NUCLEAR LEGACY CLEANUP AS A KEY FACTOR OF RADIATION AND ENVIRONMENTAL SAFETY IN THE RUSSIAN FEDERATION. BASED ON THE ACCOMPLISHMENTS OF FTP NRS-2 IN 2016–2021

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The article summarizes the accomplishments of the Federal Target Program Nuclear and Radiation Safety in 2016—2020 and up to 2030 (FTP NRS-2, Program) achieved in 2016—2021. It overviews the main results, evaluates the key challenges and relevant measures provided to address them that enabled the implementation of the program.

Keywords: *Federal Target Program Nuclear and Radiation Safety in 2016—2020 and up to 2030, FTP NRS-2, nuclear legacy facilities, radioactive waste, decommissioning.*

Practice evidences that complex national tasks can be addressed only provided their mutual coordination and consistent implementation based on targeted planning and succession of the projects. Federal Target Program Nuclear and Radiation Safety in 2016—2030 (FTP NRS-2, Program) is seen as a logical continuation of the Federal Target Program Nuclear and Radiation Safety in 2008—2015 (FTP NRS-1) seeking to provide comprehensive nuclear and radiation safety by staged resolution of accumulated nuclear legacy challenges. This includes decommissioning (DE) of all legacy nuclear and radiation hazardous facilities (NF), reprocessing of federally owned spent nuclear fuel (SNF) provided the disposal of the resulting radioactive waste (RW), processing and disposal of accumulated removable RW, isolation of facilities holding the inventories of accumulated non-removable RW and remediation of radioactively contaminated territories [1].

The Program concept proposes three scenarios for its implementation (Figure 1):

- pessimistic scenario (with an increased risk of possible radiation consequences) — maintaining safe state of NF at the expense of extra-budgetary funds only with no practical efforts implemented in the field of nuclear decommissioning and no upgrading of federal RW and SNF to an environmentally safe state;
- baseline (guaranteed) scenario providing systematic and guaranteed resolution of nuclear legacy problems suggesting a 2-fold decrease in the number of NF characterized by high and medium potential hazard levels [2], as well as decreased risks of potential radiation consequences;
- intensive scenario — maximum possible parallelization for the majority of practical activities aimed at providing nuclear and radiation safety with a final 3—4-fold reduction in the number of

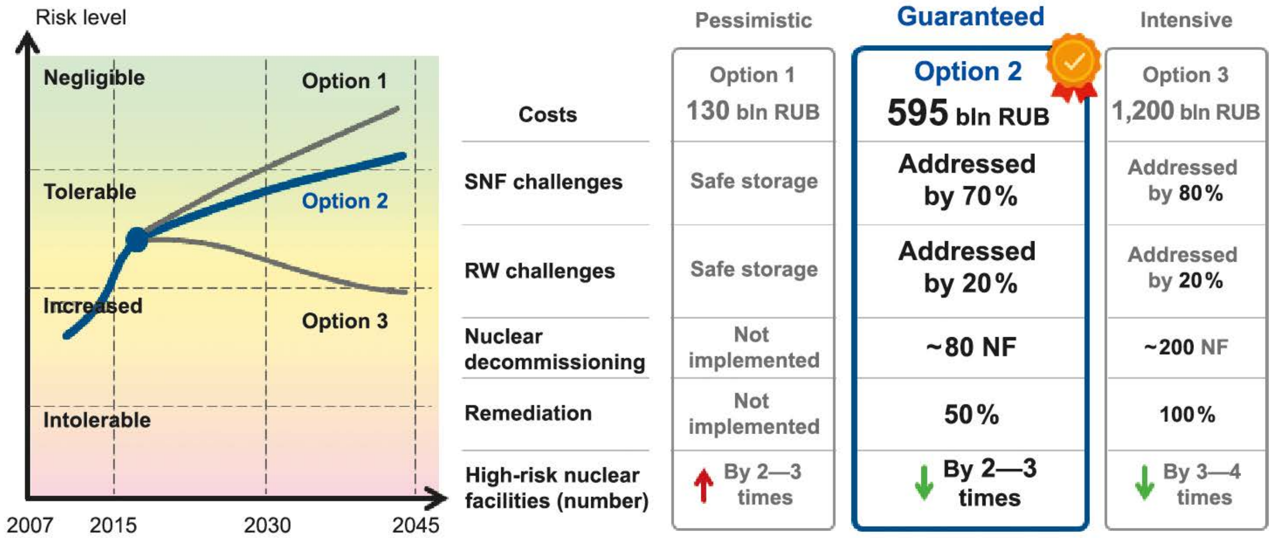


Figure 1. FTP NRS-2 implementation scenarios

nuclear and radiation hazardous facilities characterized by high and medium potential hazard levels.

