

Article

Physicochemical and Gamma-Spectrometric Characterization of Legacy Liquid Radioactive Waste from the BN-350 Reactor Facility

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Abstract

Legacy liquid radioactive waste (LRW) from the BN-350 sodium-cooled fast reactor is chemically heterogeneous and requires updated characterization for further management. This study investigated the physicochemical properties and gamma-emitting radionuclide composition of 13 LRW samples collected from four tanks (B-02/1, B-02/2, B-02/5, and B-02/6) at surface (“mirror”), middle, and lower levels. Five samples were analyzed as LRW and eight as evaporated LRW residues. Physicochemical analysis included pH, density, dry residue, alkalinity, and major inorganic components. Portable gamma spectrometry was applied to all samples, and laboratory HPGe measurements were performed for selected aqueous LRW samples. The saline LRW samples were strongly alkaline and highly mineralized, with dry residue values of 139.30–295.10 g/dm³. Tank B-02/6 contained distinct oil-containing, emulsion, and carbonate-rich alkaline aqueous phases. ¹³⁷Cs was the dominant identified gamma-emitting radionuclide, with specific activities ranging from $(1.4 \pm 0.3) \times 10^5$ to $(1.1 \pm 0.2) \times 10^8$ Bq/kg in liquid samples and up to $(6.5 \pm 1.3) \times 10^8$ Bq/kg in evaporated residues. The results show that BN-350 LRW is not a homogeneous waste stream; therefore, future monitoring, retrieval, treatment, and conditioning should be planned according to matrix type, sampling depth, vertical phase heterogeneity, and ¹³⁷Cs-dominated radiological characteristics.

Keywords: BN-350 sodium-cooled fast reactor; liquid radioactive waste; gamma spectrometry; ¹³⁷Cs



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1. Introduction

The management and characterization of accumulated radioactive waste remain essential tasks for countries that have operated early generation nuclear facilities. This issue is particularly important for sodium-cooled fast reactors, where operational and decommissioning waste differ substantially from those generated by conventional water-cooled power reactors. In addition to activated structural materials and contaminated technological systems, fast reactor facilities may contain sodium residues, sodium-contaminated equipment, highly alkaline process solutions, evaporator concentrates, sludges, and oil-containing radioactive liquids. The chemical complexity of these wastes directly affects the sampling strategy, radionuclide inventory assessment, conditioning route selection, and the long-term performance of the final waste form [1–3].

The BN-350 reactor facility in Aktau, Kazakhstan, is one of the most important examples of early industrial sodium-cooled fast reactor technology. The reactor was commissioned in 1973 and operated as part of the Mangyshlak Atomic Energy Combine, providing electricity, heat, and energy for seawater desalination. Beyond its regional importance, BN-350 represented a major technological step in the industrial development of sodium fast reactors and provided operational experience that later supported the development of subsequent BN-type reactor systems [4]. After permanent shutdown in 1999, the BN-350 reactor entered the decommissioning stage. Owing to its design features and accumulated radioactive materials, the decommissioning program was divided into several major directions, including spent nuclear fuel management, radioactive sodium management, solid radioactive waste (SRW) management, LRW management, and the preparation of reactor buildings and engineering systems for a safe state [5–7].

Several components of the BN-350 decommissioning program have already been considered in the scientific literature. Previous studies have reviewed the overall history and current status of the reactor decommissioning process [5], analyzed the condition and long-term safety of spent nuclear fuel [8], and assessed the quantity, classification, and processing prospects of accumulated SRW [9]. Recent radiological characterization of solid SRW samples from the BN-350 reactor also showed that ^{137}Cs is the dominant gamma-emitting radionuclide [10]. These studies form an important basis for the overall decommissioning strategy. However, the LRW accumulated at the BN-350 reactor facility remains less systematically described in terms of its current physicochemical state, heterogeneity, stratification behavior, and gamma-spectrometric characteristics.

LRW from the BN-350 reactor facility was formed during reactor operation and subsequent decommissioning-related activities. Its sources include decontamination solutions, washing water from the equipment and premises, secondary liquid waste from radioactive waste treatment systems, solutions associated with operations on residual sodium-containing systems, and waste streams from auxiliary technological systems. As a result, the accumulated LRW inventory is not a single homogeneous liquid phase but a complex set of alkaline saline solutions, evaporator concentrates, sludges, ion-exchange and diatomite pulps, and oil-containing radioactive waste. Earlier assessments indicated that BN-350 LRW included cubic residues, diatomite and ion-exchange pulps, and related liquid waste streams, with ^{137}Cs forming the main contribution to the activity [5].

Previous BN-350 LRW studies were primarily aimed at developing treatment technologies [11,12] rather than at providing an updated characterization of the waste after long-term accumulation. Early work on evaporator concentrate decantates showed that ^{137}Cs was the dominant radionuclide, while ^{60}Co and ^{54}Mn also influenced the selection of treatment processes [11]. Because selective sorption alone was insufficient for complete decontamination of some decantates, pretreatment by ozonation and filtration followed by ion-selective sorption was proposed [12]. Later studies considered several processing routes for BN-350 LRW, including ion-selective purification of evaporator concentrate decantates combined with cementation of other waste streams, COREBRICK technology, and joint cementation of all LRW types [13]. These works provided important technological concepts, but they did not fully resolve the need for present-day experimental data on real stratified LRW samples.

The need for updated characterization is reinforced by LRW's known behavior during long-term accumulation in tanks. High salt content, strong alkalinity, suspended solids, sludge formation, and organic or oil-containing phases can lead to stratification and phase separation. Such processes may change the distribution of radionuclides with depth and complicate representative sampling. In addition, the chemical matrix strongly affects future treatment and conditioning: high-salt alkaline solutions may influence sorption

efficiency, cement hydration, waste loading, leaching behavior of ^{137}Cs , and the mechanical performance of cementitious or alternative waste forms [2,3,14]. Experience from other decommissioning projects, including Ignalina NPP, also shows that the selection and optimization of LRW treatment technologies require detailed knowledge of waste composition, salt content, resin or perlite content, and package quality criteria [15].

Gamma spectrometry is one of the most widely used methods for identifying and quantifying gamma-emitting radionuclides in radioactive waste because it is non-destructive, sensitive, and capable of simultaneous radionuclide detection. For legacy LRW, however, gamma-spectrometric characterization can be complicated by high activity, matrix effects, sample heterogeneity, and the dominance of a single radionuclide, such as ^{137}Cs . In highly contaminated samples, the intense 661.6 keV gamma emission of ^{137}Cs and the associated Compton continuum may limit the detection of other gamma-emitting radionuclides at lower energies. Therefore, the combination of field gamma-spectrometric screening with laboratory high-resolution HPGe measurements is an appropriate approach for obtaining both operational and analytical information on LRW samples.

In this study, legacy LRW and oil-containing radioactive waste samples from the BN-350 reactor facility were investigated using physicochemical analysis and gamma spectrometry. A total of 13 samples were collected from four tanks at different sampling levels, including upper, middle, and lower layers, in order to account for possible stratification. The physicochemical characterization included measurements of pH, density, electrical conductivity, dry residue, alkalinity, and major inorganic components. Gamma-spectrometric measurements were performed using a portable Trans-SPEC-DX-100T gamma spectrometer (AMETEK ORTEC Inc., Oak Ridge, TN, USA) for preliminary in-situ assessment and a high-resolution Canberra BE5030 HPGe detector system (Canberra Industries, Inc., Meriden, CT, USA) for laboratory analysis of selected samples.

The objective of this work is to provide updated experimental data on the physicochemical properties and gamma-emitting radionuclide composition of BN-350 LRW after long-term accumulation. The results are intended to clarify the current state of the investigated waste streams, evaluate differences between saline aqueous solutions and oil-containing waste matrices, identify the dominant gamma-emitting radionuclides, and support further decisions regarding representative sampling, monitoring, treatment, conditioning, and safe long-term management of LRW from the BN-350 reactor facility.

2. BN-350 LRW Tanks and Sampling Strategy

2.1. LRW Tanks in Building 157

Liquid radioactive waste (LRW) generated during operation and decommissioning-related activities of the BN-350 reactor facility is accumulated in Building 157, which contains ten tanks for long-term LRW storage [16–18]. According to national reports and facility documentation, these tanks form the main BN-350 LRW accumulation system and include reinforced-concrete reservoirs lined with stainless steel of austenitic–ferritic grade 12Cr21Ni5 (EI811). The tanks have volumes ranging from approximately 170 to 1100 m³ and were designed to receive and store radioactive waste of different physicochemical types. The LRW accumulated at the BN-350 reactor facility originates from several technological sources, including solutions generated during sodium-residue removal and decontamination, secondary liquid waste from radioactive waste treatment systems, and wastewater from sanitary locks, special laundry, laboratories, and auxiliary systems.

Building 157 contains ten tanks of three main types: B-01, B-02, and B-03 (Figure 1). Tanks B-01/1 and B-01/2 are intended for spent ion-exchange resins and filter pulps and are equipped with a bottom drainage layer for the removal of clarified solutions. The

useful volume of each B-01 tank is 840 m³, excluding the drainage layer; B-01/1 is currently drained and non-leak-tight, while B-01/2 is considered a reserve tank.

