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PROBLEMS OF TEMPORARY STORAGE OF SNF OF RESEARCH REACTORS IN AT-REACTOR STORAGES

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The paper focuses on challenges associated with spent nuclear fuel (SNF) storage in at-reactor storage facilities of the Research Center Kurchatov Institute and SNF management methods applied during the inventory taking. The paper presents the methods for SFA and SNF canister identification. The use of radiometric methods for measuring SFAs radiation parameters and remote-operated equipment allows to reduce the influence of high radiation fields on the personnel and to protect it during the operational process. It is noted that one of the main problems associated with the long-term SNF storage is the preservation of information on the stored items and their state.

Key words: *spent nuclear fuel, ionizing radiation, radionuclides, activity, radiometric diagnostic methods.*

Introduction

State system for spent nuclear fuel (SNF) management and reprocessing basically aimed at nuclear power reactor fuel reprocessing is currently operated in Russia. Organizations operating research reactors are responsible for the long-term storage of their SNF and its reprocessing. Unfortunately, at the time of first research reactors development and construction much less attention was given to the issues associated with SNF storage and management. This was mainly due to the unavailability of proper management experience and technologies. Relevant decision making was postponed and now the time has come to address these problems immediately.

A broad experimental base is available at the National Research Center Kurchatov Institute (NRC KI) which at different time periods included 12 research nuclear reactors, some 20 experimental critical and sub-critical nuclear stands [1]. A variety of different research activities have been carried out at these facilities which resulted in a significant amount of SNF accumulated in NRC KI storage facilities. Its total activity amounts to over 10^{16} Bq. Until recently, SNF from RFT, MR, IR-8, IRT, VVR-2, OR, Romashka and Enisey research reactors was stored in NRC KI storage facilities. This fuel included operational SFAs from these reactors, some experimental SFAs for VVER and RBMK reactor types and, transportation nuclear power facilities, as well as individual FAs and their elements resulted from structural and material investigations of irradiated and spent fuel. In the past 10—12 years, extensive efforts have been made to enable such SNF reprocessing under FTP NRS and FTP NRS-2.

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NRC KI SNF shipment for reprocessing

The SNF inventory stored at NRC KI site involves SFAs with a variety of different design features, fuel compositions, levels of ^{235}U enrichment (up to 90—95 %), burn-up depth (up to 60 GW×day/t) and exposure time (up to 50 years). The state of SFA components and applied constructional materials also differs significantly. Until 1990, SNF was continuously shipped for radiochemical reprocessing to PA Mayak. In 2004, after 13 years its shipment has been resumed [2].

The following facilities at NRC KI site have been used to store irradiated and spent fuel from research reactors:

- IR-8 reactor storage pool;
- Centralized SNF storage facility;
- Temporary SNF storage facilities at R-site;
- Temporary SNF storage facilities of the Gas Plant located at a separate site.

In 2004—2017, a total of 1,023 spent fuel assemblies and transport canisters with spent fuel elements (Table 1) were shipped to PA Mayak. As the transfer operations proceed and the number of damaged SNFs grows, more technically challenging become the technologies applied for the pre-shipment treatment of the retrieved SFAs and spent fuel elements. Difficulties are also associated with the dismantlement of mechanically fragile SFAs and individual fuel elements packaging.

Challenges in the management of unconditioned SFAs

SNF management challenges associated with its pre-shipment handling are mainly due to two reasons:

- Insufficient technical information on SNF state;
- Presence of mechanical and corrosion defects resulted from nuclear fuel operation and its long-term storage.

The first reason is believed to be the consequence of long-term SFAs cooling and a natural decrease in the number of carriers possessing this technical information, both of documentary and human origin. The second one is directly related to spent fuel assemblies and fuel rods storage conditions available at relevant storage facilities, expiration of storage time and the storage capacity of these facilities, as well as the state of the packages used to store the spent fuel.

The initial stage of the project implemented in 2004—2009 mainly involved the shipment of standard SFAs of certain types [3]. In 2010, some damaged spent fuel elements were added. Such fuel required some pre-shipment operations to be performed involving spent fuel element retrieval from damaged SFAs and their repackaging into transport canisters. In particular, a big inventory of EK-10 and S-36 spent fuel elements from VVR-2 and OR reactors stored at site № 16 of the Gas Plant was retrieved and repackaged.

