ph. D. Alexander Germansky and Vladimir Desyatov (Saint Petersburg, Russia), as well as Dr. Ian Fairlie, (London, UK) for discussing our work and making valuable comments that have improved the results of our work.

Saint-Petersburg – Chelyabinsk – Visaginas
2019

Abstract

The report presents the history of graphite-moderated nuclear reactors, volumes of accumulated radiation-exposed graphite, and the process of handling graphite as radioactive waste containing radioactive carbon ^{14}C.

Analysis of environmental and biological significance of stable and radioactive carbon isotopes was conducted; natural and man-generated mechanisms of radioactive carbon ^{14}C formation were described, as well as the way of ^{14}C migration and its impact on live organisms, populations and ecosystems in general.

There is a detailed analysis of specifics of graphite-moderated reactors' decommissioning with due consideration of accidents when technological channels were damaged and graphite cladding was contaminated with trans-uranium elements.

An emphasis is made on the regulatory analysis of handling radioactive graphite, with assessment of possible strategies and concepts of handling graphite from uranium-graphite reactors during the decommissioning process.

The report contains recommendations for possible solutions of a range of issues pertaining to safe decommissioning of graphite-moderated reactors, handling of reactor graphite for ensuring its long-term isolation from living environment, and taking into account interests of all stakeholders.

The analytical report has been prepared by experts from Russia and Lithuania who worked for many years in the sphere of decommissioning of nuclear power plants and handling of spent nuclear fuel and radioactive waste.

Preparation of the report was initiated and organized by the Public Council of the South Coast of the Gulf of Finland under LLC Decommission. This work was supported by the Norwegian NGO Naturvernforbundet-Friends of the Earth Norwayas part of the project "From closed rooms to openness".

The Public Council of the South Coast of the Gulf of Finland

The Public Council of the South Coast of the Gulf of Finland (PCSCGF)is an interregional public environmental movement of the Leningrad Oblast and Saint-Petersburg under LLC Decommission, Russia

The Public Council mission is promotion of development of the South Coast of the Gulf of Finland in balance with nature on the platform of democratic principles and participation of all interested parties.

The goal of the Public Council is to protect the living environment, cultural and historical heritage, physical and spiritual health of people, and to ensure environmental and nuclear safety.

Major areas of activity of the Public Council:

- Social and economic monitoring and dissemination of information on the environment, including cultural sites, man-made facilities, and health of the population;
- Development of environmental world view on the basis ofleading Russian and internationalexperience in the sphere of preventing environmental crises at the local and global scales;
- Promotion of principles of environmental and nuclear safety, healthy lifestyle, preservation of biodiversity and conditions for balanced development of nature and society;
- Public environmental oversight over compliance with the environmental law and responding to its violation.

Participants of the Public Council are open to cooperation with everybody who shares goals of the public movement.

Representatives of the Public Council of the South Coast of the Gulf of Finland operate in Saint Petersburg and the Leningrad Oblast: Lebyazhje, Sosnovy Bor, Vistino, Ruchji, Saarkylä, Kingisepp, Ivangorod, etc.

The Public Council of the South Coast of the Gulf of Finland is a member of DecomAtom, an international network of organizations promoting safe decommissioning of nuclear power plants http://decom-atom.org/

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Acronyms and abbreviations

Bq (Becquerel) – unit of radionuclide activity in SI equal to one nuclear transformation per second; derivative units: 1 kBq = 10^3Bq; 1 MBq = 10^6Bq; 1 GBq = 10^9Bq; 1 TBq = 10^{12}Bq; 1 PBq = 10^{15}Bq; 1 EBq = 10^{18}Bq;

CATE–Closed Administrative-Territorial Entity, Russian abbreviation is ZATO;

DNA – deoxyribonucleic acid, one of three macromolecules of a cell (the other two are proteins and ribonucleic acid), which ensures preservation and transfer of the genetic code of development and activity of organisms, i.e. DNA is the carrier of genetic information;

EDC DUGR – Experimental Demonstration Center for Decommissioning of Uranium-Graphite Nuclear Reactors;

EGP-6 –a heterogeneous loop energy reactor with six loops of coolant circulation (energy graphite water reactor).

Gosatomnadzor–Russian regulator of nuclear safety (Rostekhnadzor after 2004);

GRAPA–Irradiated GRAphite Processing Approaches project;

IAEA – the International Atomic Energy Agency;

IRG – irradiatedreactorgraphite;

ISTM - interactive simulation three-dimensional models;

J – Joule, energy unit in SI;

keV – kiloelectron Volt = 10^3 electron Volt - off-system particle energy unit: 1 eV = 1.6×10^{-19}J;

µSv/sec –micro-Sievert per second = 10^{-3}Sv/sec – equivalent dose rate of ionizing radiation;

Mt – Megaton - energy unit equal to 4.184×10^{15} Joules; defined as the amount of energy released at a detonation of 1 million tons of trinitrotoluene (TNT);

Neutron fluence – a value equal to the ratio of the number of neutrons falling during a given time interval on some surface perpendicular to the direction of neutron flux propagation to the area of this surface;

NGO – non-governmental organization;

NPP – nuclear power plant;

PUGR – Russian abbreviation of industrialuranium graphite reactors for weapons-grade plutonium production;

RBMK – Russian abbreviation of high-power channel-type reactor;

RNA – ribonucleic acid, one of the three main macromolecules (the other two being DNA and proteins) that are found in cells of all living organisms; it plays an important role in coding, reading, regulation and expression of genes;

Rostekhnadzor –Russian federal executive body that develops and implements state policy and legal regulation of technological and nuclear supervision;

RW – radioactive waste;

SFA – spent fuel assemblies;

SICP – the Siberian Integrated Chemical Plant in ZATO Seversk, Tomsk region;

SNF – spent nuclear fuel;

SRW – solid radioactive waste**;**

T1/2 – half-life period of radioactive isotope;

UGR –uranium graphite reactor;

ZATO –Russian abbreviation of Closed Administrative-Territorial Entity (CATE).

Introduction

The world faces a new stage in operation of nuclear power reactors. Its specifics are related to agrowing number of decommissioned power units that either reached the end of their operating lifecycle or their operation is becoming economically not viable, environmentally unsafe or politically unacceptable.

Decommissioning of nuclear power units is associated with the need to identify safe technology for dismantling, decontamination, disaggregation, disposal and long-term isolation of radioactive materials that were created during the operation period.

Radioactive isotope of carbon ^{14}C that was formed during the operation of uranium-graphite reactors (UGR) requires a particularly careful approach in selecting technology for long-term isolation from nature and wildlife. It is a long-lived and biologically significant radionuclide, which means that the technology for its transfer to a safe state or long-term isolation must meet the criteria of environmental, social, economic and moral acceptability.

In order for all stakeholders (the society, nuclear business and the government) to assess various risks when choosing a safe ^{14}C isolation method, the authors of this expert report made an attempt to demonstrate the significance of various factors that, in their opinion, should be taken into account when adopting strategic, technological and technical solutions.

In 2018, the first power unit of the Leningrad NPP with the RBMK-1000 reactor was finally shut down. This is the oldest of eleven operating units of this type in Russia. Its decommissioning with dismantling and burial of the graphite cladding is planned. Gaining experience in making decisions on the handling of reactor graphite taking into account technological, environmental and social criteria will be further replicated in the regions where the nuclear power plants with reactors of this type are located.

History of uranium-graphite reactors and current challenges in handling radiation-exposed reactor graphite

The use of nuclear energy began with the uranium-graphite reactor (UGR) SR-1, which was built in 1942 under the stands of the University of Chicago stadium. Since then, a wide range of graphite moderator reactor designs has been developed. Most of them are power-producing research reactors used for testing materials, studies of radiation resistance, creation and testing of appliances and equipment, etc.

A significant number of the UGR reactors was specially designed, built and put into operation for production of weapons-grade plutonium.

Altogether 123 UGR reactors were built all over the world (Table 1); they include:

- Aircooled plutonium production reactors: X-10 (Oak Ridge National Laboratory, USA), Windscale Pile (Great Britain) and G1 (Marcoule, France) and others;
- Light water reactors with graphite moderator: B, D, F (Hanford, USA) and Russianuranium-graphite production reactors (UGPR) ADE, EI, and others for production of plutonium, as well as power reactors AMB and EGP in Russia and RBMK reactors in Ukraine and Lithuania;
- Reactors with carbon dioxide as primary coolant: British Magnox and AGR, French UNGG;
- High temperature helium cooled reactors: Dragon (Great Britain), THTR (Germany), Peach Bottom (USA);
- Current development of uranium-graphite reactors: in Japan (HTTR), China (TRIS-10) and South Africa (PMBR).

At present, of all the UGR reactors, ten RBMK-1000 reactors and three EGP-6 reactors in Russia, fourteen AGR reactors in the UK, and four reactors in China continue to operate in power generation mode; in Belgium there is one UNGG research reactor.

The Japanese high-temperature gas-cooled reactor at the Oarai Research Center, commissioned in 1998 and shut down after the Fukushima accident, is undergoing tests to verify compliance with the post-Fukushima safety standards, and its fate has not been decided yet.

It can be concluded that the vast majority of UGR reactors, including all (except North Korea) industrial reactors for producing weapons-grade plutonium, have been shut down and are to be decommissioned.

- The main problem of decommissioning nuclear facilities with UGR reactors is related to the need to select optimal methods for handling large volumes of spent graphite, which occupies a special place in the management of accumulated radioactive waste (RW). All spent irradiated and radioactively contaminated graphite obtained as a result of dismantling of UGR reactors can be divided into two main groups:

Table 1. Uranium-graphite reactors in different countries of the world with the years of their operation[1]

Country	Number of Reactors	Reactor Type	Operation	Graphite mass, tons
France	9	UNGG, GCR	1959-1994	23,114
Germany	2	HTGR	1967-1989	525
Belgium	1	UNGG	1956-until now	472
Italy	1	Magnox	1963-1987	2.065
Japan	2	Magnox, HTGR*	1966-until now	1.600
North Korea	1	Magnox	No information	No information
Lithuania	2	LWGR	1983-2009	4,000
Russia	31	LWGR	1954-until now	66,204
Spain	1	Magnox	1972-1990	2,440
Great Britain	46	Magnox, AGR	1947-until now	77,006
Ukraine	4	LWGR	1977-2000	~8,000**
USA	19	HTGR, LWGR, Aircooled	1942-1989	10,160
China	4	HTR,Aircooled, LWGR	1963-until now	1,560
TOTAL	**123**			**197,146**

*The HTGR reactor, commissioned in 1998, was shut down after the accident at the Fukushima nuclear power plant; its license is being updated inorder to comply with the "post-Fukushima safety standards".

** The amount of remaining graphite in the fourth power unit is not determined.

- structural graphite from which the stack of the reactor is made;
- graphite generated during repair works and liquidation of incidents and accidents at reactors.

The specific activity of reactor graphite is the predicted value and, depending on the lifecycle of the reactor, ranges from 1.1×10^{11}Bq/t to 3.7×10^{12} Bq/t at ^{14}C. The activity of graphite recovered during repair works cannot be predetermined due to the heterogeneous distribution of spills of nuclear fuel within the reactor space.

The aggregate activity of graphite is divided into two types: internal and external. Internal activity consists of several components: firstly, radioactivity of technological impurities and, secondly, accumulation in graphite, the specific activity of which increases with the neutron fluence.

For resource fluences of RBMK-1000 reactor cladding (~ 2 × 1022 neutrons/cm2), the specific activity of ^{14}C can reach 3.7×10^{12}Bq/t.

External contaminants of graphite include spills of fission products and fragments of nuclear fuel resulting from various incidents or accidents. The dose rate of γ radiation from reactor graphite of such contaminated blocks can reach 600 μSv/sat a distance of 0.5 m. As the distance from the center increases, from the graphite cladding decreases significantly.

After prolonged exposure to radiation in a reactor, graphite does not acquire any properties that could create a field of its useful application. Given the specific activity of irradiated graphite (~1 GBq/kg), it is classified as a solid RW of medium or high level of activity.

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[1] IAEA-TECDOC-1647, Progress in Radioactive Graphite Waste Management, Vienna 2010
https://www-pub.iaea.org/MTCD/Publications/PDF/te_1647_web.pdf

In addition to this, radiation-exposed graphite has the following specific properties[2] :

- Unique crystal structure and porosity that determine its physical properties and behaviorafter neutron irradiation;
- Indispensability of graphite claddingduring the entire lifecycle of thecore of the UGR reactor, and, as a result, the largest of all RW accumulated neutron fluence;
- Unevenness in both size and isotopic composition of cladding contamination and its individual graphite parts;
- Contamination of the reactor stack with long-lived biologically significant radionuclides 90Sr and ^{137}Cs, which are chemically more active and can replace stable isotopes ^{40}Ca and ^{39}K in living organisms, thereby creating additional internal radiation;
- An additional contribution of such radionuclides as ^{152,154}Eu, ^{239}Pu, etc.to the reactor cladding activity, which arose as a result of accidents and the ingress of fragments of nuclear fuel;
- Potential fire hazard of graphite and explosion hazard of graphite dust;
- High specific heat of combustion (~ 8 kcal/g) and relatively low ignition temperature of ~700°C;
- Presence of accumulated Wigner energy generated by neutron irradiation of the crystal lattice, which acquires agreater potential energythrough deformation.The amount of accumulated energy depends on the neutron flux, exposure time, and temperature. The maximum amount of accumulated energy can reach ~ 2,700 J/g, which theoretically can lead to a temperature increase of about 1,500°C in case of simultaneous energy release;
- Release of radioactive and toxic gases such as ^{36}Cl, ^{3}H from the reactor cladding.

Taking into account the above properties of irradiated graphite, during decommissioning it is required to haveintegrated planning and to implement several interrelated operations for reliable isolation of graphite from living systems.

There are two main options for handling radioactive graphite, implementation of which considers the above-mentioned properties of this radioactive waste:

- Packaging of non-conditioned radioactive graphite in containers with subsequent disposal;
- Conditioning of radioactive graphite (incineration, inert matrix isolation, etc.) with separate removal and subsequent disposal/burial of all generated graphite fractions.

