EXPERIENCE AND PROSPECTS OF SPENT NUCLEAR FUEL REPROCESSING AT MAYAK

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Abstract

Development of atomic power engineering on a global scale has made it necessary to address problems associated with spent nuclear fuel (SNF) management. Operation of nuclear facilities resulted in accumulation of large amount of SNF with various compositions and geometries. The SNF is accumulated both during electric power generation at NPPs and operation of naval propulsion reactors by surface and submarine fleet, and during research and development of new approaches to fuel management carried out at nuclear research centers.

There are two competing approaches to management of generated SNF. One approach is based on long-term storage with subsequent direct disposal (open cycle), while the other one is connected with radiochemical reprocessing (closed cycle). The Russian Federation adopted a strategy of closed nuclear cycle with SNF reprocessing and recycling of recovered products resulted from reprocessing. Implementation of this strategy is closely connected with SNF reprocessing carried out by Mayak PA.

1. INTRODUCTION

Mayak Production Association is the first industrial facility of the Russian nuclear industry. It was established to produce fissile plutonium-239. June 19, 1948 is considered to be the date of Mayak PA foundation. On this date the first nuclear reactor in the Eurasian continent reached its 100 MW designed capacity.

Radiochemical technology of plutonium extraction from the irradiated uranium became the most challenging and hazardous part of the Uranium Project. December 22, 1948 is considered to be the date when a radiochemical plant was put into operation. On this date the first batch of irradiated slugs was delivered to the radiochemical plant from the large-scale nuclear reactor.

The radiochemical plant has always been and is still an important part of an integral process flow and organizational structure of Mayak Production Association.

In spite of evident success made by the radiochemical plant at that time, it came to face new, more ambitious challenges of improving technology for weapons-grade plutonium extraction and increasing its production output. Thus, on July 25, 1953 the decision was made to construct a backup plant, which was an analogue of the radiochemical plant already in operation.

The backup plant that was commissioned in 1959 ensured systematic increase in plutonium production at operating process lines. The required amounts of nuclear material were provided in full measure. On October 1, 1971 the first and the second plant lines were integrated into a single subdivision of Mayak Chemical Combine, i.e. into a radiochemical plant (the RT-1 Plant) that started adopting SNF reprocessing technology.

On December 30, 1971 the first special train delivered spent fuel assemblies from the MR reactor of I.V. Kurchatov Institute of Atomic Energy to the fuel storage pool of the RT-1 Plant. The first process line for spent nuclear fuel fragmentation and dissolution was put into operation on March 29, 1977.

Since then more than 6300 tHM (including foreign fuel) have been delivered to the Plant for radiochemical reprocessing.

RT-1 Plant is the only SNF reprocessing plant in Russia focused on acceptance, interim storage and reprocessing of various types of SNF. The Plant is also involved in management of generated radioactive waste of any level of activity. Initially the Plant was designed for reprocessing SNF from NPPs with VVER-210, 360, 440, RBMK-1000, BN-350 and BN-600 power reactors, from research reactors of Russian and foreign research centers and from naval propulsion facilities of submarine and surface fleet. And the RT-1 Plant demonstrates sustainable development as it evolves continually and expands its technological capabilities. Today the RT-1 Plant is a versatile multiproduct facility. Current technological capabilities of transporting and reprocessing SNF, as well as handling radioactive waste are unprecedented across the globe.

Many years of SNF shipment have provided Mayak PA with vast experience in the field of transportation. Mayak PA is experienced in using all modes of transportation including railway, motor-vehicle, water and air transport. Today air transportation of irradiated research fuel is unprecedented practice in the world.

2. EXPERIENCE IN NPP SNF REPROCESSING

2.1. VVER-440

For a long time the major SNF reprocessed at the RT-1 Plant has been the SNF from VVER-440 reactors most extensively used in the European part of the Russian Federation and spread around Eastern Europe countries. After interim storage in reactor cooling ponds (3 to 5 years as a rule) SNF from VVER-440 reactors is still transported from both Russian and foreign NPPs to Mayak PA for reprocessing. The total amount of SNF transported and reprocessed over the entire history of the Plant is more than 5,300 tHM.

2.2. VVER-1000

Power-generating units with VVER-1000 and VVER-1200 reactor facilities succeed the fleet of VVER-440 reactors that are gradually being decommissioned. Today 12 power units of this type are operated in the Russian Federation; 8 more power units are under construction.

