ASSURING THE UNIFORMITY IN THE MEASUREMENTS OF RW CHARACTERISTICS DURING WASTE TRANSFER FOR DISPOSAL

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The paper discusses the comprehensive measures implemented to ensure the uniformity of measurements as regards the RW characteristics demonstrating their compliance with waste acceptance criteria for disposal. Under this framework, the following regulations have been developed by JSC VNIINM: the Unified Industry Guidelines for the Measurements of Radiation Waste Characteristics, standard measurement and test procedures, as well as the standard of the State Corporation Rosatom for monitoring physical and chemical property indicators and characteristics of the RW form.

Keywords: *measurement procedures, radioactive waste, acceptance criteria, transfer for disposal.*

Routine operations and nuclear decommissioning efforts implemented at the enterprises of the State Corporation Rosatom result in large solid (SRW) and liquid radioactive waste (LRW) inventories of various morphologies: soil, equipment, metal, construction waste, plastic compounds, personal protective equipment, decontamination waste, etc. that should be sent for further processing and/or disposal.

Federal norms and rules in the field of atomic energy use, namely Radioactive Waste Acceptance Criteria for Disposal (NP-093-14) [1], have been approved by the Federal Service for Environmental, Technological and Nuclear Supervision to provide safe radioactive waste (RW) disposal. These criteria should be observed by all entities engaged in activities associated with atomic energy use and are effective throughout the Russian Federation [2]. Based on these criteria one should develop more specific acceptance criteria for RW disposal in a particular disposal facility (RWDF). These criteria should be set forth and validated in the repository designs and in the safety analysis report which is followed by their approval based on a specific order issued by the National Operator for RW management.

The NP-093-14 states that RW generators are responsible for RW conditioning in accordance with waste acceptance criteria for disposal in a particular repository and should validate the waste compliance with these criteria either using their own resources or engaging some other specialized waste management organizations. This regulation also states that such validation should evaluate the following quantitative and qualitative indicators:

- characteristics of the radioactive inventory contained in the SRW packages;

- type of waste and its physical form;
- radiation properties;
- total activity contained in a RW package (batch);
- content and (or) concentration of nuclear hazardous fissile nuclides (NHFN);
- physical and chemical characteristics;
- waste form characteristics;
- characteristics of the waste container (transport package);
- characteristics of the RW package.

RW compliance with the waste acceptance criteria for disposal can be demonstrated either based on some actual validation of the regulated indicators (certificates issued based on design and/or operational documentation, direct or indirect measurements focused on relevant parameters of the RW processing and conditioning process, sampling and testing of the collected samples with the certificates issued by laboratories) or some analytical methods (when the RW property indicators are measured or tested). However, under various projects and nuclear decommissioning, in particular, it appears impossible to identify the waste generation sources or to ensure the homogeneity of their morphological composition at the stages of waste collection, segregation and packaging. Therefore, in this case, analytical methods seem to be the only option providing such waste compliance assessment.

In 2020, the Safety Guide RB-155-20 was developed and enacted by the Federal Service for Environmental, Industrial and Nuclear Supervision to support the enforcement of rules and norms stated in the NP-093-14 at the stage of RW compliance assessment with relevant waste acceptance criteria for disposal [3]. It provides recommendations on the RW measurement procedure, scope, methods and means, narrows down the list of cases requiring some analytical evaluation of the regulated indicators providing some general guidelines on the evaluation procedure, which, nevertheless, render such measurements/testing impossible. As regards most of the regulated RW indicators, [3] refers exclusively to the state standards focused on items similar to RW, but, nevertheless, being quite different from them, and most importantly, not taking into account the specific features of the radioactive material management processes. The Safety Guide [3] also recommends the RW generators and enterprises engaged in waste conditioning the development of particular papers (for example, standards, provisions, instructions) that would regulate the process of RW measurements, namely, the evaluation of waste characteristics (properties) that would validate their compliance with relevant waste acceptance criteria for disposal. Such papers are recommended to discuss the requirements imposed on the measurement instruments applied, as well as relevant sampling and testing methods. To ensure the reliability of the results obtained, the Safety Guide [3] recommends such measurement methods, the scope of which would cover the measured RW characteristics.