When burning irradiated graphite, the release of $^{14}CO_2$ into the atmosphere should be completely excluded due to the dangerous consequences of the inclusion of ^{14}C in the composition of DNA molecules and high collective doses that will occur worldwide.

Currently, the total amount of accumulated radioactive graphite in the world reaches 260 thousand tons[3] (Fig.1). Therefore, the problem of effective environmentally safe disposal/isolation of irradiated reactor graphite is a worldwide problem.

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[2] IAEA-TECDOC-1521 Characterization, Treatment and Conditioning of Radioactive Graphite from Decommissioning of Nuclear Reactors, September 2006 https://www-pub.iaea.org/MTCD/publications/PDF/te_1521_web.pdf

[3] IAEA-TECDOC-1647 Progress in Radioactive Graphite Waste Management, Vienna 2010 https://www-pub.iaea.org/MTCD/Publications/PDF/te_1647_web.pdf

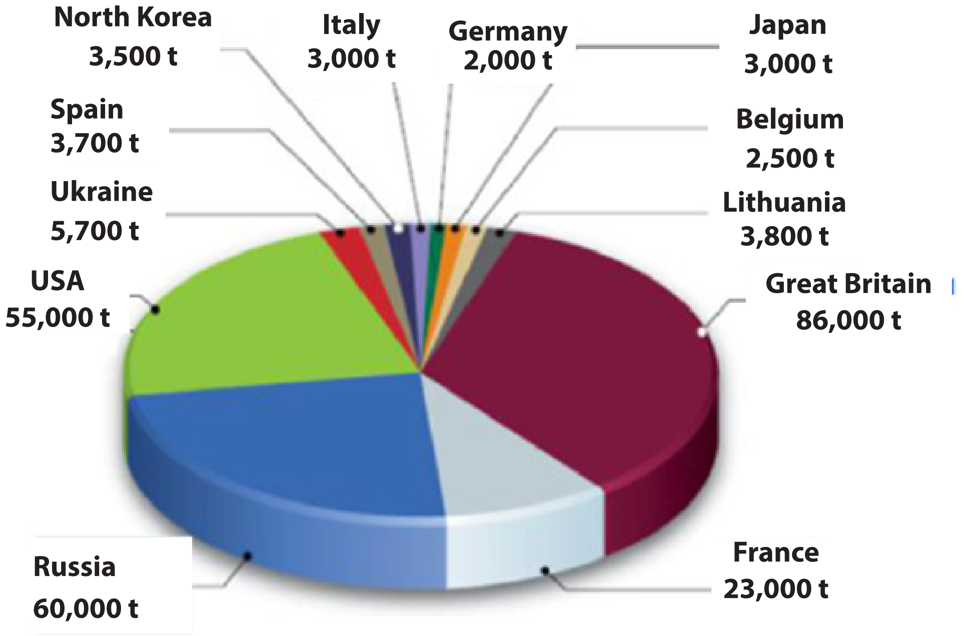

Fig. 1. Amounts of radioactive graphite in various countries of the world accumulated during operation of UGR reactors .[4]

The difference in the data on the amount of radioactive graphite accumulated all over the world presented in Table 1 and Fig. 1 can be explained by different sources of information, dates of publication (2017 and 2010), as well as different calculation methods. The calculations were based on different approaches to assessment of replaceable graphite and graphite during repair works, etc.

Various countrieshave studied a number of options for handling radioactive graphite. Nonetheless, a generally accepted approach to graphite conditioning and disposal, as well as safe dismantling of reactor cladding, has not yet been found.

Only France has specific plans for graphite waste disposal, and other countries with bigger volumes of radiation-exposed graphite have not developed such plans.

Great Britain and France continue research aimed at studying behavior, localization and release mechanisms of key radionuclides in irradiated graphite, as well as minimizing the volume of radioactive graphite for permanent isolation.

The plans for management of graphite waste in France were clearly defined by a law passed in 2006, which set target dates for the permanent isolation process.

The disposal strategy, which was approved by the regulatory body, includes disposal of graphite waste in shallow ground clay repository. The main criterion for selecting this option is cost savings, which are estimated to be an order of magnitude lower than in a deep geological formation.

At the present time, the biggest share of radioactive graphite in the UK is in still operating or shutdown nuclear reactors. The reference strategy for disposal of irradiated graphite is to place it in protective containers in a geological repository. Two design plans for decommissioning of UGR reactors were developed: for the GLEEP research reactor and the Windscale Pile reactor.

The role of the IAEA in managing reactor graphite disposal

The IAEA materials published in 2010 on the progress in research methods for solving the problems of reactor graphite[5] examined the benefits and disadvantages of the immediate decommissioning of UGR reactors. It was noted that the decommissioning strategy is determined on the basis of long-term and short-term

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[4] PavlyukA. O. O. Technical solutions and experience of EDC DUGR on handling irradiated graphite during decommissioning,International public forum-dialogue and exhibition AtomEco-2017, Moscow. 21-22 November 2017, http://www.atomeco.org/mediafiles/u/files/2017/materials/06_ATOMEKO_Pavlyuk_A.O..pdf

[5] IAEA-TECDOC-1647 Progress in Radioactive Graphite Waste Management, Vienna 2010 https://www-pub.iaea.org/MTCD/Publications/PDF/te_1647_web.pdf

costs. At the same time, it is stressed that speedydecommissioning is thedecisive factor for restoring public confidence.

Such a strategy, according to the participants of the IAEA discussion, would demonstrate to the public that the sites can be cleaned, rehabilitated and prepared for new types of use. Therefore, at present, the technical specialist community must offer technological means to achieve an early and safe decommissioning.

In 2016, the IAEA recognized the potential danger of the current world related to handling, disposal and permanent isolation of irradiated reactor graphite from shutdown research-type, production and power-generating uranium-graphite reactors. The idea was supported to establish an international center for development of safe technologies for the treatment of radioactive graphitein the Russian Federation.

Such a center was created on the basis of the Tomsk Experimental Demonstration Center for Decommissioning of Uranium-Graphite Nuclear Reactors (EDC DUGR). Germany and France also participate in this GRAPA (Irradiated GRAphite Processing Approaches) project[6]. It is planned that within three years the Experimental Demonstration Center will develop an industrial technology for safe irradiated graphite handling. GRAPA is an international project of the International Atomic Energy Agency (IAEA), which is aimed at solving problems associated with irradiated graphite handling.

The aim of the project is to deal with a wide range of problems, including the determination of the properties of graphite radioactive waste, development of safe technologies for the extraction of graphite from reactors, its processing, temporary storage and disposal. This can be achieved through integration of the existing experience of different countries and R&D enhancement.

One of the results of the GRAPA project was the rejection of costly and inefficient methods, such as the method of dismantling graphite cladding under water, previously adopted in France.

An essential feature of the GRAPA project is its commitment to utilize technology of a full-scale pilot demonstration of technical solutions and their further implementation.

According to the project participants, in the period of three years, the Experimental Demonstration Center has made significant progress in development of safe technologies for dismantling graphite reactor stacks and testing and assessment of methods for characterizing, processing, decontamination of graphite, and in-situ disposal of uranium-graphite reactors.

Due to the high levels of radioactivity, disassembly of graphite stacks cannot be performed by humans; this should be done by sophisticated robots that need to be developed and trained.

In order to disassemble RBMK reactor stacks, it will be necessary to design and build a full-scale simulator,together with the corresponding software development and training of a robotized complex and operators.

Given the significant results and the existing team of specialists committed tofinding joint solutions to the problem, the IAEA plans to take a step forward and continue to further develop and support projects aimed at solving the problem of graphite radioactive waste disposal.

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[6] International Irradiated Graphite Center http://www.atomeco.org/mediafiles/u/files/2017/materials/07_Bagryanov_Oblikovyj_proekt_grafitovogo_centra_v4_AtomEco_Russian.pdf

Regulatory framework of handling irradiated graphite in the Russian Federation

Based on the current legislation, irradiated graphite of decommissioned NPP units (RBMK-1000) is a type of radioactive waste, because further use of graphite is not possible.

The legislation of the Russian Federation regulates handling of radioactive waste in two main federal laws:

- Federal Law On the Use of Atomic Energy[7] ;
- Federal Law On Radioactive Waste Management and on Amending Certain Legislative Acts of the Russian Federation [8].

Additionally, the following international conventions and federal laws can be attributed to regulatory sources containing legal norms in the sphere of decommissioning of nuclear installations and storage facilities:

- Convention on Nuclear Safety (Vienne, 1994)[9];
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Vienne, 1997)[10];
- Federal Law on Radiation Safety of the Population[11];
- Federal Law On Environmental Protection[12];
- Federal Law On Environmental Expertise[13];
- Federal Law On the Electric Power Industry[14].

Decrees of the Government of the Russian Federation:

- On the Federal Executive Bodies Implementing State Administration of the Use of Atomic Energy and State Regulation of Safety in the Use of Atomic Energy[15];
- Provision on Licensing of Activities in the Field of Atomic Energy Use[16];
- Provision on Development and Approval of the Federal Regulations in the Field of Use of Atomic Energy [17].

In addition to this, there are various federal rules and regulations in the field of atomic energy use and sanitary rules in the field of radiation safety, developed by compliance monitoring authorities.

To date, the following documents have been developed: Rules for safe decommissioning of nuclear installations of the nuclear fuel cycle (NP 057 04), nuclear-powered vessels (NP-037-02), research nuclear facilities (NP-028-01), industrial reactors (NP-007-98), etc.

In general, safety assurance requirements for decommissioning of such nuclear installations and storage facilities are stipulated by the General Safety Provisions for Nuclear Power Plants (NP-001-15) and the Safety Rules for Decommissioning of NPP Power Units (NP-012-16, approved by the Order of Rostekhnadzor No. 5 dated January 10, 2017).

The description of the program for decommissioning of a nuclear power unit is also included into the Safety Guide RB-013-2000 Requirements to the Contents of an NPP Power Unit Decommissioning Program(approved by Resolution No. 13 of the Gosatomnadzor of the Russian Federation dated November 4, 2000).

Based on regulatory documents, decommissioning of a nuclear installation hasbeenrecognizedas activities carried out after the removal of nuclear fuel and nuclear materials from the nuclear power unit, aimed at achieving the specified final state of the NPP unit, eliminating

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[7] Federal Law “On the Use of Atomic Energy”http://docs.cntd.ru/document/9014484

[8] Federal Law On Radioactive Waste Management and on Amending Certain Legislative Acts of the Russian Federation http://docs.cntd.ru/document/902288595 http://docs.cntd.ru/document/902288595

[9] Convention on Nuclear Safety http://docs.cntd.ru/document/902060584

[10] Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management http://docs.cntd.ru/document/901944128

[11] Federal Law On Radiation Safety of the Population http://docs.cntd.ru/document/9015351

[12] Federal Law On Environmental Protection http://docs.cntd.ru/document/901808297

[13] Federal Law On Environmental Expertise http://docs.cntd.ru/document/9014668

[14] Federal Law On the Electric Power Industry http://docs.cntd.ru/document/901856089

[15] On the Federal Executive Bodies Implementing State Administration of the Use of Atomic Energy and State Regulation of Safety in the Use of Atomic Energy http://pravo.gov.ru/proxy/ips/?docbody=&prevDoc=102125569&backlink=1&&nd=102107605

[16] Provision on Licensing of Activities in the Field of Atomic Energy Use http://pravo.gov.ru/proxy/ips/?docbody=&prevDoc=102141573&backlink=1&&nd=102164278

[17] Provision on Development and Approval of the Federal Regulations in the Field of Use of Atomic Energy http://www.pravo.gov.ru/proxy/ips/?docbody=&prevDoc=102128108&backlink=1&&nd=102050331

the use of the unit as an energy source and ensuring safety of workers (personnel), population and the environment.

The Rules NP-012-16 establish that at all stages of the life cycle of the NPP unit prior to its decommissioning, the operating organization must plan its decommissioning by developing the concept for decommissioning of the NPP unit and its subsequent revision (clarification). These rules also stipulate the norm for development of such Concept for all NPP units within two years after these rules become effective, that is, no later than February 22, 2019.

Currently, two scenarios for decommissioning of nuclear power plants are enshrined in legislation:

- liquidation of an NPP unit, or
- disposal of an NPP unit.

Liquidation of a nuclear power unit involves decontaminationof buildings, structures, systems and elements of the NPP unit contaminated with radionuclides to an acceptable level in compliance with the applicable radiation safety standards and (or) their dismantling, handling of generated radioactive waste and other hazardous waste, as well as preparation of the site of the decommissioned NPP unit for further restricted or unrestricted use.

There are two alternative options for liquidation of an NPP power unit: immediate liquidation of a nuclear power unit and delayed liquidation of a nuclear power unit.

Immediate liquidation of a nuclear power unit is a way of implementing the “Liquidation of the NPP unit” option, in which dismantling or decontamination of buildings, structures, systems and elements of the NPP unit begin immediately after the NPP unit is shut down. For instance, the “Concept for decommissioning power units of the Leningrad NPP with RBMK-1000” provides for the immediate liquidation option.

Delayed liquidation of a nuclear power unit is a way of implementing the “Liquidation of an NPP unit” option, in which dismantling or decontamination of buildings, structures, systems and elements of the NPP unit begin after they are safely stored at the site of the decommissioned NPP unit for a long time, until the content of radioactive substances in them fall stop redetermined levels as a result of natural decay.

Disposal of a nuclear power unit is an option of decommissioning an NPP unit, providing for creation of a radioactive waste disposal system at the NPP site.

Based on the classification of radioactive waste approved in the Russian Federation (approved by Decree of the Government of the Russian Federation No. 1069 of October 19, 2012), all radioactive waste, apart from the state of aggregation and other hazard criteria, is divided into six classes. This classification is applied only to removable radioactive waste.

Radioactive waste of **the first class** (most dangerous) includes solid and solidified high-level radioactive waste, which must be disposed of with a preliminary decay period in order to reduce their heat release at radioactive waste burial sites.

