Treatment and disposal of wet operational radioactive waste at Bohunice V1 NPP

CASE STUDY

KP-JAVYS-007

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Foreword

In 2021, the European Commission (EC) adopted a new proposal for a Council Regulation[1] establishing a dedicated financial programme for decommissioning nuclear facilities and managing Radioactive Waste (RAW). This instrument covers the co-funding of the decommissioning programmes of Bulgaria, Slovakia, and the decommissioning of the Joint Research Centre (JRC). A separate Council Regulation[2] was adopted for the decommissioning programme of Lithuania.

The EC JRC is mandated to foster the spread of decommissioning knowledge across all the European Union Member States and facilitate knowledge sharing arising from implementing the abovementioned decommissioning programmes, funded by the Nuclear Decommissioning Assistance Programme (NDAP).

The decommissioning operators from the NDAP (NDAP Operators) implemented and tested a knowledge management methodology in 2021 through Project ENER/D2/2020-273. Using this methodology, the NDAP Operators can develop Knowledge Products that are currently available to share with other European stakeholders. In addition, this methodology is under implementation in the JRC Nuclear Decommissioning and Waste Management Directorate (NDWMD), which becomes a knowledge generator extracting the knowledge from the ongoing decommissioning activities at the different sites (Geel, Ispra, Karlsruhe, and Petten).

The JRC NDWMD aims to become a Centre of Excellence in nuclear decommissioning knowledge management and develop a decommissioning knowledge platform which allows exchanging information and building on the best practices in the EU inside the multi-annual financial framework (2021 – 2027) strategy. The operational phase of the project is expected to start in 2024 to develop ties and exchanges among EU stakeholders and document explicit knowledge and make it available through multi-lateral knowledge transfers on decommissioning and waste management governance issues, managerial best practices, technological challenges, and decommissioning processes at both operational and organisational level, to develop potential EU synergies.

This is a Knowledge Product prepared by the JAVYS, a.s. for the NDWMD.

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[1] Council Regulation (Euratom) 2021/100 of 25 January 2021 establishing a dedicated financial programme for the decommissioning of nuclear facilities and the management of RAW, and repealing Regulation (Euratom) No 1368/2013

[2] Council Regulation (EU) 2021/101 of 25 January 2021 establishing the nuclear decommissioning assistance programme of the Ignalina nuclear power plant in Lithuania and repealing Regulation (EU) No 1369/2013

PRODUCT DESCRIPTION

A team of experts from JAVYS, a.s. (a Nuclear and Decommissioning company) Slovakia prepared a case study report on the treatment and disposal of V1 Nuclear Power Plant (NPP) wet operational RAW. The product conveys the experience gained during the execution of the following Bohunice International Decommissioning Support Fund (BIDSF) projects:

- C7-D2 – Sampling, Analysis and Characterisation of "Wet Waste",
- C7- D3 – Sampling, Analyses and Characterisation of Ra-Sediments in Storage Tanks,
- C7-B – Treatment of Historical Waste – Sludges and Sorbents,
- C7-C – Treatment and Conditioning of Historical Waste and
- C9.4 – Design and Erection of New Disposal Facilities for low-level and very low-level waste from V1 NPP Decommissioning at NRR Mochovce.

The European Commission sponsors these projects through the Nuclear Decommissioning Assistance Programme (NDAP) and the Slovak National Nuclear Fund.

ABSTRACT

This case study treats operational liquid radioactive waste at V1 NPP in Jaslovské Bohunice. These wastes were produced during the operation and in the first phases of the V1 NPP decommissioning as a by-product of the active water purification systems. There are two groups of operational liquid RAW - concentrates and spent resins. Due to the high content of solid particles and sediments, these wastes could not have been collected, transported, and treated using the existing facilities. For these reasons, a project was defined to collect and treat these wastes close to the storage tanks.

This study focuses on the actual process of collection and treatment of operational liquid RAW implemented within the BIDSF project C7-B, *"Treatment of Historical Waste - Sludges and Sorbents"*. Other related activities, such as the characterisation of liquid RAW, conditioning into fibre-concrete containers (FCCs) and disposal of the solidified RAW, are described to an appropriate extent to complete the overall picture of the management of this type of waste.

OBJECTIVE

To provide specific experiences of implementing treatment of wet operational radioactive waste project from the Employer's perspective, identifying the necessary steps and essential project details critical to the project's success.

APPROACH

This document was developed by the JAVYS project team from the division responsible for implementing the decommissioning of V1 NPP. The team incorporated experiences from preparing and implementing the execution of the BIDSF projects, emphasising the C7-B Project, "*Treatment of Historical Waste-Sludges and Sorbents.*"

RESULTS, FINDINGS, AND INSIGHTS

The results of this Study make the reader familiar mainly with experience from the actual treatment of operational liquid RAW from the operation of WWER-type reactors at V1 NPP in Jaslovské Bohunice. The treatment process of liquid RAW is not universal. It depends on the type of reactor of the relevant NPP, method of operation, specific physical, chemical, and radiological properties of the waste and available transport and treatment technology. Nevertheless, we believe that within this study, the reader can find tips, criteria, or limitations that can be applied in other cases.

TARGET USERS

This knowledge product is intended for personnel of decommissioning and waste management (D&WM) operators, personnel of NPP's still under operation, regulatory bodies or any other personnel who are involved in NPP decommissioning planning, specifically for the removal of liquid RAW from the NPP´s operation. Although this knowledge product focuses on the case where the contractor performs the above activity, it is also suitable for D&WM operators who will implement the management of operational liquid RAW with their personnel. In the case of the Contractor-based approach to the management of liquid RAW from operations, a wide range of professions are required on the part of the Client/Employer, responsible for the preparation of Tender documents and selection of the project Contractor, project management, licensing process, technical issues, chemical regimes control, nuclear, radiation and standard safety, project funding, and other activities.

APPLICATION, VALUE, AND USE

The study provides practical experience for preparing and implementing the treatment of liquid RAW from the NPP operation. Emphasis is paid to the activities and circumstances requiring special attention in implementing the BIDSF project C7-B— “*Treatment of Historical Waste—Sludges and Sorbents.*” Chapter 4, titled "*Summary of Lessons Learned*," summarises the lessons learned.