In addition to the NP-093-14 and the RB-155-20 requirements, regulated RW indicators should be evaluated in keeping with the Russian legal framework on the measurement uniformity. Thus, the Federal Law on the Uniformity of Measurements [4] states that such measurements should be implemented under activities performed in the field of atomic energy use, are referred to the state measurement uniformity regulation, should be implemented according to some certified methods (procedures) and using specifically approved types of tools previously subjected to necessary calibration testing. Thus, RW assessment focused on the waste indicators and validation of waste compliance with the acceptance criteria for disposal requires the development and certification of relevant measurement procedures.

At the federal level, the GOST R 8.563-2009 [5] and the GOST 8.010-2013 [6] provide relevant requirements on their contents and documentation procedure with some additional requirements on RW measurements procedures, namely, their contents and documentation existing in the field of atomic energy use that were established by the GOST R 8.932-2017 [7] and by Order of the State Corporation Rosatom of October 31, 2013 No. 1/10 NPA [8].

In addition, the GOST R 8.932-2017 [7] divides the measurement methods into standard and operational. If similar measurement (testing) operations and rules are applied for different objects (nevertheless, being of a same type) and different (but akin) measurement conditions to evaluate the same indicators, then a standard methodology that would state the requirements for all objects and/or conditions is recommended to be developed [7]. Such methods require no metrological certification, but, nevertheless, provide quantitative metrological characteristics reflecting the achieved minimum level of metrological support and the technical capacity of a laboratory. Based on standard methods one should develop and certify the operational measurement methods to be directly implemented at the enterprise: their accuracy indicators are validated experimentally or numerically considering the scope of a particular methodology and the measurement instruments applied in accordance with the GOST R 8.997-2021.

VNIINM has been engaged by the State Corporation Rosatom in the methodological support development focused on the measurements of RW characteristics. Thus, VNIINM has developed the Unified Industry-Wide Guidelines (UIG) on the Measurement of Radiation Waste Characteristics [9], standard methods enabling the measurements of radiation characteristics and physical and chemical waste properties, as well as the RW form indicators and the standard of the State Corporation Rosatom for the compliance assessment of these indicators with the waste acceptance criteria for disposal.

Compliance assessment of radiation RW characteristics

To set a general measurement procedure under the compliance assessment of radiation RW characteristics, UIG have been developed and approved by the State Corporation Rosatom. The UIG provide sampling recommendations as regards the waste of various morphologies, recommendations on the selection of measurement methods and tools, processing and reporting of the measurement results. They give guidelines on the use of modern instrumental methods based on alpha, beta, gamma spectrometry providing minimum errors in the measurements of radiation RW characteristics.

In addition to the UIG, a few standard methods have been developed to measure the specific activity of easy-to-detect (EDR) and hard-to-detect (HDR) radionuclides in RW of various origins using gamma and liquid scintillation (LS) spectrometry methods, as well as a calculation method with the radionuclide vector method used to evaluate the HDR activity in RW packages previously tested at RADON facilities [10]. Table 1 overviews the characteristics of the developed standard methods summarizing them in the form of industry-wide instructions.