In 2015 and 2016 Mayak PA implemented activities on preparation of the facilities for acceptance and reprocessing of SNF from VVER-1000 reactors for the purpose of enhancing cost-effectiveness of the reprocessing facility and increasing the capacity rate of the RT-1 Plant.

In the framework of this Project the RT-1 Plant developed and implemented a new transportation flow chart for VVER-1000 SNF handling supported by nuclear and radiation safety analysis and execution of all necessary permitting documents. Cold tests were performed that used a shipping cask for VVER-1000 SNF and a full-size SFA simulator.

Pilot hot shipment of SNF from the Rostov NPP was carried out in December 2016. The first 12 SFAs from VVER-1000 were accepted and reprocessed at the radiochemical plant of Mayak PA using a new transportation flow chart.

The results of this work enabled Mayak PA to transport to the radiochemical plant and to reprocess SNF from VVER-1000 reactors, including experimental, defective and leaking SFAs on regular basis from 2017. Reprocessing of SNF from VVER-1000 and involvement of uranium and plutonium thus recovered into production of nuclear fuel for NPPs will ultimately provide closure of the nuclear fuel cycle for VVER-1000.

2.3. Fast Reactor SNF

The history of reprocessing of this type of fuel at the RT-1 Plant goes as far back as 1983, when the Plant started reprocessing SNF of BN-350 reactor (now located in the territory of the Republic of Kazakhstan). After the USSR breakup, shipments of BN-350 SNF from Kazakhstan to Mayak PA were stopped.

Later on when BN-600 reactor facility was commissioned at the Beloyarsk NPP, reprocessing of the fuel from this reactor was initiated. From then on, reprocessing of SNF from the BN series reactors has become a routine process for the Plant; one of three process lines of the RT-1 Plant is dedicated especially for handling SNF of this type. The total amount of such fuel reprocessed at the Plant is more than 500 tHM.

In 2018 BN-800 reactor facility that is the next reactor facility of this series, was commissioned at the Beloyarsk NPP. Taking into account experimental nature of fast neutron reactors and plans to convert the core of the BN-800 reactor facility to 100% loading with mixed uranium-plutonium fuel, Mayak PA started preparing for MOX-fuel reprocessing. The first experimental reprocessing of MOX-fuel from BN-600 reactor (8 SFAs) was carried out in 2012 and 2013. It demonstrated technical readiness of the facility for handling mixed uranium-plutonium fuel. The first shipment of SNF, including the MOX-fuel, from the BN-800 reactor for radiochemical reprocessing will take place in 2020.

3. EXPERIENCE IN REPROCESSING SNF FROM RESEARCH AND NAVAL PROPULSION FACILITIES

3.1. SNF from Research Reactor Facilities

The fuel from the research reactors and facilities is characterized by a wide variety of both geometry of the fuel assemblies being used and the corresponding fuel compositions.

20 research reactors are currently in operation in Russia. The research reactor SNF is reprocessed at the RT-1 Plant, Mayak PA, after interim storage at the research center sites.

Versatility of radiochemical reprocessing of SNF implemented at Mayak PA makes it possible to reprocess (recycle) the majority of currently used fuel assemblies of nuclear research facilities. It is worth noting that several significant projects aimed at expanding the range of SNF types suitable for reprocessing have been recently implemented at the RT-1 Plant. Reprocessing of such fuel compositions as U-Mo, U-C, U-N, U_{met} and of such a complex composition as U-Be, was initiated between 2011 and 2016.

The project focused on adopting a technology for electrochemical dissolution of fuel was completed at the RT-1 Plant in 2018. This is one of the key points that will allow the Plant to become a multi-fuel facility capable of reprocessing all possible (currently in use) fuel compositions including such a complex one, as uranium-zirconium fuel. The first experimental operations on dissolution of uranium-zirconium SFAs from the research reactor at A.I. Leipunsky Institute of Physics and Power Engineering were conducted in 2019. In the future the electrochemical dissolution technology can be used to solve the problem of handling corium (damaged fuel) of the Fukushima Daiichi NPP, Japan, and to reprocess plutonium metal and its alloys.

The promising project that can be implemented at Mayak PA in the near future is reprocessing SNF with uranium-thorium fuel composition from the Elk River NPP, USA, currently stored in Italy. Feasibility study performed at Mayak PA demonstrated that this fuel can be reprocessed based on the process scheme currently in use at the RT-1 Plant without major upgrade of the production facility and deterioration in the end product quality. Taking into account considerable amount of SNF with uranium-thorium fuel composition mainly from research reactor facilities accumulated all over the world, the potential for its reprocessing at Mayak PA is significant and prospective.