The **second class** waste also includes solid highly active and medium-active long-lived radioactive waste (half-life of more than 31 years), which must be disposed of with no preliminary decay in order to reduce their heat release at radioactive waste burial sites.

The **third class** includes solid and solidified medium-active and low-activity long-lived radioactive waste to be disposed in the shallow disposal facilities at a depth of up to 100 meters.

The **fourth class** includes solid and solidified low-level radioactive waste to be disposed of in the shallow disposal facilities located at the same level as the ground surface.

The **fifth class** includes liquid medium-active and low-level radioactive waste to be disposed of in deep geological repositories.

The **sixth class** includes radioactive waste generated during extraction and processing of uranium ores, as well as during implementation of activities not related to extraction and processing of mineral and organic raw materials with a high content of natural radionuclides, which must be disposed of at the surface-level disposal facilities.

In accordance with the Criteria of radioactive waste attribution to specific radioactive wastes and criteria for classification of removable radioactive wastes (approved by Decree of the Government of the Russian Federation

No.1069[18] of October 19, 2012), irradiated graphite from NPP units cannot be classified as specific radioactive waste and it is classified as removable radioactive waste. Based on the above classification, most of the irradiated graphite is radioactive waste of the second class.

Currently, based on the legislation in place, radioactive waste of the second class must be buried in deep geological repositories. However, such repositories have not yet been created.

Natural and man-generated mechanisms of ^{14}C formation

The structural core of living organisms andecosystems consists mainly of carbon compounds.This element is involved in the natural cycle in the biosphere. Primarily, two stable isotopes are present in nature: ^{12}C (98.892%) and ^{13}C (1.108%).

Out of the four radioactive isotopes (^{10}C, ^{11}C, ^{14}C and ^{15}C), only the long-lived ^{14}C ($T_{1/2}$ = 5,730 years) is an environmental hazard, as it is incorporated into the carbon cycle of the biosphere. The other isotopes, with half-lives from 2.45 seconds (^{15}C) to 20.33 minutes (^{11}C) are not environmentally significant.

The content of ^{14}C in the natural environment is 10^{-10}%. This is a pure low-energy beta emitter with maximum particle energy of 156 keV.

^{14}C is formed under natural and artificial conditions as a result of several nuclear reactions involving thermal neutrons.

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[18] Government of the Russian Federation. Decree of January 1, 2012 on the Criteria of liquid, solid and gaseous waste attribution to radioactive wastes, criteria ofradioactive waste attribution to specific radioactive wastes and criteria for classification ofremovable radioactive wastes. http://docs.cntd.ru/document/902376375

[19] I. Y. Vasilenko, V. A.Osipov, V. P. Rublevsky, Radioactive carbon, magazine Priroda, 1992, № 12, p. 59-65. http://evolution.powernet.ru/library/vasilen.htm

Natural mechanisms of ^{14}C formation

^{14}C is constantly formed in the lower layers of the stratosphere as a result of secondary neutrons of cosmic radiation impacting the nuclei of atmospheric nitrogen according to the reaction $^{14}N(n, p)^{14}C$.

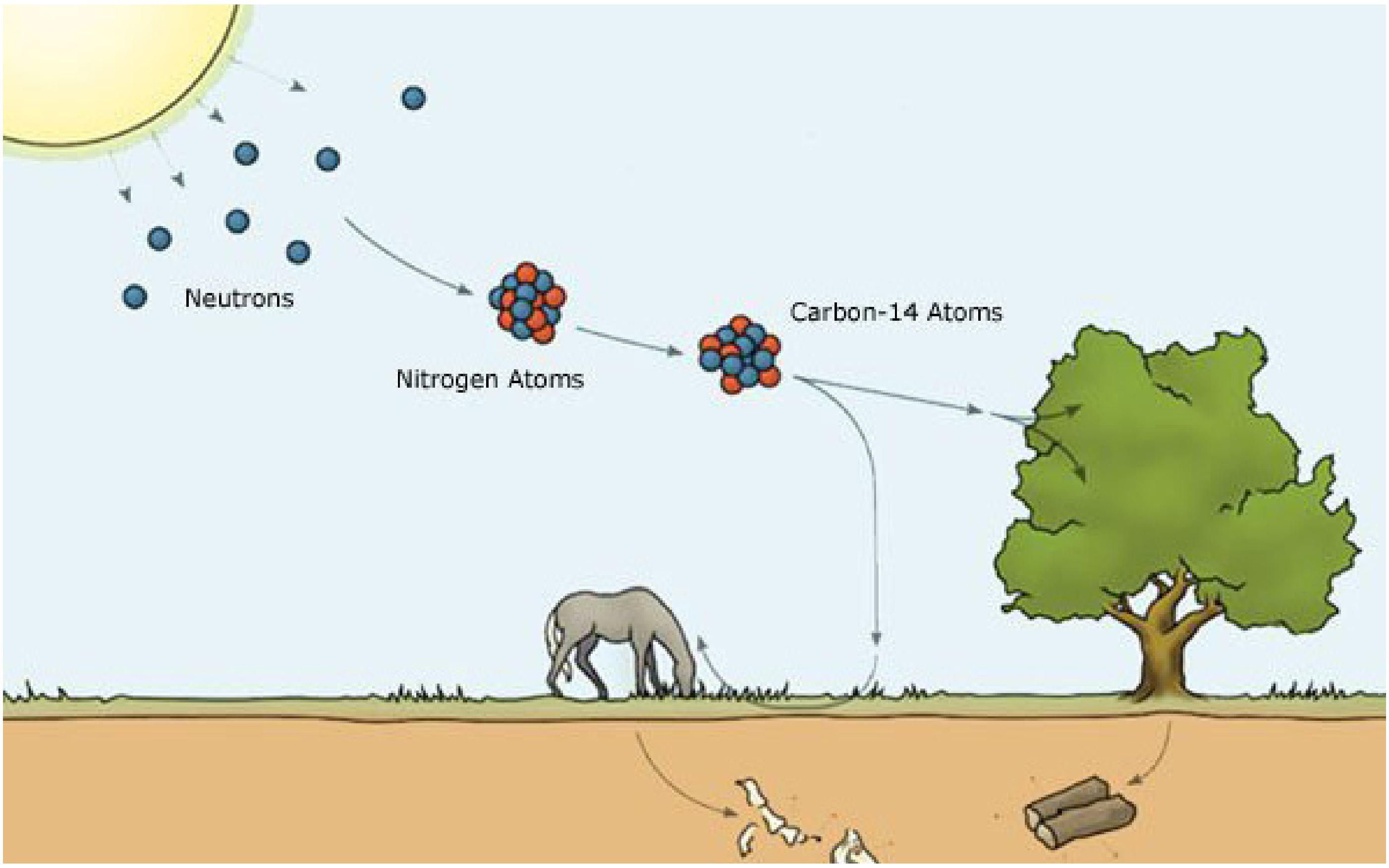
Formation of ^{14}C occurs in the reaction of neutron capture by a nitrogen nucleus, followed by emission of a proton: $^{14}N(n, p)^{14}C$.

There are other reactions that create cosmogenic ^{14}C in the atmosphere, in particular when neutrons collide with nuclei of the less common stable ^{13}C isotope, when gamma-ray emission occurs: $^{13}C\ (n, \gamma)^{14}C$; and also when a neutron is captured byan oxygen atom with emission of an alpha particle $^{17}O\ (n,\alpha)^{14}C$. However, the rate of formation as a result of the last two reactions is many times lower due to the lower prevalence of initial nuclides and smaller cross-sections for the reaction of interaction between neutrons and atoms.

The planetary ecosystem with a certain ratio between stable and radioactive carbon isotopes has formed as a result of the evolutionary process over millions of years. That is why a revolutionary change (increase) in the concentration of man-generated ^{14}C in the natural environment over just a few decades due to nuclear explosions and emissions and discharges of nuclear energy enterprises presents a great environmental and hygienic problem.

According to various sources, the cosmogenic (global) rate of ^{14}C formation is from 1 to 1.5 PBq/year. In terms of weight it is from 8 to 12 kg/year. The average content of natural radionuclides in the atmosphere and biosphere remains constant: 227 ± 1 Bq/kg of carbon.

The total amount of cosmogenic ^{14}C in the biosphere is estimated at 8.5 EBq. With 0.3% in the stratosphere, 1.6% in the troposphere, 4% on the surface of the Earth, 2.2% in the upper intermixing layers of the ocean, 92% in the deep layers of the ocean, and 0.4% in sea-floor deposits [20].



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[20] Hazardous substances in the environment. Radioactive substances. Encyclopedicedition. /Ed.byI. Y. Vasilenko et.al., Saint-Petersburg,NPO Professional, 2007, p. 188

Anthropogenic mechanisms of ^{14}C formation

^{14}C formation as a result of explosions

Anthropogenic ^{14}C is mainly formed, similar to natural carbon-14, by neutrons (arising in large quantities from nuclear bomb explosions) absorbed by ^{14}N nuclei in the atmosphere. The number of nuclides depends on the type of bomb (atomic or thermonuclear), its design (materials used), and power (neutron flux density). The release of ^{14}C during explosions by the synthesis reaction (hydrogen bomb) is estimated at 0.65 PBq/Mt, and it is almost five times lower (0.12 PBq/Mt) in case of the fission reaction (atomic bomb).

On July 16, 1945 the United States conducted the first nuclear test in the state of New Mexico, at the Alamogordo test site. The charge was approximately equal to 20 kilotons of trinitrotoluol(TNT) equivalent. It is estimated that from the time of the explosion of the first atomic bomb in 1945 until 1980 (when the treaty came into force banning nuclear weapon tests in the atmosphere, in outer space and under water), 249.2 PBq of ^{14}C was formed as a result of 423 tests of nuclear weapons in the atmosphere[21]. In total, more than 2,000 nuclear tests were conducted in the world in the atmosphere, under water and underground.

The maximum concentration of ^{14}C was registered in the atmosphere in 1963-1964. Itwas twice as much as the pre bomb era background level.

By 1978, the concentration of “bomb” ^{14}C exceeded the background level in average by 30%. At the same time the maximum concentration was observed in the region of 30° north and south latitudes and the minimum was registered in the tropics.

A significant release of ^{14}C occurred during the Chernobyl accident[22] , when, according to experts, up to 300 tons of reactor graphite could have been thrown onto the roofs of neighboring buildings as a result of the explosion, and after than the remaining 1,500 tons of reactor graphite continued burning for 10 days. This process of burning resulted in there lease of carbon-14 into the atmosphere in the form of $^{14}CO_2$ and ^{14}CO. Estimated activity of released ^{14}C is unknown.

14C formation during operation of nuclear reactors

^{14}C nuclide is formed in the active zone of nuclear reactors of any type, where there are powerful neutron fluxes that interact with the materials of reactor structures, material of the coolant, moderator, cooling system of the moderator, fuel, and their impurities.

The existing nuclear power plants of the former USSR in Russia, Ukraine, and Lithuania mainly use water-moderated pressurized water-water double-loop reactors (VVER 440, VVER-1000, and VVER-1200), uranium-graphite single-loop reactors (AMB 100, AMB-200, EGP-6, RBMK-1000, and RBMK-1500), and fast neutron reactors (BN-350 and BN-600, BN-800). The first and second groups of reactors are similar to the corresponding types of foreign reactors (PWR and LWGR) in terms of ^{14}C generation rate and its release into the environment.

Three RBMK-1000 reactors in Ukraine and two RBMK-1500 reactors in Lithuania were shut down with extraction of nuclear fuel. They are being prepared for dismantling.

In Russia, eleven RBMK-1000 reactors and four EGP-6 reactors are still in operation. One RBMK-1000 and one EGP-6 reactors are operated without energy generation. They are shut down, waiting for unloading of nuclear fuel and decommissioning.

A distinctive feature of RBMK reactors is the presence in the active core of a large amount of graphite moderator, cooled by a stream of nitrogen-helium mixture. The presence of nitrogen leads to a significant generation rate of ^{14}C , which reaches 2-3 TBq/(GWe /year) through the reaction $^{14}N(n,p)^{14}C$, and this is approximately an order of magnitude greater than in VVER reactors [23].

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[21] Vasilenko I. Y., V. A. Osipov, V. P. Rublevsky, Radioactive carbon, Priroda, 1992, № 12, p. 59-65 http://evolution.powernet.ru/library/vasilen.htm

[22] Igor’ Osipchuk, Facts, 25 April 2003 https://fakty.ua/75759-kogda-stalo-yasno-chto-ochicshat-kryshi-chaes-ot-radioaktivnyh-zavalov-pridetsya-vruchnuyu-silami-tysyach-chelovek-pravitelstvennaya-komissiya-poslala-tuda-soldat

[23] V. P. Golenetsky, S.P. Kirdin. Radioactive carbon in the biosphere. Moscow, 1979, cited in I. Y Vasilenko, V. A. Osipov, V. P. Rublevsky. Radioactive carbon, Priroda, 1992, № 12, p.p. 59-65. http://evolution.powernet.ru/library/vasilen.htm

In the graphite cladding of the RBMK reactor, radiocarbon is also generated as a result of $^{13}C(n,\gamma)^{14}C$ reaction, but the rate of formation in this reaction is five orders of magnitude lower due to the low concentration of 13C and a smaller cross-section of this reaction.

The rate of radiocarbon formation also occurs as a result of reactions $^{15}N(n,\alpha)^{14}C$, $^{17}O(n,\alpha)^{14}C$ and $^{16}O(p,3p)^{14}C$. However, these rates are also insignificant due to low concentrations of isotopes and a small cross-section for interaction of these reactions with neutrons.

Formation of ^{14}C in uranium-graphite reactors largely depends on the fluid cooling the graphite stack. Thus, the specific activity of ^{14}C in the UGR reactors of the Siberian Integrated Chemical Plant that are purged with nitrogen is 8–10 times higher than in AGR reactors purged with carbon dioxide.

In addition to the above-described radiocarbon formation reactions, various impurities are activated in the graphite reactor stack, structural elements, and nuclear fuel.

Another mechanism of contamination of graphite reactorcladding is its direct contact with other parts of the reactor core.