Table 1. Standard measurement methods for radiation RW characteristics

Method	Method description	Measurement range	Measurement error
OI 001.871-2019			
Measurement method for the specific activity of gamma-emitting radionuclides found in such waste types as construction waste, plastic compound, fragments of equipment, PPE, soil in packages and standard containers with a capacity of up to 3.1 m^3	In situ gamma spectrometry involving a numerical method proving efficiency-based calibration	From 100 to 10^8 Bq/kg	Not more than 70 % at $P = 0.95$
OI 001.872-2019			
Load preparation and measurements of specific activities from gamma-emitting radionuclides via gamma spectrometry in waste sampled from construction waste, plastic compound, fragments of equipment, PPE, soils	Gamma spectrometry of small volume loads under laboratory conditions	From 0.1 to 10^8 Bq/kg	No more than 30 % at $P = 0.95$
OI 001.873-2019			
Load preparation and measurements of specific activities from plutonium isotopes using the LS spectrometry method in samples of construction waste, plastic compound, equipment fragments, PPE, soils	LS spectrometry of alpha radiation from ^{238}Pu, $^{239+240}$Pu isotopes and beta radiation from ^{241}Pu assuming preliminary radiochemical separation of plutonium by extraction, ion exchange or extraction chromatography methods and chemical yield measurements according to ^{236}Pu or ^{242}Pu tracer	From 10 to 10^7 Bq/kg	No more than 40 % at $P = 0.95$
OI 001.874-2019			
Load preparation and measurement of specific activities from uranium isotopes by the spectrometry method in waste samples collected from construction waste, plastics, fragments of equipment, PPE, soils	LS spectrometry of alpha radiation from ^{234}U, ^{235}U, ^{238}U isotopes assuming preliminary radiochemical uranium separation by extraction or extraction chromatography methods and chemical yield measurements according to the ^{232}U tracer	From 10 to 10^5 Bq/kg	No more than 40 % at $P = 0.95$
OI 001.875-2019			
Load preparation and measurement of ^{90}Sr specific activity by LS spectrometry in waste samples collected from construction waste, plastic compound, fragments of equipment, PPE, soils	LS spectrometry of beta radiation from ^{90}Sr assuming preliminary radiochemical separation of strontium and chemical yield measurements according to the ^{85}Sr tracer	From 10 to 10^5 Bq/kg	No more than 40 % at $P = 0.95$

Continuation of table

Method	Method description	Measurement range	Measurement error
	OI 001.950-2021		
Measurement method focused on the specific activity of tritium in waste of different morphologies	LC spectrometry of beta radiation from ^{3}H using the 307 Sample Oxidizer unit providing its separation from solid waste samples	From 200 to 10^{11} Bq/kg	No more than 30 % at $P = 0.95$
	OI 001.951-2021		
Measurement method focused on the specific activity of ^{14}C in waste of different morphologies	LC spectrometry of beta radiation from ^{14}C using the 307 Sample Oxidizer unit providing its separation from solid waste samples	From 10^{2} to 10^{10} Bq/kg	No more than 30 % at $P = 0.95$
	OI 001.952-2021		
Measurement method focused on the specific activity of ^{36}Cl in waste of different morphologies	LS spectrometry of beta radiation from ^{36}Cl involving preliminary sample decomposition in a tube furnace with chlorine-containing component captured in a gas trap and chlorine separation based on extraction chromatography	From 50 to 10^{10} Bq/kg	No more than 60 % at $P = 0.95$
	OI 001.986-2022		
Measurement method focused on the specific activity of ^{63}Ni in waste of different morphologies	LS spectrometry of beta radiation from ^{63}Ni with the preliminary separation of Ni from the samples based on the extraction chromatography method	From 20 to 10^{8} Bq/kg	No more than 40 % at P = 0.95 assuming chemical Ni yield measurements; no more than 60 % at $P = 0.95$ if no control measurements of chemical Ni yield are in place
	OI 001.987-2022		
Measurement method focused on the specific activity of ^{129}I in waste of different morphologies	LS spectrometry of beta radiation from ^{129}I preceded by sample decomposition in a tube furnace with the iodine-containing component captured by a gas trap or iodine leaching from the sample by NaOH solution and subsequent iodine separation by extraction chromatography	From 10 to 10^{6} Bq/kg	No more than 60 % at $P = 0.95$
	OI 001.988-2022		
Measurement method focused on the specific activity of ^{55}Fe in waste of different morphologies	LS spectrometry of ^{55}Fe Auger Electrons preceded by preliminary iron separation from the samples by the extraction chromatography method	From 20 to 10^{8} Bq/kg	No more than 40 % at $P = 0.95$ assuming chemical iron yield measurements; no more than 60 % at $P = 0.95$ if no control measurements of chemical iron yield are in place
	OI 001.904-2020		
Measurements focused on the specific activity of hard-to-detect radionuclides in solid radioactive waste via the radionuclide vector method based on the measured specific activities of reference radionuclides	Specific activity of HDR in a RW package calculated based on the previously identified regression dependency between the specific activities of EDR and HDR	–	Calculated. Depends on the errors in EDR and HDR specific activity measurements