KEYWORDS

DECOMMISSIONING, DECONTAMINATION, NUCLEAR POWER PLANT, WWER, V1 NPP, WET OPERATIONAL WASTE, TREATMENT, DISPOSAL, OPERATIONAL RAW, SOLIDIFIED RAW, CONCENTRATES, SPENT RESINS, SORBENTS, RAW CHARACTERIZATION, ACTIVE WATER TREATMENT SYSTEMS, ABOVE-LIMIT ACTIVITY, FIBRE CONCRETE CONTAINER, REPOSITORY.

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LIST OF ACRONYMS AND DEFINITIONS

ALARA	As Low as Reasonably Achievable
BIDSF	Bohunice International Decommissioning Support Fund
C7-B	V1 NPP Decommissioning project “Treatment of Historical Waste – Sludges and Sorbents”
C7-C	V1 NPP Decommissioning project “Treatment and Conditioning of Historical Waste”
C7-D2	V1 NPP Decommissioning project “Sampling, Analysis and Characterisation of “Wet Waste””
C7-D3	V1 NPP Decommissioning project “Sampling, Analyses and Characterisation of Ra-Sediments in Storage Tanks”
C9.4	V1 NPP Decommissioning project “Design and Erection of New Disposal Facilities for LLW and VLLW from V1 NPP Decommissioning at NRR Mochovce”
CB 801:V1	Civil Building 801:V1 (V1 NPP Auxiliary Building)
D&WM	Decommissioning and Waste Management
FCC	Fibre Concrete Container
IAEA	International Atomic Energy Agency
JAVYS, a.s.	Jadrová a vyraďovacia spoločnosť a.s.
LLW	Low-Level Waste
LRAW	Liquid Radioactive Waste
MoE SR	Ministry of Environment of the Slovak Republic
NPP	Nuclear Power Plant
NRA SR	Nuclear Regulatory Authority of the Slovak Republic
NRR	National Radioactive Waste Repository in Mochovce
OECD/NEA	Organisation for Economic Co-operation and Development/ Nuclear Energy Agency
PHA SR	Public Health Authority of the Slovak Republic
PPE	Personal Protective Equipment
RA	Radioactive
RAW	Radioactive Waste
SIAL®	Aluminosilicate matrix, applied by AMEC Nuclear International Limited (Contractor of C7-B Project) to solodyfy the wet operational waste of V1 NPP
ŠOV 1,2,4,6	Active Water Treatment Systems 1, 2, 4, 6 of V1 NPP
TSÚ RAO	Facility for RAW Treatment and Conditioning
V1 NPP	V1 Nuclear Power Plant, Jaslovské Bohunice
VLLW	Very Low-Level Waste
WWER	Water-Water Energetic Reactor

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1. INTRODUCTION

Every nuclear power plant (NPP) decommissioning project in the operation termination phase faces complex challenges. These include the critical tasks of transporting the spent nuclear fuel and removing and managing the radioactive waste (RAW) generated during the NPP operation. Special attention must be paid to liquid RAW, as managing this type of waste represents an increased risk regarding nuclear and radiation safety.

This Report deals with the experience of managing liquid RAW (LRAW) from the V1 NPP operation in Jaslovské Bohunice. Specific tips and lessons learned can also make the treatment of operational liquid RAW more efficient in other nuclear decommissioning projects. This includes, for example, the need for thorough characterisation of liquid RAW before its processing, selection of liquid RAW treatment technology, solving the requirement to minimise the final product's volume, optimising radiation protection, etc.

1.1. The Liquid Radioactive Waste Treatment Challenge

LRAW treatment is the most challenging area of management worldwide. This issue's complexity results from the stored waste's characteristics, an inhomogeneous mixture of solids, liquids, dissolved salts, and crystals [1]. The inhomogeneity and changing properties of stored waste cause uncertainties in the characterisation and quantification of the waste as well as technical problems related to the transport and treatment of the waste.

In the case of V1 NPP in Jaslovské Bohunice, approximately 700 m^3 of radioactive sorbents, crystalline sediments, and sludge have accumulated since the beginning of operation. These were stored in tanks in the auxiliary building and represented a constraint for the early V1 NPP decommissioning.

The case study captures the process of managing LRAW from the V1 NPP operation, including characterisation, removal, treatment, conditioning, transport, and final disposal. The challenges and lessons learned related to planning and implementing these activities are the reason for sharing knowledge in this field.

1.2. Constraints

Time constraints

The Nuclear Regulatory Authority of the Slovak Republic, as a Regulator in the nuclear safety area, required that liquid RAW from the V1 NPP operation be treated before the start of the V1 NPP decommissioning. The presence of this waste in the NPP during the decommissioning activities increases radiation risks and the risk of RAW leakage into the working or living environment. Therefore, given the strategy and schedule of the V1 NPP decommissioning, it was necessary to treat the operational liquid RAW as early as possible.

Technical and legislative constraints

Operational liquid RAW from the V1 NPP had to be treated, under the binding documentation, into aform that meets the requirements for acceptance in the Bohunice RadWaste Treatment Centre for further treatment into final package form, the requirements for disposal at the National RadWaste Repository (NRR) in Mochovce and the requirements for transport.

Financial constraints

The Operator had to provide financing for treating the operational liquid RAW by contractors and for the subsequent conditioning and disposal at the NRR in Mochovce.

1.3. Relevance

This case study disseminates information not currently publicly available on managing the wet operational waste of a WWER-type NPP, which is to be addressed in the early decommissioning stages. Attention is also paid to specific measures to optimise radiation protection while treating sludge and sorbents, as these were LRAW with relatively high activity of up to 10^7 Bq/kg.

This product could be highly relevant for nuclear decommissioning and waste management (D&WM) operators and regulatory bodies that will address the decommissioning of NPPs in the future or are in the early decommissioning phases. They may obtain comprehensive information on the management process of operational wet RAW of WWER-type reactors. The case study provides a basis for developing a proper plan for handling the operational wet RAW and selecting an optimal processing method.

2. SCOPE AND STRUCTURE OF THE CASE STUDY

This document provides a comprehensive case study on managing operational LRAW from the Bohunice V1 NPP. The document is structured as follows:

- Background on the V1 NPP and its liquid RAW from the NPP operation.
- Description of the operational liquid RAW management process is stated. The process includes analysis, removal, treatment, conditioning, transport, and final disposal.
- Selected aspects of the liquid RAW treatment process with specific attention to optimising radiation protection while removing and treating operational liquid RAW.
- Organisational and human aspects, regulatory, licencing and quality aspects.
- Overall results and benefits for operators and other organisations.
- Finally, a summary of the lessons learned from the whole document.