3.2. SNF from Naval Propulsion Facilities

Russia is operating five icebreakers including Taymyr (1988), Sovetskiy Soyuz (1989), Vaygach (1990), Yamal (1992), 50 Let Pobedy (2007) and one icebreaking LASH-carrier Sevmorput (1988).

Interim storage of ice-breaker fleet SNF is performed at floating maintenance bases and onshore storage facilities of FSUE Atomflot. Part of SNF of the ice-breaker fleet is unloaded from the storage facilities of nuclear ice-breakers by the floating maintenance base (Lotta vessel) and is stored in TUK-120 casks at Atomflot storage site. Later on the ice-breaker fleet SNF will be transported on regular basis for reprocessing at Mayak PA by railroad in special vehicles.

4. EXPERIENCE IN FOREIGN SNF SHIPMENT

Beyond the boundaries of Russia, there are NPPs with VVER-440 and VVER-1000 reactor facilities constructed from Russian designs and research reactors that use nuclear fuel of Russian origin.

History of international shipments to Mayak PA goes as far back as 1971 when the RT-1 Plant was established. It was at that time when VVER-210 fuel from the GDR was delivered to the Plant.

As far as NPP fuel is concerned, since then shipments from 8 countries, such as Hungary, Finland, Germany, Bulgaria, Czechia, Slovakia, Armenia and Ukraine have been performed. More than 2,400 t of foreign fuel was reprocessed using capacities of the RT-1 Plant.

KS-150 SNF from the Slovak NPP is currently stored at Mayak PA and will be reprocessed at Cutting and Canning Department upon completion of reprocessing SNF from AMB and EGP-6.

Since 2006 high-enriched SNF from foreign research reactors of Russian origin from 13 countries has been delivered to Mayak PA in the framework of the Russian-American RRRFR Program (Russian Research Reactor Fuel Return). For this purpose multimodal transport scheme has been implemented. The joint international project has made it possible to remove high-enriched uranium potentially suitable for the manufacture of nuclear weapons from more than ten countries. Each shipment was unique in its kind. It posed challenging technical problems and required overcoming difficulties associated with SNF import into the Russian Federation. Implementation of international contracts for return and reprocessing of spent nuclear fuel from foreign research institutes allowed the region to fulfill large-scale environmental programs.

In the framework of a separate project in September 2015 liquid SNF based on aqueous solution of uranyl-sulphate enriched to 90% U-235 was imported from the IIN-3M research reactor in Uzbekistan to the territory of Russia. Preparatory work included development of a technology and a set of equipment for discharge of the liquid SNF from the reactor into the interim storage tanks, the SNF reloading into the shipping cans, as well as equipment for loading of canned liquid SNF into SKODA VPVR/M cask using a transfer cask. Besides, a technology and special equipment were developed to receive cans with liquid SNF at Mayak PA. The batch of liquid SNF (about 27 litres) in TUK-145/C (Type C package that includes SKODA VPVR/M cask and a shock-absorber) was delivered by the AN-124-100 aircraft to Russia for reprocessing at the radiochemical plant, Mayak PA.

5. NUCLEAR LEGACY PROBLEMS

5.1. Experience in Defective SNF Handling

Another indicator of the RT-1 Plant versatility is its capability of handling defective irradiated fuel assemblies.

Mayak PA took part in several projects, including the international ones, connected with transportation and reprocessing of defective SFAs. One of the first projects implemented in 2010 was focused on transportation of leaking fuel of the RA research reactor from Serbia and Montenegro (Vinča Nuclear Institute). Later on the defective fuel assemblies from the Paks NPP, Hungary (2014) and Kozloduy NPP, Bulgaria (2016) were delivered to Mayak PA.

Significant efforts have been made by Mayak PA to prepare for handling defective and out-of-specification fuel of the RBMK-1000 reactors.

The RBMK-1000 power reactors are operated at the Leningrad NPP, the Kursk NPP and the Smolensk NPP located in the European part of Russia. Annually about 3500 SFAs are unloaded from the RBMK-1000 reactors. Then the SFAs are stored in the reactor storage pools and stand-alone on-site wet storage facilities.

