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Abstract

Development and attestation of gamma-ray non-destructive assay measurement methodologies for use by inspectors of the Russian Federal Service for Environmental, Technological, and Nuclear Oversight (Rostekhnadzor, formerly Gosatomnadzor or GAN), as well as for use by Russian nuclear facilities, has been completed. Specifically, a methodology utilizing the gamma-ray multi group analysis (MGA) method for determining plutonium isotopic composition has been developed, while existing methodologies to determining uranium enrichment and isotopic composition have been revised to make them more appropriate to the material types and conditions present in nuclear facilities in the Russian Federation. This paper will discuss the development and revision of these methodologies, the metrological characteristics of the final methodologies, as well as the limitations and concerns specific to the utilization of these analysis methods in the Russian Federation.

Introduction

The Russian Federal Service for Environmental, Technological, and Nuclear Oversight (Rostekhnadzor, formerly Gosatomnadzor or GAN) is responsible for the licensing of nuclear facilities as well as the development of, and inspection to, regulations for nuclear and radiation safety, material control and accounting (MC&A), physical protection (PP), radioactive waste management, and industrial safety. The United States Department of Energy (U.S. DOE) established a partnership with Rostekhnadzor in 1995 to develop a program designed to train and equip Rostekhnadzor Material Protection Control and Accounting (MPC&A) inspectors to inspect MPC&A activities at nuclear facilities. As part of this partnership, the U.S. DOE has provided support to Rostekhnadzor in developing a rigorous inspection and inspection-training program, and has additionally provided several non-destructive assay (NDA) instruments to enable Rosteckhnadzor to quantitatively verify characteristics of nuclear material during inspections.

In order that the provided NDA equipment can be utilized for MC&A purposes, Russian regulations require that the instruments, methodologies used to analyze measurement results, and the nuclear material used to calibrate instruments, be certified and attested to ensure quality assurance. The U.S. DOE supported the All-Russian Institute of Inorganic Materials (VNIINM) in the development and attestation of NDA uranium enrichment measurement methodologies utilizing the Canberra U/Pu Inspector with high-purity germanium (HPGe) and sodium iodide (NaI) detectors which were provided to Rostekhnadzor by the U.S. DOE. These methodologies were completed and attested in 2000. Since development of these methodologies, the U.S. DOE has further supported the development of a compendium of common NDA methods for MC&A.

This compendium was completed in 2002 and identified limitations in the uranium enrichment methods. Additionally, the compendium included draft methodologies that were commonly needed both by Rostekhnadzor inspectors and Russian facilities, specifically, the measurement of plutonium isotopic composition utilizing the Canberra U/Pu Inspector system, and the measurement of uranium and plutonium mass utilizing neutron coincidence counters. Rostekhnadzor and VNIINM have recently completed work to revise the three uranium enrichment methodologies to address limitations identified in the 2002 compendium and by operators, in addition to work to develop a methodology for the measurement of plutonium isotopic composition utilizing the Canberra U/Pu Inspector instrument. The goal of this work was to develop methodologies that would enable Rostekhnadzor inspectors and Russian facility operators to perform effective measurements of uranium enrichment and plutonium isotopic composition.

Overview of Method Development

Development of the revised uranium enrichment and the plutonium isotopic composition methodologies involved performing measurements of both certified and working reference materials to define the accuracy and precision of the methodologies over a wide range of conditions. The first phase of the work involved performing a series of laboratory measurements utilizing certified reference materials traceable to national standards. The results of these measurements served as the basis for the accuracy and precision values that were included in the final methodologies, as well as for the development of draft versions of the methods. The draft versions of the methodologies were then tested at Russian nuclear facilities to assess the applicability of the accuracy and precision values determined from the laboratory measurements in field environments, as well as to identify any limitations in the methodologies. Comments from Rostekhnadzor inspectors involved in the laboratory and facility testing were incorporated into the final methodologies, which were submitted for attestation.