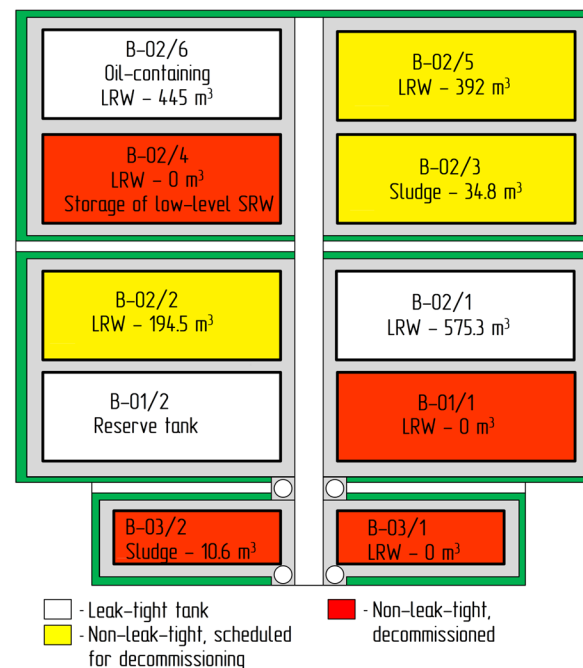


Figure 1. Scheme of the BN-350 LRW tanks in Building 157 with indications of filled volumes.

Six tanks, B-02/1–B-02/6, are intended for evaporator concentrates from the second evaporator unit. The total volume of each tank is 1056 m³, and the useful volume is approximately 1000 m³. Tanks B-02/1 and B-02/6 are leak-tight, whereas tanks B-02/2, B-02/3, and B-02/5 are non-leak-tight and scheduled for decommissioning. Tank B-02/4 is dry after repairs and currently contains SRW. Tank B-02/6 differs from the other B-02 tanks because it contains oil-containing radioactive waste in the upper part and alkaline aqueous solution in the lower part, with approximately comparable phase volumes. Two tanks, B-03/1 and B-03/2, are intended for evaporator concentrates from the first evaporator unit. The total volume of each tank is 180 m³, and the useful volume is 160 m³. Tank B-03/1 is drained and not leak-tight.

The main volume of accumulated BN-350 LRW is represented by saline solutions, while ion-exchange pulps and organic radioactive waste in the form of spent oils are present in smaller quantities. As of 24 July 2023, approximately 1650 m³ of different types of BN-350 LRW were accumulated in Building 157. This inventory includes chemically different aqueous saline and oil-containing waste matrices, which are important for sampling, analysis, and subsequent treatment selection.

2.2. Waste Types and Selected Tanks

The selection of tanks for sampling was based on the actual waste types present in Building 157 and the need to characterize the main LRW matrices. Since most of the accumulated BN-350 LRW is represented by saline evaporator concentrates, tanks B-02/1, B-02/2, and B-02/5 were selected as representative alkaline saline LRW objects. Tank B-02/6 was included because it contains a different matrix: oil-containing radioactive waste, polyphenylmethylsiloxane (PFMS), water–oil emulsion, and an alkaline aqueous solution.

Thus, four tanks were selected for sampling: B-02/1, B-02/2, B-02/5, and B-02/6. Together, these tanks cover the two principal waste groups considered in this study: inorganic aqueous LRW and organic/oil-containing radioactive waste. This selection is important because these waste types differ in origin, physical state, chemical composition,

and expected behavior during filtration, dilution, gamma-spectrometric analysis, sorption, and conditioning.

2.3. Sampling Levels and Sample Identification

Because the LRW has been accumulated in the tanks for a long period, vertical heterogeneity and phase separation were expected. In this study, vertical heterogeneity refers to differences in waste composition within a tank caused by long-term settling, phase separation, or the accumulation of oil-containing phases near the surface. Therefore, samples were collected from three conditional levels: the surface (“mirror”), middle level, and lower level. This approach allowed a comparison of physicochemical properties and radionuclide distribution as a function of sampling depth.

A total of 13 samples were collected from four tanks. The volume of each sample was 1 L. Based on sampling conditions, waste state, and transport requirements, five samples were transported in liquid form, while eight samples were evaporated to dryness before transportation. In this work, the latter are referred to as evaporated LRW residues because they were prepared from liquid waste samples and should not be interpreted as independently generated SRW. This approach was selected because the total activity of the collected samples reached 612 MBq/L in terms of ^{137}Cs , and transport of such radioactive liquid waste requires special justification and packaging. The main characteristics of the collected samples are summarized in Table 1.

Table 1. Characteristics of BN-350 LRW samples collected from Building 157.

Tank	Sampling Location	Volume of Liquid Samples, dm ³	Number of Evaporated LRW Residues	^{137}Cs Activity of Liquid Samples, MBq/L	^{137}Cs Activity of Evaporated LRW Residues, MBq/L
B-02/1	Surface (“mirror”)	0	1	—	89.04
	Middle level	0	1	—	102.60
	Lower level	0	1	—	132.00
B-02/2	Surface (“mirror”)	0	1	—	39.31
	Middle level	0	1	—	38.26
	Lower level	1	—	19.63	—
B-02/5	Surface (“mirror”)	0	1	—	30.04
	Middle level	0	1	—	122.90
	Lower level	1	—	22.11	—
B-02/6	Surface (“mirror”)	1	—	0.06	—
	Middle level	1	1	6.93	6.93
	Lower level	1	—	2.53	—
Range	—	5	8	51.26	561.07
Permitted limit	—	—	—	up to 60	up to 600

The collected sample set included three evaporated LRW residues from tank B-02/1, two evaporated LRW residues and one liquid sample from tank B-02/2, two evaporated LRW residues and one liquid sample from tank B-02/5, and three liquid samples from tank B-02/6. The B-02/6 samples are particularly important because they represent different physical phases: oil-containing material from the surface layer, emulsion or intermediate material from the middle level, and alkaline aqueous liquid from the lower level. The location and operational status of these tanks are shown in Figure 2.

The total activity of the liquid samples was 51.26 MBq/L, while the total activity of the evaporated LRW residues was 561.07 MBq/L. These values did not exceed the transport

limits used for the selected packaging approach: up to 60 MBq/L for liquid samples and up to 600 MBq/L for evaporated LRW residues.

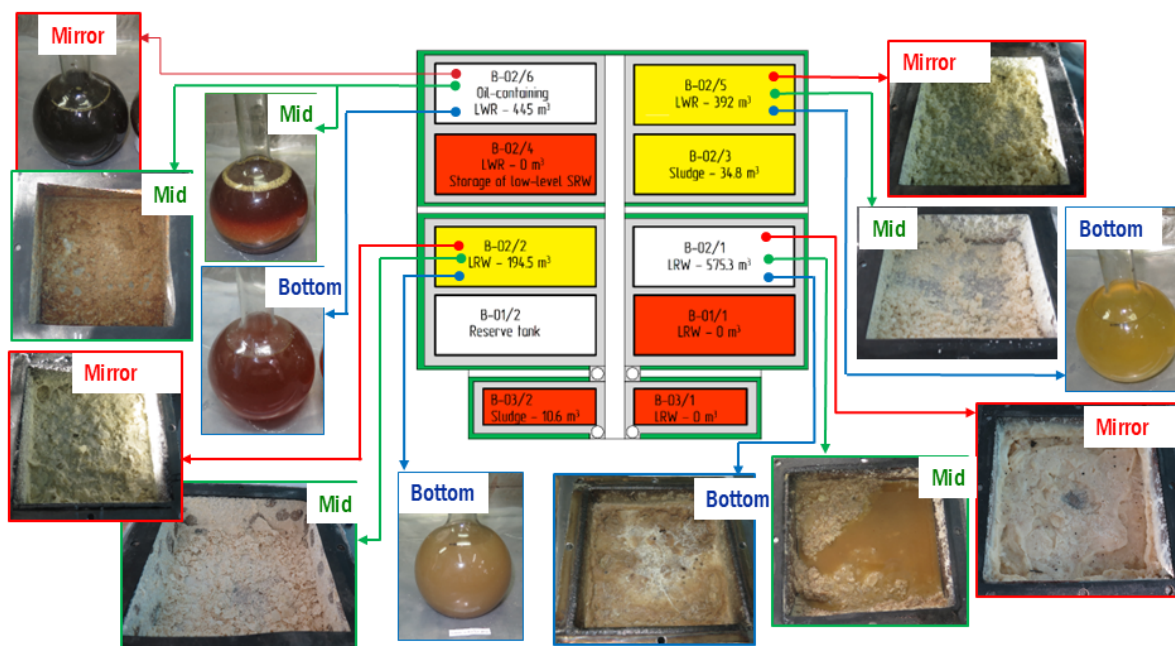


Figure 2. Appearance of collected BN-350 LRW samples with indications of sampling locations.

3. Materials and Methods

3.1. Sample Transport and Preparation

After sampling, the collected BN-350 LRW samples were prepared for transportation to the National Nuclear Center of the Republic of Kazakhstan for subsequent physicochemical and gamma-spectrometric characterization. The transport packages and vessels used for LRW samples and evaporated LRW residues are shown in Figure 3. Because not all collected LRW samples could be transported in liquid form under the available packaging conditions, two preparation approaches were used: five samples were transported as liquids, whereas eight samples were evaporated to dryness before transportation. As defined in Section 2, these samples are referred to as evaporated LRW residues and should not be confused with independently generated SRW.