Radiocarbon ^{14}C is also formed in nuclear fuel. The rate of its formation depends mainly on the concentration of nitrogen impurities in nuclear fuel. With its usual content (0.001 0.002%), the rate of ^{14}C formation is 0.4–2.5TBq/(GW×year), and in the coolant-moderator water it is in the range of 0.2–0.5TBq/(GWe×year) [24].

The highest normalized emissions of ^{14}C is 10 – 17TBq/(GW×year) are observed in heavy water reactors (PHWR, CANDU).

Summarizing the above information, it can be said that radioactivity of irradiated graphite in UGR reactors is determined by the following processes:

- activation of impurities in graphite and the resulting dominance of nuclides ^{3}H, ^{14}C, ^{60}C, $^{36}C1$;
- contamination of the surfaces of graphite blocks with activation products, for example ^{14}C from induced nitrogen and contact with other contaminated ^{60}Co, ^{55}Fe and ^{3}H reactor parts.
- contamination of the surfaces of graphite blocks with nuclear materials and fission products as a result of incidents with fuel spills, etc.

^{14}C formation as a result of reprocessing of spent nuclear fuel from nuclear reactors

Radiocarbon ^{14}C is one of the components in emissions of nuclear fuel recovery plants. According to current estimates, spent fuel elements contain up to 66% of ^{14}C, which was generated as a result of neutron activation of fuel and coolant impurities[25].

In the course of fuel elements' reprocessing, the maximum release of ^{14}C occurs in the first twelve hours after their dissolution[26]. The reprocessing of fuel elements with a mass of 1,500 tons/year, results in ^{14}C emissions of 18.5 TBq/year.

A plant for processing fuel rods of light-water reactors produces 0.46 GBq/(MW×year) of ^{14}C and 2.5 GBq/(MW×year) from fuel rods of high-temperature reactors with gas coolingper year [27].

It was assumed that the concentration of ^{14}C will have doubled by the year 2000, and the ratio of radioactive carbon to stable $^{14}C/^{12}C$ will have decreased due to higher rates of stable isotope formation through combustion of fossil hydrocarbons [28]. (Suess effect).

If carbon energy is replaced by nuclear energy in order to reduce the impact on the climate, we can expect an increase in negative consequences for biota due to an increase in ^{14}C emission.

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[24] Bylkin B. K., V. P. Rublevsky, A. A. Khrulev, V. A. Tischenko // Nuclear technology abroad. 1988. № 1. P. 17—20

[25] Babayev N. S.et al.Nuclear power engineering, humans and the environment. Ed. byA. P. Aleksandrov, Moscow. Energoatomizdat, 1984, p. 168.

[26] Hazardous substances in the environment. Radioactive substances. Encyclopedic edition. Ed. by I. Y. Vasmlenko et al. Saint-Petersburg, NPO Professional, 2007, p. 188

[27] Bonka Het al. Production and Emission of Carbon-14and its Radiological Significance// Res.Commun. 4 Congr. Int. A/RP. Paris, 1977.V. 3, .P.945-948

[28] Hazardous substances in the environment. Radioactive substances. Encyclopedic edition. Ed. by I. Y. Vasmlenko et al. Saint-Petersburg, NPO Professional, 2007, p. 188

Impact of ^{14}C radiocarbon on living organisms

Despite the extremely low content of ^{14}C radiocarbon in the biosphere (the share of radioactive carbon at the levels of natural background radiation corresponds to about one atom per trillion (10^{12}) atoms of all carbon), an increase of its concentration can have very significant negative consequences. Nuclear physicist Andrei Sakharov used to warn humanity about this [29].

^{14}C takes part in metabolic processes together with the stable carbon, thus it penetrates into all organs, tissues, and molecular structures of living organisms.

The effect of radiocarbon on DNA and RNA of biological objects is associated with the action of beta particles and nitrogen recoil nuclei resulting from decay in accordance with the ^{14}C-->^{14}N pattern. The phenomenon of radioactive recoil is due to the fact that when releasing an alpha particle, the atom itself bounces in the opposite direction, colliding with the molecules encountered in its path and knocking electrons out of them.

In addition to this, the damaging effect is associated with a change in the chemical composition of molecules due to the conversion of carbon atoms into nitrogen atoms. Such transformations in genetic structures of cells are called transmutations, and the genetic effects they cause are called transmutation effects.

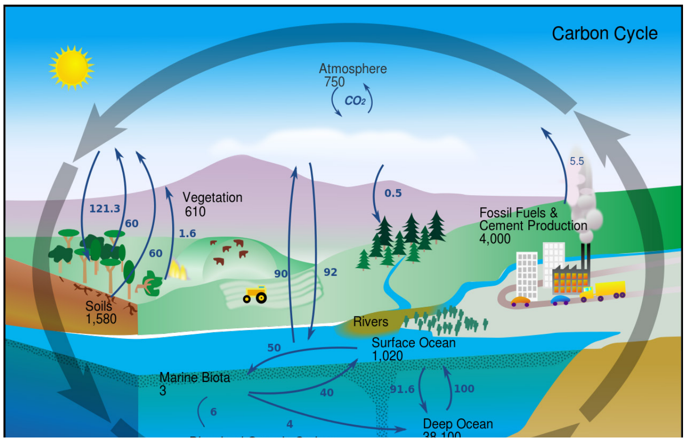
It happens so that the human body undergoes about four billion transmutation effects associated with ^{14}C on an annual basis, or hundreds of such effects every second. At the same time, it is believed[30] that such DNA damage can hardly or never be restored by the system of cellular repair and is, therefore, nonreversible[31].

In this case, DNA damage caused by nuclear transformations ^{14}C-->^{14}N can initiate the loss of genetic information at the rate of nuclear decay of radiocarbon, being nothing but a nuclear-biological clock that measures the life span.

The fact of the high genetic significance of transmutation caused by ^{14}C transformation, incorporated into DNA molecules, is theoretically substantiated and experimentally proved. Moreover, this effect is also manifested in low-level exposure close to the natural background radiation.

Variations in the concentration of radioactive carbon in the atmosphere in recent centuries have demonstrated that the period is dominated by the spike after 1945, caused by nuclear weapons tests that were conducted until 1963. After the adoption of a moratorium on testing nuclear weapons in the atmosphere, a decline in this concentration began, which continues till the present day.

The analysis of male and female mortality showed that the consequences of the spike of ^{14}C concentration reach their maximum for the male population after 6 to 7 years, and for the female population after 25 years. It is obvious that the profile of the parabolic curves is practically identical, which further underlines the common-cause of the increased mortality of both men and women in the corresponding historical period, despite the difference in the coordinates of the maximum rate. The ^{14}C impact on the natural mortality during this period can be visualized if its dynamics are presentedalong the same historical scale together with the change in concentrations of radiocarbon, as illustrated for Denmark and Norway in Fig. 2.



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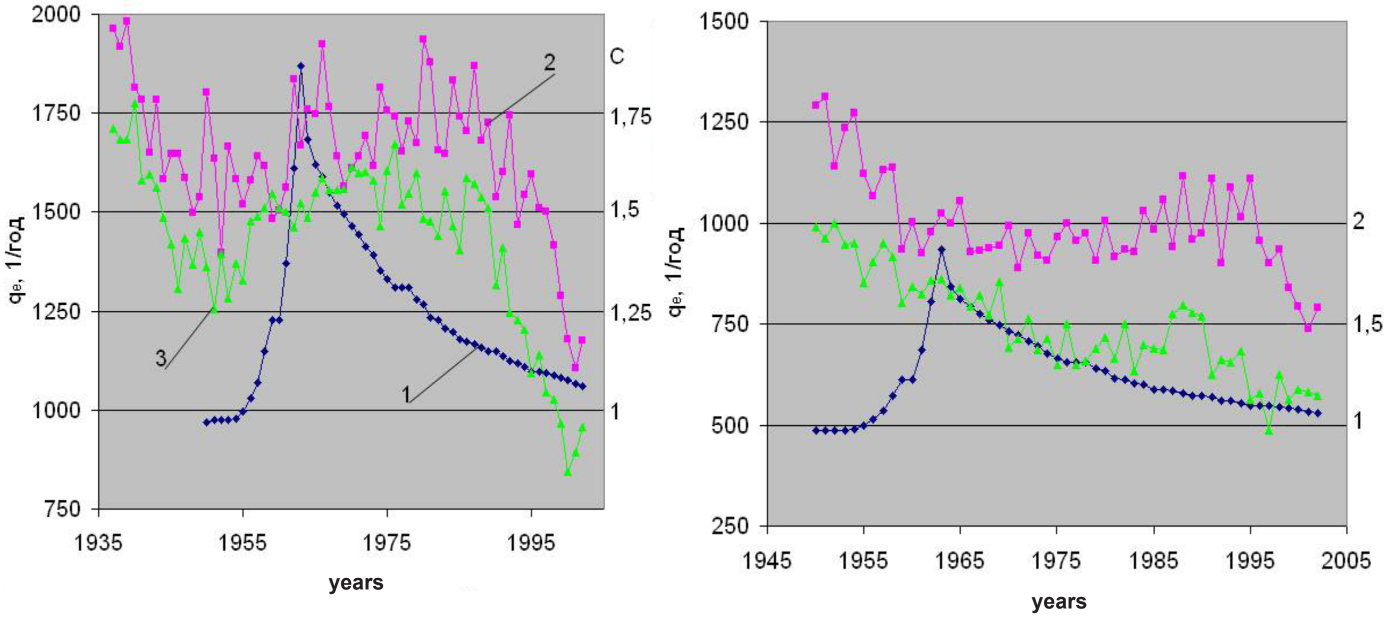
[29] Sakharov A. D. Radioactive carbon of nuclear explosions and non-threshold biological effects. In:Atomicenergy, Volume 4, issue 6, 1958. p. 576-580.

[30] Rublevsky V.P., S.P Golenetsky, G. S. Kirdin. Radioactive carbon in the biosphere. Moscow, Atomidat, 1972, 172 p.

[31] Hazardous substances in the environment. Radioactive substances. Encyclopedic edition. Ed. by I. Y. Vasmlenko et al. Saint-Petersburg, NPO Professional, 2007, p. 190

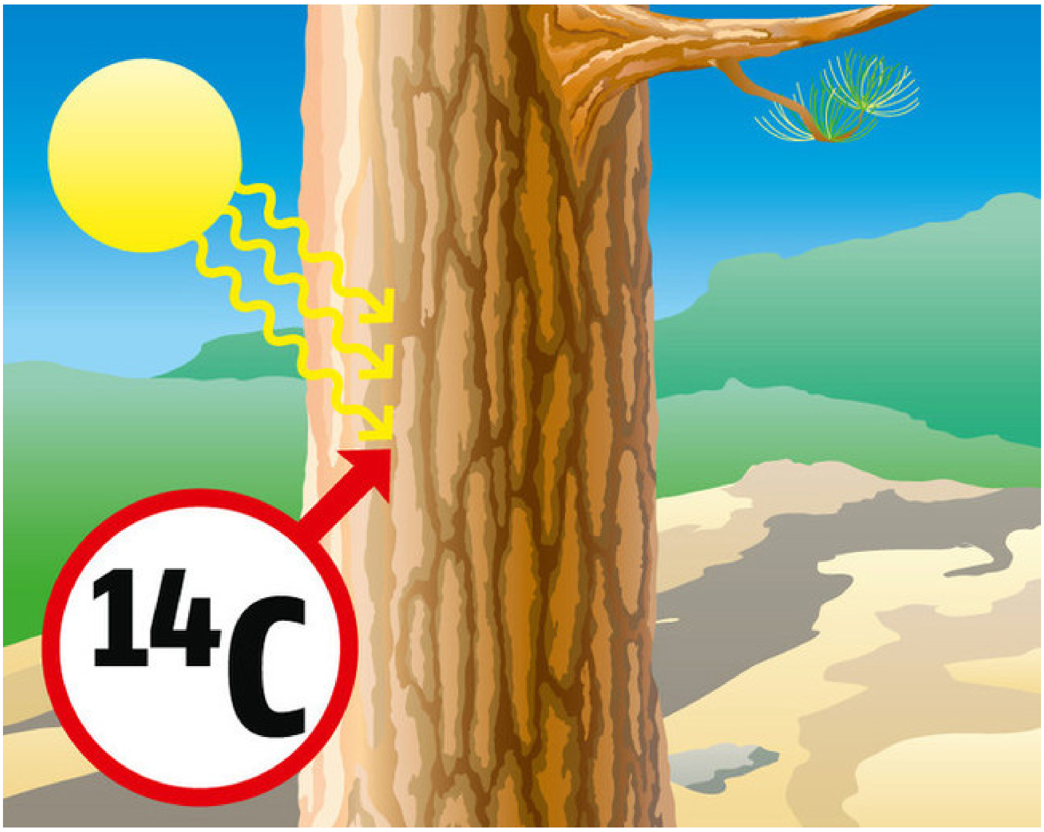
Fig.2. Dynamics of ^{14}C concentration in the atmosphere and natural mortality of the population aged 60 [32]
men on the left, women on the right



Men

Women

It can be concluded that secure isolation of reactor graphite from the biosphere during decommissioning of UGR reactors is an important criterion for safety and successful decommissioning of all reactors of this type, including RBMK.



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[32] Aleksander Germansky, Radiocarbon and Mortality, 2006 http://gealeksandr.narod.ru

Migration of ^{14}C in the natural environment

As a result of atmospheric processes, radiocarbon is transported over long distances from the sources of emission. Oxidized to $^{14}CO_2$, it enters the natural carbon cycle.

In the course of photosynthesis, ^{14}C accumulates in plants; animal organisms and humans receive it through the food chain, mainly by ingestion, the contribution through breathing does not exceed 1%.

Only 10% of ^{14}C from the atmosphere is absorbed by terrestrial biocenosis, the remaining 90% is fixed by marine organisms, mainly plankton [33].

The time constant of ^{14}C exchange is 5–25 years at the surface layers of the ocean and within the range of 100 –1000 years at the level of deep layers. The full exchange of both ^{14}C and stable ^{12}C covers 300 – 500 years.