Attestation of methodologies used for MC&A purposes is required by Russian regulatory documents, and is similar to the U.S. DOE requirement that measurement methods be qualified and approved. Both attestation and qualification are required to ensure that MC&A measurements have proper quality assurance, meet performance requirements, and ensure traceability of measurement results to a national base of reference materials. Attestation involves the review and statistical evaluation of a series of measurements demonstrating the performance of methodologies, and results in accuracy and precision values for the measurement methodology under a variety of conditions. The specific requirements governing the attestation of methodologies in Russia are described in the regulatory document entitled ‘State system for ensuring the uniformity of measurements. Procedures of measurements’ (GOST R 8.563-96), and a series of regulatory documents on the adequacy of measurement methods and results (GOST R ISO 5725 – 2002, parts 1-6). For methodologies to be utilized by a single agency, approval must be obtained by the agency-designated metrology institute. Russian nuclear facilities are operated by Rosatom (formerly Minatom), which has designated VNIINM as the lead metrology institute. For methodologies to be used by multiple agencies, a State metrology laboratory must approve the methodologies. Since the methodologies were to be used by both Rostekhnadzor, as well as by Rosatom facility operators, it was desirable to obtain State metrological approval. The Urals Science and Research Institute of Metrology (UNIIM) as well as the VNIINM metrology department were utilized to review and approve these methodologies. After approval by UNIIM and VNIINM, they were accepted as State-level methodologies and written to the State register.

Revision of Uranium Enrichment Measurement Methodologies

The three methodologies developed by VNIINM in 2000 for quantitative measurement of uranium enrichment utilize the Canberra U/Pu Inspector with high-purity germanium (HPGe) and sodium iodide (NaI) detectors, Genie2000 measurement software utilizing the enrichment meter (IMCA) analysis and the gamma-ray multi group analysis for uranium (MGAU). The limitations to the three uranium enrichment methodologies developed by VNIINM identified in the 2002 NDA compendium were mainly due to the fact that the majority of the development and testing of the methodologies was performed in laboratory conditions. Operation in field conditions revealed several limitations to the methodologies, including the unnecessary requirement for three parallel measurements and one-thousand-second measurement times for each measurement, understated measurement uncertainty for recycled uranium, and inadequate assessment of the effects of container thickness on measurement accuracy and uncertainty. To ensure that the revised methodologies did not exhibit the same limitations, extensive field testing was included in the development of the revised methodologies.

Uranium isotopic reference materials were utilized for the routine use and development of the methodologies developed in 2000. These reference materials were certified to the State level, could be utilized by multiple agencies, and could be used to define material properties to be included in accounting records. Unfortunately, these reference materials were of insufficient diameter for the collimators routinely used with the Canberra U/Pu inspectors, and were not of infinite thickness. As a result, the Research Institute of Atomic Reactors (RIAR) was tasked to fabricate, certify and distribute uranium NDA standards of infinite thickness and appropriate diameter to Rosatom facilities for use by both Rostekhnadzor inspectors and facility operators. Certification and distribution of these standards was not complete when work to revise the uranium methodologies was initiated, so VNIINM was additionally tasked to rapidly develop a single set of state certified uranium reference materials to be used in revision and testing of the methodologies. This single set of reference materials were completed in 2004, and contained five reference materials of approximately 215g total uranium mass, with uranium-235 enrichments (mass fraction) of 0.7%, 3.5%, 21.0%, 35.9%, and 89.9%.

Utilizing this as well as other sets of uranium reference materials, VNIINM, in coordination with Rostekhnadzor, performed extensive laboratory measurements to study effects of performing single measurements with decreased measurement times, of variable and compound container thicknesses, the presence of recycled uranium and effects of large uranium masses on the accuracy and precision of the methodologies. Based on these studies, work to revise the methodologies proceeded with specified measurement times of 300, 500 and 1000 seconds. Additionally, empirical formulas were developed to allow bias correction of measurement results for the effects of container thickness, including the effects of containers composed of multiple materials. Finally, the effects of the presence of U-232, or more correctly the daughter product Th-228, from the process of recycling uranium were analyzed. For the IMCA methodologies with either the NaI or HPGe detectors, limits on the ratio of U-232 to U-235 mass were established for a range of time since chemical separation (from 1 month with U-232/U-235 of 4.2×10^{-8}, to 48 months with ratio of 1.6×10^{-9}). For the MGAU methodology, limits on the ratio of U-232 to U-235 mass were established for a range of time since chemical separation (from 5 months with U-232/U-235 of 1.8×10^{-8}, to 48 months with ratio of 3.2×10^{-9}). Results of the laboratory measurements were used to develop draft versions of the modified methodologies, and all measurement data was compiled and provided to the UNIIM institute for review.