For liquid samples, an excepted package was designed and manufactured as a utility model patented in the Republic of Kazakhstan [19]. The package included a transport container with five cylindrical vessels for LRW samples, sealed lids, and a fixation system. The free space between the vessels and the container walls was filled with sorbent material. Radiation safety calculations showed that transportation of the five LRW samples required additional shielding; therefore, a 20 mm lead shield was included in the package design. Under these conditions, the calculated gamma dose rate on the external surface of the package did not exceed 5 $\mu\text{Sv/h}$ above the natural background level.

Before physicochemical analysis, LRW samples were homogenized and then filtered through paper filters to remove suspended particles. Evaporated LRW residues were reconstituted with distilled water before analysis using the amount of water corresponding to the nominal original sample volume (1 L) for each residue obtained from the corresponding LRW sample. This procedure was intended to transfer the soluble fraction of the evaporated residue into the aqueous phase and to provide a consistent basis for comparison with the original LRW samples. It should not be interpreted as a complete restoration of volatile components, separated oil phases, or all insoluble/suspended material originally present in the waste. After reconstitution, the samples were filtered before physicochemical analysis;

therefore, the reported chemical composition refers to the reconstituted aqueous phase used for analysis. Samples intended for gamma-spectrometric analysis were transferred into standard measurement vessels and labeled according to sample type, tank number, and sampling level. The mass of each measurement sample was recorded before analysis.

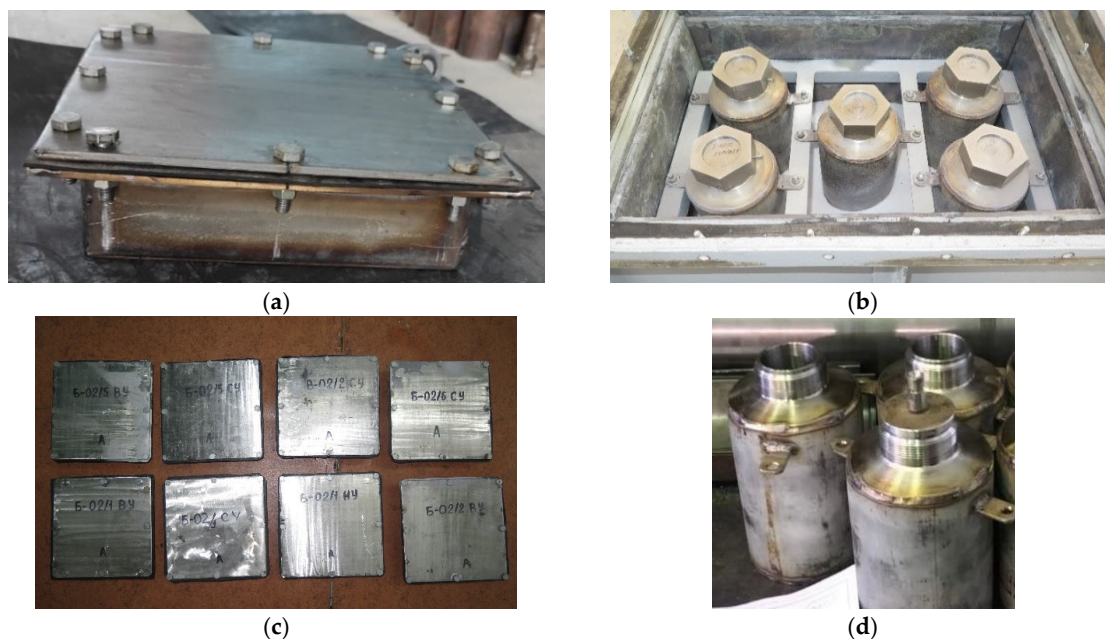


Figure 3. Transport package for radioactive waste: (a,b) containers for transportation of vessels with evaporated LRW residues and LRW samples, respectively; (c,d) vessels with evaporated LRW residues and LRW samples, respectively.

3.2. Physicochemical Analysis

Physicochemical characterization was performed for LRW samples and aqueous solutions prepared from evaporated LRW residues. The analyzed parameters included pH, dry residue, electrical conductivity, density, chlorides, alkalinity, sulfates, nitrites, nitrates, bicarbonates, and oxalates. These parameters were selected to describe the chemical matrix of the waste and to support the comparison of saline aqueous LRW and oil-containing radioactive waste.

The physicochemical analysis was performed using standardized methods based on GOST standards. According to GOST 26449.1-85 [20], dry residue, density, chlorides, alkalinity, sulfates, and bicarbonates were determined. Dry residue was determined gravimetrically according to GOST 26449.1-85 by evaporation of a filtered aliquot of the test solution, drying at 160 °C, and subsequent weighing to constant mass. According to GOST 33045-2014 [21], nitrites and nitrates were measured. Oxalates were determined according to GOST 22180-76 [22]. Additionally, pH was determined using universal indicator paper, and electrical conductivity was measured using the conductometric method.

In this study, the term “dry residue” is used only as a physicochemical parameter expressed in g/L. It should not be confused with evaporated LRW residues, which are prepared from selected liquid samples for transportation and analysis.

3.3. Portable In Situ Gamma-Spectrometric Measurements

Preliminary identification of gamma-emitting radionuclides and determination of their specific activity were carried out at the temporary storage location of the waste containers using a portable Trans-SPEC-DX-100T gamma spectrometer. Before sample measurements, a background spectrum was recorded at the measurement location. Energy and efficiency

calibration of the spectrometer were performed using bulk reference sources RgU, RgTh, RgK, and OMACH with certified activities of ^{137}Cs , ^{152}Eu , and ^{241}Am .

Qualitative analysis of the gamma spectra was performed using Maestro software (<https://www.ortec-online.com/products/software/maestro-mca>, accessed on 4 August 2026). Quantitative analysis of the identified radionuclides was carried out using Anal-Gamma software (Institute of Nuclear Physics, Almaty, Kazakhstan). The measurement time for each sample ranged from 2 to 5 min, depending on the count rate and spectrum accumulation conditions. Measurements were performed at source-to-detector distances of up to 425 mm, selected according to sample activity and the loading of the digital multichannel analyzer.

The sample masses and sampling locations used for portable gamma-spectrometric measurements are presented in Table 2.

Table 2. Samples used for portable gamma-spectrometric measurements.

No.	Sample Name	Sampling Location	Mass, g
1	LRW No. 1	Tank B-02/2, lower level	107.86
2	LRW No. 2	Tank B-02/5, lower level	101.11
3	LRW No. 3	Tank B-02/6, surface (“mirror”)	79.89
4	LRW No. 4	Tank B-02/6, middle level	84.03
5	LRW No. 5	Tank B-02/6, lower level	65.66
6	Evaporated LRW residue No. 1	Tank B-02/1, surface (“mirror”)	26.19
7	Evaporated LRW residue No. 2	Tank B-02/1, middle level	34.49
8	Evaporated LRW residue No. 3	Tank B-02/1, lower level	23.23
9	Evaporated LRW residue No. 4	Tank B-02/2, surface (“mirror”)	7.45
10	Evaporated LRW residue No. 5	Tank B-02/2, middle level	10.35
11	Evaporated LRW residue No. 6	Tank B-02/5, surface (“mirror”)	10.32
12	Evaporated LRW residue No. 7	Tank B-02/5, middle level	9.77
13	Evaporated LRW residue No. 8	Tank B-02/6, middle level	3.95

3.4. Laboratory HPGe Gamma-Spectrometric Measurements

Laboratory γ -spectrometric measurements were performed for selected LRW samples using a high-resolution γ -spectrometric system consisting of a BE5030 high-purity germanium detector with a DSA1000 spectrum analyzer (Canberra Industries, Inc., Meriden, CT, USA) and Genie-2000 software version 3.3. Measurements were carried out in standard measurement vessels with fixed geometries. To reduce the contribution of natural background radiation, the detector and the measured sample were placed inside lead shielding.

Because of the high activity of the original LRW samples, selected samples were diluted in 5% high-purity nitric acid before laboratory measurements. The dilution scheme is presented in Table 3. Samples LRW No. 3 and LRW No. 4 from tank B-02/6, corresponding to the surface and middle levels, represented oil-containing radioactive material. These samples did not dissolve or become diluted in the nitric acid medium; therefore, laboratory HPGe measurements using this preparation approach were not performed for them. Table 4 shows the dilution scheme for laboratory HPGe gamma-spectrometric measurements.

Table 3. Selected samples used for portable gamma-spectrometric measurements.

No.	Sample Name	Sampling Location	Dilution of Original Sample	Final Volume, mL
1	LRW No. 1	Tank B-02/2, lower level	1/2500	50
2	LRW No. 2	Tank B-02/5, lower level	1/2500	50
3	LRW No. 5	Tank B-02/6, lower level	1/500	50

Table 4. Chemical composition of analyzed alkaline saline LRW samples from the BN-350 reactor facility.