The transition coefficient in the atmosphere - terrestrial plants chain equals one. Equilibrium is established after two-three months. Plants may also receive ^{14}C from soil.

The content of ^{14}C in animal organisms correlates with its content in plants during the previous year. In 1963–1964, after numerous nuclear and thermonuclear weapons tests in the atmosphere, the content of ^{14}C in vegetable products, milk and meat increased approximately twofold in comparison with the with background values.

There can be local points of ^{14}C contamination. For instance, plants growing at a distance of 1-2 km from the NPP pipe contain 50–90% more of ^{14}C than plants growing at a distance of 20–30 km [34].

All carbon on the Earth is concentrated in two basins – the sedimentary and exchange basins.

Carbon of the sedimentary basin constitutes more than 99.83% of all terrestrial carbon (organic and inorganic carbon of sedimentary rocks, coal, oil, and other minerals) and it practically does not participate in natural exchange processes; it enters the cycle only after organic fuel combustion.

Carbon of the exchange basin, which contains about 0.17% of the total amount of carbon on the Earth, with more than 90% of this amount in the deep waters of the ocean, is involved in the cycle of its individual reservoirs: atmosphere, biosphere, hydrosphere, etc.

The carbon cycle in nature consists, as it were, of two cycles running in parallel in the land and sea parts of the biosphere connected by the atmosphere.

The rate of carbon exchange between the reservoirs of the exchange basin is diverse:

- Several years is the average time a CO_2 molecule stays in the atmosphere before it enters the ocean water;
- Several hundreds of years is the average time it takes for CO_2 molecule to move from the deep ocean waters to the atmosphere;
- Several hundreds of millions of years is the average time a carbon molecule stays in sedimentary rocks before it is transported to the atmosphere.

Thus, sedimentary rocks play a role of a certain kind of repository for radiocarbon (both natural and artificial), in which it decays and leaves the natural cycle.

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[33] Vasilenko I. Y. Et al.// Atomic Energy. 1980. Volume.49, issue 6, p. 299 – 303.

[34] Rublevsky V.P. Radioactive carbon in the biosphere. Moscow. 1979. 152 p.

Existing and possible strategies and concepts for handling uranium-graphite reactors after their permanent shutdown

The UGR reactors in the process of decommissioning were designed in the USSR in the 60s of the last century. This was done without conceptual development of plans for their future decommissioning, dismantling, and long-term solution of the issues of radioactive waste management, including irradiated reactor graphite.

The attempts to find a solution based on the available experience demonstrate that a long-term strategy for safe management of radioactive waste and spent nuclear fuel is more complicated than it seemed in the past, and that this problem has not only technological, but also social, environmental, economic, and moral dimensions. So far no universal solution has been identified, that is why the delayed option constitutes a common strategy.

There are three options for the concept of decommissioning nuclear power units: conservation, burial and liquidation that correspond to the three stages of the IAEA classification: preservation under supervision, restricted use of the site, and unrestricted use of the site. In the United States, these three methods are referred to as "safe storage", "entombment", and "removal".

Let us consider some of the options for management strategies that are currently available.

UGR reactor decommissioning under the «In-situdisposal» concept [35]

IAEA does not approve of in situ entombment. In Russia the specificity of such conceptual solution of decommissioning uranium-graphite reactors is determined, first of all, by the fact that the reactor was operated underground at a depth of 20 meters. In addition, the graphite cladding of the reactor is contaminated with trans uranium radionuclides, which have got there as a result of accidents related to the destruction of the covers of fuel elements (blocks) and technological channels.

It was decided that this facility can be attributed to the category of a "specific type of radioactive waste" and in accordance with the "Concept of Decommissioning of Industrial Uranium Graphite Reactors under the Radiation Safety Option of On-site Disposal" approved on 28.12.09.

This was the first experience of decommissioning under the "in situ entombment" scenario of the PUGR EI-2 reactor, which had worked for 32 years at the Closed Administrative-Territorial Entity (CATE, Russian abbreviation is ZATO) Seversk in the Tomsk region. This dual-purpose reactor was used for production of plutonium and for centralized heating of the city with population of 100 thousand people. The project was implemented in the period from 2011 to 2015.

After the removal of spent nuclear fuel and bringing the reactor to a nuclear safe condition, the following activities were carried out:

- All inactive equipment was dismantled;
- The lower part of the reactor was entombed with waterproof concrete, which provided additional reinforcement of the main supporting structures;
- The side steel structures were filled with concrete;
- Graphite cladding located 20 meters below ground level was isolated using a specially designed barrier material based on the composition of clays and minerals from deposits in the Siberian region;
- All openings in the concrete vessel of the reactor and cavities of the reactor space were filled with the barrier material;
- The upper part of the reactor was closed with a

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[35] A.O. Pavlyuk,Experience of EI-2 uranium-graphite reactor decommissioning, Demonstration Center for Decommissioning of Uranium-Graphite Nuclear Reactors.Materials of the 5thInternationalConference, Tomsk, September 13–16, 2016 http://earchive.tpu.ru/bitstream/11683/32525/1/conference_tpu-2016-C33_p508-512.pdf

reinforced concrete slab that provides protection against fire and blast waves and sealed with the barrier material;

- All rooms were decontaminated and the building above the reactor was dismantled; the radioactive wastes from dismantling and decontamination of the building structures were prepared for burial.
- The thickness of the barrier above the cladding is 5 m, under it 6 m, along the perimeter 12 m.

In total, 4.5 thousand cubic meters of clay mixtures were used within the reactor shaft and 36.6 thousand cubic meters outside the reactor shaft;

A barrier made of natural materials (clay, sand, crushed stone) was built on the surface, with the total volume of material used reading 86,000 cubic meters;

The constructed facility has the status of a Special Radioactive Waste Disposal Site, where long-term monitoring is carried out. Subsequently transfer to a radioactive burial site is planned.

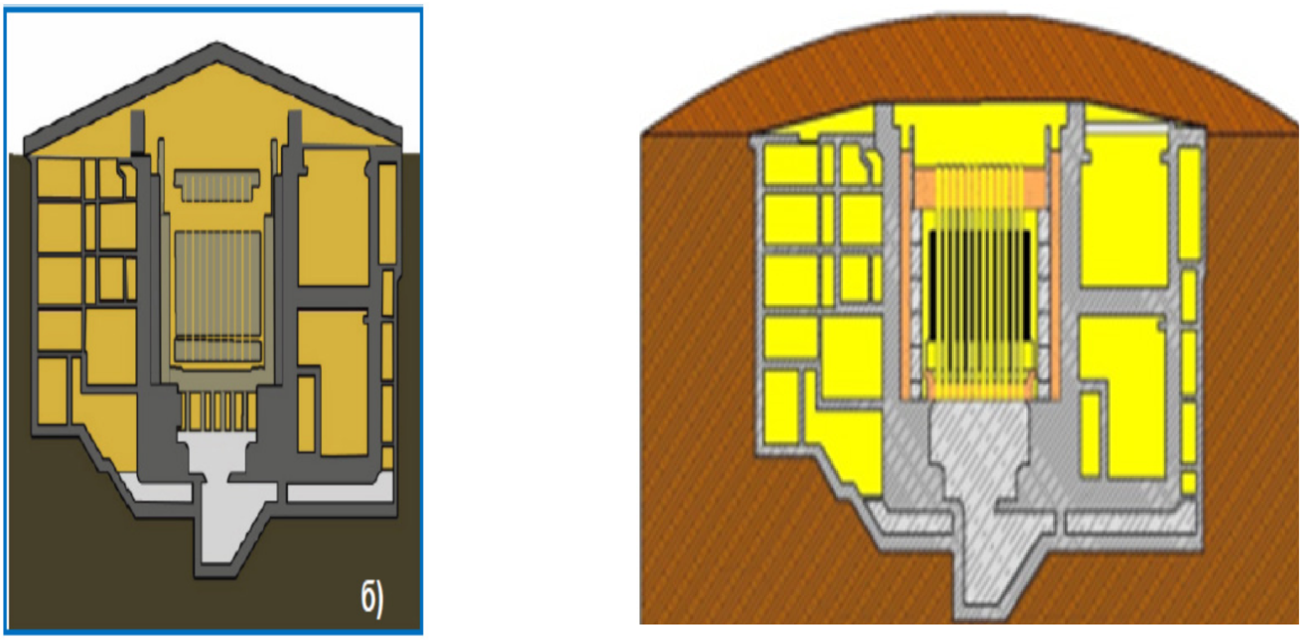

Fig.3.Cross-sectional view of the underground reactor rooms of the PUGR EI-2 before (left) and after entombment (right).

Fig. 4. View of PUGR EI-2 above ground facilities before (left) and after entombment (right)

Advantages of the in-situ disposal method:

- There is no need to remove highly active radioactive waste for subsequent packaging, transportation and disposal;
- It is relatively cheap as it is not necessary to disassemble reactor fragments and dispose of radioactive wastes separately depending on their hazard class;
- Relatively low radiation exposure for personnel compared to the dismantling and transportation options for fragments of the reactor.

Short comings of the in-situ disposal method [36]:

- Difficulties in removing and subsequent entombment of the facility in case of security barrier damage;
- Proximity of groundwater, danger of leaching, and danger of ^{14}C inflow into drinking water aquifers.

UGR reactor decommissioning under the "Green Mound" concept

The Green Mound concept [37] for NPP decommissioning has been developed and patented by the Research and Design Institute of Installation Technology (NIKIMT Atomstroy, Russia) [38].

Let us consider its possible implementation for decommissioning two uranium-graphite reactors at the Ignalina NPP with RBMK-1500 reactors of 1,500 MW each.

What makes decommissioning of power units with RBMK reactors more complicated is the great weight of 1,800 tons of irradiated graphite in each reactor containing, in addition to the biologically significant ^{14}C ($T1/2$= 5,730 years), considerable contamination with trans-uranium elements.

Given the high specific activity of 0.3 - 1.0 GBq/kg of graphite cladding, including ~130 MBq/kg of ^{14}C isotope, and provided a political decision on immediate decommissioning is taken, the concept of "Green Mound" is worth considering.

This method does not require dismantling of the E structure(the upper bioshield –a steel drum 3.0 m high filled with Urals crushed stone) to provide access to the graphite brickwork, its disassembly, sorting of graphite blocks by activity level, their loading into containers and transportation for conditioning and burial.

It can be expected that the cost of implementation of the Green Mound concept for the Ignalina NPP will be significantly lower compared with other alternative options providing for dismantling, decontamination and isolation of radioactive waste in deep disposal sites to be constructed in geologically acceptable areas.

The Green Mound option in the form of an underground on-site disposal facility has already been implemented in Russia for the dual-purpose industrial UGR reactor at the Siberian Chemical Combine in ZATO Seversk, Tomsk region. The In-situ Burial option is designed for the ADE, ADE-2 and ADE-3 reactors located in an underground space at a depth of 250 m at the Mining and Chemical Combine (MCC) in ZATO Zheleznogorsk, Krasnoyarsk Territory.

In contrast to all Russian and Ukrainian RBMK reactors, the graphite cladding of the two RBMK-1500sat the Ignalina NPP is 6.0 m above the terrain, which is at +8.4 m and on a multi-kilometer slab of Cambrian clay. Such location of the reactor makes it possible to consider the concept of entombment of the Ignalina NPP reactors on site in compliance with the Green Mound technology patented by NIKIMTAtomstroy. Under this scenario, the possibility of groundwater leaching of radionuclides in the Green Mound at the height of the third floor of a residential building is quite unlikely in the next centuries.

An important argument for adoption of the Green Mound concept is the use of a specially developed preservative "F" [39] for protection of graphite and metal structures from contact with oxygen.

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[36] Serebryakov B.E. On unacceptable on-site burial of reactors. http://www.proatom.ru/modules.php?name=News&file=article&sid=8666

[37] TutinovaE. V., S.V. Korovkin.Mound technology for isolation of decommissioned nuclear power plants. AtomicEnergy, 20.11.2014 http://www.atomic-energy.ru/technology/53116

[38] NIKIMTAtomstroy, Rosatomenterprise http://www.nikimtatomstroy.ru/

[39] Tuktarov M. A. et al. Reactor graphite conditioning for decommissioned uranium-graphite reactors for burial purposes // Atomic Energy, June 8, 2016 http://www.atomic-energy.ru/articles/2016/06/08/66585

An important argument for adoption of the Green Mound concept is the use of a specially developed preservative "F" for protection of graphite and metal structures from contact with oxygen.

Filling of the reactor cavities and its metal structures with preservative "F" will ensure protection from metal corrosion and radionuclide insulation for up to 300 years when short lived radionuclides decay. After this time, it is possible to expect that the advance of science will provide for safer disposal technologies and possible use of irradiated reactor graphite in the national economy. In the next 70-100 years, irradiated graphite, if needed, can be extracted from the mound and used without much difficulty.

According to the current estimates, on-site disposal of irradiated reactor graphite is 2-3 times cheaper than "dirty and dusty" off-site disassembly, irradiation of personnel, increased risks of contamination of the natural environment with biologically significant ^{14}C, as well as 36Cl, 3H, and other radioactive isotopes.

As part of the RBMK-1500 power units preparation for on-site entombment, it is necessary to reduce its height from +50.0 to +25.2 meters (floor of the reactor hall). To do this, it is necessary to preliminarily remove the tent roof, steel wall columns with hinged reinforced concrete panels. Some of these reinforced concrete panels can be placed on the surface of the reactor hall floor to protect against falling aircrafts and other unauthorized actions from above.