Field Testing of the Revised Uranium Enrichment Measurement Methodologies

Using the laboratory testing results and the draft methodologies, extensive field testing plans were developed to assess the applicability and limitations of the methodologies in field conditions. The first of these field tests was performed at Mayak by personnel from Mayak, VNIINM, Rostekhnadzor and the Russian Metrological Training Center (RMTC) at the Institute of Physics and Power Engineering (IPPE), and included measurements of low and high enriched uranium oxide. Additionally, measurements were performed on four batches of low enriched uranium with a range of U-232 concentrations. Results from the field test at Mayak indicated that the draft revised methodologies were well suited to the measurements of material, and validated the bias correction algorithms developed during the laboratory testing for material container effects. No major limitations were noted, though extensive measurements with the MGAU methodology were not permitted due to information security restrictions. A workshop was conducted to resolve comments from the field test at Mayak, and it was determined that MGAU measurements would be the focus of a second field test to be conducted at the Siberian Group of Chemical Enterprises (SGChE).

The second field test conducted at the Sublimation and Chemical & Metallurgical Plants at the SGChE included measurements of LEU and HEU uranium hexafluoride and oxide, recycled LEU hexafluoride and oxides, as well as LEU metal. The measurement results verified the laboratory determined uncertainty and accuracy values and validated that within the ranges of U-232 concentration defined in the methodologies the time between conversion of chemical form had no influence on the measurement results. The field tests also demonstrated that all methods allow measurement of uranium enrichment in hexafluoride, oxide and metal forms. A workshop with participation from personnel from VNIINM, Rostekhnadzor, RMTC and UNIIM was conducted to finalize the methodologies.

Following the final workshop, personnel from Rosteknadzor and RMTC revisited Mayak to reanalyze data from measurements of recycled uranium to investigate whether the Ortec version of MGAU (U235View of the Ortec MGA++ analysis package) would result in reduced bias, especially for material processed within 6 months. Measurement results of material with processing dates ranging from 2 days to 12 months were reanalyzed with the U235View analysis package with no improvement in analysis results; measurements of material processed within 5 months resulted in extreme bias, similar to that observed with MGAU. Additional investigation into this effect is necessary to allow MGAU-type analysis to be used for recently processed material.

Accuracy and Precision of the Uranium Enrichment Measurement Methodologies

The accuracy and precision values for the uranium enrichment methodologies were determined for uranium-235 enrichment ranges of 0.7% - 90% for a variety of container thickness, collimators and measurement times of 300, 500 and 1000 seconds. Attestation of the methodologies was based on measurement of state certified uranium oxide reference samples, but can be utilized with reference materials certified at the state, agency or facility level with appropriate accuracy. For the IMCA method with HPGe detector, attested values are available for collimators of 25, 18 and 10 mm with container thickness of 0.4 – 15.5 mm steel equivalent. For the MGAU method with a HPGe detector, attested values are available for container thickness of 0 – 7.5 mm steel equivalent. For the IMCA method with NaI, attested values are available for collimators of 44, 18 and 10mm with container thickness of 0.4 – 15.5 mm steel equivalent. Examples of the metrological characteristics of the revised uranium methodologies are included in Tables 1-3. The metrological characteristics of the methodologies will need to be reviewed in 2011 when they expire, per Russian regulation.

Table 1. Metrological characteristics of methodology to determine U-235 enrichment with U/Pu Inspector, IMCA analysis software and HPGe detector with a collimator of 25mm

Time, s	Range of measured ^{235}U mass fractions, %	$CR_{0.95(3)}$, % (reproducibility limit)	σ_R (δ), % (reproducibility RMQD)		δ_C, %	δ, %	
			(n=1)	(n=3)		(n=1)	(n=3)
Container (packaging) wall thickness: 4.0 to 7.0 mm.							
300	0.09 - 0.30	23.3	16.6	5.6	26.5	19.3	23.3
	0.30 - 1.50	7.8	5.6	4.0	9.5	7.4	7.8
	1.50 - 10.00	2.4	1.7	2.0	3.4	2.8	2.4
	10.00 - 20.00	1.4	1.0	1.9	2.5	2.2	1.4
	20.00 - 40.00	1.1	0.8	1.7	2.1	2.0	1.1
	40.00 – 90.00	0.8	0.6	1.5	1.8	1.7	0.8
	Over 90.00	0.6	0.4	1.4	1.6	1.5	0.6
1000	0.09 - 0.30	12.9	9.2	5.6	15.3	11.6	12.9
	0.30 - 1.50	4.3	3.1	4.0	6.3	5.3	4.3
	1.50 - 10.00	1.4	1.00	2.0	2.6	2.3	1.4
	10.00 - 20.00	0.9	0.6	1.9	2.2	2.1	0.9
	20.00 - 40.00	0.6	0.4	1.7	1.9	1.8	0.6
	40.00 – 90.00	0.4	0.3	1.5	1.6	1.6	0.4
	Over 90.00	0.3	0.2	1.4	1.5	1.4	0.3