Table 1. Research reactor SNF shipped from NRC KI to PA Mayak in 2004 – 2017

Year of shipment	SNF from VVR-2 and OR reactors				SNF from Enisey facility	SNF from MR reactor	SNF from IR-8 reactor	SNF from RFT reactor
	SFAs with SF rods		Transport canisters with spent fuel rods					
	EK-10	S-36	EK-10	S-36			IRT-3M	
2004	–	–	–	–	–	64	–	–
2005	–	–	–	–	–	128	–	–
2006	–	–	–	–	–	–	40	–
2007	–	–	–	48	–	–	–	–
2008	24	8	–	–	–	–	–	–
2009	44	20	–	–	–	–	–	–
2010	17	10	35	2	–	–	–	–
2011	7	–	57	–	–	–	–	–
2012	8	–	16	8	–	–	–	–
2013	17	3	15	4	80	–	–	–
2014	–	–	–	–	100	12	–	–
2015	–	–	–	–	–	32	32	–
2016	–	–	–	–	–	–	–	128
2017	–	–	–	–	–	–	–	64
SUBTOTAL:	117	41	123	62	180	236	72	192
	158		185					
TOTAL	343				180	236	72	192

At the initial stage, segregation of SNF from VVR-2 and OR reactors was performed by means of detailed visual inspection of the Gas Plant site cells. A portative video camera was used to select certain conditioned SFAs stored under water.

In the first place, during the visual inspection of SNF storage cells SFAs having no visible external mechanical or geometrical defects as specified in relevant requirements of industrial standard OST 95 10297-95 applied to SNF shipped for reprocessing were chosen. Compliance with these requirements suggested that these SFAs should be considered as properly conditioned. Unconditioned SFAs detected during such visual inspection were identified based on spent fuel element type: either as S-36 or EK-10 [3].

Two techniques have been developed to identify such spent fuel element types:

1. Weighting fuel assemblies and individual S-36 and EK-10 fuel elements under water of the SNF storage pool [4];
2. Evaluating the emission spectra of irradiated S-36 and EK-10 fuel rods [4].

Weighting method was based on the fact that EK-10 spent fuel element containing SFAs were 30 g heavier than those with S-36.

Weighting is considered to be rather simple and convenient method enabling to identify spent fuel assembly by spent fuel element type. However, this process turned to be impossible to implement in some cases as the cladding of some degraded fuel elements was damaged and their integrity could've been compromised by weighting. In such cases, radiometric method was applied based on the ratio between the counting rates at the peak of total absorption of ^{137}Cs radiation and the characteristic radiation of uranium within 95—110 keV range [4]. This method is considered as non-destructive analysis method allowing to maintain the integrity of the fuel element, since it does not suppose any mechanical operations to be performed during the measurement process.

Following the identification process, the identified unconditioned SFAs from VVR-2 and OR reactors having some visible mechanical or geometrical defects or in some other way technically inconsistent with OST 95 10297-95 requirements were dismantled to retrieve individual spent fuel elements. These elements were firstly placed into temporary storage canisters and then repackaged into non-tight ones intended for transportation [5].

Unconditioned SFA decomposition by individual spent fuel elements is considered to be feasible in accordance with relevant certification permit provisions. The latter ones suggest that loading of non-tight transportation canisters with EK-10 and S-36 spent fuel elements into TUK-19/5 casks and their transportation is permitted if the technical state of these spent fuel elements complies with relevant requirements of the OST 95 10297-95 standard [5].

Figure 1. Retrieval of spent fuel elements from unconditioned SFAs under water using a purpose designed tool

As previously noted, dismantlement operations suggesting SFA decomposition on individual elements and their further packaging into temporary storage canisters were performed under water in storage pool №16. Design features of the pool allowed to arrange for and perform all necessary operations. All fuel element retrieval operations were performed using manual remote tools. If manual retrieval was not possible, the external cladding of the unconditioned SFAs from VVR-2 reactor was cut into pieces.

These operations were performed in SNF storage pool under water layer using remote tools as well. A purpose designed tool made a longitudinal section of the outer SFA walls. Tube assemblies used as channels for coolant flow together with the fuel elements were subsequently retrieved from it (Figure 1).