Since 2012 activities have been underway to switch over to a safer dry method of the RBMK-1000 SNF storage at the Central Storage Facility at Mining and Chemical Combine in Zheleznogorsk (Krasnoyarsk region). In compliance with the approved procedure, sealed SFAs without major rack defects (i.e. on-specification SFAs) are subject to dry storage at on-site storage facilities and transportation to the Central Storage Facility. Dry storage of defective and leaking SFAs (out-of-specification SFAs) at on-site storage facilities, their transportation and acceptance at the Central Storage Facility were not provided for. Therefore, as an alternative option of handling out-of-specification SFAs from the RBMK-1000, their reprocessing at Mayak PA was proposed.

With the aim of validating and testing engineering solutions, in 2011 a pilot batch of leaking SNF was delivered for reprocessing from Leningrad NPP power unit No.2 using well-proven and simple to operate TUK-11 casks. Preliminary disintegration of SFAs into fuel bundles was carried out in the hot cell of power unit No.2. In 2014 a batch of sealed out-of-specification SNF (22.4 t) was transported for reprocessing in metal concrete TUK-109 casks from the central spent nuclear fuel storage facility of the Leningrad NPP. Disintegration of SFAs into fuel bundles was carried out in the hot cell of the central SNF storage facility. Thus, depending on the SFA condition and capabilities of the facilities, several logistics options for the RBMK-1000 SNF transport were implemented.

Since 2015 the RBMK-1000 SNF has been transported to Mayak PA in the framework of the federal target program in the amount of up to 30 tons per year. Uranium recovered in the course of the RBMK-1000 SNF reprocessing is used efficiently in combination with recovered uranium resulting from reprocessing of

other SNF types for the purpose of product batching and producing commercial batches of uranyl nitrate hexahydrate with specified parameters of enrichment and uranium-232 isotope content.

Thus, out-of-specification and defective RBMK-1000 fuel is regularly delivered to the RT-1 Plant and reprocessed according to the standard transport flow chart. The main condition to be fulfilled is placing defective SFAs into sealed package (can) before their dispatch to Mayak PA.

5.2. Removal of SNF from Naval Onshore Bases

On June 7, 2017 the first SNF batch from Andreev Bay (Murmansk region) was transported on board Rossita container ship for subsequent reprocessing at the RT-1 Plant. The first batch included 350 SFAs, each of which contained up to 20 kilograms of SNF. It should be noted that a total of 22 thousand fuel assemblies are stored in the storage facility, which corresponds to the contents of 100 naval nuclear propulsion reactors. Shipment of the first SNF batch is an example of successful multilateral international cooperation aimed at solving challenging problems of nuclear legacy in the North-West of Russia, enhancing nuclear and radiation safety and improving the environmental situation.

SNF and radioactive waste handling facilities, as well as engineering systems were established in the framework of the federal target program *Industrial Disposal of Weapons and Military Equipment from 2011 to 2015 and for the Period till 2020* in cooperation with governments of Great Britain, Norway, Sweden, Italy, as well as with European Commission and Northern Dimension Environmental Partnership (contributors to the NDEP Support Fund are the European Union, Belgium, Great Britain, Germany, Denmark, Canada, Netherlands, Norway, Russia, Finland, France and Sweden; the Fund manager is the European Bank for Reconstruction and Development). The total budget for construction of infrastructure and improvement of radiation environment at Andreev Bay for the period starting from 1999 exceeded 8 billion rubles. The established SNF handling infrastructure will help reduce the time of SNF removal by more than a factor of three.

5.3. AMB Reactors

One of the most pressing problems in the field of nuclear and radiation safety is management of SNF from AMB reactors. Two AMB reactors of the Beloyarsk NPP were shut down in 1989. SNF was unloaded from the reactors, and it is currently stored in cooling ponds at the Beloyarsk NPP and at ‘wet’ storage facility at Mayak.

Spent fuel assemblies from AMB reactors have the following defining features: about 40 types of fuel compositions and large dimensions (SFA length makes approximately 13 m). The main problem of storing the assemblies at the Beloyarsk NPP is corrosion of basket-tube holders and the cooling pond linings.

Range of works concerning management of SNF from AMB reactors is provided with a view to reprocessing the fuel at Mayak. As of today, methods and process regulations of radiochemical reprocessing of SNF from AMB reactors were chosen and substantiated. In 2011 pilot reprocessing of fuel from AM reactor (analogue of SNF from AMB reactor) was performed. Construction of Cutting and Canning Department is underway.