No.	Sampling Location	Dry Residue, g/dm ³	Alkalinity, mol/dm ³	Chlorides, g/dm ³	Sulfates, g/dm ³	Carbonates, g/dm ³	Bicarbonates, g/dm ³	Oxalates, g/dm ³	Silicates, g/dm ³	Fe, g/dm ³	Nitrites, g/dm ³	Nitrates, g/dm ³	NH ₄ ⁺ , g/dm ³	Density, g/cm ³
1	B-02/2, lower level	145.00	0.31	19.96	6.40	2.48	14.11	3.97	2×10^{-6}	0.02	34.25	42.20	0.25	1.12
2	B-02/5, lower level	139.30	0.25	32.93	6.40	0.11	1.71	3.86	0.02	<0.01	22.75	48.65	<0.01	1.13
3	B-02/6, lower level	295.10	2.40	0.56	6.78	132.00	<0.01	5.19	2×10^{-6}	0.01	0.88	1.66	1.30	1.10

Energy and efficiency calibration of the HPGe spectrometer were performed using bulk reference sources RgU, RgTh, RgK, and OMACH with certified activities of ^{137}Cs , ^{152}Eu , and ^{241}Am . Qualitative and quantitative analyses of the gamma spectra were performed using Genie-2000 software. The counting time for each sample was 30 min.

Portable gamma-spectrometric measurements were used for rapid screening of all LRW samples and evaporated LRW residues, while laboratory HPGe measurements were used for high-resolution confirmation of selected aqueous LRW samples. This combination provided operational screening data for the full sample set and confirmatory high-resolution data for selected LRW samples.

4. Results and Discussion

4.1. Physicochemical Characteristics of LRW Samples

The physicochemical characterization showed that the investigated BN-350 LRW samples include alkaline saline LRW and oil-containing LRW. The alkaline saline LRW samples had pH values above 12 and contained substantial amounts of dissolved salts; therefore, they should be considered concentrated alkaline saline radioactive waste rather than dilute aqueous radioactive waste. Several samples had a light-yellow color (Figure 2), which was associated with the presence of stable oil emulsions. The oil-containing LRW samples from tank B-02/6 were visually and physically different from the alkaline saline LRW samples, and they represented viscous alkaline liquids with pH values above 10.8.

The chemical composition of the analyzed alkaline saline LRW samples is given in Table 4. These samples correspond to the lower levels of tanks B-02/2, B-02/5, and B-02/6. The dry residue ranged from 139.30 to 295.10 g/dm³, confirming the high salt content of the waste matrix. The lower-level samples from B-02/2 and B-02/5 had comparable dry residue values of 145.00 and 139.30 g/dm³, respectively. In contrast, the lower-level sample from B-02/6 had a substantially higher dry residue of 295.10 g/dm³ and alkalinity of 2.40 mol/dm³.

The chemical composition shows clear matrix differences between the selected tanks. The lower-level alkaline saline LRW samples from B-02/2 and B-02/5 are characterized by high chloride, nitrite, and nitrate concentrations, which are typical of evaporator-concentrate-type LRW. In contrast, the lower-level alkaline saline sample from B-02/6 contains a high carbonate concentration of 132.00 g/dm³, low chloride content, and low nitrate/nitrite concentrations. This indicates that the lower aqueous phase of B-02/6 is chemically different from the evaporator-concentrate samples from B-02/2 and B-02/5.

The oil-containing LRW samples from B-02/6 also differed from the alkaline saline LRW samples (Table 5). The surface sample had a density of 0.875 g/cm³ and a kinematic viscosity of 63.10 mm²/s, while the middle-level sample had a density of 1.03 g/cm³ and a kinematic viscosity of 1.35 mm²/s. The middle-level sample was identified as a stable oil–water emulsion. The pH values of the aqueous extracts were 10.78 for the surface sample and 13.44 for the middle-level sample.

Table 5. Characteristics of oil-containing LRW samples from tank B-02/6.

No.	Sampling Location	Density, g/cm ³	Kinematic Viscosity, mm ² /s	pH of Aqueous Extract	Notes
1	B-02/6, surface (“mirror”)	0.875	63.10	10.78	Oil-containing phase
2	B-02/6, middle level	1.03	1.35	13.44	Stable oil–water emulsion

These results confirm that B-02/6 contains vertically differentiated waste phases: an oil-containing surface layer, a stable oil–water emulsion at the middle level, and a

concentrated alkaline carbonate solution at the lower level. Therefore, B-02/6 cannot be characterized by a single averaged sample and should be considered a heterogeneous multiphase waste matrix.

According to the initial chemical and radiological data [11,16], B-02/1, B-02/2, B-02/3, and B-02/5 contain evaporator concentrates from the second evaporator unit, with dry residue values generally ranging from 120 to 400 g/L and ^{137}Cs activity from approximately 39 to 516.5 MBq/L, depending on the tank and sampling level. In contrast, B-02/6 includes an oil phase at the surface and alkaline liquid at lower levels, with lower reported ^{137}Cs activity in the oil-containing phase and a substantially different chemical composition. The full tank-wide dataset is provided in Appendix A, Table A1.

Thus, the physicochemical data show that BN-350 LRW should not be treated as a single homogeneous waste stream. The samples from B-02/2 and B-02/5 represent nitrate–chloride alkaline saline LRW, whereas B-02/6 contains oil-containing, emulsion, and carbonate-rich alkaline phases. This distinction is important for further treatment because technologies suitable for nitrate–chloride saline LRW may not be directly applicable to oil-containing or emulsion-type radioactive waste.

4.2. Gamma-Spectrometric Characterization

Gamma-spectrometric measurements were performed for all five LRW samples and eight evaporated LRW residues. The spectra showed that the gamma-emitting activity of the investigated samples was dominated by ^{137}Cs . A typical spectrum obtained using the portable gamma spectrometer is shown in Figure 4. The main full-energy peak corresponds to the 661.6 keV gamma line of ^{137}Cs . Peaks associated with ^{214}Bi , ^{228}Ac , and ^{40}K were attributed to natural background radiation.

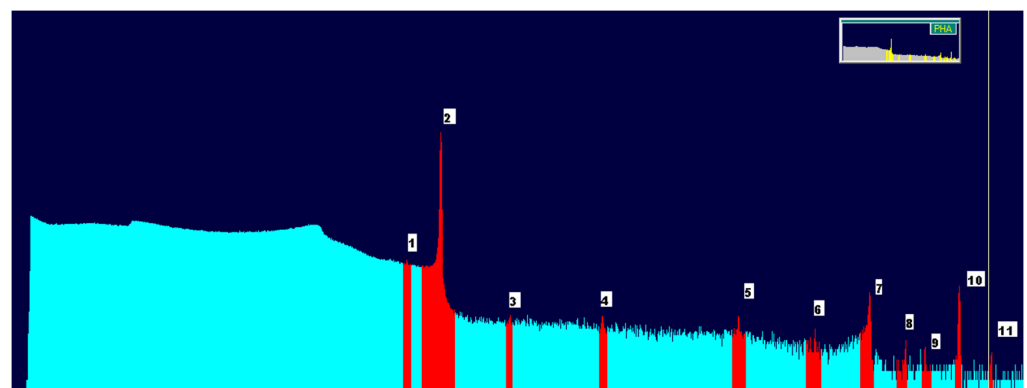


Figure 4. Typical gamma spectrum of BN-350 LRW samples and evaporated LRW residues. Peak assignment: 1—609 keV, ^{214}Bi background; 2—661.6 keV, ^{137}Cs ; 3—768 keV, ^{214}Bi background; 4—911 keV, ^{228}Ac background; 5—1120 keV, ^{214}Bi background; 6—1238 keV, ^{214}Bi background; 7—1323.2 keV, summing peak caused by ^{137}Cs gamma radiation; 8—1378 keV, ^{214}Bi background; 9—1408 keV, ^{214}Bi background; 10—1460.8 keV, ^{40}K background; 11—1509 keV, ^{214}Bi background.

The ^{137}Cs -specific activities determined using the portable gamma spectrometer are summarized in Table 6. Among the LRW samples, the highest activities were measured in the lower-level alkaline saline LRW samples from B-02/2 and B-02/5: $(1.0 \pm 0.2) \times 10^8$ and $(1.1 \pm 0.2) \times 10^8$ Bq/kg, respectively. In contrast, the surface oil-containing LRW sample from B-02/6 had a much lower ^{137}Cs -specific activity of $(1.4 \pm 0.3) \times 10^5$ Bq/kg.

Overall, the measured ^{137}Cs -specific activity varied by more than three orders of magnitude across the investigated sample set, from $(1.4 \pm 0.3) \times 10^5$ Bq/kg in the B-02/6 surface oil-containing sample to $(6.5 \pm 1.3) \times 10^8$ Bq/kg in the evaporated LRW residue from the surface level of B-02/2. For LRW samples only, the ^{137}Cs -specific activity ranged from $(1.4 \pm 0.3) \times 10^5$ to $(1.1 \pm 0.2) \times 10^8$ Bq/kg.

Table 6. Results of portable gamma-spectrometric analysis of BN-350 LRW samples and evaporated LRW residues.