Research reactor SNF pre-shipment handling results in relatively big amount of high-level and intermediate level waste (RW). It should be noted that all the operations listed above are quite time- and labor-consuming. When implemented under water a significant reduction in personnel radiation exposure is reached. However, the specific features of such operations, resulted RW, as well as doses should be accounted for at research reactor pre-decommissioning stage and development of relevant decommissioning designs finalizing the life cycle of such facilities.

Methods for managing SNF from space nuclear power facilities

Pre-shipment handling of SNF from the Romashka storage facility has required some additional operations. This facility holds spent nuclear fuel from transportation research nuclear installations. In 2013, for the first time after a long break, SFAs from research space nuclear facility Enisey were shipped for reprocessing. This installation, developed and tested in 1960—80's, was designed based on a thermal emission system converting thermal energy of a nuclear reactor into power using power generating channels (EGK) fitted inside the reactor core.

Prior to Enisey SNF shipment for reprocessing, EGK had to be properly treated to separate EGK end elements, retrieve fuel parts followed by their subsequent packaging into transport canisters enabling their further shipment for reprocessing.

Design of Enisey SFAs containing irradiated fuel (96% enriched uranium dioxide) suggests that transport casks TUK-19/8 can be used to ship them to the reprocessing plant. This has been specified in relevant provisions of a certificate permit that had been granted for this transportation package.

Based on the provisions of the abovementioned certificate permit, during transportation to the reprocessing plant radioactive content of TUK-19/8 can include fuel parts (elements) of Enisey's EGK installation packaged into sealed non-reusable transport canisters. Transport canister is a metal tube with its bottom and upper lid made of steel (mark 12Х18Н10Т). A rubber ring ensures the sealing capacity of the tube. Only parts and elements of Enisey's EGK with a length of less than 500 m are allowed to be shipped for reprocessing. Two fuel EGK Enisey parts, one above the other, can be packaged into one transport canister.

Sealed transport canisters are shipped inside 19-2-63 overpacks of TUK-19/8 transport casks. 19-2-63 overpack's structural elements are shell, neck, tie, spacer grids, plug and lid. Overpack's structure is bottomless ensuring that all the water from its cavities is drained during reprocessing operations at the plant. The overpack is placed on a frame of TUK-19/8 cask's inner cavity.

Ten transport canisters can fit into one 19-2-63 overpack. The canisters are hung inside the overpack on collars. Thus, one 19-2-63 overpack can be used for joint transportation of 20 fuel parts of EGK Enisey installation. Shipment of TUK-19/8 casks containing fuel parts of EGK Enisey installation inside sealed transport canisters may be carried out by rail or by road.

EGK fuel part length accounted for some 500 mm and its total length with top and bottom end

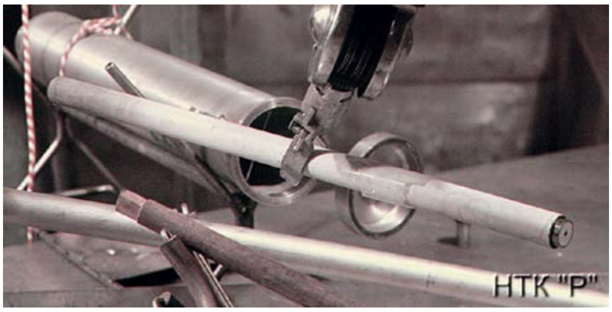

Figure 2. Segregation of EGK end elements using machine handling device

elements was about 650 mm. The main task of pre-shipment operations was to remove ~ 70 — 75 m long top and bottom end elements. A shielded box equipped with a machine handling device and a conductor casing was used to perform these operations (Figure 2). Segregated elements were placed into a canister designed for radioactive waste collection. One transport canister could accommodate 2 fuel part items. The canister was sealed and put inside the 19-2-63 overpack.

Overpacks filled with fuel elements were placed into purpose-designed baskets for temporary storage. RW resulting from these operations were segregated by specific activity level and packaged into disposal canisters.