The above scenarios were evaluated and the baseline scenario was selected by the Government of the Russian Federation as the Program concept providing guaranteed resolution of nuclear legacy problems and involving the establishment of all elements required for the development of a national RW and SNF management system.

FTP NRS-2 was divided into three five-year stages aimed at providing NRS in the following areas:

1. Establishment of key infrastructure facilities for SNF and RW management.

2. Practical solution of problems related to past activities.

3. Development of control and support systems for nuclear and radiation safety and providing enhanced protection of the personnel at nuclear facilities, the public and the environment from radiation exposure.

4. Scientific-methodological and informational support of activities related to NRS.

Program performance can be evaluated through seven target indicators and a summary indicator (Figure 2). Basically, about 60 % of its activities contribute to the targets. For each year of FTP NRS-2 implementation the consolidated indicator and all targets were met or exceeded due to timely work execution, monitoring and regular assessment of the progress in the Program implementation and possible risks of deviations, as well as the use of optimization mechanisms and of those providing the redistribution of financial, engineering, labor and time resources.

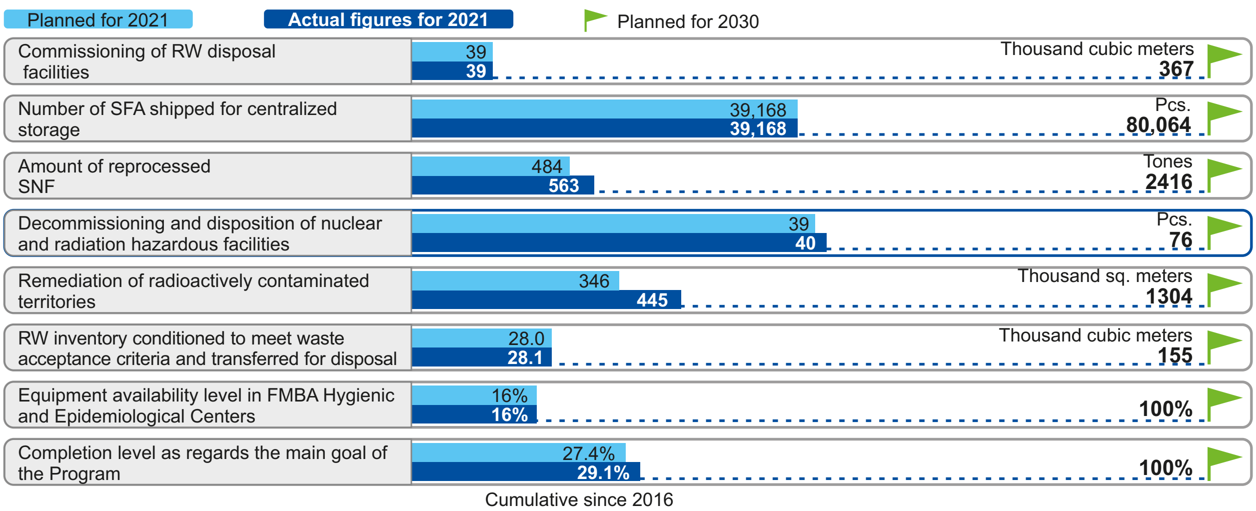


Figure 2. Progress in the achievement of FTP NRS-2 targets and FTP NRS-2 indicator as of the end of 2021

The Program includes a large number of activities with only few of its key focus areas governing its effectiveness and therefore deserving more in-depth consideration, namely:

- RW management and infrastructure development under the Unified State System for Radioactive Waste Management [3];
- management of spent nuclear fuel;
- decommissioning of nuclear legacy facilities and site cleanup.