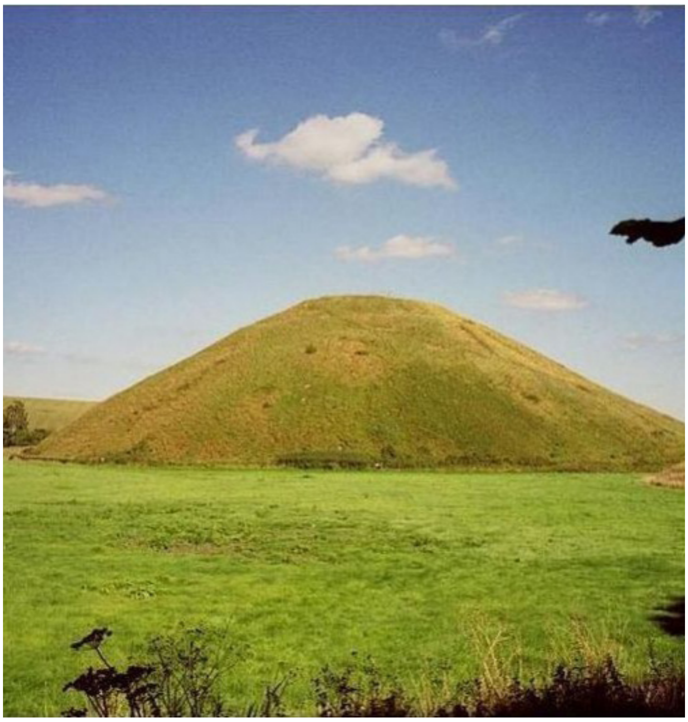
The following advantages of the Green Mound concept can be identified:

- No dismantling, disaggregation, decontamination, transportation of equipment and metal structures of the reactor are required;
- There is no need to dismantle technological and other reactor channels and no need to dismantle, condition, package, and transport about 7,600 tons of graphite cladding of the two reactors for burial in the deep geological repository;
- Construction of an expensive deep geological repository for long-lived radioactive wastes is not required; all highly active and long-lived radioactive wastes in protective containers are placed in the cooling ponds and other power unit spaces after removal of the spent nuclear fuel;
- There is no work with explosive graphite dust and no contamination of the biosphere with hazardous radionuclides ^{14}C, ^{36}Cl, ^{3}H contained in graphite, radiation exposure for is considerably reduced;
- Financing of works listed1-4 is not required;
- In the vicinity of the Ignalina NPP there are large deposits of quartz sand for unstriped filling of the internal spaces of the units with radioactive wastecontainers, as well as Cambrian clays for external sealingof the structures of the units and subsequent backfilling of soil with strengthening vegetation.

Two green mounds 80.0m high and 200.0 m in diameter at their foot on the site of two RBMK-1500 units at the Ignalina NPP can become an ecologically, economically and socially acceptable solution for the Ignalina NPP decommissioning.

Drawbacks of the Green Mound concept:

- Transfer of the nuclear wastes to future generations;
- the need for physical protection of the green mounds from unauthorized access, and ensuring comprehensive environmental monitoring in the area of their disposal.



UGR decommissioning options with remote dismantling of graphite cladding for disposal and monitored storage

In the event that political decisions are made to decommission the UGR reactor without the in-situburial or Green Mound options, the key challenge is to dismantle and ensure effective technologies for management of irradiated radioactive graphite.

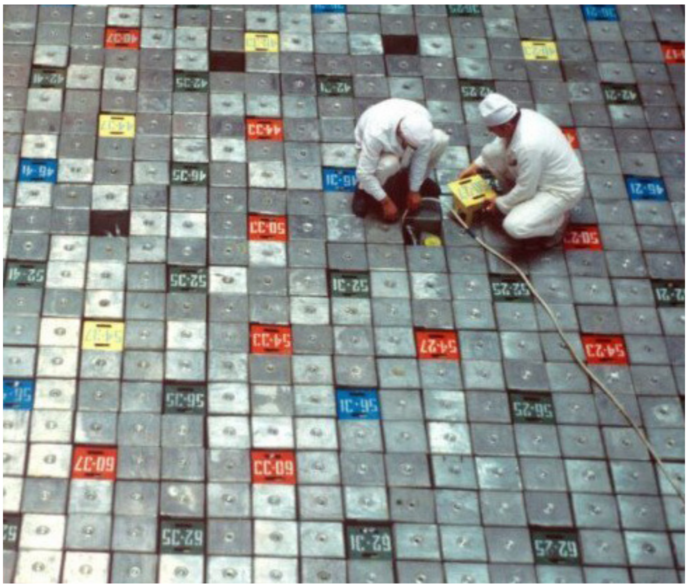
During the UGR dismantling process, the designed-protective barriers are deliberately destroyed. As a result, there is an increased risk of discharging radioactive substances in solid, liquid and gaseous states, as well as in the form of aerosols, outside the power unit.

Properties of irradiated reactor graphite that must be taken into account for planning the disassembly and removal of the graphite cladding.

At resource fluence of ~2×10^{22} neutron/cm^2, the thermal conductivity of graphite remains at a low level and the mechanical strength is reduced.

Chemical reactions of graphite only occur only with extremely strong reagents such as, for example, concentrated nitric acid.

Облученный графит удовлетворяет большинству общих требований, предъявляемых к твердым РАО, пригодным для захоронения.



Irradiated graphite meets most of the general requirements for solid radioactive waste suitable for disposal. However, the assessment of the acquired activity of graphite moderators and other graphite parts used in nuclear reactors shows that irradiated graphite cannot be accepted for disposal without preliminary treatment, as during its disposal it is necessary to ensure isolation from the ecosphere for the entire period of its potential hazard, which is tens of thousands of years.

Let us consider the stages of irradiated graphite preparation for dismantling of RBMK-1000 reactors.

Access to the graphite cladding of the reactor is covered by upper protective metal structures. For RBMK-1000 these are: G structure (steel beams and plates), E structure (steel drum 3.0 m high, 12.0 m in diameter, backfilled with crushed stone), steel build-up paths, steam and water communications and steel jacket of the reactor space (CG scheme).

Before the beginning of work on removal of graphite cladding it is necessary to remove all 2,488 reactor channels. In order to perform these works in accordance with requirements of the Radiation and General Industrial Safety Regulations, it is necessary to develop an activity management plan with the sequence of disassembling operations and the plan of restricted access to the graphite cladding.

Taking into account the high radiation background and acquired surface looseness of graphite blocks resulting in dust formation, dismantling of cladding should be performed remotely with the use of robotic complexes.

The need for careful planning of the dismantling process requires simultaneous consideration of many factors characterizing both the condition of the unit being decommissioned, the equipment used, and the planned operations.

As a rule, it is very difficult to take all this into account correctly by means of speculative conclusions, and, therefore, there is a great risk of making decisions that do not ensure the required level of safety.

The IAEA recommends the use of layouts and models of the reactor and the unit as a whole in order to prepare personnel for dismantling procedures. The current level of information technology development, including technologies for creating computer video games, makes it possible to have quite reliable 3D real-time modeling of physical processes.

The available experience in preparation for UGR graphite cladding dismantling of EGR highlights appropriateness and efficiency of development of interactive simulation three-dimensional models (ISTM)[40] for practicing procedures of graphite masonry dismantling, as well as for training the personnel who will be performing such works.

The results of the conducted research enabled the Experimental Demonstration Center for Decommissioning of Uranium-Graphite Nuclear Reactors (EDC DUGR), (ZATO Seversk, Tomsk region) to take out a patent for the Method of removal of the graphite cladding of nuclear reactors, which will ensure implementation of the work on decommissioning of uranium-graphite nuclear reactors under the option Liquidation option. [41]

Specialists of EDC DUGR offered to perform the work on complete removal of graphite cladding through an opening in the upper metal structures, with preservation of load-bearing and protective properties of the upper metal structures. This approach will reduce aerosol emissions and avoid increasing gamma radiation doses in the reactor central hall. Dismantling of reactor structural elements, including graphite cladding, is planned to be performed using a remotely operated manipulator. Removal of the graphite cladding blocks is carried out without forced fragmentation, which prevents an increase of radioactive waste and formation of radioactive graphite dust.

All safety systems are maintained in working condition for the duration of the work. The openings above the reactor are closed with specially designed and manufactured protective covers that protect the personnel from reactor radiation and at the same time ensure the required access to the internal structures.

Graphite cladding decontamination is one of the preliminary treatment stages before long-term isolation.

The purpose of irradiated graphite decontamination is removal of radionuclides from its volume for transfer of graphite radioactive waste from one class of removable solid radioactive waste to another. This can reduce the costs of its disposal, as in this case a near-surface disposal can be used instead of deep burial.

When analyzing the risks associated with the choice of IRG decontamination technology, it is important to ensure that ^{14}C does not acquire a “biogenic form” - $^{14}CO_2$ because, in this case, when it enters the natural environment, radiocarbon dioxide is absorbed by plants during photosynthesis and migrates along food chains.

It should be remembered that the total activity of accumulated reactor graphite in the world is ~730 PBq. This is almost 3 times more than the “bomb” (~249 PBq) that arose during atomic explosions in the atmosphere (1945 - 1980). Thus, if IRG enters natural ecosystems in the form of $^{14}CO_2$, the negative consequences can be very significant.

In Russia and other countries numerous research works are carried out to study the possibilities of irradiated graphite decontamination, i.e. its purification from long-lived nuclides, as well as from nuclides with high γ-activity due to thermal influence on graphite of various liquid and gas media, such as acids, alkalis, molten salts, steam, helium, nitrogen, etc. on graphite, and plasma treatment of the surface of irradiated graphite blocks.

Preliminary results of decontamination of irradiated graphite by argon and steam have shown that when decontaminated by argon the release of radionuclides from the graphite volume is about 20%, and when decontaminated by steam the yield of long lived radionuclides reaches up to 65%, but this process is accompanied by the loss of mass of graphite itself.

There were experimental studies of decontamination of technological channels’ rings at the Kursk NPP by air and in molten salts. The results of the experiment showed that when graphite is decontaminated with air at a temperature of ~700°C, it is possible to remove 90 - 95% of radioactive carbon-14, with simultaneous loss of graphite mass in the range of ~25-35%.

If these losses were in the form of $^{14}CO_2$ and were released into the natural environment, then this experience cannot be considered positive and such technologies should be prohibited by law.

In addition to liquid and gas decontamination of irradiated reactor graphite, plasma treatment for decontamination of the surface of irradiated graphite blocks was studied. The plasma discharge was ignited between the treated surface of the graphite block serving as a cathode, and the collector, which in this case was an anode. The graphite block surface was dispersed and radioactive ^{14}C was deposited on the electrode collector.

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[40] Chujko D. V.Useofimitationmodellingfordismantlingreactor units of Phase I ofBeloyarskaya NPP. Moscow, 2014 http://tekhnosfera.com/primenenie-imitatsionnogo-modelirovaniya-dlya-demontazha-reaktornyh-ustanovok-pervoy-ocheredi-beloyarskoy-aes#ixzz69EO5va6X

[41] Rosatom received a new patent for an invention in the field of uranium-graphite reactor decommissioning https://www.rosatom.ru/journalist/news/rosatom-poluchil-novyy-patent-na-izobretenie-v-oblasti-vyvoda-iz-ekspluatatsii-uran-grafitovykh-reak/

In addition to liquid and gas decontamination of irradiated reactor graphite, plasma treatment for decontamination of the surface of irradiated graphite blocks was studied. The plasma discharge was ignited between the treated surface of the graphite block serving as a cathode, and the collector, which in this case was an anode. The graphite block surface was dispersed and radioactive ^{14}C was deposited on the electrode collector.

Different options were explored for handling graphite radioactive wastes in order to ensure their long-term isolation from natural ecosystems. The most extensive research has been conducted in Great Britain, Russia and France, although the final and generally accepted solution for their conditioning and disposal remains unidentified. In practice, the most common currently used option is long-term storage (delayed permanent disposal).

The following three major options for permanent disposal of spent graphite have been considered:

- Direct disposal after appropriate packaging;
- Disposal after incineration with subsequentash conditioning, as well as the capture of aerosols and radioactive gases with the transfer to the solid fraction;
- Disposal after chemical treatment (liquid and/or-gaseous extraction) and conditioning (filling, encapsulation, etc.) and proper packaging.

Direct disposal of graphite waste

Selection of the strategy– on-sitedisposal, disposal in a near-surface or deep disposal facility of radioactive waste– depends on a number of technical and economic factors, including the location of a nuclear installation.

Both near-surface disposal facilities and deep geological formations were considered for direct disposal in repositories. Multiple studies have shown that according to the classification of radioactive waste,[42] the larger part of irradiated graphite (UGR reactor cladding graphite) belongs to the second class of radioactive waste, which is to be disposed in deep geological formations without preliminary storage in order to reduce their heat release.

Emergency graphite containing spilled waste is not uniform in its contamination. At its sorting and separation during removal of the graphite cladding of UGR reactors, emergency graphite will be classified as class 1 waste that also must be buried in deep repositories.

Replaceable graphite products were exposed for a much shorter time (5 - 15 years) compared to the cladding blocks (~45 years), so their specific activity is lower, and is directly related to the time of exposure.

With regard to graphite of power-producing UGR reactors, the estimated amount of the removed graphite of class 1 (emergency graphite) will be 1,500 tons, class 2 – 22,000 tons (cladding), class 3 (liners, rings, etc.) – 7,500 tons (Fig. 4).