No.	Sample	Sampling Location	¹³⁷ Cs-Specific Activity, Bq/kg
1	LRW No. 1	Tank B-02/2, lower level	$(1.0 \pm 0.2) \times 10^8$
2	LRW No. 2	Tank B-02/5, lower level	$(1.1 \pm 0.2) \times 10^8$
3	LRW No. 3	Tank B-02/6, surface (“mirror”)	$(1.4 \pm 0.3) \times 10^5$
4	LRW No. 4	Tank B-02/6, middle level	$(1.8 \pm 0.4) \times 10^6$
5	LRW No. 5	Tank B-02/6, lower level	$(1.3 \pm 0.3) \times 10^7$
6	Evaporated LRW residue No. 1	Tank B-02/1, surface (“mirror”)	$(4.5 \pm 0.9) \times 10^8$
7	Evaporated LRW residue No. 2	Tank B-02/1, middle level	$(3.4 \pm 0.7) \times 10^8$
8	Evaporated LRW residue No. 3	Tank B-02/1, lower level	$(6.0 \pm 1.2) \times 10^8$
9	Evaporated LRW residue No. 4	Tank B-02/2, surface (“mirror”)	$(6.5 \pm 1.3) \times 10^8$
10	Evaporated LRW residue No. 5	Tank B-02/2, middle level	$(5.2 \pm 1.0) \times 10^8$
11	Evaporated LRW residue No. 6	Tank B-02/5, surface (“mirror”)	$(6.0 \pm 1.2) \times 10^8$
12	Evaporated LRW residue No. 7	Tank B-02/5, middle level	$(6.1 \pm 1.2) \times 10^8$
13	Evaporated LRW residue No. 8	Tank B-02/6, middle level	$(1.0 \pm 0.2) \times 10^8$

The evaporated LRW residues showed higher ¹³⁷Cs-specific activities than most LRW samples, ranging from $(1.0 \pm 0.2) \times 10^8$ to $(6.5 \pm 1.3) \times 10^8$ Bq/kg. This reflects the concentration of dissolved and nonvolatile components during evaporation. Therefore, these samples should be interpreted as concentrated residues derived from LRW, not as independent SRW generated during decommissioning.

A clear vertical difference was observed in tank B-02/6. The ¹³⁷Cs-specific activity increased from the surface oil-containing phase to the middle emulsion phase and then to the lower alkaline saline aqueous phase: $(1.4 \pm 0.3) \times 10^5$, $(1.8 \pm 0.4) \times 10^6$, and $(1.3 \pm 0.3) \times 10^7$ Bq/kg, respectively. Therefore, the lower aqueous phase contained approximately two orders of magnitude more ¹³⁷Cs than the surface oil-containing phase. This indicates that ¹³⁷Cs is preferentially associated with the aqueous/salt phase rather than with the oil-containing phase.

The portable gamma spectra also contained a peak at 1323.2 keV, which was assigned to the summing of two 661.6 keV gamma quanta from ¹³⁷Cs. This effect was caused by high counting load during the measurement of samples with high ¹³⁷Cs activity. In addition, the high ¹³⁷Cs content produced a strong Compton continuum below 661.6 keV, which limited the reliable identification and activity determination of weaker gamma emitters in this energy region.

Laboratory HPGe measurements were performed for selected alkaline saline LRW samples to confirm the portable gamma-spectrometric results. A typical laboratory gamma spectrum is shown in Figure 5. The spectrum is dominated by the 661.6 keV gamma line of ¹³⁷Cs, while no additional gamma-emitting radionuclides were reliably identified under the applied measurement conditions.

The laboratory HPGe results are summarized in Table 7. For LRW No. 1 and LRW No. 2, the measured ¹³⁷Cs-specific activity was $(8.6 \pm 1.7) \times 10^7$ Bq/kg for both samples. These values agree within uncertainty with the portable gamma-spectrometric results of $(1.0 \pm 0.2) \times 10^8$ and $(1.1 \pm 0.2) \times 10^8$ Bq/kg, respectively. For LRW No. 5 from the lower level of B-02/6, the HPGe result was $(1.2 \pm 0.2) \times 10^7$ Bq/kg, which is also consistent with the portable measurement result of $(1.3 \pm 0.3) \times 10^7$ Bq/kg.

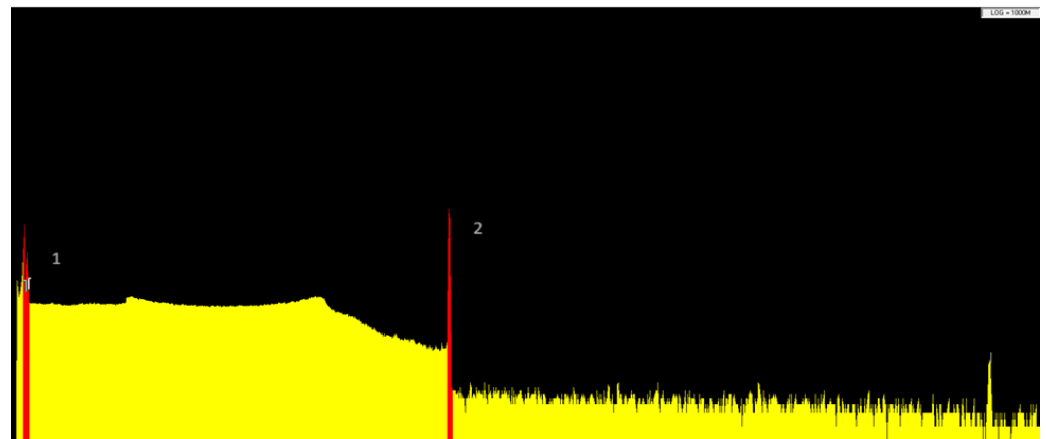


Figure 5. Typical gamma spectrum of selected BN-350 LRW samples obtained under laboratory HPGe measurement conditions. The spectrum is dominated by the 661.6 keV gamma line of ^{137}Cs , with an elevated continuum/background region visible at lower energies. Peak assignments: 1—X-ray region associated with ^{137}Cs decay products; 2—661.6 keV gamma line of ^{137}Cs .

Table 7. Results of laboratory HPGe gamma-spectrometric analysis of selected BN-350 LRW samples.

No.	Sample	Sampling Location	^{137}Cs -Specific Activity, Bq/kg
1	LRW No. 1	Tank B-02/2, lower level	$(8.6 \pm 1.7) \times 10^7$
2	LRW No. 2	Tank B-02/5, lower level	$(8.6 \pm 1.7) \times 10^7$
3	LRW No. 5	Tank B-02/6, lower level	$(1.2 \pm 0.2) \times 10^7$

The agreement between portable and laboratory measurements confirms that the portable gamma spectrometer provided reliable screening data for ^{137}Cs in the investigated samples. Laboratory HPGe spectrometry provided high-resolution confirmation for selected alkaline saline LRW samples. The oil-containing samples from the surface and middle levels of B-02/6 could not be analyzed using the applied laboratory dilution procedure because they did not dissolve or become diluted in 5% nitric acid, confirming their distinct matrix behavior.

4.3. Comparison with Previous Studies and Implications for Further BN-350 LRW Management

The present results should be considered in the context of earlier BN-350 LRW studies and broader experience in the treatment of alkaline saline radioactive waste. Earlier BN-350 investigations were primarily technology-oriented and focused on the feasibility of processing evaporator concentrates [11–13], whereas the present work provides updated experimental characterization of actual LRW samples after long-term accumulation. This distinction is important because the current waste condition may differ from that considered during earlier process-development studies.

Earlier studies of BN-350 evaporator concentrates showed that the waste in tanks B-02/1, B-02/2, B-02/3, and B-02/5 consisted mainly of decantate and sludge phases. The decantates were characterized by alkaline to strongly alkaline pH values and significant salt contents. For example, pH values of 9.0–12.1 and salt contents of 60–127 g/L were reported for decantates from tanks B-02/1, B-02/2, B-02/3, and B-02/5 [11,12]. The present results confirm the same general waste type for B-02/2 and B-02/5, but they show higher dry residue values in the currently analyzed lower-level alkaline saline LRW samples: 145.00 and 139.30 g/dm³, respectively. The lower-level sample from B-02/6 had an even higher dry residue of 295.10 g/dm³, indicating a more concentrated alkaline salt matrix. Thus, the

present data demonstrate both continuity with earlier BN-350 LRW studies and the current chemical heterogeneity of the accumulated waste.

A comparison between previous BN-350 LRW studies and the present work is summarized in Table 8. The comparison shows that the main practical issue has shifted from identifying possible processing schemes to obtaining updated matrix-specific data needed for sampling, waste separation, and selection of treatment and conditioning routes.

Table 8. Comparison of previous BN-350 LRW studies and the present work.

Source	Main Object	Key Findings	Relevance to the Present Study
Savkin et al. [11]	BN-350 evaporator concentrate decantates and slurries	^{137}Cs was the dominant radionuclide, but ^{60}Co and ^{54}Mn also affected treatment. Direct selective sorption was insufficient; ozonation and filtration before selective sorption were proposed. Cementation of slurries was tested.	Provides the first experimental basis for BN-350 LRW treatment and shows that chemical forms and complexing agents can affect radionuclide removal.
Dmitriev et al. [12]	BN-350 evaporator concentrates accumulated in tanks	Evaporator concentrates consisted of decantate and sludge. The proposed scheme included ozonation, filtration, selective sorption, cementation of sludge and filtration deposits, and long-term storage of spent sorbent.	Demonstrates that BN-350 LRW management requires separation of liquid and solid/sludge fractions and that volume reduction is possible only after radionuclide removal.
Savkin and Ostashkina [13]	BN-350 LRW processing technology options	Three options were considered: ion-selective purification + cementation, COREBRICK, and joint cementation of all LRW types. The advantage of joint cementation was shown from a technical and economic viewpoint, while further technological refinement was required.	Shows that final technology selection depends on waste composition, matrix type, and feasibility of obtaining acceptable conditioned waste forms.
Present work	Actual BN-350 LRW samples from B-02/1, B-02/2, B-02/5, and B-02/6 tanks	The analyzed wastes are strongly alkaline and salt-rich. ^{137}Cs is the dominant identified gamma-emitting radionuclide. B-02/6 contains oil-containing, emulsion, and aqueous carbonate-rich phases with different ^{137}Cs levels.	Provides updated experimental data needed for representative sampling, phase-specific waste separation, and selection of further treatment and conditioning approaches.