Radioactive waste management

Under FTP NRS-2, safe management of accumulated RW inventory, as well as the establishment of waste management infrastructure designed to treat the waste resulting from the operation of nuclear facilities, nuclear decommissioning and remediation of radioactively contaminated sites are seen as its most important focus areas. It involves certain activities providing the removal of RW Class 3 and 4 from storage facilities (SF), their processing, conditioning to bring them in accordance with waste acceptance criteria for disposal and their transfer to the National RW Management Operator (FSUE NO RAO) for disposal [4].

In 2016—2021, radioactive waste was removed from storage facilities operated by branches of JSC Rosenergoatom Concern, FSUE FEO, FSUE RADON, FSUE Atomflot and other nuclear enterprises. Since 2016, a total of 28.1 thousand cubic meters of waste have been conditioned to meet RW acceptance criteria for disposal and handed over for disposal.

Safe RW management is believed to be impossible without the development of USS RW infrastructure facilities. Over the past years of Program implementation, commissioned were three facilities constituting to the second section of a near-surface disposal facility for radioactive waste (NSDF) established at JSC UECC site (Novouralsk). Given the first section commissioned in 2015, the total NSDF design capacity amounted to 55 thousand cubic meters with its operation (RW acceptance for disposal) expected to be completed in 2036 (Figure 3). Under FTP NRS-2, it is planned to build two more NSDF in the area of the SCC and PA Mayak sites with a total design capacity of over 367 thousand cubic meters. In addition, reconstruction is underway at some existing RW storage facilities providing an increased safety level. For example, in 2019, completed was the reconstruction of a temporary RW storage facility (first section) at FSUE RADON site with a design operational life of up to 50 years. Facilities designed to provide safe RW management at nuclear power plants and other nuclear enterprises are currently being established.

Figure 3. NSDF designed for RW Class 3 and 4 at UECC site

Construction of an underground research laboratory (URL) has been started which is seen as a first practical step towards the establishment of a deep disposal facility (DGR) for RW Class 1 and 2. Completed was the construction of high-voltage power lines extending to 37 km, internal railway lines; construction of some administrative and domestic infrastructure facilities has been launched with necessary pre-excavation activities being underway at the site. At the same time, R&D is underway providing in-depth study of rock mass properties, development of long-term monitoring programs, additional analysis of the DGR potential impact zone, etc. [5]. Development of a "digital URF twin" visualizing various operations and studies to be performed during URF construction and operation has been started [6]. According to the existing schedule, after 2026, construction of the 1st URF section is to be completed and the R&D are to be launched (Figure 4).

Spent fuel management

The strategy for the safe management of spent nuclear fuel in Russia provides for a comprehensive approach applied to ship the SNF away from nuclear power plants and nuclear enterprises and to provide its centralized long-term storage (for certain SNF types) and reprocessing.

By the end of 2021, dry SNF storage was provided for 39,200 pcs. of spent fuel assemblies (SFA) from Leningrad, Kursk and Smolensk NPPs with RBMK-1000 reactor units and accounting for over 35% of this SNF type accumulated as of the beginning of 2016. Available capacities provide transportation and accommodation for an average of 6,000 to 8,000 SFA from RBMK-1000 reactor units per year. Provided that this performance is maintained,

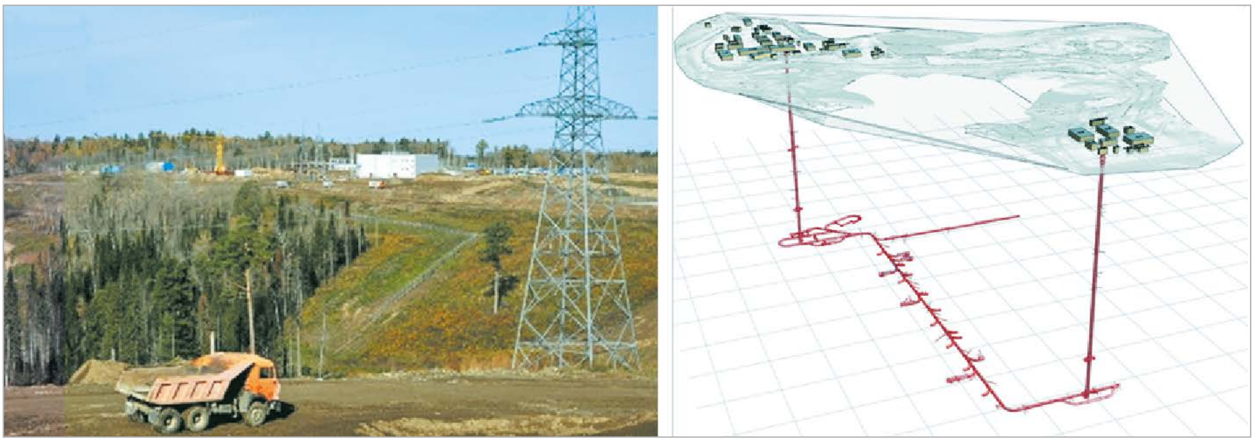


Figure 4. Construction site for the URL's 1st section and URL layout at the Yeniseiskiy site