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[42] Decree of the Government of the Russian Federation № 1069of 19.10.2012 On the criteria for attributing solid, liquid and gaseous waste to radioactive waste http://pravo.gov.ru/proxy/ips/?docbody=&nd=102160207&rdk=1

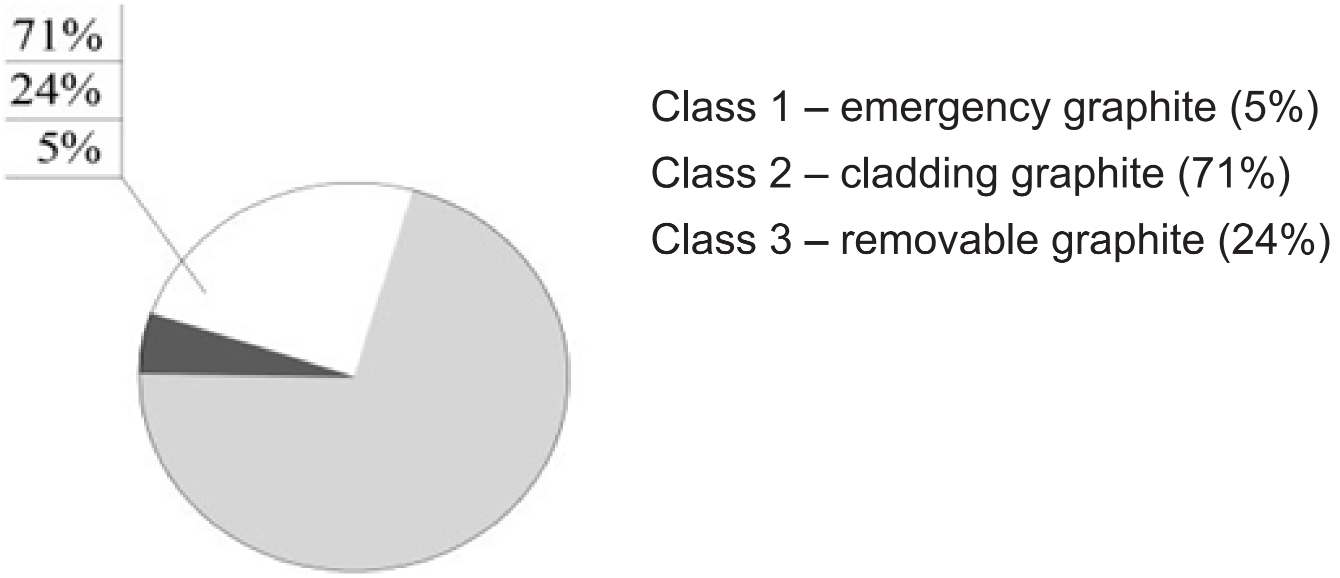

Fig. 4. Break down of irradiated reactor graphite from Russian power reactors, which can be attributed to different classes of radioactive wastes

In graphite cladding in the locations of irradiated fuel particles containment with the period of exposure up to three years, the spectrum of γ-radiation of irradiated graphite is determined by short lived fission fragments of ^{134}Cs, ^{144}Ce, ^{106}Ru, ^{155}Eu, etc., and in the period from 3 to 50 years - by radionuclides ^{60}Co, ^{137}Cs and ^{155}Eu.

During this period, the high level of the gamma background of the reactors is mainly due to the high-energy γ-quanta accompanying the β decay of ^{60}Co (half-life of 5.27 years).

According to the estimates of the Kurchatov Institute Research Center, the radiation level from a graphite block after 10 years of exposure will reach the criterion for transportation (Fig. 5), i.e., the limit on the dose rate when transporting packages with graphite radioactive waste. This will allow safe and less expensive handling of graphite.

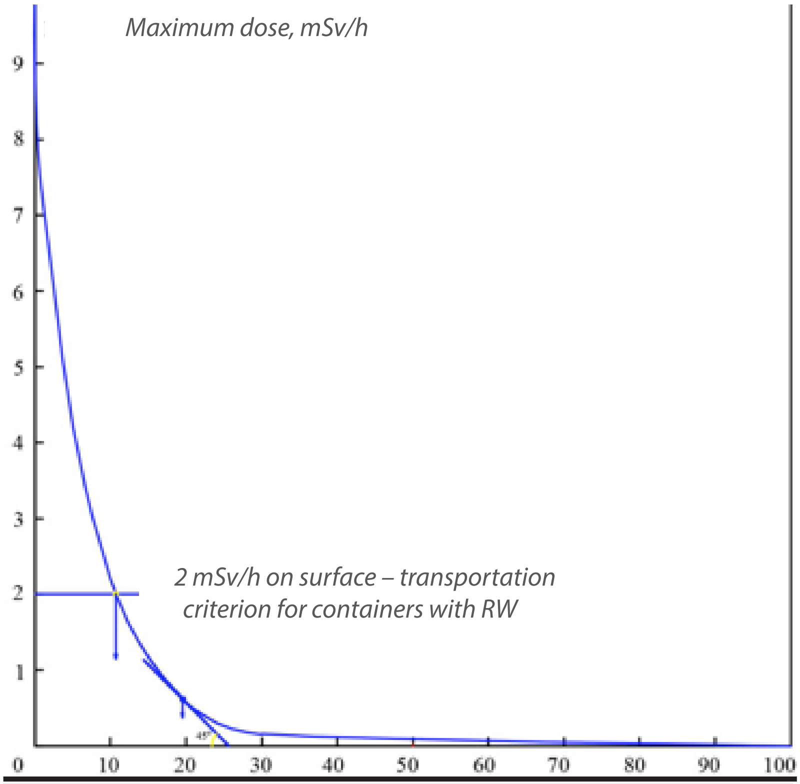

Fig.5. Radiation rate from a graphite block after 10 years of storage decreases and reaches the admissible value for transportation

The local concepts of decommissioning the power units with RBMK-1000 reactors provide for dismantling options (immediate or delayed) for reactor units with further packaging of graphite waste in containers and transporting them to the burial site. Special containers have been developed for near-surface and deep disposal options (Fig.6).

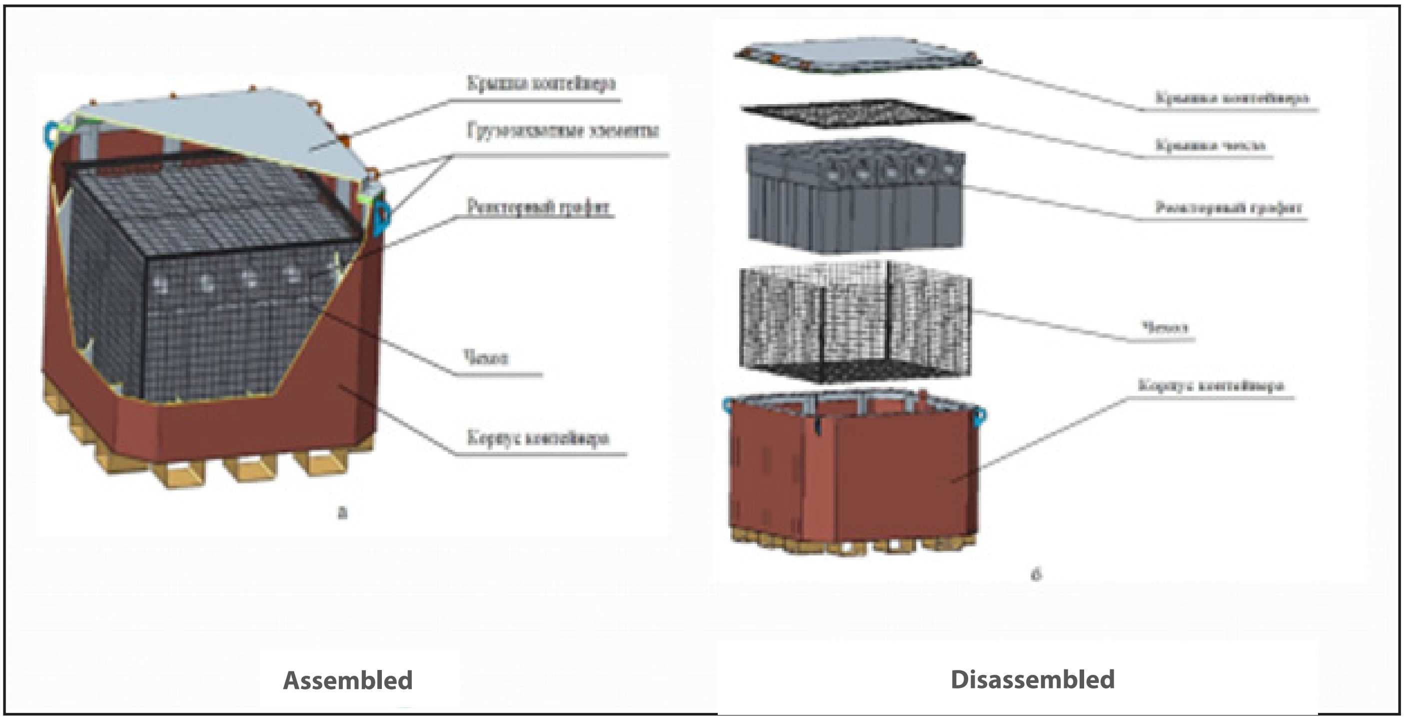

Fig. 6. General type of graphite packaging containers for deep or near-surface disposal

The first stage of UGR reactor decommissioning (preparation for unit liquidation) is unloading of spent nuclear fuel, that is, bringing the reactor to a nuclear safe condition. This stage, which takes 7 - 8 years before the unit dismantlement, maximizes the benefits of radioactive decay by reducing radiation exposure during subsequent disassembly of the graphite cladding.

In the second phase of decommissioning, disassembly of the reactor's graphite cladding should be performed layer wise, in separate blocks. Removal of the graphite blocks from the core and their placement in containers will be carried out remotely using robotic means and special technological equipment.

The technological sequence of reactor graphite conditioning includes the following combined operations:

- Moving graphite blocks into the measuring chamber, for radiation measurements to determine specific activity, radionuclides, presence of nuclear materials and gamma radiation dose rate;
- Sorting the graphite blocks by activity and nuclear material availability (to optimize graphite placement in containers);
- Compact packaging of graphite blocks in containers;
- Preparation and placement in a container of graphite rings, liners, technological channels, etc., previously extracted from the core;
- Backfilling of graphite dust into the free cavities of the container and solidifying its contents;
- Sealing container lids;
- Container decontamination (if removable contamination is present);
- Parameter screening and issuing container data sheets.

Disposal after incineration with subsequent ash conditioning

In order to reduce the volume of graphite waste for final disposal, the option of incineration with subsequent disposal of ash was considered. For conventional incineration process, it was found that graphite to ash ratio is ~160, so the total volume of radioactive waste to be disposed of will be significantly lower than the original irradiated graphite, although the ash will be waste of higher hazard class.

For burning graphite, preliminary heating of its whole volume to the temperature not lower than 300°C is required, and intensification of burning occurs at 1,200 - 1,300°C.

The prospect of incineration of graphite waste for final disposal raises the following problems:

- Difficulty of burning reactor graphite due to its quality;
- Emission of radioactive gases containing ^{14}C, ^{36}Cl, ^{3}H and the need to capture them for conversion to solid fraction;
- Processing and immobilization of ashes containing radionuclides;
- The need to crush graphite into sufficiently small fragments prior to incineration, while eliminating the release of dust into the environment.

In order to eliminate the release of residual radioactive gases into the environment, the graphite combustion system should be equipped with an efficient filtration system consisting of a pre-filter, a backwash filter, and a high efficiency air filter to capture all radioactive particles and aerosols.

From combustion products, radioactive carbon dioxide $^{14}CO_2$ can be captured by alkaline washing in an irrigation column using water suspension of calcium hydroxide Ca $(OH)_2$. At interaction of carbon dioxide with calcium hydroxide, insoluble stable calcium carbonate $CaCO_3$ is formed by the following reaction:

$$Ca(0H)_2 + C0_2 = CaC0_3 + H_20$$

Calculations show that when capturing 3.67 tons of total carbon dioxide produced by burning of one ton of graphite, 6.17 tons of anhydrous calcium hydroxide is consumed; and as the final product of capturing radioactive carbon dioxide, 8.34 tons of anhydrous calcium carbonate is formed, which is solid radioactive waste. At graphite density of 1.6 g/cm^3, its volume will be ~0.625 m^3, and at calcium carbonate density of 2.3 g/cm^3 its volume will reach 3.63 m^3 that is almost six times the initial volume of irradiated graphite.

In case of contamination with ^{36}Cl, the combustion system should also be equipped with a wet scrubber to neutralize the resulting hydrochloric acid and to reduce chlorine emissions in the exhaust gases. To retain other gaseous pollutants (e.g., NO_x), it is necessary to install an additional filtration system and solve the problem of tritium retention.

Thus, the method of graphite incineration as an alternative to its disposal as solid radioactive waste requires serious environmental and feasibility studies.

Disposal after inert matrix isolation

In addition to direct burial of irradiated graphite, options for their immobilization in various inert matrices have been considered. Different matrix materials were evaluated: cement, polymers, resins, bitumen, glass, and ceramics. Out of all potential matrix materials, cement and mineral matrices have been studied in the greatest detail.

The cement slurry was prepared from three parts of blast furnace slag and one part of Portland cement. Grinded graphite was mixed with cement mortar and the mixture was poured into 200-litre metal barrels. Mechanical strength, shape integrity, chemical properties, radiation resistance, thermal stability, and impact resistance were assessed to demonstrate the suitability of the compound for final disposal. The use of the cement matrix is consistent with the criteria for the acceptability of radioactive waste for disposal.

An interesting simple method of immobilization of graphite contaminated with uranium and actinides has been proposed. After grinding, graphite is mixed in stoichiometric proportions with powders of Al and Y, Ce, and Ti oxides. Then, after heating, high-temperature synthesis takes place in hermetically sealed steel containers. The resulting compound is characterized by ~4 g/cm^3 ensity.

In high-temperature synthesis, Y atoms can be replaced by uranium and actinide atoms. The compound with ^{14}C and all significant isotopes blocked in this structure has the form of a stable inert composite material ready for burial. This technology is considered environmentally safe.

Disposal after coating and impregnation

The purpose of coating and impregnation is to immobilize graphite waste and protect it from oxidizing gases or moisture. The epoxy resin is considered to be the best compared to other materials, and hardening takes place within a few days at ambient temperature, which eliminates the need for heat treatment. Compressive strength tests have shown an improvement in the Poisson's coefficient of approximately 1.7 times that of pure graphite. This is an important result in reducing the risk of graphite damage during storage.

Leaching tests showed a reduction in leaching rates for major isotopes of up to two orders of magnitude. This method is capable of effectively immobilizing the vast majority of radionuclides present in graphite and it will protect the environment from possible container damage during storage.

Conclusions

When decommissioning UGR reactors, a serious challenge is safe handling and long-term isolation of graphite from the reactor core.

To date, there are no internationally recognized solutions to ensure safe isolation of spent reactor graphite for as long as it is dangerous. It is considered that this period of time lasts 10 half-life periods for ^{14}C, that is, 57,300 years.

The tangibility of global negative consequences for nature and people was demonstrated by the doubling of the concentration of environmentally and genetically significant $_{14}C$ radiocarbon in the atmosphere, affecting the genetic apparatus, during the mass tests of nuclear and thermonuclear weapons by the early 1960s.