The present gamma-spectrometric results are consistent with earlier BN-350 studies showing that ^{137}Cs is the main gamma-emitting radionuclide in the accumulated LRW. Earlier investigations also reported activation products such as ^{60}Co and ^{54}Mn [11,12]. In the present work, these radionuclides were not reliably detected. This difference should be interpreted carefully and may be related to radioactive decay, differences in analytical procedures, and the spectral limitations of direct gamma-spectrometric measurements.

Radioactive decay is particularly important for ^{54}Mn and ^{60}Co . The half-life of ^{54}Mn is about 312 days, while that of ^{60}Co is about 5.27 years; therefore, after more than two decades, ^{54}Mn would be expected to decay almost completely, and ^{60}Co would decrease to only several percent of its initial activity. In contrast, ^{137}Cs has a half-life of about 30 years and remains the dominant gamma-emitting radionuclide. In addition, the present measurements were performed directly, without radiochemical separation or preliminary ^{137}Cs removal. In high-activity samples, a ^{137}Cs summing peak at 1323.2 keV was observed close to the 1332.5 keV line of ^{60}Co , whereas the second main ^{60}Co line at 1173.2 keV and the main ^{54}Mn line at 834.8 keV were not reliably identified.

The original spectrum-processing protocols did not include calculated decision thresholds or minimum detectable activities for non-detected ^{60}Co and ^{54}Mn . Therefore, numerical Lc/MDA values are not reported in this study. According to [23,24], characteristic limits depend on the measurement model, continuum/background counts in the region

of interest, counting geometry, detector efficiency, counting time, gamma-emission probability, sample mass or dilution factor, and uncertainty components. Therefore, ^{60}Co and ^{54}Mn should be interpreted as not being reliably detected under the applied direct gamma-spectrometric conditions, rather than as completely absent from the waste.

The behavior of tank B-02/6 is particularly important. Unlike B-02/2 and B-02/5, which contain nitrate–chloride alkaline saline LRW, B-02/6 contains oil-containing waste, a stable oil–water emulsion, and a concentrated, carbonate-rich alkaline phase. The measured ^{137}Cs activity increased from the oil-containing surface layer to the middle emulsion and then to the lower aqueous/salt phase. This shows that ^{137}Cs is preferentially associated with the aqueous/salt phase rather than with the oil-containing phase. From a practical viewpoint, the oil-containing surface layer cannot be used as a representative indicator of the whole B-02/6 inventory. A single surface sample from this tank would significantly underestimate the ^{137}Cs activity of the lower aqueous phase.

This finding supports the need for matrix- and level-specific sampling of multiphase LRW tanks. Tanks containing oil phases, emulsions, and alkaline aqueous solutions should not be characterized using only surface samples or a single averaged sample. For such tanks, representative characterization before retrieval, treatment, or conditioning should include sampling from the surface, middle, and lower zones, with separate evaluation of oil-containing, emulsion, and aqueous/salt phases. The present data show that B-02/6 should be treated as a multiphase waste object rather than as a single liquid waste stream.

The high salt content of the investigated LRW is another important factor. The lower-level alkaline saline LRW samples from B-02/2 and B-02/5 are nitrate–chloride-rich solutions, whereas the lower-level sample from B-02/6 is a carbonate-rich alkaline solution. These matrices are chemically different and should not be expected to behave similarly during conditioning. In cementation, high salt loading can affect hydration reactions, setting time, mechanical strength, water separation, ^{137}Cs leaching, and the long-term durability of the waste form. In addition, nitrate–chloride-rich and carbonate-rich LRW may require different binder formulations, pretreatment steps, or waste loading limits. Therefore, the present results support a matrix-specific approach rather than the direct application of a single treatment method to all BN-350 LRW.

The relevance of this conclusion is also supported by the broader waste-management experience of sodium-cooled fast reactors. The IAEA report on waste from innovative reactor systems identifies sodium-wetted combustible waste, sodium-wetted metallic waste, and bulk sodium from cooling systems as SFR-specific waste streams and notes that sodium reacts with moisture and air, forming highly caustic NaOH ; therefore, sodium must be removed or neutralized before subsequent treatment or storage [1]. Although the present study does not investigate metallic sodium itself, the strongly alkaline and highly mineralized character of BN-350 LRW, together with concentrated residues and oil/emulsion phases, reflects the same general engineering challenge of SFR waste management: the waste is controlled not only by radionuclide inventory, but also by sodium-related alkaline chemistry, salt loading, and phase heterogeneity. This interpretation is consistent with operating and decommissioning experience from other SFRs summarized in IAEA-TECDOC-1691 [25]. BN-600 operating experience shows that sodium systems can be operated reliably when supported by appropriate monitoring, leak detection, localization, and maintenance measures; however, this experience also confirms that sodium-related systems require dedicated technological controls. French SFR decommissioning experience shows that sodium draining, residual sodium neutralization, washing/decontamination, and the management of sodium-related secondary wastes are central operations during dismantling [25]. Therefore, the BN-350 LRW should be considered not as ordinary aqueous radioactive waste but as a legacy SFR waste stream in which alkaline saline solutions,

carbonate-rich phases, oil-containing layers, emulsions, and concentrated residues require separate characterization and matrix-specific treatment before final conditioning.

The present results are also consistent with broader studies of cesium removal from highly mineralized alkaline radioactive waste. Studies on simulated alkaline high-level waste solutions have shown that ^{137}Cs removal from saline–alkaline media remains a key technological task and that sorbent performance depends strongly on solution composition, competing ions, sorbent stability, and the possibility of repeated sorption–desorption cycles [14]. For BN-350 LRW, this implies that sorption-based treatment should be selected not only on the basis of ^{137}Cs activity but also with consideration of total salt content, alkalinity, carbonate/nitrate/chloride composition, organic or oil-containing phases, and potential complexing components, as further illustrated by recent studies on sorbent-based approaches for LRW conditioning. Gordienko et al. [26] investigated low-temperature desorption of an LRW simulant from expanded perlite and showed that water removal from the perlite–simulant system was mainly physical, with no detectable release of organic or inorganic volatile compounds other than water vapor under the studied conditions. Although that study was performed using a simulant rather than real BN-350 LRW, it demonstrates that sorbent-based and drying-based approaches must be evaluated not only by radionuclide activity, but also by water retention, thermal behavior, gas release, and matrix stability. For the present BN-350 LRW samples, this is relevant because nitrate–chloride alkaline saline LRW, carbonate-rich alkaline LRW, and oil-containing phases may behave differently during sorption, drying, or conditioning.

If cementation is selected as one of the subsequent conditioning routes, the retention of ^{137}Cs should also be experimentally verified in actual BN-350 LRW matrices. Recent work on cement-based immobilization of irradiated uranium–graphite fuel from the IGR reactor showed that ^{137}Cs leaching is a key performance indicator for cementitious radioactive waste forms [27]. Although the waste type differs from BN-350 LRW, the same principle applies: the suitability of a cementitious matrix cannot be assessed only from initial ^{137}Cs activity, waste loading, or compressive strength, but should also include leaching behavior, matrix chemistry, and compatibility with the waste composition.

From the point of view of future BN-350 LRW processing, the present characterization supports several practical conclusions. First, alkaline saline LRW and oil-containing LRW should be considered as separate waste streams. The oil-containing phase from B-02/6 has much lower ^{137}Cs activity than the aqueous/salt phase, but it poses a separate technological challenge due to viscosity, emulsion stability, and poor compatibility with aqueous dilution procedures. Second, nitrate–chloride evaporator concentrates from B-02/2 and B-02/5 and carbonate-rich alkaline liquid from B-02/6 should not be assumed to have the same treatment behavior. Third, evaporated LRW residues must be interpreted as concentrated products derived from LRW samples, not as independent SRW; their higher ^{137}Cs -specific activities reflect concentration during evaporation.

These findings also have implications for radiological inventory assessment. Since ^{137}Cs dominates the measured gamma spectra, it should serve as the primary radionuclide for operational gamma monitoring, shielding evaluation, and rapid screening of BN-350 LRW samples. However, gamma spectrometry alone cannot provide a complete radiological inventory for waste acceptance or final disposal purposes. Pure beta emitters, weak gamma emitters, alpha emitters, or radionuclides masked by the ^{137}Cs Compton continuum may require targeted radiochemical analysis. Therefore, the present gamma-spectrometric results provide a robust basis for gamma-emitting radionuclide characterization, while future work should include additional radionuclide-specific analysis if required by the conditioning or disposal acceptance criteria.