about 80% of the accumulated SNF inventory of this type can be transferred for long-term storage by 2030.

SNF from VVER-440, BN-600, VVER-1000 reactor units, unconditioned SNF (leaky fuel and fuel considered unsuitable for dry storage) from RBMK-1000 units, SNF from research reactors at JSC SSC RF — IPPE, JSC SSC RIAR, Research Center Kurchatov Institute and NRNU MEPhI, irradiated SFAs from production uranium-graphite reactors (PUGR), as well as SNF from nuclear power plants of the nuclear fleet are transported to FSUE PA Mayak site for temporary storage and reprocessing providing the extraction of useful substances for their further recycling and disposal of unrecycled components. In 2016—2021, a total of 563 tons of SNF was reprocessed, which accounts for about a quarter from the planned indicators assumed under the Program completion. Significant increase in SNF reprocessing rate will be provided following the commissioning of a pilot demonstration center (PDC) at MCC site and a SNF reprocessing complex at PA Mayak site designed for SNF from AMB reactor units.

On the whole, development of new infrastructure facilities plays an important role in the SNF management system. Over the past decade, consolidated SNF management complex for SNF management has been established at MCC site (Figure 5). Its main facilities were constructed as early as within the framework of FTP NRS-1: a facility for dry long-term storage of spent nuclear fuel from RBMK-1000 and VVER-1000 reactor units; upgraded wet SNF storage facility with an increased design capacity; the first start-up complex of the PDC. Under FTP NRS-2, completed were the key construction and installation activities providing the establishment of the second start-up PDC complex with a design capacity of up to 255 tons of SNF per year. By the end of 2021, the technical readiness of the facility amounted to 98% with its construction expected to be completed in 2022. PDC commissioning will reduce the total costs of the federal budget spent on the reprocessing of federally owned SNF from VVER-1000 reactor units providing timely emptying of wet SNF storage facility capacities the service life of which is limited. In the future, methods designed to reprocess the spent fuel from fast neutron reactors are planned to be tested at the PDC, which is required to close the nuclear fuel cycle and to switch on two-component nuclear power (with thermal and fast neutron reactors).

Under FTP NRS-2, reprocessing of spent fuel assemblies from AMB-type reactors, which due to their design features (large overall dimensions, complex structure and specific fuel composition) cannot be reprocessed according to the reprocessing methods applied at PA Mayak's RT-1 plant, is seen as a most challenging task. To address this challenge, FSUE PA Mayak is establishing a complex designed for the reprocessing of SNF from AMB reactor units that will enable the shipment of SNF from the Beloyarsk NPP, its treatment (cutting, packaging) and its disposition. Also, this project will provide opportunities for future reprocessing of other outsized SNF types.

Figure 5. SNF management complex at MCC site

In addition to large-scale practical efforts, the Program involves some R&D addressing the development and upgrading of reprocessing technologies designed for various types of spent nuclear fuel and their pilot testing. The new research seeks to maximize the recovery of useful elements contained in spent nuclear fuel, as well as to minimize the waste inventory resulting from the reprocessing and to provide its safety.

Decommissioning of nuclear legacy facilities and remediation of contaminated areas

To date, a big number of nuclear facilities has completed their operation according to their design purpose, therefore, relevant decommissioning activities are to be planned and arranged for. In 2016—2021, a wide range of different facilities was subject to decommissioning, including nuclear fuel cycle facilities, nuclear power units, PUGR, research reactors and installations, radioactive waste storage facilities, etc. In 2016—2021, decommissioned was a total of 40 nuclear and radiation hazardous facilities at JSC AECC, FSUE PA Mayak, JSC SCC, JSC VNIINM, PJSC NCCP, etc.