Shipment of pilot VVER-type SFAs (MR reactor) for reprocessing

MR reactor, developed and constructed in 1962—1963, reached its design capacity of 20 MW in 1964. In terms of its design, it was the first research reactor of a new type — channel-type water submerged reactor. To implement the tests and investigations associated with fuel elements, fuel and structure materials the reactor was equipped with 9 loop-type facilities enabling to explore thermal, hydrodynamic and strength parameters of power reactor cores and basic equipment intended for various purposes under conditions being as far as possible similar to actual reactor operations. Pilot SFAs of VVER, RBMK, OK, VM and other were tested, i. e. covering almost all types of power and transport reactors developed in the middle of the 20th century. For a long time, irradiated assemblies of the above-mentioned types were stored in purpose-designed storage facility being held inside sealed canisters of different diameter. In particular, VVER type pilot SFAs were packaged into 90 mm diameter canisters and, in keeping with RUS/053/B(U)F-96T (Rev. 7) certificate permit provisions [6], could not be loaded into TUK-19 transport casks. To enable

Figure 3. Console of the hot cell equipped with manipulators

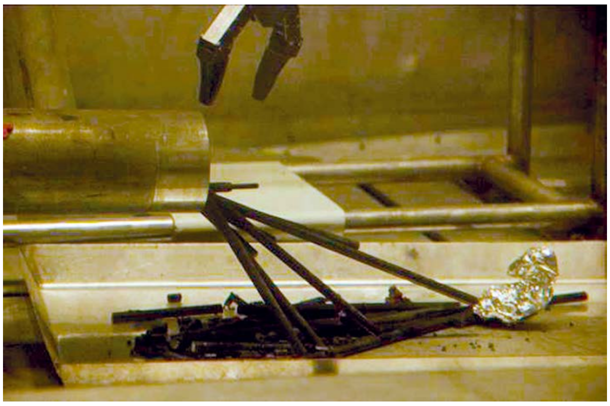

Figure 4. Fuel rods repackaging inside the hot cell

its shipment for reprocessing it was decided to repackage it into sealed 76 mm diameter transport canisters. These operations were performed in a shielded box of Romaska complex (Figure 3).

For this purpose, canisters were put inside the box and mounted on the lift-turntable above the pallet opposite each other. All handling operations with fuel rods were performed by remotely controlled manipulators (Figure 4). In this way, 20 canisters were repackaged.

Challenges for managing SNF from RFT research reactor

RFT reactor was the predecessor of MR reactor being the first Russian research reactor powered by enriched uranium-based fuel designed for material research [7, 8]. The first tests of experimental fuel elements intended to be used in NPP reactors, transport installations and research reactors being under development at that time were started in late 1952. At the initial stage, their aim was to find the best fuel assembly structures and fuel compositions, and later on these were mainly focused on investigating their performance including longevity tests carried out under various conditions.

Reactor's loops were used to test fuel rods designed for the first nuclear power plant (reactor AM), research reactors RFT, VVR-S, VVR-M, IRT, SM and other, as well as fuel rods for other NPPs and nuclear power facilities designed for different purposes.

Operational SFAs of RFT research reactor are non-standard fuel assemblies which required certificate permits and technical specifications to be developed to enable their shipment for reprocessing under provisions of OST 95 10297-95 [9, 10]. In 2015, developed and published was certificate permit RUS/0135/B(U)F-96T [9] on the package design and shipment of RFT spent nuclear fuel in transport cask TUK-19 suggesting that the SFAs are put inside sealed canisters. Inventory of SNF storage facility located inside building 109 was taken to identify SFAs from RFT. This project involved investigation of the canisters by means of collimated radiometry and spectroscopy methods. SFAs retrieval from storage cells was performed using lifting and transportation devices available in the storage facility.

Remotely controlled Brokk-90 mechanism equipped with "Gamma-pioneer" measuring complex and a video system [11] enabled to visualize SFA tags and evaluate equivalent dose rate (EDR) distributions in detector's collimation angle over the length of the canister. Spectrometric surveys were performed using semiconductor detector of γ-radiation. Total EDR was measured with standard verified dosimeters UIM2-2D. The distance between the canister and the detector was recorded in canister passports.

This project involved:

- Identification of canister tags;
- Identification of SFAs radiation characteristics;
- Issuance of SFA passports indicating its ID number and the ID number of the cell where it was stored and where it will be placed.