Table 1 evidences that the developed standard measurement methods for the RW characteristics have covered the widest possible range of radionuclides and their specific activity measurements. Therefore, these can be used not only as a basis when developed are different operational RW characterization methods, but also those measurement techniques that would provide reliable data on the radionuclide contamination of materials at the stage of their removal from regulatory control.

Each method has been experimentally tested both on genuine and mockup RW: their accuracy indicators have been validated and their content have been evaluated as meeting the requirements established for the measurement methods in the field of atomic energy use according to [5]—[8], which has been confirmed by expert judgements made by the specialists of the VNIINM's metrological department performing the functions of the Head Scientific Metrological Office of the Rosatom State Corporation (HSMO).

To provide the compliance of measurement quality control procedures with the GOST R 8.984-2019 requirements [11], certain algorithms have been developed to monitor the accuracy of the measurements (measurement errors) focused on the specific activities of gamma-emitting radionuclides found in RW placed into various packages, including RW disposal containers, involving the use of some certified tools. A detailed description of the developed algorithms and certified objects is given in [9].

Monitoring over the physical and chemical RW properties and the waste form characteristics

The NP-093-14 provisions regulate quite a wide scope of indicators constituting to the physical and chemical RW properties and the waste form characteristics. The following indicators should be monitored when the waste is handed over for disposal: morphological (chemical) composition, content of corrosive, complexing, toxic, infectious (pathogenic), organic rotting, biologically active, flammable, self-igniting, oxidizing substances, chemical reactivity, flammability, explosiveness, free liquid content, including organics, heat release and gas formation. According to the NP-093-14, in case of RW immobilized in a solid waste form the following RW characteristics should be evaluated prior to waste transfer for disposal: mechanical strength, homogeneity, porosity, density, gas and water permeability, leaching stability, radiation, thermal and biological resistance.

Nevertheless, a few inaccurate definitions provided in the NP-093-14 manifest themselves at the stage RW evaluation according to the above indicators established for the physical and chemical RW properties preceding waste transfer for disposal:

- for some indicators no exact definition is provided, namely, *regarding the free liquid content, the content of organic rotting, biologically active and decomposing substances*;
- there are no lists that would state the specific substances subject to such evaluation, provided are only their groups according to relevant properties, for example, *content of complexing substances, content of corrosive substances, etc.*;
- no quantitative indicators have been established, in particular, as regards *the content of corrosive substances, the content of oxidizing substances, the content of organic decaying, biologically active and decomposing substances, etc*.

To observe the compliance with the requirements imposed on the RW acceptance criteria for disposal, some standard measurement methods have been developed by VNIINM. These methods can be used to measure the indicators associated with the physical and chemical properties of waste (Table 2), during quality test measurements of cement compounds with RW (Table 3). Another standard is the Rosatom State Corporation standard developed to assess the compliance of these indicators and waste form characteristics with the waste acceptance criteria for disposal (hereinafter referred to as the Standard).

Table 2. Standard measurement methods addressing physical and chemical RW properties