Isolation of industrial RW storage reservoirs B-1 and B-25 at SCC site with a total capacity of 280,000 m^3 is considered as a most large-scale effort completed in the first years of FTP NRS-2 implementation (Figure 6). Lessons learned from the isolation of a similar facility B-2 implemented in 2012 under FTP NRS-1 and the use of more efficient methods helped to reduce the project implementation time to 5 years instead of the originally planned 10—15 years. Currently, the isolated facilities are monitored along with the processes ongoing in the aquatic environment and soils outside the perimeter of the storage facilities, as well as the behavior of engineered safety barriers available at the site.

Large-scale efforts were implemented to decommission building No. 804 at AECC site, the length of which was about 1 km. Due to the emergency state of the facility, the dismantlement of its structures has required the use of non-standard engineering solutions. Project was launched in 2016: first necessary preparations were done in this area and the required infrastructure was established. Since 2017, direct efforts on the dismantlement of building structures, process and engineering equipment have been implemented. In 2019, the facility was eliminated completely; by the end of 2021, the remediated area amounted to about 170,000 m^2 (Figure 7). Based on the control radiation survey, the radiation-safe state of the site was recognized. In the decommissioning process, a number of optimization solutions were developed and implemented to increase the performance and also to minimize waste generation during the decision-making on methods and technologies to be used to decontaminate and dismantle the building structures. Detailed radioactive contamination cartograms were used, whereas the practice providing for continuous removal of a 2-cm surface layer was abolished, thereby resulting in a manifold reduction in the amount of generated RW. In general, these

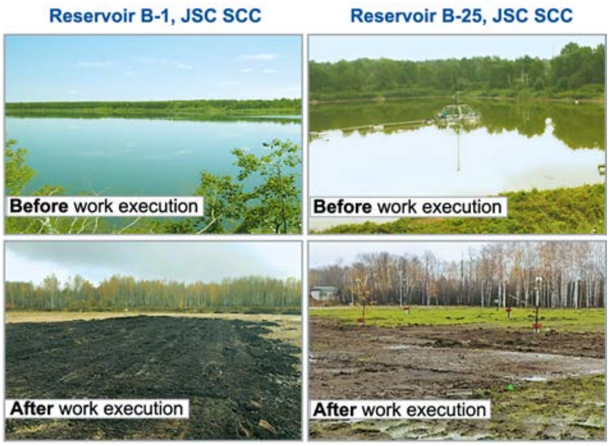


Figure 6. Water reservoirs B-1 and B-25 at SCC site before and after the operations were completed

Figure 7. Building No. 804 of at AECC site before and after its decommissioning was completed

Figure 8. Dismantling operations at the nuclear support vessel Lepse

solutions provided a saving of about 1.5 billion rubles from the federal budget. In 2020, decommissioning of building No. 802 at AECC site was started. Structurally, this building is a twin of an already decommissioned building No. 804. Decommissioning of building No. 802 is scheduled to be completed in 2024.

As for PUGR in 2016—2021, decommissioning efforts were implemented at the sites of PDC UGR (PUGR ADE-3, ADE-4 and ADE-5) and FSUE MCC (PUGR AD and ADE-1).

By the end of 2021, at PUGR ADE-4 and ADE-5, completed were the concreting operations on the bottom of the mines from the level of — 22.0 m to the level of — 12.0 m. Long-length solid RW was removed from PUGR ADE-3. At PUGR AD and ADE-1, reactor shafts were backfilled with barrier materials; work is underway to fill the ex-core premises.

A long-term international project on the decommissioning of nuclear support vessel Lepse was completed under FTP NRS-2 (Figure 8): it was included into the list of nine top-priority projects under the Strategic Master Plan developed by order of the State Corporation Rosatom and sponsored by the Northern Dimension Environmental Partnership Support Fund. The project was implemented under international global cooperation. The project has resulted in two-unit packages formed: a stern one with LRW tanks and a bow one with SNF.

In 2016—2017, unit packages were shipped to the Nerpa Shipyard. SNF pre-unloading operations were performed, design and operational documentation for a purpose-designed mobile structure was developed, necessary equipment was manufactured and supplied to the site. In 2018, completed was the conditioning of RW from the dismantling of the vessel (stern unit-package) with a volume of about 300 cubic meters. Subsequently it was handed over for long-term storage. In 2020—2021, SNF was unloaded from stern unit package, and in 2020—2021, it was shipped and processed at PA Mayak site.