3. CASE STUDY

This case study depicts the wet operational RAW (sludges and sorbents) management of a WWER-type NPP: V1 NPP in Slovakia, which had two Units. Each Unit was in operation for approximately 28 years. Approximately 700m^3 of LRAW has accumulated from the V1 NPP operation. In compliance with international recommendations from the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development/ Nuclear Energy Agency (OECD/NEA), operational LRAW must be removed before NPP decommissioning starts.

The LRAW management process includes the analysis, removal, treatment, conditioning, transport, and final disposal. Operational LRAW of V1 was categorised into A, radioactive sorbents and B, crystalline sediments and sludge. The categorisation is applied to obtain categories with mutual properties and, therefore, the management process. During the preparation and implementation of the treatment of this damp waste of V1 NPP, the focus was on minimising the final product volume while complying with the relevant binding regulations and constraints. Remotely operated equipment and specific radiation protection measures are necessary when treating the operational LRAW. The final product of LRAW must correspond to the approved package forms of RAW (case of V1 NPP). Planning of LRAW management requires knowledge of the properties of the LRAW, as there are physical and radiological requirements for the treated product to be further conditioned and transported for final disposal.

This case study includes lessons learned in planning, processed optimisation, radiation protection, organisational recommendations, licencing and regulatory requirements, and other aspects.

3.1. Sources of Information

The sources of information used to develop the Case Study are internal documents of Jadrová avyraďovacia spoločnosť a.s. (JAVYS, a.s.), mainly documentation related to specific V1 NPP decommissioning projects: C7-D2, C7-D3, C7-B, C7-C, C9.4, e.g., Project Completion Reports (PCRs) and operating procedures (see Section 5).

3.2. Background

3.2.1. Operational liquid RAW within the V1 NPP decommissioning process

Based on the Slovak Government Decision No. 801/99 of September 1999, the Slovak Republic has undertaken to shut down and decommission the V1 NPP in Jaslovské Bohunice. The first unit of the V1 NPP was shut down on 31 December 2006, and the second was shut down on 31 December 2008. The main parameters of the V1 NPP are summarised in **Figure 1**.

Location	Jaslovké Bohunice
Units	2
Reactor type	WWER 440-V230
Thermal output	1.375 MW
Fuel	UO_2 (1.8/2.4/3.6 %U^{235}, modified 3.82 %%U^{235})
Moderator and coolant	H_2O
Number of loops	6

Figure 1. Bohunice V1 Nuclear Power Plant main parameters

Since the commissioning of individual V1 NPP Units in 1978/1980, approximately 700 m^3 of radioactive sorbents, crystalline sediments, and sludges had been accumulated in the storage tanks in the V1 NPP auxiliary operations building, which constituted a constraint for the early decommissioning of the V1 NPP. The Slovak Nuclear Regulatory Authority (NRA SR) required the removal of the operational liquid RAW before the decommissioning implementation. The Regulator's position on this issue was based on the provisions of the legislation and the approaches and recommendations of the IAEA and OECD/NEA international organisations. For example, the IAEA Safety Reports Series No. 36 - Safety Considerations in the Transition from Operation to Decommissioning of Nuclear Facilities [2], in section 3.8, states that the treatment and conditioning of operational RAW during the decommissioning period is an important safety factor, as the presence of RAW may adversely affect the decommissioning process safety. Also, the IAEA Safety Standards—Decommissioning of Facilities Using Radioactive Material [3] mentions the requirement for removing operational RAW from a nuclear facility after its shut-down for operation termination purposes. The Authority further justified its position by stating that treating all stored operational RAW before the start of the decommissioning process and separating the management of operational RAW from the management of decommissioning RAW is a good practice used worldwide. This approach will significantly reduce the radiation risk and the risk of RAW leakage into the working or living environment.

Operational liquid RAW should be removed before decommissioning is implemented. The proactive regulator (NRA SR in the case of Slovakia) may require this.

3.2.2. Mechanism of liquid radioactive waste production at V1 NPP

Liquid RAW from the NPP operation can be simplistically characterised as a by-product of cleaning radioactive operating fluids. The main operating fluid of the V1 NPP and the leading carrier of radioactive contamination was the primary circuit coolant (demineralised water with various impurities). During the reactor's operation, various contaminants were introduced into the primary coolant: corrosion products containing both stable and radioactive nuclides, fission products penetrating through the leaks in fuel assemblies, and impurities supplied with additional water or dosed chemicals.

Impurities in the form of mechanical particles can cause deposits to form, leading to clogging of the routes and reduced thermal transmittance. In turn, fission products and radioactive nuclides increase the activity of the primary circuit. Removing undesirable impurities continuously from the primary circuit coolant was necessary to avoid these negative phenomena. In addition to cleaning the primary circuit coolant, other operating fluids were also needed. For the above purposes, the following systems were in operation at V1 NPP:

- Continuous primary circuit coolant purification system,
- Drainage and organised leak purification system,
- Treatment of unorganised leaks and wastewater,
- Water purification system of the refuelling storage pool and the boric acid emergency storage tank,
- Steam Generator Blowdown Treatment System,
- Boric acid regeneration and preparation system,
- Gas and gaseous waste treatment system.

The most widespread technology used to clean the operating fluids was **spent resin purification**. In this way, purifying waters with lower salt concentrations is practical. The purified waters are pumped through a spent resin mass filling (cation exchange resin, anion exchanger, other mixtures), where the undesirable impurities are collected. At the end of their service life, spent resins lose their filtering capacity and must be replaced. Spent resins are exported from the treatment system filters through transport water to storage tanks where they, together with spent activated carbon and other mechanical filter particles, form LRAW, referred to as radioactive sorbents. They are characterised by considerable heterogeneity and undergo further degradation over time, which is associated with changes in physical and chemical properties. **Figure 2** shows the radioactive sorbents immediately before their removal from the storage tanks and before their treatment.

Another method of purification of operating fluids contaminated with radionuclides is **distillation**, which is used to purify the liquid media with higher salinity. The principle is to evaporate a water solution, producing steam and a thickened residue (concentrate). After condensation, the steam is purified, and the condensate is returned to the process or discharged outside the NPP after control. The thickened residue - radioactive concentrate is stored as liquid RAW with a view to treatment by one of the solidification technologies. During prolonged storage, solid particles fall out of the saturated solution and form a sludge phase at the bottom of the tanks. Another phenomenon associated with the storage of radioactive concentrate is the formation of crystals on the walls and other structures of the storage tanks, which is caused by the high boric acid content. These facts significantly complicate further management of this type of waste. **Figure 3** shows the radioactive concentrates at the time immediately before their removal from the storage tanks and before their treatment.