Method	Method description	Measurement range	Measurement error
OI 001.907-2020			
Measurement method focused on the content of organic decaying, biologically active and decomposing substances contained in RW	In case of LRW, measured is the total and inorganic carbon content in aqueous media using carbon analyzers based on infrared detectors with the organic carbon content calculated based on their difference. In case of SRW, calculated is the organic matter content by mass loss after RW sample ignition to constant mass after chlorides and carbonates removal from the sample	LRW: from 1 to 100 mg/dm^3; SRW: from 1 to 500 g/kg	No more than 30 % at P = 0.95
OI 001.908-2020			
Measurement method for the free liquid content in RW	Measurement of the liquid mass that can be separated by mechanical action on the RW sample material, for example, via drainage, centrifugation or filtration. The selected exposure type would depend on the morphology of the RW material and its water content	From 2 to 33 % from the mass of the radioactive material contained in the package	No more than 1 % (abs.) at P = 0.95
OI 001.906-2020			
Measurement method for heat release from the RW	Numerical assessment of heat release from a RW package based on the measured activities (specific activities) of nuclides contained in the waste assuming some additional measurements of its wall temperature	From 10 to 3 kW/m^3	Depends on the radionuclide content and the errors in their measured specific activities, no more than 80 % at P = 0.95

Table 3. Standard measurement methods used under the cement RW compound quality testing

Method	Description of the method	Measurement range	Measurement error
OI 001.909-2020			
Testing method for the mechanical strength of cement RW compounds	Measured are the minimum stresses that would result in the destruction of purposely fabricated control samples of the cement RW compound under static load conditions assuming constant load increase followed by the resulting stress calculations	Compressive strength from 1 to 50 MPa (from 10.2 to 509 kgf/cm^2)	No more than 50 % at $P = 0.95$
OI 001.915-2020			
Testing method for the thermal stability of cement RW compounds	Comparison of the mechanical strength indicators for the key cement RW compound samples after 30 freeze-thaw cycles in the temperature range from −40 °C to +40 °C and the compression performance of control samples that have not been subjected to testing assuming an equivalent hardening time	Compressive strength from 1 to 50 MPa	No more than 50 % at $P = 0.95$
OI 001.917-2020			
Testing method for cement RW compound resistance to prolonged water exposure	Comparison of the mechanical strength indicators for the key cement RW compound samples upon 90 days of water exposure and the compression performance of control samples that have not been subjected to testing assuming an equivalent hardening time	Compressive strength from 1 to 50 MPa	No more than 50 % at $P = 0.95$
OI 001.919-2020			
Testing method for the chemical resistance of cement RW compounds via the long-term leaching method	Under the method developed to test the chemical resistance of cement RW compounds experiencing prolonged exposure to an aqueous medium (water resistance) the rate of radionuclide leaching from control samples into a contact aqueous medium is estimated based on the radionuclide activities measured in it within certain periods of time	Radionuclide leaching rate from $1 \cdot 10^{-7}$ to $1 \cdot 10^{-1}$ g cm^{-2} day^{-1}	No more than 35 % ($P = 0.95$), during radionuclide activity measurements with an error of no more than 10%

To develop the standard measurement methods for the physical and chemical RW properties and those applied during the quality testing of the cement RW compounds, the following tasks have been completed:

- optimal measurement and testing methods have been selected, validated and experimentally tested (these methods had to comply with the key requirements, namely, reliability of the results obtained, simplicity, ease of introduction at enterprises, the widest possible scope of application);
- the RB-155-20 recommendations have been adopted;
- for the first time, specific operations required to be performed by the personnel of enterprises seeking to provide some experimental confirmation of RW compliance with the acceptance criteria for disposal have been developed;
- control procedures have been established to check the measurement quality;
- indicators demonstrating the accuracy of the involved measurements have been established.

The Chemistry Department of the Moscow State University has provided scientific support during the standard development. The standard regulates the processes implemented when checked is the waste compliance with the acceptance criteria for SRW disposal in accordance with the NP-093-14 requirements. It sets up the procedure that should be followed to evaluate the compliance of waste held in RW packages according to its physical and chemical properties and the waste form characteristics, as well as relevant standard measurement and testing methods.

The standard will be applied to evaluate:

- the compliance of RW (or a RW batch) with waste acceptance criteria for disposal as regards the chemical content (complexing, oxidizing, corrosive, toxic substances) if no data is available on the materials involved in the waste generation processes;
- the physical and chemical properties of RW (or a RW batch): flammability, explosiveness, gas formation, reactivity, content of flammable and spontaneously combustible substances, content of organic decaying, infecting (pathogenic), biologically active and decomposing substances, free liquid content;
- the parameters related to the characteristics of the waste form (or the RW batch): homogeneity, porosity, density, gas permeability, water permeability, biological and radiation resistance.