Overall, the present study complements earlier BN-350 LRW processing studies by providing updated experimental information on the actual condition of selected waste streams after long-term accumulation. Earlier studies established possible technological routes, including ozonation, filtration, selective sorption, and cementation [11–13]. The present results show that any full-scale treatment route must be supported by current matrix-specific characterization. The main scientific contribution of this work is the demonstration that BN-350 LRW is not a single homogeneous waste stream, but a set of chemically and radiologically distinct matrices: nitrate–chloride alkaline saline LRW, carbonate-rich alkaline LRW, oil-containing radioactive waste, stable oil–water emulsions, and evaporated LRW residues.

From an engineering perspective, the results indicate that BN-350 LRW should be managed as a set of matrix-specific waste streams rather than as a homogeneous liquid waste. The alkaline saline aqueous phase should be subjected to clarification or filtration before radionuclide-removal operations, followed by treatment focused primarily on ^{137}Cs , which is the dominant identified gamma-emitting radionuclide. However, the selection of ^{137}Cs -removal media should account for the high mineralization and alkaline composition of the LRW, because competing alkali ions, nitrate/carbonate species, and high ionic strength may affect sorption or ion-exchange efficiency. Oil-containing and emulsion phases should be separated and characterized independently before conditioning, since the B-02/6 results demonstrate that surface oil-containing material and lower aqueous phases differ substantially in radiological characteristics. Evaporated LRW residues should also be considered separately, because they represent concentrated salt-rich products of the corresponding LRW samples. Direct conditioning of such residues in cementitious matrices may be limited by salt loading and matrix compatibility; therefore, immobilization options should be selected only after waste-form compatibility testing. Thus, the present characterization supports a treatment strategy based on phase separation, matrix-specific pretreatment, ^{137}Cs -oriented aqueous treatment, and separate conditioning assessment for oil-containing materials and concentrated residues.

Thus, the data obtained in this study provide an experimental basis for the next stage of BN-350 LRW management. They support a sampling strategy that accounts for vertical heterogeneity, the separation of waste streams by matrix type, selection of appropriate pretreatment and conditioning methods, and use of ^{137}Cs as the principal gamma-emitting radionuclide for operational monitoring. At the same time, additional studies on sorption behavior, oil-phase treatment, cementation compatibility, leaching resistance, and non-gamma-emitting radionuclides are required before the final selection of a full-scale conditioning route.

5. Conclusions

This study provides an updated physicochemical and gamma-spectrometric characterization of legacy LRW accumulated at the BN-350 reactor facility after long-term storage.

The investigated alkaline saline LRW is highly alkaline and strongly mineralized. Two main types were identified: nitrate–chloride alkaline saline LRW and a chemically distinct carbonate-rich alkaline solution. In addition, tank B-02/6 contains a multiphase system consisting of an oil-containing layer, a stable oil–water emulsion, and a concentrated aqueous phase. This confirms that such tanks cannot be represented by a single averaged sample and require level-specific characterization to account for vertical phase heterogeneity.

Gamma-spectrometric analysis showed that ^{137}Cs is the dominant identified gamma-emitting radionuclide. Its activity varies widely depending on the waste matrix and phase. The higher activities observed in evaporated residues are due to concentration

during evaporation and should be interpreted as concentrated products derived from LRW samples, not as independent waste forms.

A pronounced vertical distribution of ^{137}Cs was observed in the multiphase tank. The radionuclide is mainly associated with the aqueous/salt phase, while the oil-containing phase contains significantly lower activity. This demonstrates that surface sampling alone is not representative of such systems and may underestimate the activity in the lower aqueous/salt phase.

Portable gamma spectrometry results were confirmed by laboratory HPGe measurements, which showed good agreement and supported the use of portable methods for rapid ^{137}Cs assessment in alkaline aqueous LRW samples.

Overall, BN-350 LRW should be considered a heterogeneous system consisting of chemically and physically different waste matrices. The presence of oil-containing phases, stable emulsions, high dissolved salt content, and phase-dependent ^{137}Cs distribution supports the need for matrix-specific retrieval, phase separation, pretreatment, and conditioning evaluation before immobilization. For operational gamma control, ^{137}Cs is the key radionuclide, while complete radionuclide inventory assessment may require additional targeted analyses of pure beta emitters, alpha emitters, weak gamma emitters, and radionuclides masked by ^{137}Cs -dominated spectra.

6. Patents

Patent for utility model: “Transport Packaging Container for Transportation of Liquid Radioactive Waste”. Authors: Korovikov, A.G.; Yakovlev, V.V.; Sadykov, K.S.; Bogomolova, I.N.; Kabylbekov, A.K.; Sultan, Y.Y. No. 12250 dated 22 May 2026 RSE “National Institute of Intellectual Property” of the Ministry of Justice of the Republic of Kazakhstan, 2026.

Author Contributions: Conceptualization, V.V.B. and Y.T.K.; methodology, O.S.B.; software, R.S.; validation, V.B., A.N. and R.S.; formal analysis, K.S. and Y.Y.B.; investigation, A.N., O.S.B. and R.S.; resources, O.S.B. and Y.T.K.; data curation, V.B. and R.S.; writing—original draft preparation, K.S.; writing—review and editing, K.S.; visualization, Y.Y.B. and A.N.; supervision, V.V.B. and Y.T.K.; project administration, V.V.B.; funding acquisition, V.V.B. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

LRW	Liquid radioactive waste
SRW	Solid radioactive waste
NPP	Nuclear power plant
PFMS	Polyphenylmethylsiloxane
HPGe	High-purity germanium detector

Appendix A

Table A1. Chemical composition and ¹³⁷Cs-specific activity of LRW in Building 157 tanks according to initial tank data.

Tank and Sampling Location	Dry Residue, g/L	Alkalinity, g-eq/L	Hardness, g-eq/L	Chlorides, g/L	Nitrates, g/L	Nitrites, g/L	NH ₄ ⁺ , g/L	Fe, g/L	Oxidizability, g/L	Sulfates, g/L	Silicic Acid, g/L	Oxalates, g/L	Bicarbonates, g/L	Surfactants, g/L	¹³⁷ Cs Activity, MBq/L	Waste Type
B-01/2, surface	2.0	0.008	0.001	0.17	0.66	0.001	0.026	0.001	0.20	0.200	0.001	0.001	0.001	0.001	0.444	Pulp
B-01/2, middle level	2.1	0.008	0.001	0.17	0.69	0.001	0.028	0.001	0.20	0.290	0.001	0.001	0.006	0.001	0.500	Pulp
B-01/2, lower level	2.1	0.008	0.003	0.30	0.72	0.001	0.028	0.001	0.20	0.290	0.001	0.001	0.008	0.001	0.540	Pulp
B-02/1, surface	285.0	0.30	0.006	28.35	25.50	2.19	0.035	0.001	1.16	21.30	0.410	65.5	0.190	0.026	179.0	Evaporator concentrate, second evaporator unit
B-02/1, middle level	340.0	0.46	0.007	33.60	25.55	2.75	0.042	0.001	2.28	24.50	0.580	74.5	0.280	0.050	375.3	Evaporator concentrate, second evaporator unit
B-02/1, lower level	400.0	0.63	0.007	35.40	26.97	3.21	0.043	0.001	2.96	28.10	1.640	92.0	0.300	0.080	516.5	Evaporator concentrate, second evaporator unit
B-02/2, surface	185.0	0.30	0.006	17.72	17.45	0.15	0.036	0.001	0.20	14.70	0.820	63.2	0.200	0.060	120.3	Evaporator concentrate, second evaporator unit
B-02/2, middle level	190.0	0.31	0.006	21.27	17.74	0.45	0.046	0.001	1.0	18.70	1.030	90.2	0.200	0.060	115.3	Evaporator concentrate, second evaporator unit
B-02/2, lower level	210.0	0.31	0.010	21.30	20.60	0.62	0.048	0.001	1.1	18.80	1.090	97.2	0.210	0.080	128.0	Evaporator concentrate, second evaporator unit
B-02/3, surface	128.0	0.08	0.009	14.20	20.20	0.92	0.042	0.001	0.20	15.49	0.390	72.0	0.080	0.090	39.0	Evaporator concentrate, second evaporator unit
B-02/3, middle level	138.0	0.09	0.010	15.40	20.60	0.94	0.042	0.001	0.60	16.66	0.410	83.0	0.080	0.027	43.5	Evaporator concentrate, second evaporator unit
B-02/3, lower level	140.0	0.09	0.011	15.90	22.71	0.94	0.046	0.001	0.60	17.69	0.490	83.7	0.080	0.027	47.0	Evaporator concentrate, second evaporator unit
B-02/5, surface	120.0	0.16	0.013	10.60	18.50	1.11	0.024	0.001	0.44	13.30	0.390	52.2	0.130	0.017	68.5	Evaporator concentrate, second evaporator unit
B-02/5, middle level	140.0	0.17	0.013	15.72	19.50	1.16	0.024	0.001	0.50	13.96	0.550	54.9	0.140	0.017	280.3	Evaporator concentrate, second evaporator unit
B-02/5, lower level	154.0	0.20	0.015	17.72	22.70	1.40	0.024	0.001	0.92	14.45	0.550	64.7	0.210	0.017	403.3	Evaporator concentrate, second evaporator unit
B-02/6, surface	Oil	—	—	—	—	—	—	—	—	—	—	—	—	—	5.5	Oil
B-02/6, middle level	150.0	2.1	0.011	10.60	2.35	1.33	0.071	0.001	51.9	4.900	1.180	51.9	0.400	0.052	15.8	PFMS/Na-K
B-02/6, middle level	150.0	2.2	0.013	10.63	2.48	1.40	0.077	0.001	79.2	4.650	1.640	79.0	0.460	0.052	22.5	PFMS/Na-K