Table 2. Metrological characteristics of methodology to determine U-235 enrichment with U/Pu Inspector, MGAU analysis software and HPGE detector

Time, s	Range of measured ^{235}U mass fractions, %	$CR_{0.95(3)}$, %	σ_R (δ), %		δ_C, %	δ, %	
			(n=1)	(n=3)		(n=1)	(n=3)
Container (packaging) wall thickness: 0 to 2.0 mm incl.							
300	0.30 - 1.00	6.0	11.2	6.1	1.9	21.8	12.1
	1.00 - 5.00	2.5	4.6	2.5	1.5	8.5	5.0
	5.00 - 20.00	1.7	3.2	1.7	1.7	5.9	3.5
	20.00 - 40.00	1.3	2.4	1.3	1.5	4.4	2.6
	40.00 - 90.00	1.6	2.8	1.9	1.2	5.6	3.9
	90.00 - 95.00	4.3	7.5	5.0	1.3	14.9	10.4
1000	0.30 - 1.00	3.3	6.1	3.3	1.7	11.9	6.6
	1.00 - 5.00	1.4	2.5	1.4	1.4	4.9	2.7
	5.00 - 20.00	1.0	1.8	1.0	1.2	3.5	1.9
	20.00 - 40.00	0.7	1.3	0.7	1.1	2.5	1.4
	40.00 - 90.00	1.1	1.7	1.1	1.1	3.5	2.3
	90.00	2.6	4.1	2.6	1.2	8.9	6.3

Table 3. Metrological characteristics of methodology to determine U-235 enrichment with U/Pu Inspector, IMCA software and NaI detector with a collimator of 18mm and container thickness of 0.4-1.0mm steel equivalent.

Range of measured ^{235}U mass fractions, %	σ_r, % (repeatability RMQD)	σ_R , %		δ_C, %	δ, %	
		n=1	n=3		n=1	n=3
	Measurement time of 300 s					
0.30 - 1.50	5.4	12.1	8.1	4.3	23.7	16.1
1.50 - 10.00	1.5	3.4	2.3	2.2	6.9	4.9
10.00 - 20.00	0.8	1.9	1.3	1.7	4.0	3.0
20.00 - 40.00	0.6	1.4	0.9	1.5	3.1	2.4
40.00 - 90.00	0.3	0.9	0.6	1.3	2.2	1.8
Over 90.00	1.0	0.7	0.5	1.1	1.8	1.4
	Measurement time of 1000 s					
0.09 - 0.30	6.1	13.7	9.1	6.5	27.1	18.7
0.30 - 1.50	2.9	6.6	4.4	4.3	13.4	9.5
1.50 - 10.00	1.0	2.2	1.5	2.2	4.8	3.6
10.00 - 20.00	0.6	1.3	0.9	1.7	3.0	2.4
20.00 - 40.00	0.4	0.9	0.6	1.5	1.9	2.3
40.00 - 90.00	0.3	0.7	0.5	1.2	1.8	1.5
Over 90.00	0.2	0.5	0.3	1.0	1.4	1.2

Plutonium Isotopic Measurement Methodology Development

The 2002 VNIINM compendium of NDA methodologies contains a draft version of a methodology utilizing the Canberra U/Pu Inspector, Genie2000 and the gamma-ray multi group analysis (MGA) software. This methodology was not attested, but was used as guidance for development of facility specific methodologies. To enable Rostekhnadzor inspectors to perform measurements of plutonium isotopic composition at Rosatom facilities that have not established facility-specific methodologies, VNIINM developed a development and testing plan for Pu isotopic methodologies utilizing the U/Pu Inspector and MGA software. This plan contained laboratory and field testing phases similar to those for revision of the uranium methodologies.