Figure 2. Radioactive sorbents in the storage tank

Figure 3. Radioactive concentrates in the storage tank

3.3. Operational Liquid Radioactive Waste Management Process

Figure 4 shows a simplified process of managing operational liquid RAW. In the first phase of solving the problem of removing operational liquid RAW, specific projects were defined to characterise the relevant waste. These were the Bohunice International Decommissioning Support Fund (BIDSF) projects C7-D2 "Sampling, Analysis and Characterisation of “Wet Waste" (2005) [4] and C7-D3 "Sampling, Analyses and Characterisation of Ra-Sediments in Storage Tanks" (2005) [5]. The results of these projects were reflected in the subsequent assignment of the BIDSF C7-B project “Treatment of Historical Waste—Sludges and Sorbents” (2012-2015), which considered the available data related to the addition and removal of waste in storage tanks between the characterisation and treatment of the waste.

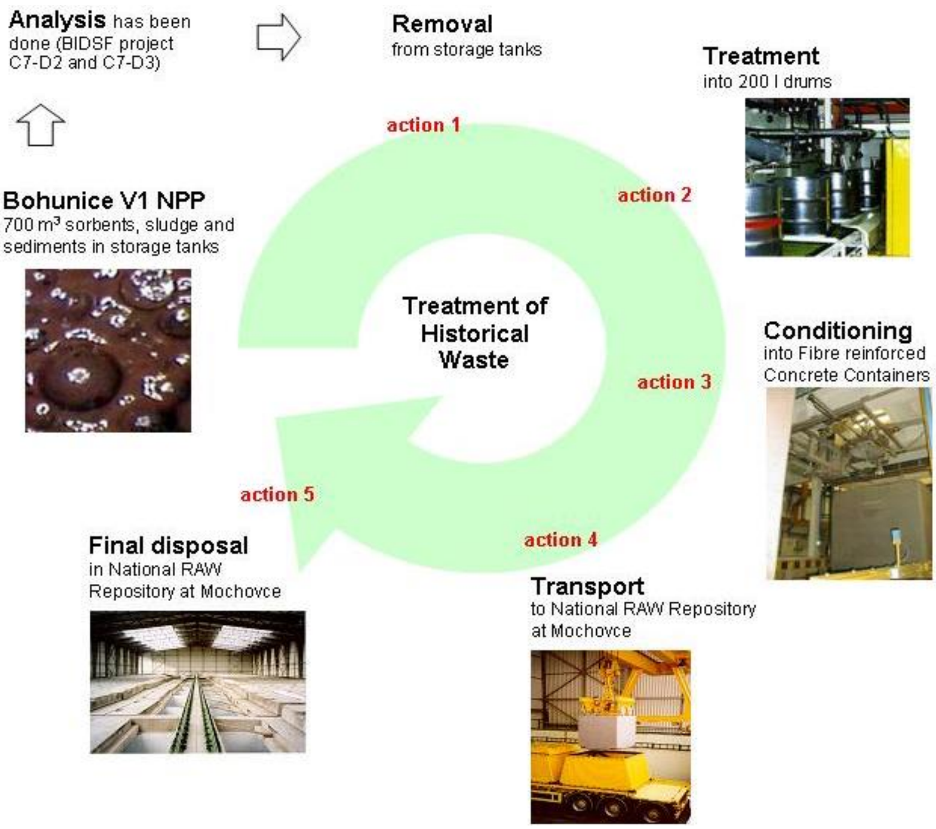

Figure 4. Process of operational liquid radioactive waste management

Based on the characterisation, the relevant liquid RAW was divided into two categories: (a) radioactive sorbents and (b) crystalline sediments and sludge, described as follows.

Category A waste - radioactive sorbents

They were stored in tanks ZT20N-1 to 4 in the V1 NPP auxiliary building (**Figure 5**—shown in red). They contained wet-absorbing materials from the cleaning equipment filters, such as resins, other radioactive sorbents (ceramsite, anthracite, and activated carbon), and other admixtures. These materials are stored as mixtures and contain other impurities. At the time of characterisation, the total amount of RAW in tanks ZT20N-1,2,3,4 was estimated at 439 m^3 (158 tons of dry mass).

The sludge share of radioactive resins represented more than 20%. The gamma activity of radioactive resins from V1 NPP reached values of up to $2x10^7$ Bq/kg.

Category B waste - crystalline sediments and sludge

They were stored in ZT10N-1 to 10 tanks in the V1 NPP auxiliary building (**Figure 5**– shown in yellow). They contain crystalline sediments from alkaline saturated solutions (liquid radioactive concentrate) with a total volume of 211 m^3 (140 tons of dry mass).

Almost half of category B waste (roughly 100 m^3) was fine sludge. The gamma activity of crystalline sediments and sludge ranged from 10^6 to 10^7 Bq/kg.

The predominant radionuclides in both types of liquid RAW were Co60 and Cs137.

Sampling, characterisation, and analysis of liquid RAW are always the first steps, as their results are used to select the appropriate treatment method and the further management of the final product produced.