Table 4 presents the basic standard measurement and testing methods established by the Standard for the compliance assessment of the radioactive materials contained in the RW packages according to their physical and chemical properties.

Table 4. Standard measurement and testing methods focused on the physical and chemical properties of radioactive material contained in RW packages established by the Standard

Tested/measured parameter	Testing/measurement method	Measurement range/positive test result criterion	Measurement error
	Morphological composition		
Mass fraction of the RW component	Gravimetric method – mass fractions of the components making up the SRW are calculated based on their mass measured in the package	From 1 to 100 %	No more than 1 % (abs.) at $P=0.95$
	The content of complexing substances		
Total content of complexing substances in the RW package	Concentrations of individual complexing substances in LRW or water extract from the SRW samples are measured and then recalculated into the total content of complexing substances in the RW package	In keeping with the applied methods of quantitative chemical analysis	
Mass fraction of complexing substances in the radioactive contents of the RW package	The total content of complexing substances in RW is estimated according to their binding degree by water-soluble complex compounds with europium	From 0.20 to 5 %	No more than 15 % at $P=0.95$
	Content of oxidizing substances		
Total content of oxidizing substances in a RW package	Concentrations of individual oxidizing substances – nitrate ions (NO_3^-), chromate ions (CrO_4^{2-}), dichromate ions ($Cr_2O_7^{2-}$), perchlorate ions (ClO_4^-) and permanganate ions (MnO_4^-) – measured in LRW or in the water extract from SRW samples followed by subsequent conversion of the measurement results into the total content of oxidizing substances in the RW package	In keeping with the applied methods of quantitative chemical analysis	
Oxidizing ability	Combustion duration for SRW material mixtures with a combustible substance compared against the combustion duration identified for the SRW material involving a mixture of potassium bromate with a combustible substance	SRW sample mixed with cellulose at a ratio of 1:1 or 4:1 does not ignite and does not catch fire or has an average burning time exceeding this indicator for potassium bromate mixed with cellulose at a ratio of 3:7	–
Mass fraction of peroxides in terms of active oxygen (O) in organic LRW	The content of organic peroxides in organic LRW measured by the iodometric method	From 0.05 to 5 %	No more than 30 % at $P=0.95$
	Content of corrosive substances		
Total content of corrosive substances in a RW package	Concentration of individual corrosive substances, in particular, aggressive carbon dioxide (CO_2), magnesium ions (Mg^{2+}), ammonium ions (NH_4^+), caustic alkalis (Na^+ and K^+), chloride ions (Cl^-), sulfate ions (SO_4^{2-}), nitrate ions (NO_3^-) in LRW, namely, in a sample of free liquid from a RW package or an aqueous extract from SRW samples measured and subsequently recalculated into the total content of corrosive substances in the package	In keeping with the applied methods of quantitative chemical analysis	
	Content of chemical toxic substances		
Waste hazard class according to the degree of negative impacts produced on the environment	Calculation of approximate water-transport index for the acetate-buffer extract (pH = 4.8) from the samples of SRW or solidified LRW based on the measured concentrations of individual toxic substances	In keeping with the applied methods of quantitative chemical analysis	
	Flammability		
Flammability group assessment: maximum temperature increment during sample testing;	Assessment of sample behavior under temperature conditions promoting combustion	From 0 to 600 °C	No more than 10 °C at P = 0.95
Reduced mass of samples due to testing		From 0 to 100 %	No more than 10 % at P = 0.95