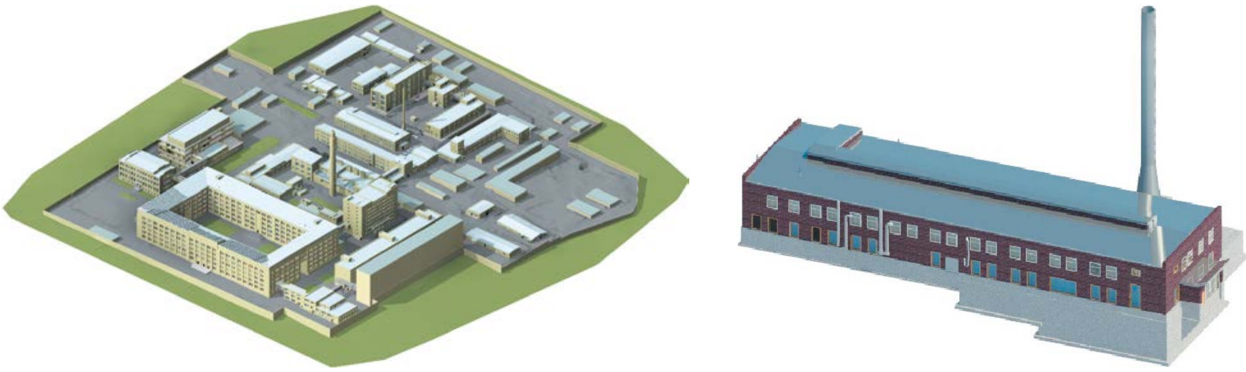
Two nuclear-powered icebreakers Siberia and Arctica are planned to be decommissioned under FTP NRS-2. These projects have been implemented since 2016, and in 2021, the radiation-contaminated areas and equipment of the icebreaker Siberia were either completely decontaminated or removed, final inspection of the ship was completed and it was handover to the operating organization. Decontamination of the ship's premises and premises intended for RW management is underway at icebreaker Arctica.

In 2022, decommissioning was underway at 30 nuclear and radiation hazardous facilities.

The lessons learned from these projects revealed the urgent need for the establishment of a centralized system for the decommissioning of nuclear legacy facilities and the use of optimal engineering solutions during the work implementation. FSUE RADON is seen as its basis: in 2018, it was entrusted with functions of a specialized nuclear operator.

To test this system, former site of JSC VNIIKhT is used (Moscow, Kashirsk highway, 33). Nuclear decommissioning and cleanup activities initiated at this site under FTP NRS-2 are ongoing with an emphasis placed on in-depth surveys, establishment of necessary infrastructure and improved efficiency of pre-design solutions. For these purposes, the developed digital information model of the site is used with some clarifying surveys being implemented. Currently some end-state options are being considered, which would also help to identify whether it can be further used following NRHF decommissioning, including an option providing for its unrestricted economic use.

Methodological and engineering support and its development is considered an important focus area in the arrangement of decommissioning activities. To date, a safety guide has been published providing certain recommendations on the development of nuclear decommissioning concepts, instructions for KIRO (comprehensive engineering and radiation



DIM of a site DIM of a facility

Figure 9. DIM visualization

surveys) planning and execution, industry-wide standards are expected to be published soon, a set of measures is being implemented to develop digital information models (DIM) of sites — digital twins of facilities containing KIRO data (Figure 9). This approach is supposed to become an integral part of the decommissioning arrangements [7]. A number of engineering solutions have been adopted for the decommissioning of various nuclear legacy facilities with uranium-graphite reactor dismantling methods seen as the key ones, including their pilot implementation and methods providing graphite RW certification.

Remediation of territories contaminated due to past activities or sites undergoing decommissioning is seen as another important area of the Program. In 2016—2021, a total of 444,700 m^2 of radioactively contaminated areas, including more than 12,000 m^2 of ownerless sites, was remediated in the constituent entities of the Russian Federation: Moscow, Leningrad, Ulyanovsk, Sverdlovsk regions, the republics of Karelia and Tatarstan. In total, 10 regions of Russia were affected by these operations.