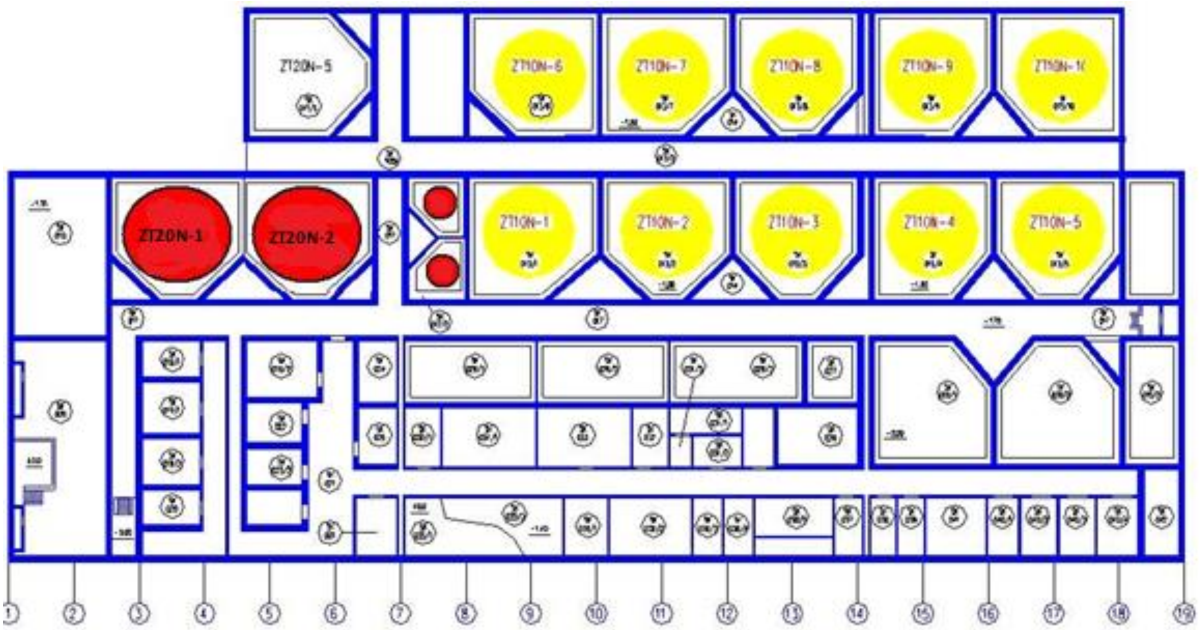

Figure 5. Liquid radioactive waste storage tanks in the V1 NPP auxiliary building

The actual removal of liquid RAW from the storage tanks and its treatment into solid form was carried out through the BIDSF C7-B project "Treatment of historical waste—sludges and sorbents" (2012-2015), implemented by contracting services.

Firstly, it was necessary to solve the removal of the liquid RAW from the storage tanks. This activity was carried out using a remotely controlled pumping device. In the case of crystalline sediments, it was first necessary to chemically dissolve these sediments.

This was followed by drainage, waste treatment and finally, fixation in an aluminosilicate matrix. Fixation occurred directly in a 200 L drum using a mobile fixation unit (**Figure 6**).

The following diagram (**Figure 7**) shows the basic phases of the operational liquid RAW treatment process at V1 NPP.

Figure 6. Mobile fixation unit

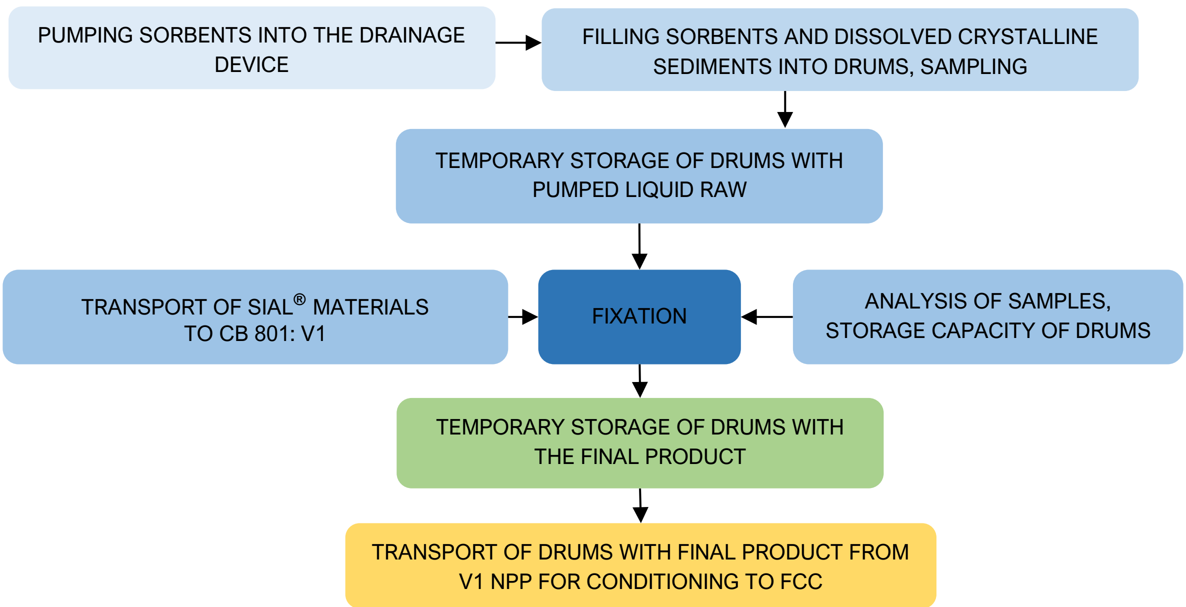

Figure 7. Basic diagram of the operational liquid radioactive waste treatment process

Produced drums with solidified RAW were subsequently loaded into fibre concrete containers (FCCs) at the JAVYS, a.s. facilities and filled with cement grout to form the final package form for RAW suitable for long-term disposal. The FCCs prepared this way were gradually transported and disposed of in disposal vaults at the NRR in Mochovce. Slovakia already had a National Radioactive Waste Repository before the V1 NPP decommissioning itself. Still, its capacity has been extended to meet the needs of RAW from the V1 NPP decommissioning. Expansion of the existing capacity of the NRR in Mochovce for disposal of produced Low-Level Waste (LLW) was implemented using the construction of new disposal facilities (3rd double-row, see **Figure 8**, **Figure 9**) within the BIDSF project C9.4 "Design and Erection of New Disposal Facilities for LLW and VLLW from V1 NPP Decommissioning at NRR Mochovce" (2016-2019) [6].

A country that carries out an NPP decommissioning project must ensure the entire liquid RAW management process, from its removal from storage tanks to processing into a solidified form, temporary storage, and conditioning into a form suitable for long-term disposal at a repository designated for a given type of RAW.

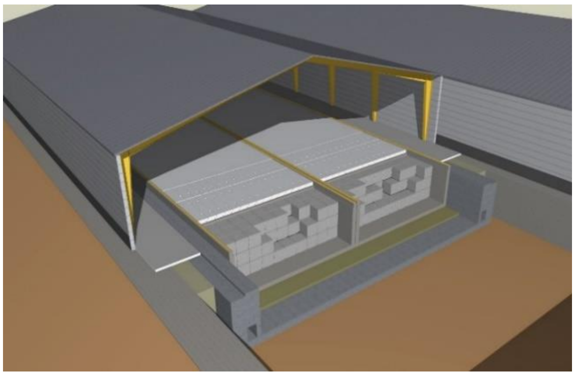

Figure 8. Concept – Disposal facility for LLW (3rd double-row)

Figure 9. Placing the FCC into the box (LLW repository)

Note: 3rd double-row was planned identically to the existing 1st double-row.