γ-emission spectra of individual SFAs were measured by a gamma locator equipped with a spectrometric CdZnTl-based (CZT-based) semiconductor detector (Figure 5) [7]. Measurements showed that ^{137}Cs was the main radionuclide contributing to the radiation dose. Other radionuclides were also present, but their activity was much lower than the one of ^{137}Cs. SFA activity was further evaluated based on γ-radiation spectral response characteristics.

Uranium characteristic radiation peaks and an intensive peak associated with ^{137}Cs exposure are typically observed in the area corresponding to about 100 keV of SFA γ-radiation spectrum. Due to the low energy resolution of the detector, two

Figure 5. Gamma locator for individual SFA spectrometry survey

peaks of uranium radiation corresponding to 96 and 113 keV are visible on the spectrum consisting of superimposed peaks of characteristic radiation $E = 94.5$ keV ($UK_{\alpha2}$) and $E = 98.43$ keV ($UK_{\alpha1}$); $E = 114.45$ keV ($UK_{\beta2}$) and $E = 111.30$ keV ($UK_{\beta1}$). These emission peaks in the γ-spectrum indicate that a significant concentration of uranium atoms is present in the SFA. It is the registration of these uranium characteristic radiation lines that the method of uranium-containing mass identification is based upon. These lines are driven by ^{137}Cs radiation being a decay product, i. e. combination of ^{137}Cs intense radiation with uranium characteristic radiation indicates that SNF is contained inside the package [4, 12].

A total of 192 operational RFT SFAs were selected during the inventorying project to be sent for reprocessing in 2016—2017.

Main results of the project on research reactor SNF removal from NRC KI site

The number of research reactor SFAs held in NRC KI storage facilities has been significantly reduced. Technical facilities for SNF management were extensively renovated, new methods enabling to monitor its state were developed resulting in significant decrease of collective doses for personnel engaged in these activities. However, some issues associated with research reactor SNF long-term storage at the NRC KI site have been revealed.

Degradation of SFA and fuel rod protective cladding during their long-term storage is seen as a most pressing challenge. Practice shows that SFA storage in pools results in intensive corrosion of SFA metal structures, their swelling, thus, causing some difficulties associated with their subsequent packaging before their shipment for reprocessing. Protective barrier degradation results in radionuclide release into the pool water. Preservation of knowledge on the radioactive content of these storage facilities is viewed as an important challenge associated with SNF long-term storage considering natural personnel turnover and information holder loses. The latter one necessitates periodic checks of storage facilities' inventory, thus, increasing the costs of SNF management and its retrieval from the storage cells. Management of high-level waste generated during SNF handling operations is viewed as another important issue. These RW have complex radionuclide content and high activity requiring special premises to be arranged for their storage and methods enabling to identify their radionuclide composition to be developed. After long-term efforts on SNF shipment to the reprocessing plant, mainly experimental SNF is now left in NRC KI storage facilities. This SNF requires particular certificate permits to be issued allowing its transportation for reprocessing inside TUK-19 casks. Remaining fuel differs significantly by its composition, enrichment and burnup levels. Its management is associated with large labor and dose costs required to perform relevant pre-shipment operations. Moreover, no reprocessing technologies are currently available at PA Mayak for some SNF types.

In the last 15 years, the following challenges have been revealed by NRC KI while performing SNF preshipment management:

- Inventory of SNF and HLW storage facilities should be checked;
- New methods for safe SNF and RW management should be developed and their binding to specific provisions of already available methods should be done;
- Reliable information storage system with nuclear data on the inventory held in storage facilities should be developed;
- Work flows and methods enabling further management of HLW resulting from SNF pre-shipment handling should be developed;
- Issues associated with managing SNF and HLW from research reactors decommissioning should be addressed.

Practice has shown that the developed and applied remote radiation control methods are quite effective in terms of personnel protection from high radiation doses. Gamma-locators with semiconductor γ-radiation detectors enable identifying fuel-containing masses based on uranium characteristic radiation emission. All necessary facilities for SNF management are available at NRC KI site including purpose-designed test stands, hot cells, capacities for SNF and HLW storage. The SNF and HLW management technologies developed appeared to be of high-demand in research reactor decommissioning.

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