VNIINM and several other Rosatom institutes and facilities have certified Pu isotopic reference materials suitable to establish accuracy and precision values for the methodology. Due to limitations in the amount of americium (Am) and neptunium (Np) containing material VNIINM can retain on-site, certified reference materials at both VNIINM and IPPE were utilized for the laboratory measurements. Specifically, materials with Pu-239 isotopic mass fraction ranging from 79-94%, Am-241 isotopic mass fraction of 1.4-2.9% and Np mass fractions of .005-2.5% were utilized at VNIINM, while items with Pu-239 isotopic mass fractions of 60% and 97%, as well as Am-241 isotopic mass fractions of 1% and 184% available at IPPE were utilized. These laboratory measurements focused on addressing limitations with the draft Pu methodology noted during operation at facilities, specifically the effects of Am and Np impurities, container thickness and measurement times. The laboratory measurements indicated that the presence of Am had little effect on the measurement results, especially for Pu-239, mainly due to the use of filters available with the U/Pu Inspector system. The presence of Np impurities did introduce a bias to the Pu-239 and other major isotopic fractions, and as a result a limitation of 2.5% Np/Pu mass ratio was introduced to the methodologies. Further, laboratory measurements indicated that while container thickness had little effect on the measurement results of Pu-239 isotopic fraction, that thickness of greater than 10mm steel equivalent drastically reduced the precision of measurements of the isotopic mass fraction of other major Pu isotopes. Finally, measurement times less than 300 seconds resulted in insufficient statistics for stable results in most situations, and as such measurement times of 300, 500 and 1000 seconds were used in the methodology. Results of the laboratory measurements were used to develop a draft version of the methodology, and all measurement data was compiled and provided to the UNIIM institute for review.

Testing of the draft methodology was performed at SGChE to assess performance and identify limitations under field conditions. These tests were performed by personnel from SGChE, VNIINM and Rostekhnadzor with a variety of Pu samples with both known and unknown Pu isotopic, Am and Np levels. Results of the measurements verified the uncertainty resulting from the laboratory measurements in nearly all tests. In a number of measurements, however, the measured Am-241 content exhibited bias and uncertainty that exceed those determined from laboratory measurements. Based on this, Am-241 accuracy and precision values were adjusted in the methodologies to more appropriately reflect the performance in field conditions. Further, the field measurements indicated that the lower limit of Pu-238 that the methodology can measurement effectively to be $4 \cdot 10^{-3}$%. Finally, there were situations when the instrument gave warning messages for insufficient statistical information for when measuring samples with low Pu-239 mass fraction; the draft methodology was modified to include a paragraph referring to such a situation.

A second field test was conducted at Mayak and included participation of personnel from Rostekhnadzor, VNIINM and RMTC. The goal of the second field test was to validate the results of the first field test over a wider range of material types, as well as to compare measurement results with a system utilizing an Ortec coaxial detector and the Fixed-Energy, Response Function Analysis with Multiple Efficiencies (FRAM) software analysis program. Several Pu

samples with a variety of burn-up levels and time since chemical separation were utilized for this second field test, allowing the measurement results to be used to verified the accuracy and precision levels defined from the laboratory testing, as well as to define accuracy and precision for a wide range of Pu burn-up and age. Additionally, the coaxial system with FRAM analysis software was demonstrated to have performance characteristics similar to that of the U/Pu system with the MGA methodology. No major limitations in the measurement methodology were noted, and all measurement results were submitted to UNIIM for metrological attestation.

Accuracy and Precision of Plutonium Isotopic Measurement Methodology

The accuracy and precision level of the plutonium isotopic fraction methodology was determined for a variety of Pu isotopic mass fractions in containers with less than 10mm of steel equivalent thickness for counting times of 300, 500 and 1000 seconds. Examples of metrological characteristics of the methodology for 300 and 1000 second measurements are included in Tables 4 and 5. The metrological characteristics of the methodologies will need to be reviewed in 2011, when they expire.