To date, the total radioactivity of accumulated reactor graphite in the world (~730 PBq) is almost 3 times greater than that generated by nuclear and thermonuclear explosions (~249 PBq).

Thus, the safe long-term isolation of reactor graphite accumulated in the world is a global challenge.

There are risks of additional local ^{14}C contamination in the vicinity of the existing NPPs, which can lead to negative consequences in the area of their location.

The RBMK-1000 reactor of the first unit of the Leningrad NPP is the first of eleven Russian units of this type that will be used for testing safe decommissioning technologies, including handling of 1,700 tons of irradiated reactor graphite containing ^{14}C.

The Leningrad NPP operator has adopted the strategy of immediate dismantling[43] , which is recommended by the IAEA. It will provide for the possibility to use the experience of the plant operating personnel; it is economically justified, and it meets expectations of the general public.

In addition, the Roadmap for Establishing an Experimental Demonstration Engineering Center (EDC) for Decommissioning NPP Units with Channel-type Reactors was adopted at the Leningrad NPP.[44]

It is important that the following features of the Leningrad NPP site should be taken into account when accumulating such experience in decommissioning under the conditions of increased risks of negative impact on the environment:

- The Baltic Sea is a habitat protected by the 1992 Convention for the Protection of the Marine Environment of the Baltic Sea Region (the Helsinki Convention)[45] ;
- The Gulf of Finland is a water body of water of the highest fishing category;
- Over 8,000 people work in the radius of 1 km from the Leningrad NPP under decommissioning;
- In the area of Sosnovy Bor nuclear cluster and in the city of Sosnovy Bor, a genotoxic effect was detected, as a result of which pine seeds have severe cytogenetic damage , and the percentage of these statistically significant results in the Leningrad NPP area is three times higher, and in the town of Sosnovy Bor two times higher than in the control area

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[43] Concept of decommissioning of the Leningrad NPP units with RBMK -1000 reactors, Moscow. 2015. 66 p., approved by the General Director of ROSENERGOATOM in 2015

[44] Letter №9/Ф09/189044 onconcluding remarks to the Decommissioning Concept of 22.11. 2019 signedbyVladimirPereguda, Directorofthe Leningrad NPP, addressed to the Public Council of the South Coast of the Gulf of Finland, 7 pages.

[45] Convention for the Protection of the Marine Environment of the Baltic Sea Region http://docs.cntd.ru/document/1900924

of pine seeds selection near Bol'shaya Izhora settlement (30 km from the LNPP towards Saint-Petersburg).

From this perspective, decisions will be made during the Leningrad NPP decommissioning that may affect social, environmental, economic, and moral interests of different stakeholders and future generations. All this should be taken into account in operation of the Experimental Demonstration Engineering Center that is being established on the basis of the Leningrad NPP.

It is of crucial importance that such Experimental Demonstration Engineering Center should accumulate not only technological experience of decommissioning and handling of reactor graphite, but also the experience of interaction with all stakeholders: authorities at all levels, local government bodies, independent experts, including environmentalists, and the concerned public.

The above circumstances require thorough planning, careful selection of strategic, technological and technical solutions that are socially and environmentally safe, economically acceptable and ensure protection of nature and people of present and future generations. To this end, the authors of this report consider it appropriate to give recommendations to different stakeholders for their consideration.

Recommendations

For the Government of the Russian Federation together with the State Atomic Energy Corporation "Rosatom".

Taking into account the fact that nowhere in the world there are technologies for conversion of irradiated reactor graphite to a safe condition (isolation) for the period of time when it remains dangerous for living systems, we consider it advisable to recommend: assessment of the possibility to revise the principle of obligatory burial of irradiated reactor graphite (type of radioactive waste) towards long-term controlled storage of this waste; this will have certain benefits:

- Firstly, it is easier to monitor the state of engineering and natural safety barriers of these radioactive wastes;
- Secondly, in the event of new safe and scientifically substantiated ways of radioactive waste disposal, it will be possible to dispose of radioactive waste based on such new technologies;
- Thirdly, controlled storage is safer based on the ability to have access for elimination of negative consequences in the event of an unplanned accident or emergency, whether natural or man generated.

Recommendations

For the Leningrad Oblast Government together with the Saint-Petersburg Administration

To consider establishment of an interregional environmental laboratory in the agglomeration of St. Petersburg and the Leningrad region to conduct comprehensive environmental monitoring at the South Coast of the Gulf of Finland in accordance with the recommendations of the Presidential Council on Civil Society Development and Human Rights.[47]

Recommendations

For the Legislative Assembly of the Leningrad Oblast

Together with the expert community, to analyze the practice of decision-making on placement and safety assessment of radiation-hazardous facilities in the Leningrad Region, and on its basis to develop and adopt the regional law "On the powers of the Leningrad Region government authorities in the field of ensuring radiation safety of the population and the use of nuclear energy",

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[46] Integrated environmental expert assessment of anthropogenic impact on the population and environment of nuclear power facilities located in Sosnovy Bor city district, Report on activities of V.G. Khlopin Radium Institute, Book 1, 143 p., approved in December 2011 by V. P. Tishkov, doctor of science, acting GeneralDirector of V.G. Khlopin Radium Institute, reg. № 3643 - ИК

[47] Recommendationsof the Presidential Council for the Development of Civil Society and Human Rights following the 28th visiting meeting (128th) in the Leningrad region on 15-19 October 2018.http://president-sovet.ru/presscenter/news/read/5657/

which would ensure greater public involvement in the decision-making process in promoting nuclear energy-related projects, including decommissioning.

A similar recommendation was made by the Presidential Council for the Development of Civil Society and Human Rights following the 28-th visiting meeting in the Leningrad region on 15-19 October 2018.

Recommendations

For the Leningrad NPP operator (Rosenergoatom)

- To postpone disassembly and dismantling of the graphite cladding of the RBMK-1000 reactors at the Leningrad NPP and other uranium-graphite reactors until safe, environmentally and economically acceptable industrial technologies for its utilization, long-term isolation or conversion into non-radioactive state are developed;
- Due to extreme danger of irradiated graphite at all stages of transportation, such works should be carried out only in an emergency and for minimum possible distances from the sites where irradiated graphite is accumulated;
- To consider the possibility of using mound technology for temporary (100-300 years) isolation of irradiated reactor graphite from all types of uranium-graphite reactors to prevent ^{14}C radiocarbon leaching by water and to minimize negative consequences of handling reactor graphite immediately after final shutdown of power units. Eventually the reactor installation can be buried in accordance with the requirements for radioactive waste disposal under acceptable radiation and environmentally safe conditions.

Recommendations

For local self-governing bodies of Sosnovy Bor

To create a Public Council on the Environment and Energy under the Sosnovy Bor Administration similar to the Council in Visaginas (Lithuania), which successfully advises local authorities on social, environmental aspects, and issues arising during decommissioning of the nuclear power plant. Such Council (7-8 persons) may include NPP veterans, NPP trade union representatives, municipal deputies, representatives of the concerned public.

Authors of the report

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He graduated from the Faculty of Physics and Mechanics of the Leningrad Polytechnic Institute in 1976, worked as a research engineer at the Alexandrov Research Institute of Technology (NITI), Sosnovy Bor, Leningrad region. He participated in testing of nuclear power units of nuclear submarines, author of a number of scientific and technical reports.

In1980-1993, he was are searcher and head of the group on mathematical modeling and experimental research of ecosystems at the Sosnovy Bor Regional Environmental Laboratory under the Khlopin Radium Institute (Saint-Petersburg).

One of the initiators (2003) of the creation of an international network of non-governmental organizations "DecomAtom"[49] to study the complex solutions of technological, social, environmental, economic and other problems in the process of decommissioning of power units in nuclear satellite towns.

He is the organizer and one of the authors of the report "Concepts of Decommission Plan for Old Nuclear Power Reactors. the plan for decommissioning NPPs that have worked out their design life. Guiding Principles from Environmental NGOs" [50] , which was presented at

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[48] http://decommission.ru/english/

[49] http://decom-atom.org/

[50] http://greenworld.org.ru/sites/default/greenfiles/conception_eng_1610.pdf

Rosatom State Corporation, international conferences, and the IAEA (Vienna, 2008).

He organized and was one of the experts of the "Conclusions of Public Assessment of the Concept of Decommissioning the Leningrad NPP units with RBMK-1000 reactors" [51].

Oleg Bodrov is the author of dozens of scientific, social and political articles, interviews on the safety problems of nuclear facilities published in Russia, EU countries, USA, Japan and South Korea.

VladimirKuznetsov - physicist, Chairperson of the Association of Veterans of the Ignalina NPP[52] , deputyhead of the Public Council on the Environment and Energy under the Mayor of the town of Visaginas, Lithuania.

He is a graduate of the Chapaevsk College of Chemistry and Technology (1959) and the Tomsk Polytechnic Institute (1969). He worked as a boiler operator of a thermal power plant and head of the heat supply section of the city of CATE Seversk, Tomsk region.

Since 1970 he was an engineer of the Leningrad NPP under construction, turbine room foreman, mechanical engineer, head of shift, and deputy head of the reactor shop for operation. He was Deputy Chief on Reactor Shop Operation of the Ignalina (1980) and Chernobyl (1987-1989) Nuclear Power Plants. At the Chernobyl NPP he organized and implemented a reliable quality control of sealing of technological channels of the reactor after completion of its core removal.

In 1992-2006 he worked as an engineer and head of the Fuel Laboratory at the Ignalina NPP Nuclear Safety Department. Author of the feasibility study and participant in implementation of the project on afterburning spent fuel assemblies of the shutdown reactor located next to the reactor in operation.

He implemented a number of technical proposals in the Ignalina NPP (INPP) projects to improve safety reliability and of the INPP units (replacement of cast iron industrial circuit pumps with steel ones, refusal to install 44 vapor sensors in the separator drum, protection of feed water filter cover against metal erosion, refusal to control the oil wedge pressure in the electric motors of the primary circuit pump, etc.). In Tekos company (Lithuania), together with NUKEM (Germany), supervised the development of technology for handling and disposal of severely damaged and leaky fuel assemblies from the RBMK-1500 reactor. He published a number of articles on decommissioning of nuclear power plants in Atomic Strategy journal, as well as an interview to Nuclear Engineering magazine (London 2018).

He participated as an expert in international public assessment of the Concept of decommissioning the Leningrad NPP units with RBMK-1000 reactors.

Participant and speaker at twelve international conferences and round tables on nuclear power problems and decommissioning of nuclear power units with uranium-graphite type RBMK reactors: Vienne (IAEA, 2017, 2018, 2019), Prague (2017), Bulgaria (Kozloduy, 2018), Ukraine (Chernobyl, 2017), Armenia (Yerevan, 2018), Sochi (Atom Expo, 2018, 2019), St. Petersburg (2017), Peterhof (2017), Visaginas, Lithuania (2018), Minsk, Belarus (Atom-Eco, 2019), Pech, Hungary, (Atom-Eco, 2019).

Oleg Muratov - physicist, candidate of technical sciences. In 1973 he graduated from the Faculty of Physics and Mechanics of the Leningrad Polytechnic Institute. After graduating, he worked for more than 27 years at the Central Research Institute named after Academician A.N.Krylov, where he rose from an engineer to deputy head of the department of nuclear, radiation and environmental safety.

Since 2001, head of the Radiation Technology Department of LLC TVELL (St. Petersburg), his specialty is radiation safety problems in decommissioning and disposal of nuclear and radiation-hazardous facilities and handling of radioactive waste.

Oleg Muratov is a member of the of the Public Council of Rosatom State Corporation, leading expert-coordinator of the Higher Expert Commission of the Public Council, Executive Secretary of the North-West Branch of the Nuclear Society of Russia, member of the Central Board of this organization.

Author of more than 190 scientific works, including one scientific invention and 16 inventor's certificates and patents for inventions. He was awarded medals "300 years of the Russian Navy", "50 years of the nuclear submarine fleet", and a silver medal of P.L. Kapitsa for a scientific invention; one of the experts who prepared the report "Concepts of the plan for decommissioning of

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[51] http://decommission.ru/wp-content/uploads/2019/04/Konception_LAES_24.04.2019_nasite_obrez.pdf

[52] http://otcc.lt/

nuclear power plants that worked out their design life. Proposals of Public Environmental Organizations", St. Petersburg, 2008[54] .

Andrei Talevlin - PhD in Law, Associate Professor at Chelyabinsk State University, Chairperson of the regional public movement "For Nature"[55], and expert of Decom-Atom[56] international network of public organizations to promote safe decommissioning of nuclear power plants and safe handling of radioactive waste and spent nuclear fuel.

In 1999, he graduated with honours from the Law Department of the Chelyabinsk State University. He received his PhD with a thesis on "Problems of Legal Regulation of Radioactive Waste Management".

He is the author and lecturer of the advanced course "Legal Regulation of Atomic Energy Use", he also teaches as well as lecturer of land law at the Chelyabinsk State University.

Andrei is actively engaged in community activities.

He repeatedly represented environmental interests of local population groups in courts of law.

Following his lawsuit, in 2002 the Supreme Court of the Russian Federation invalidated the Order of the Government of the Russian Federation on Importation of Spent Nuclear Fuel from the Nuclear Power Plant "Paksz" (Hungary). As a result, the illegal import of 370 tons of spent nuclear fuel from the Hungarian nuclear power plant into the Chelyabinsk region was prevented.

One of the experts in international public assessment of the Concept of decommissioning the Leningrad NPP units with RBMK-1000 reactors, Sosnovy Bor, Chelyabinsk, Visaginas. [57]

Currently, he works with the issues of legal support for decommissioning of nuclear facilities that have reached their design limits.

He provides consulting and practical legal assistance to victims of radiation exposure as part of the pro bono legal aid of the Russian Bar Association.

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[54] https://za-prirodu.ru/

[55] http://decom-atom.org/

[56] http://decom-atom.org/

[57] http://decommission.ru/wp-content/uploads/2019/04/Konception_LAES_24.04.2019_nasite_obrez.pdf