3.4. Technology Considerations

To implement the safest and least time-consuming treatment of operational liquid RAW, it is essential to choose a technological treatment process following the already approved procedures and restrictions. In our case, it was necessary to ensure that the final product after liquid RAW treatment corresponded to the approved package forms of RAW, which can be stored in the NRR in Mochovce.

According to JAVYS´s regulations, an FCC containing a precisely defined solidified RAW as a package form is designated for disposal at NRR. When processing liquid RAW, the matrix (cement, bituminous, aluminosilicate) in which the liquid RAW is homogeneously fixed is crucial. In this case, an aluminosilicate matrix was used (**Figure 10**). Each new package form of RAW is subject to a relatively demanding and lengthy process of approval by the regulatory authority after submitting the relevant safety analyses.

Choosing a liquid RAW treatment technology that assumes a new, unapproved packaged form of RAW prolongs the entire RAW treatment process through a demanding licensing process, including safety analyses, with the risk of the authorities disapproving the proposed package form.

The requirement of compliance of the proposed technology of liquid RAW treatment with the list of approved package forms of RAW was included in the assignment of the C7-B project "Treatment of Historical Waste – Sludges and Sorbents ". Based on this, it was possible to exclude technical proposals that did not correspond to the approved list of RAW package forms in procuring the C7-B project.

Figure 10. Liquid radioactive waste fixed in an aluminosilicate matrix in a 200 L drum

3.5. Logistic Considerations

In the frame of liquid RAW treatment, a special emphasis should be placed on minimising the amount of the final product (in this case, 200 L drums with fixed RAW). This requirement is stated in the current legislation of the Slovak Republic and relates to the costs of further conditioning and final disposal of RAW. The tender documents already considered this requirement to select the project contractor as an essential criterion for the proposals' assessment. As a result, the tenderers for the project had to calculate and state the expected number of drums produced with fixed RAW already in their proposal. When calculating the quantity of the final product, the tenderer had to consider several requirements, the most important of which are the following:

Physical requirements for the final product [7]

- Compressive strength >5 $N.mm^{-2}$ (MPa)
- Leachability index >6

Radiological requirements for the final product [7][8]

- To receive solidified RAW for cementation to FCC, the total volume activity $\beta + \gamma$ must be less than 2.10^{11} $Bq.m^{-3}$.
- For the reception of solidified RAW for cementation to FCC, the maximum mass activity of radionuclides emitting alpha radiation must not exceed the value of 4000 $Bq.g^{-1}$ in any place inside the package form.
- The obligation to declare and to comply with the max. content of monitored radionuclides in each drum with solidified RAW.

Transport requirements for the final product [9]

- **Standard transport conditions**: The dose rate at any point of the outer surface of the shipment cannot exceed **2 $mSv.h^{-1}$.**
- **Conditions of exclusive use**: The dose rate on the outer surface of the shipment cannot exceed **10 $mSv.h^{-1}$.**
- **Standard conditions of transport:** The dose rate at any point on the surface of the means of transport cannot exceed the value of **2 $mSv.h^{-1}$**, and at 2 m from the surface of the means of transport cannot exceed **0.1 $mSv.h^{-1}$**.

Based on the mentioned criteria, it was necessary to calculate the maximum weight of a dry mass of the liquid RAW, which can still be fixed in the packaging material to meet the requirements mentioned above for the final product. As part of the implementation of the liquid RAW treatment, it was necessary, from the point of view of minimising the amount of the final product, to consistently monitor and evaluate the amount of fixed dry mass of liquid RAW in each drum. Exceeding the quantity of the final product (number of drums) would have been, in terms of the contract, dealt with by penalising the Contractor, which would have represented the costs of conditioning and disposal of the final product produced in excess compared to the contractually determined quantity.

The requirements for the properties of the final product defined in the binding documentation significantly determine the method of liquid RAW treatment and the setting of the entire process. These requirements relate to the conditions for treating drums with fixed RAW, disposing of FCCs with RAW in the NRR in Mochovce, and the conditions for RAW transporting.

By applying and checking compliance with the above-mentioned specific requirements, the final product's number of drums and, thus, the associated costs for further conditioning and disposal were minimised.

3.6. Methodology Considerations

For the liquid RAW treatment process, it is necessary to define a quantity that will be used to quantify the waste objectively, both from the point of view of characterisation, processing, and production of the final product, as well as from the financial point of view.

For these purposes, the weight of the dry mass of liquid RAW was chosen as a relevant quantity. Dry mass is defined as the non-evaporable fraction in a liquid RAW sample. The dry mass was determined by evaporating the liquid portion from the weight of the sample, and the non-evaporable residue - dry matter - was calculated based on the difference in weight before and after drying. The samples were dried in a drying room heated to 105°C for 90 minutes, then cooled in a desiccator for 60 minutes and weighed on analytical scales with an accuracy of 0.001g.

The methodology for monitoring the weight of the processed dry mass of liquid RAW proved reliable and demonstrable for quantifying the liquid RAW treatment process. It was applied throughout the entire implementation of the C7-B.

3.7. Radiation Protection Considerations

Due to the relatively high activity of the processed liquid RAW (up to 10^7 Bq/kg), radiation protection was one of the most critical issues. The following text describes specific measures for optimising radiation protection when implementing the C7-B project "Treatment of Historical Waste—Sludges and Sorbents."

1 Workplace zoning

To prevent the uncontrolled spread of possible contamination with radioactive substances, the workplace of pumping and processing radioactive sorbents was divided into several zones depending on the dose rate level and the risk of contamination. All zones were clearly defined and marked (e.g., lined with foil of different colours, separated by pillars with a chain, etc.). At the entrance to the zone, tables were placed with the basic rules for the activities performed in the given zone. The division of the workplace into zones is shown in **Figure 11**.

Figure 11. Division of the workplace into zones

The colour marking of the zones was chosen as follows:

- **Green zone** – areas where only raw materials were handled, and no radioactive materials entered. Smearable contamination in these zones was limited to 0.3 Bq/cm^2.
- **Yellow zone** – areas in which manipulations were carried out, drums with pumped radioactive sorbents were temporarily stored before processing, or drums with the final product before transport from the auxiliary facilities building. In these zones, the drums were closed during handling. Smearable contamination in these zones was limited to 0.3 Bq/cm^2.
- **Green-yellow zone** – transport areas where clean raw materials were handled and the final product in 200 L drums. Between individual manipulations, the foil on the floor was changed so that the transport package forms were not contaminated with radioactive substances. Smearable contamination in these zones was limited to 0.3 Bq/cm^2.
- **Red zone** – areas where open drums filled with radioactive sorbents were handled (filling drums with drained sorbents or fixing sorbents into aluminosilicate matrix). In these zones, there is the highest risk of spreading contamination with radioactive substances. Smearable contamination in these zones was limited to 1 Bq/cm^2.
- **Blue zone** – premises where JAVYS employees performed works related to the sorting and storage of RAW. Smearable contamination in these zones was limited to 1 Bq/cm^2.