Continuation of table

Tested/measured parameter	Testing/measurement method	Measurement range/positive test result criterion	Measurement error
Presence of easily flammable and spontaneously combustible substances			
Flash point during LRW testing	LRW sample heating at a given rate along with periodic ignition of the released vapors in the Pensky-Martens apparatus seeking to demonstrate whether a flash occurs at a recorded temperature	From 0 to 300 °C	No more than 2 °C at P=0.95
The ability of SRW and LRW to ignite when exposed to air	Exposure of SRW and LRW samples to air with the time to ignition being recorded	SRW or LRW are referred to the category of pyrophoric substances if the sample gets ignited during the test	–
Explosibility			
Presence of organic explosives in a RW package	Testing by gas analyzers seeking to identify organic explosives	RW meets the criterion if there's no evidence of organic explosive occurrence	–
The content of explosive inorganic substances in RW, which are concentrated salt solutions, salt residues and melts	Measurements focused on the content of explosive inorganic substances: nitrate ions (NO_3^-), nitrite ions (NO_2^-), ammonium (NH_4^+), urea ($(NH_2)_2CO$), hydrogen peroxide (H_2O_2), hydrazine (N_2H_4)	In keeping with the applied methods of quantitative chemical analysis	
Explosive properties of RW material	Explosive properties of RW samples tested by the flash method	RW is referred to explosive substances if a characteristic flash occurs during the test	–
Gas formation			
Specific gas formation rate	The susceptibility of RW form to gas formation tested either assuming its interaction with distilled water or not, assessment of the control sample in terms of its behavior and measurement of the released gas volume	From 0.1 to 100 dm³/(kg·h) (assuming water exposure); from 0.01 to 5 dm³/(kg·h) (assuming no water exposure)	No more than 15 % at P=0.95
Concentration of infectious (pathogenic) substances			
The degree of RW decontamination when contaminated with pathogens of infectious diseases characterized with increased resistance	Inoculation of microorganisms contained in the RW and assessment of growth in their colonies	RW meets the criterion if no growth of colonies is detected	–
Homogeneity of the RW form			
Contents of chemical elements	Mass fractions of chemical elements in RW form samples measured by the X-ray fluorescence spectrometry method	From 1 % wt. to 90 % wt. (from 10 to 900 mg/g)	No more than 25 % at P=0.95
Porosity of the RW form			
Sample porosity (pore volume fraction)	Porosity of control RW form samples tested based on the hydrostatic weighing method or using a helium pycnometer	From 0 % to 70 %	No more than 10 % at P=0.95
Density of the RW form			
Apparent density	Apparent density of RW form sample measured by the hydrostatic weighing method	From 0.2 to 5 g/cm³	No more than 0.01 g/cm³ at P=0.95
True density	True density of a RW form sample measured by the pycnometric method	From 1 to 7 g/cm³	No more than 0.005 g/cm³ at P=0.95
Gas permeability of the RW form			
Gas permeability	Gas permeability measured for RW form samples by the vacuum and/or manometric method	From 10^{-11} to 10^{-8} m/(Pa·sec) (vacuum method); 10^{-18} to $2\cdot10^{-12}$ m/(Pa·sec) (gauge method)	No more than 10 % at P=0.95

Continuation of table

Tested/measured parameter	Testing/measurement method	Measurement range/positive test result criterion	Measurement error
Water permeability of the RW form			
The maximum water pressure under which no flows are yet observed through the RW form samples	Water supply to the bottom end surface of the RW form sample assuming a stepwise increase in its pressure by 0.2 MPa until some water flow indications appear on the top end surface of the sample in the form of drops or a wet spot	The RW form meets the criterion if the maximum water pressure measured during the tests remains within the established limits	–
Biological resistance of the RW form			
Mechanical strength. Compressive strength	Compared are the compressive strength indicators for the key waste form samples exposed to biodestructing microorganism impacts and the requirements of federal norms and rules in the field of atomic energy use the the NP-019-15 [12]	From 1 to 50 MPa (from 10.2 to 509 kgf/cm^2)	No more than 50 % at P = 0.95
Radiation resistance of the cement RW compound			
Compressive strength	Compared are the mechanical strength and water resistance indicators for the key samples of the cement RW compound irradiated with gamma quanta or electrons up to an established absorbed dose and the control cement RW compound samples that have not been tested assuming an equivalent hardening time	From 1 to 50 MPa (from 10.2 to 509 kgf/cm^2)	No more than 50 % at P = 0.95
^{137}Cs and ^{90}Sr leaching rate		From $1 \cdot 10^{-7}$ to $1 \cdot 10^{-1}$ g/(cm^2·day)	No more than 35 % (P = 0.95) when the radionuclide activity is measured assuming an error of no more than 10 %