It should be noted that State Corporation Rosatom pays special attention to the distribution of information about the Program activities. Based on the accomplishments of the 1st FTP NRS-2 stage (2016—2020), an information and analytical report was published, which is publicly available on the official website of the Program фцп-ярб2030.рф with its hard copies distributed among a number of interested federal executive authorities and organizations. 13 technical tours and 16 round tables were held to discuss the events listed in the Program engaging members of the Public Council of the State Corporation Rosatom, representatives of enterprises involved in the Program, environmental and public organizations, local administrations, expert and scientific communities, as well as the media. Certainly, this work will be further continued.

Challenges faced during FTP NRS-2 implementation

FTP NRS-2 implementation is greatly affected by federal budget cuts, as well as the expenditure planning horizon, which, in the Russian Federation, is limited to a three-year perspective. At the same time, such activities as construction, reconstruction of facilities and decommissioning are carried out over a fairly long period of over four years. Sufficient funding is seen as a key to their successful implementation since halted operations can cause the disruption of production processes, increased radiation risks and higher final costs of the projects. Additional financial investments are required for temporary mothballing of the facilities, their maintenance in a safe condition and, subsequently, for work resumption.

At the end of 2020, due to significant federal budget cuts in terms of funds intended for the implementation of the second FTP NRS-2 stage, the Program management was forced to reduce the rate of RW disposal and abandon a number of projects on the remediation of radioactively contaminated territories. Financial resources were prioritized for the timely completion of operations that were already underway by postponing the start of new activities to a later period. Under these circumstances, the deadlines indicating the achievement of FTP NRS-2 target indicators had to be reconsidered as well: the indicators the achievement of which was initially planned under the 2nd stage of the Program were adjusted downwards and shifted to the 3rd stage (2026—2030) assuming its increased funding.

Conclusion

Over the six years of FTP NRS-2 implementation, 9 infrastructure facilities were put into operation, including a final disposal facility for SRW Class 3 and 4 with a design capacity of 39,300 m^3 (~ 10 %

considering the final target of the Program). The required operation rate was picked up and some qualitative changes have been achieved in terms of SNF and RW management.

Important results have been reached in the management of federally owned SNF: 563 tons of SNF from various types of reactor units have been reprocessed and about 40,000 pieces of RBMK-1000 spent fuel assemblies have been emplaced into long-term storage facilities. Storage facilities operated by JSC SSC RF — IPPE were freed from SNF by 92.8 %. Removal and reprocessing of SNF from AM, VT, TES-3, EK-10 was completed, whereas, for naval SNF it was completed by 91.5 %.

28,100 cubic meters of radioactive waste (~ 18 % of the final target) have been handed over for disposal. 40 NRHFs have been decommissioned at 15 sites; remediated was a total of 444,700 square meters of radioactively contaminated areas.

At the second stage of the Program (2021—2025), most part of operations required for the establishment of infrastructure necessary to address nuclear legacy problems and to manage spent nuclear fuel is planned to be completed. The key milestones of this phase include:

- PDC commissioning at FSUE MCC;
- commissioning of a disposal facility for RW Class 3 and 4 with a design capacity of over 90,000 m^3;
- completed construction of a complex designed for container SNF storage and its management at Smolensk NPP;
- commissioning of a RW management complex at Kursk NPP;
- commissioning of RW processing complex at FSUE RADON;
- commissioning of a medical unit No. 5 operated by the FMBA of Russia in Volgodonsk, Rostov Region.

In addition, VVER-1000 SNF reprocessing is planned to be started at MCC's PDC. It's also planned to complete VVER-440 and BN-600 SNF reprocessing at the RT-1 plant, to transfer over 70 % of RBMK-1000 SNF for long-term storage and to complete SNF removal from the sites of JSC SSC RF — IPPE in Obninsk, NRNU MEPhI in Moscow, Tomsk Polytechnic University in Tomsk, National Research Center Kurchatov Institute in Moscow and its branch in Gatchina. As it comes to RW management and nuclear decommissioning, full-scale measures are expected to process the accumulated RW inventory of 25,000 m^3 and to hand it over for disposal and to clean up over 15 nuclear legacy sites, including three PUGR.

Success in the implementation of the Program goals confirms the high social significance of FTP NRS-2 and ensures consistent accident-free resolution of accumulated nuclear legacy challenges, steady reduction of environmental risks and new high-tech job gains at the final stages of nuclear facility life cycle.

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