2 Establishment of sanitary premises

Sanitary premises were established where movement between zones with different radiation parameters was required. Sanitary premises were used to prevent the spread of possible contamination from zones with a higher risk of contamination to zones with a lower risk of contamination.

3 Floor covering with plastic foil

When possible, the floor of the zone was lined with plastic foil. The foil's level of contamination was regularly checked, and if it exceeded the monitored level, the film was replaced.

4 Separate use of PPE in individual zones

Separate Personal Protective Equipment (PPE) (e.g., gloves, overalls, etc.) were set aside in green zones, clearly distinguishable by colour or in some other way from the PPE used in other zones. This prevented possible uncontrolled contamination of the green zone by already-used PPE from different zones.

5 Separate manipulations in green-yellow zones

In green-yellow zones, the handling of input raw materials and the handling of the final product were carried out separately. Between individual manipulations, the level of smearable contamination of the floor or foil on the floor was checked. If the monitored level was exceeded, the foil was replaced.

6 Regular monitoring of surface contamination in zones

A precise monitoring program was established for the entire workplace, which included monitoring all zones, technological equipment, and transport package forms. The contractor's employees monitored the working environment. Monitoring protocols were available to the employer's radiation protection department employees, who independently monitored the working environment according to operating regulations.

7 Transport of drums with the final product

Before transporting drums with the final product from CB 801: V1, the contractor's employees monitored the smearable surface contamination and dose rate on the drums' surfaces. The monitoring protocol was handed over to the responsible employee of the V1 NPP radiation protection department, who issued a permit for the transport of drums from V1 NPP to the designated place.

8 Shielding of radiation sources

Concrete mobile shielding blocks (see **Figure 12**) minimised the dose load. During its fixation, it was mainly used to shield the drums with liquid RAW. Thus, the dose load of the worker dosing the aluminosilicate matrix and the fixation device operator was significantly reduced. Also, the sorbent pumping route from the ZT20N-1 tank was shielded with lead plates in the place where it passes through the control room of the sorbent pumping and drainage unit. A layer of 3.5 cm of lead shielded the drainage device from two sides, where the personnel moved during the standard work performance. During the most exposed activities (measuring the strength of drums with the final product, taking samples from drums, etc.), workers used special protective equipment, e.g., shielding vests, glasses, etc.

Figure 12. Drainage equipment shielding

9 Transport and handling means

For handling drums with pumped liquid RAW or with the final product, the following specific handling means were used to minimise receiving of individual effective doses:

- **Conveyor belt for transporting drums to the rotating jib crane**: used to move drums with fixed RAW to the rotating jib crane, from where they were grabbed without an operator and loaded onto the body of the transport vehicle. The facility's main goal was to minimise the receipt of individual effective doses when handling drums.
- **Conveyor belt for transporting drums with liquid RAW for fixation:** It transported drums with liquid RAW to the fixation facility, where the waste was fixed into an aluminosilicate matrix.
- **Rotating jib crane:** It loaded drums onto the body of the means of transport. The main goal of the crane was to eliminate the presence of service personnel during the drum loading and thereby minimise personal loads.
- **Concrete shielding placed on IVECO transport semi-trailer:** It shielded ionising radiation during the transport of drums with higher RAW activity so that the dose rate at 2 m met the required value (0.1 mSv/hour). The shielding was 15 cm thick and placed on the body of an IVECO semi-trailer.
- **Electric manually controlled trolley:** It was used to handle drums. The truck's design minimised the doses when handling drums with RAW.

Figure 13. Conveyor belt for transporting drums to the rotating jib crane

Figure 14. Conveyor belt for transporting drums with liquid RAW for fixation

Figure 15. Rotating jib crane

Figure 16. Semi-trailer with concrete shielding

Figure 17. Electric manually controlled trolley

3.8. Organisational Considerations

Even though the actual treatment of operational liquid RAW in this case was ensured by the contractor, the presence and participation of the employer's qualified employees played a key role, especially in the following areas:

1. **Project procurement:** preparing tender documents and selecting the project contractor.
2. **Licensing process:** support in developing a licensing plan and licensing documentation, communication with regulatory authorities, solving interfaces with other projects, etc.
3. **Operational constraints:** The operational staff monitored and minimised the impact of the preparation and implementation of liquid RAW treatment on ongoing V1 NPP operational activities.
4. **Nuclear safety:** monitoring the compliance of design and production of treatment facilities, prescribed facility tests and the treatment with nuclear safety requirements.
5. **Radiation safety:** approval of procedures from the point of view of radiation safety, monitoring of radiation doses, and supervision of compliance with radiation safety principles.
6. **Control of chemical regimes:** Some chemical analyses had to be performed in duplicate (by both the Contractor and the Employer) to validate and justify the results before the regulatory authority and the Employer. It was mainly about declaring liquid RAW's processed dry mass content and meeting the acceptance criteria at the NRR in Mochovce.

Even if the contractor treats operational liquid RAW itself, the D&WM operator must have qualified employees in procurement, licensing process, operation, nuclear safety, radiation safety, and control of chemical regimes.

3.9. Regulatory and Licensing Considerations

The following institutions were involved as regulatory authorities in the preparation and implementation of the operational liquid RAW treatment process:

1. NRA SR for supervision of nuclear safety,
2. Public Health Authority of the Slovak Republic (PHA SR) for supervision of radiation protection,
3. Ministry of Environment of the Slovak Republic (MoE SR) for environmental impact assessment.

These authorities issued permits for implementing relevant activities (14 decisions) and then supervised fulfilling the specified conditions.

From the point of view of obtaining the necessary permits, the open and transparent approach of the employer's responsible employees to the regulatory authorities, including preliminary consultations and the joint search for optimal procedures, has proven itself.