References

1. International Atomic Energy Agency. *Status and Trends of Nuclear Fuels Technology for Sodium Cooled Fast Reactors*; IAEA Nuclear Energy Series No. NF-T-4.1; IAEA: Vienna, Austria, 2011.
2. Petrov, V.A.; Ojovan, M.I.; Yudin, S.V. Material Aspect of Sustainable Nuclear Waste Management. *Sustainability* **2023**, *15*, 11934. [\[CrossRef\]](#)
3. Ojovan, M.I.; Lee, W.E.; Kalmykov, S.N. *An Introduction to Nuclear Waste Immobilisation*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2019.
4. Troyanov, V.M.; Kamaev, A.A. Evolution of fast reactors. The role of a BN-350 reactor. *At. Energy* **2024**, *136*, 222–232. [\[CrossRef\]](#)
5. Mukhamedov, N.; Toleubekov, K.; Vityuk, G.; Bekmuldin, M.; Dolzhikov, S. Decommissioning of the BN-350 Fast Neutron Reactor: History Review and Current Status. *Energies* **2025**, *18*, 3486. [\[CrossRef\]](#)
6. Skvortsov, A.I.; Safutin, V.D.; Yamov, V.Y.; Zavadskii, M.I. Conditioning a BN-350 power-generating unit for safe storage. *At. Energy* **2005**, *98*, 65–68. [\[CrossRef\]](#)
7. Nosov, Y.V.; Rovneiko, A.V.; Tashlykov, O.L.; Shcheklein, S.E. Decommissioning features of BN-350, -600 fast reactors. *At. Energy* **2019**, *125*, 219–223. [\[CrossRef\]](#)
8. Sapatayev, Y.; Samarkhanov, K.; Yakovlev, V.; Prozorova, I.; Bochkov, V.; Pospelov, V. Radiation Characteristics and Safety Assessment of the BN-350 Fast Reactor's Spent Nuclear Fuel Model under Long-Term Dry Storage Conditions. *Appl. Sci.* **2026**, *16*, 4764. [\[CrossRef\]](#)
9. Mukhamedov, N.; Baklanov, V.; Moldagulov, M.; Toleubekov, K.; Surayev, A.; Yagudin, A.; Kanatnikov, S. The BN-350 Reactor Decommissioning: Quantitative Analysis and Prospects for Solid Radioactive Waste Management. *Energies* **2025**, *18*, 4651. [\[CrossRef\]](#)
10. Mukhamedov, N.; Surayev, A.; Dolzhikov, S.; Toleubekov, K.; Medetbekov, B. Radiological Characterization of Solid Radioactive Waste Generated during the Decommissioning of the BN-350 Reactor. *Appl. Sci.* **2026**, *16*, 4936. [\[CrossRef\]](#)
11. Savkin, A.E.; Slastennikov, Y.T.; Sinyakin, O.G.; Arustamov, A.E.; Baldov, A.N. Feasibility of processing of accumulated liquid radioactive waste from BN-350 reactor. *Radiochemistry* **2001**, *43*, 311–314. [\[CrossRef\]](#)
12. Dmitriev, S.A.; Lifanov, F.A.; Savkin, A.E.; Lachenov, S.M.; Baldov, A.N.; Slastennikov, Y.T.; Sinyakin, O.G.; Arustamov, A.E. Technical Proposals on Processing Evaporator Concentrates, Accumulated at the BN-350 Reactor in Kazakhstan. In Proceedings of the WM'01 Conference, Tucson, AZ, USA, 25 February–1 March 2001.
13. Savkin, A.E.; Ostashkina, E.E. Technical and Economic Assessment of the Processing Technologies of BN-350 LRW. *Vopr. At. Nauk. Tekhniki Ser. Mater. Sci. New Mater.* **2023**, *4*, 119–128. (In Russian)
14. Milyutin, V.; Nekrasova, N.; Kozlov, P.; Slobodyuk, A.; Markova, D.; Shaidullin, S.; Feoktistov, K.; Tokar, E.; Tutov, M.; Egorin, A. Removal of Cs-137 from Liquid Alkaline High-Level Radwaste Simulated Solution by Sorbents of Various Classes. *Sustainability* **2023**, *15*, 8734. [\[CrossRef\]](#)
15. Ignalina Nuclear Power Plant. *Analysis of Technologies for Handling Liquid Radioactive Waste: Lessons Learned from Implementation at Ignalina NPP*; Knowledge Product KP-03; European Commission: Ignalina, Lithuania, 2021.
16. Committee of Atomic and Energy Supervision and Control of the Ministry of Energy of the Republic of Kazakhstan. *National Report of the Republic of Kazakhstan for the 6th Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*; Committee of Atomic and Energy Supervision and Control of the Ministry of Energy of the Republic of Kazakhstan: Astana, Kazakhstan, 2017; 102p. Available online: https://www.iaea.org/sites/default/files/national_report_of_kazakhstan_for_the_6th_review_meeting_-_english.pdf (accessed on 8 July 2026).
17. Committee of Atomic and Energy Supervision and Control of the Ministry of Energy of the Republic of Kazakhstan. *National Report of the Republic of Kazakhstan for the Joint 8th and 9th Review Meeting of the Convention on Nuclear Safety*; Committee of Atomic and Energy Supervision and Control of the Ministry of Energy of the Republic of Kazakhstan: Nur-Sultan, Kazakhstan, 2022; 76p. Available online: https://www.iaea.org/sites/default/files/23/11/kazakhstan_cns_national_report_joint_8th_and_9th_rm.pdf (accessed on 8 July 2026).
18. Committee of Atomic and Energy Supervision and Control of the Ministry of Energy of the Republic of Kazakhstan. *National Report of the Republic of Kazakhstan for the 8th Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*; Committee of Atomic and Energy Supervision and Control of the Ministry of Energy of the Republic of Kazakhstan: Astana, Kazakhstan, 2024; 79p. Available online: <https://www.iaea.org/sites/default/files/2025-08/kazakhstan-national-report-8rm-english.pdf> (accessed on 8 July 2026).
19. Korovikov, A.G.; Yakovlev, V.V.; Sadykov, K.S.; Bogomolova, I.N.; Kabylybekov, A.K.; Sultan, Y.Y. Transport Packaging Container for Transportation of Liquid Radioactive Waste. Kazakhstan Utility Model Patent No. 12250. 22 May 2026. Available online: <https://gosreestr.kazpatent.kz/Utilitymodel/Details?docNumber=437826> (accessed on 8 July 2026).

20. GOST 26449.1-85; Stationary Desalination Distillation Plants—Methods for Chemical Analysis of Saline Waters. Interstate Council for Standardization, Metrology and Certification: Moscow, Russia, 1985. Available online: <https://vsegost.com/Catalog/38/38969.shtml> (accessed on 29 June 2026).
21. GOST 33045-2014; Water. Methods for Determination of Nitrogen-Containing Matters. Interstate Council for Standardization, Metrology and Certification: Moscow, Russia, 2014. Available online: <https://vsegost.com/Catalog/58/58829.shtml> (accessed on 8 July 2026).
22. GOST 22180-76; Reagents. Oxalic Acid. Specifications. USSR State Committee for Standards: Moscow, Russia, 1976. Available online: <https://vsegost.com/Catalog/81/8165.shtml> (accessed on 8 July 2026).
23. ISO 11929-2:2025; Determination of the Characteristic Limits (Decision Threshold, Detection Limit and Limits of the Coverage Interval) for Measurements of Ionizing Radiation—Fundamentals and Application—Part 2: Advanced Applications. ISO: Geneva, Switzerland, 2025. Available online: <https://www.iso.org/obp/ui#iso:std:iso:11929:-2:ed-3:v1:en> (accessed on 28 July 2026).
24. International Atomic Energy Agency. *Determination and Interpretation of Characteristic Limits for Radioactivity Measurements: Decision Threshold, Detection Limit and Limits of the Confidence Interval*; IAEA Analytical Quality in Nuclear Applications Series No. 48; IAEA: Vienna, Austria, 2017; 162p. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/AQ-48_web.pdf (accessed on 28 July 2026).
25. International Atomic Energy Agency. *Status of Fast Reactor Research and Technology Development*; IAEA-TECDOC-1691; IAEA: Vienna, Austria, 2012; 846p. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1691_web.pdf (accessed on 28 July 2026).
26. Gordienko, Y.N.; Bochkov, V.S.; Nokanova, A.D.; Bukina, O.S.; Baklanova, Y.Y.; Saparbek, E. Low-temperature desorption of LRW simulant from perlite: Temperature and purging influence according to TGA/DSC–MS data. *Recent Contrib. Phys.* **2026**, *2*, 62–72. [CrossRef]
27. Bukina, O.S.; Sabitova, R.R.; Kukushkin, I.M.; Baklanova, Y.Y.; Baklanov, V.V.; Skakov, M.K.; Gradoboev, A.V. Leaching behavior of Cs-137 from cement-based matrices for immobilization of irradiated uranium–graphite fuel. *J. Nucl. Eng.* **2026**, *7*, 47. [CrossRef]

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