At the same time, a process flowchart of shipment of SNF from AMB reactors was established. The flowchart includes a range of technical activities and arrangements at Mayak and the Beloyarsk NPP, as well as works on forming a special train with unique TUK-84 transportation packages for delivery of SNF from AMB reactors. As a result, a holder with SNF assemblies from AMB reactors, subject to intermediate storage at Mayak, was shipped in November, 2016.

Today the project is of significant importance in the field of nuclear and radiation safety in the atomic sector, because it enables reprocessing of SNF from the first and the second shut-down units of the Beloyarsk NPP (a total of 122 holders). Rosenergoatom JSC in its turn will be able to begin their decommissioning. Establishing a system for management of SNF from AMB reactors will give Mayak an opportunity to begin accepting on regular basis the SNF using the adopted transport flowchart, and to remove the whole stock of the fuel from AMB reactors from the Beloyarsk NPP, which will meet the most important challenge in the field of nuclear and radiation safety.

The beginning of cutting and reprocessing of SNF from AMB reactors is scheduled for 2024. SNF stored at the storage facility at Mayak PA should be reprocessed in the first place, then prospectively the entire amount of fuel from the Beloyarsk NPP pools will be delivered at Mayak for reprocessing.

5.4. EGP-6

At the moment there is no decision concerning the back-end of the single type of SNF, i.e. fuel from EGP-6 reactors (the Bilibino NPP). This is a long fuel assembly (as SNF from AMB reactors), its fuel composition is similar to the composition of one of AMB fuel versions, that is why reprocessing of this type of SNF will be possible at Mayak after Cutting and Canning Department starts its operation. However, the project implementation demands extremely high expenses because of the great distance to the Bilibino NPP, lack of infrastructure for retrieval of SNF and its further shipment from the NPP site, and necessary transport infrastructure around the site.

6. PROSPECTS AND NEW PROJECTS

Considering very significant amount of SNF from VVER-1000 accumulated in the territory of the Russian Federation, as well as the rate of construction progress for NPPs with reactors of this type, both in RF and abroad, the RT-1 Plant focuses in the first place at increasing the amount of fuel reprocessed for SNF of this type. With this in view, upgrading the second process line is scheduled. The line will be equipped with a heavy-duty cutting machine (as in the 3d line) and a voloxidation unit that allows containing tritium and solving the problem of tritium condensate discharge into the storage ponds.

Commissioning of the second fast neutron reactor (BN-800) in Russia and a prospect of constructing units with BN-1200 reactors make it necessary to increase capacity of reprocessing SNF from fast neutron reactors, including MOX-fuel. The current capacity of the RT-1 Plant can make 400 tHM/year. Completion of the RT-1 Plant upgrading is scheduled for 2022. The upgrading will enable increase in amount of reprocessed SNF from thermal reactors to 600 tHM and over, including possibility to reprocess fuel from at least three units with fast neutron reactors.

RT-1 Plant will be technically capable of reprocessing necessary amount of any SNF type, including defective and out-of-specification ones. Thus the Plant will completely meet requirements and fulfil tasks of potential customers.

Upgrading the 3d line enabled reprocessing of SNF of foreign design. In 2017 Mayak successfully implemented the project on demonstration reprocessing of a mock-up of TVS-Kvadrat (square SFA), i.e. a complete analogue of foreign assemblies from PWR reactors.

7. CONCLUSION

It is worth mentioning the following RT-1 achievements of recent years:

- equipment of the reprocessing facilities at RT-1 Plant was upgraded, which enabled expansion of the range of the fuel reprocessed (RBMK-1000, BN-MOX, VVER-1000, both standard and in baskets) and significant increase in uranium product output;
- SNF from atomic submarines is shipped from Andreev Bay on regular basis, the RT-1 Plant will become the culminating point in the process of solving the problem of nuclear legacy of Northwest Russia;
- technology of reprocessing SNF with uranium-beryllium, uranium-carbide, uranium-molybdenum fuel compositions was adopted;
- technical capability of reprocessing SFA of foreign design was demonstrated;
- technology of reprocessing SNF with uranium-zirconium fuel composition was developed and adopted;
- technical capability of reprocessing SNF with uranium-thorium fuel composition was confirmed.

For the period from 2025 to 2030 the main vectors of the RT-1 development are:

- increasing rates of reprocessing to 600 tHM and over;

- implementing HLW partitioning methods;
- arranging integrated production for U-Pu fuel fabrication.

Even now current capabilities of the RT-1 Plant provide solutions of the most complicated technical problems concerning closure of the nuclear fuel cycle, thus enabling increase in nuclear and radiation safety level at nuclear facilities.