3.10. Quality Considerations

A Quality Assurance Plan was developed at the beginning of the project implementation, and quality management was maintained throughout the project. The Quality Assurance Plan defines:

1. **Responsibilities and powers:** The project's basic organisational structure, team members' competencies and responsibilities, and workers' qualifications requirements were defined.
2. **Method of communication:** The project team's communication method was determined. To ensure quality assurance in the project implementation process, the contractor prepared monthly progress reports and submitted them to the employer, which were discussed at regular monthly meetings.
3. **Management of documentation** required as part of project implementation.
4. **Technical documentation** developed during the project.
5. **Methods of project monitoring and control**

The quality system addressed all contractual conditions and the employer's requirements from the current situation during the project duration.

3.11. Results

In the frame of management of LRAW originating from the operation of V1 NPP in Jaslovské Bohunice, the following activities were carried out: the characterisation of LRAW (BIDSF Projects C7-D2, C7-D3); retrieval of LRAW from storage tanks and treatment of LRAW into solidified form in 200l drums (BIDSF Project C7-B); conditioning of final product via cementation into FCCs (at JAVYS's nuclear facility); transportation and final disposal of the produced FCCs in the NRR in Mochovce. The case study highlights some practical experiences obtained while preparing and implementing the C7-B Project - "*Treatment of Historical Waste – Sludges and Sorbents* ". These experiences concern the selection of LRAW treatment technology based on the results of characterisation and following approved package forms for final disposal, the requirement to minimise the volume of the final product while complying with applicable regulations and restrictions, the methodology for monitoring the amount of treated LRAW, measures to ensure radiation protection and other aspects of the process.

Project C7-B, "Treatment of Historical Waste – Sludges and Sorbents", was implemented from 15th June 2012 to 14th May 2015 (35 months). After obtaining the relevant permits from the regulatory authorities of the Slovak Republic, the contractor removed, modified, and processed into an approved solidified form all operational LRAW located in the storage tanks ZT20N-1 to 4 and ZT10N-1 to 10 in the V1 NPP auxiliary building. In total, 715 m^3 of liquid RAW containing 427 tons of dry mass were processed, while 5417 pieces of 200 L drums with liquid RAW fixed in an aluminosilicate matrix were produced [10]. After being conditioned into FCCs, these drums were gradually disposed of at NRR in Mochovce.

The contractor cleaned the storage tanks and handed them to the employer (see **Figure 18**). All activities within the project's scope (C7-B) were carried out safely without endangering worker's health or the environment.

Figure 18. Cleaned storage tanks

3.12. Benefits

The volume and properties of the wet operational waste differ according to the decommissioning project. Every decommissioning project must carry out its characterisation, decision on the treatment method, etc. However, the information and lessons learned in this case study provide benchmark information, and the lessons learned provide a basis to avoid errors and save time for more demanding decommissioning activities.

D&WM operators across Europe can obtain insights from JAVYS´s experience to ensure proper planning, management, and decision-making when addressing the wet operational waste of their NPP to be decommissioned/under decommissioning.

These insights and recommendations can provide specific benefits for subsequent decommissioning process, such as:

1. Development and regularly update through records of stored liquid RAW.
2. Continuous treatment of operational liquid RAW immediately after its generation prevents the degeneration of waste and the formation of sediments, as well as many complications in future removal, transport, and waste processing. At the same time, this saves funds for future characterisation and more financially demanding waste retrieval and processing.
3. Maintain the chemical regime in the storage tanks to prevent waste degradation and crystalline sediment formation.
4. Monitoring waste's radiological properties to minimise personal doses when handling waste and choosing a treatment method.
5. Equip storage tanks with a device for effective homogenisation of liquid RAW to take representative samples and obtain objective data on the state of the waste.

4. LESSONS LEARNED

This section summarises aspects, lessons learned, and recommendations verified in practice from the process of treating liquid RAW from the V1 NPP operation that have required special attention and that can generally significantly impact the feasibility of the process itself, whether from the technical, legislative, time or ultimately the financial point of view.

It is essential to take these aspects, lessons learned, and recommendations into account at the stage of preparing tender documents and selecting a contractor for the treatment of liquid RAW or the stage of planning for the future treatment of liquid RAW. JAVYS, a.s. recommends for other D&WM operators:

Planning and processes optimisation aspects

1 **Removing operational waste before decommissioning:** Operational LRAW should be removed before decommissioning is implemented.

2 **Accelerate waste treatment process:** Minimising the time interval between waste characterisation and treating LRAW is desirable.

3 **Prioritise waste analysis to treatment:** Sampling, characterisation, and analysis of LRAW are always the first steps in proper planning, as their results are used to select the appropriate treatment method and the final product.

4 **Waste classification and treatment:** The outcome of the characterisation should be a classification of radioactive liquid waste according to the treatment method.

5 **Dry mass weight as a key performance indicator: JAVYS, a.s. recommends monitoring the quantity of LRAW treated based on the "dry mass weight of LRAW."** Dry mass is the non-evaporable fraction in a sample of LRAW. The methodology for monitoring the dry mass weight of LRAW treated has proven reliable and demonstrable for quantifying the LRAW treatment process.

6 **Minimise the quantity of the final product:** To reduce the costs for further treatment and disposal, minimisation of final waste must be considered, in our case, 200 L drums with fixed RAW.

Decision-making processes aspects

1 **Outsource the waste management process?** The D&WM operator decides whether to process the LRAW into a fixed form within its capacity or by the contractor, prioritising efficiency.

2 **Always approved waste package forms:** JAVYS a.s. Recommends selecting the technology of LRAW treatment following the list of approved package forms for disposal in the designated repository. New or unapproved package forms of RAW significantly prolong the entire treatment process.

Radiation protection aspects

1 **Robotic devices:** The safe removal and transport of LRAW for further processing is a highly complex and sophisticated activity that significantly impacts the success of the entire process. To minimise the effective receipt of individual doses, robotic devices that do not require the presence of service personnel are recommended.

2 **ALARA optimisation:** Optimising radiation protection during transport and treatment of liquid RAW is essential. This document provides an overview of the measures to optimise radiation protection applied during the implementation of the C7-B project "Treatment of historical waste—sludges and sorbents" of the Bohunice Programme.

Organisational recommendations

1 **Operator's qualified personnel:** Even if the contractor implements the actual treatment of the operational LRAW (outsourced), the D&WM operator must have competent staff in the procurement, licensing, operation, nuclear safety, radiation safety, and chemical regimes control areas.

Licensing and regulatory aspects

1 **Engage with the regulator:** In terms of obtaining the necessary licenses/permits, the employer's responsible staff's open and transparent approach towards the regulatory authorities, including prior consultation and joint search for optimal procedures, has proven helpful.

This case study contains recommendations for D&WM operators and nuclear operators that may be implemented during plant operation.

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