The draft Standard has been agreed with the enterprises of the State Corporation Rosatom, STC NRS and the Federal Service for Environmental, Technological and Nuclear Supervision. Positive feedback was received from its scientific and technical review held by a working group that engaged experts from NO RAO, RADON, FEO, VNIIAES, PA Mayak, Rosenergoatom Concern, Radium Institute. The metrological examination of the draft Standard was implemented by HSMO and Atomstandart. The standard measurement and test procedures given in the Standard correspond to the measurement requirements observed in the field of atomic energy use [5]—[8].

The standard is awaiting its approval by the order of the State Corporation Rosatom and thereby will become binding on all RW management enterprises of the industry, including the organizations involved in RW conditioning in accordance with waste acceptance criteria for disposal and validation of RW compliance with the waste acceptance criteria for disposal in accordance with the requirements of federal norms and rules the NP-093-14 [1], as well as the organizations engaged in the design development of RW conditioning methods and equipment.

Interlaboratory comparison tests (ICT) are viewed as an important element contributing to the unity of measurements and as an essential external quality control tool under the performed measurements. Under ICT, the enterprises engaged in such tests measure the characteristics of control samples fabricated purposefully by a provider organization.

As an accredited ICT provider, annually VNIINM implements around 15–20 programs in the field of laboratory measurements focused on the product characteristics and environmental samples under the contracts signed with the Rosatom State Corporation, TVEL and other organizations (reports on ICT performed since 2019 have been regularly posted on the official VNIINM's website). To ensure the uniformity in terms of measured RW characteristics, including the radiation ones (specific and total activity of gamma-emitting radionuclides), some ICT practices that have not been implemented before should be introduced. Based on these data, one may assess the correctness and reliability of the evaluated radiation RW package characteristics at each enterprise engaged in ICT, identify and eliminate the problems associated with the arrangement and implementation of such measurements, provide the comparability of their findings across the enterprises of the sector involved in RW transfer for disposal at NO RAO sites.

Conclusions

VNIINM that has been contracted by the State Corporation Rosatom is deploying a measurement system focused on the RW characteristics and their compliance assessment with waste acceptance criteria for disposal. These efforts resulted in the following standards:

- the Unified Industry-Wide Guidelines (UIG) on the Measurement of Radiation Waste Characteristics;
- standard measurement methods for the specific activities of radionuclides in waste of various morphologies based on gamma and LS spectrometry methods;
- standard procedure for HDR specific activity measurements in solid RW via the radionuclide vector method based on the specific activities measured for the reference radionuclides;
- standard measurement methods focused on the physical and chemical RW properties (the content of organic rotting, biologically active and decomposing substances, free liquid, heat generation);
- standard measurement methods implemented under the quality testing of cement RW compounds;
- Standard of the State Corporation Rosatom on the Compliance Assessment of Physical and Chemical RW Properties and Characteristics of the RW Form with Waste Acceptance Criteria for Disposal.

All standard methods discussed in the above standards have been subjected to a metrological review implemented by HSMO and Atomstandard and comply with the requirements established for the measurement methods in the field of atomic energy use.

Based on the developed standard measurement procedures, VNIINM is currently elaborating some operational methods that would be used to measure the radiation RW characteristics in the Competence Centers for nuclear decommissioning run by the TVEL company taking into account the equipment available at the enterprises and the required field of application.

The set of developed documents is thought as a basis for the compliance assessment of RW with waste acceptance criteria when the waste is transferred to the National Operator for disposal, planning relevant operations and their implementation. Methods involved in the measurements of the radiation characteristics can be used to measure the specific activity of radionuclides in waste when these are removed from regulatory control.

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