Table 4. Metrological characteristics of methodology to determine Pu isotopic fraction with the U/Pu Inspector and MGA software for a counting time of 300 seconds

Isotope	Range of measured mass fractions, %	σ_r, % (repeatability RMQD)	σ_R, % (reproducibility RMQD)		δ_C, %	δ, %	
			n=1	n=3		n=1	n=3
^{238}Pu	0.040 - 0.200	3.1	6.0	3.1	2.2	14.2	7.5
	0.200 - 1.000	1.4	2.6	1.4	0.9	6.1	3.4
	1.000 - 2.000	0.9	1.2	0.9	0.3	4.7	2.2
^{239}Pu	60.00 to 70.00 incl.	0.6	0.9	0.6	0.8	4.9	2.8
	70.00 - 80.00	0.3	0.5	0.3	0.6	2.6	1.4
	80.00 - 90.00	0.2	0.4	0.2	0.4	1.8	1.0
	90.00 - 97.50	0.2	0.2	0.1	0.1	0.6	0.3
^{240}Pu	2.50 - 3. 50	4.9	11.0	7.3	1.5	21.4	14.3
	3.50 - 6.00	1.8	4.0	2.7	1.0	7.8	5.2
	6.00 - 10.00	1.5	3.4	2.3	1.0	6.6	4.5
	10.00 - 20.00	1.2	2.7	1.8	0.9	5.3	3.6
	20.00 - 25.00	0.8	1.9	1.3	0.7	3.7	2.5
^{241}Pu	0.010 - 0.100	3.0	5.9	3.1	2.0	13.9	7.4
	0.100 - 1.000	1.5	3.5	2.3	1.2	6.9	4.6
	1.000 - 5.000	1.3	2.6	1.3	1.1	6.0	3.2
	5.000 - 10.000	0.8	2.3	1.2	1.0	3.9	2.7
^{241}Am	0.002 - 0.010	8.5	19.0	12.7	2.2	37.1	24.8
	0.010 - 0.030	5.0	9.0	5.0	2.1	21.4	12.0
	0.030 - 0.100	2.8	5.3	2.8	1.8	12.7	6.7
	0.100 - 0.500	1.3	3.0	2.0	1.2	5.9	4.0
	0.500 - 3.000	1.0	1.4	1.2	0.9	5.5	2.9
	3.000 and above	0.5	1.0	0.7	0.4	2.0	1.4

Table 5. Metrological characteristics of methodology to determine Pu isotopic fraction with the U/Pu Inspector and MGA software for a counting time of 1000s

Isotope	Range of measured mass fractions, %	σ_r, % (repeatability RMQD)	σ_R, % (reproducibility RMQD)		δ_C, %	δ, %	
			n=1	n=3		n=1	n=3
^{238}Pu	0.004 - 0.040	9.0	20.2	13.5	2.4	39.4	26.2
	0.040 - 0.200	1.1	2.4	1.6	1.5	4.8	3.4
	0.200 - 1.000	0.6	1.4	0.9	0.3	2.7	1.8
	1.000 - 2.000	0.3	0.6	0.4	0.2	1.2	0.6
^{239}Pu	60.00 - 70.00	0.2	0.5	0.3	0.2	1.0	0.7
	70.00 - 80.00	0.1	0.3	0.2	0.1	0.6	0.4
	80.00 - 90.00	0.1	0.2	0.1	0.1	0.4	0.3
	90.00 - 97.50	0.03	0.1	0.1	0.1	0.2	0.2
^{240}Pu	2.50 - 3. 50	2.0	4.5	3.0	1.5	8.8	6.0
	3.50 - 6.00	0.6	1.3	0.9	1.0	2.7	1.9
	6.00 - 10.00	0.5	1.0	0.7	0.7	2.0	1.5
	10.00 - 20.00	0.3	0.6	0.4	0.5	1.3	0.9
	20.00 - 25.00	0.2	0.5	0.3	0.5	1.1	0.8
^{241}Pu	0.010 - 0.100	0.7	2.6	1.8	2.0	5.7	4.3
	0.100 - 1.000	0.5	2.0	1.2	2.0	4.3	3.3
	1.000 - 5.000	0.4	1.2	1.0	1.5	3.9	2.8
	5.000 - 10.000	0.4	1.0	0.9	1.5	3.1	2.0
^{241}Am	0.002 - 0.010	3.9	8.7	5.8	1.5	16.9	11.3
	0.010 - 0.030	2.0	4.0	2.0	1.1	9.4	4.7
	0.030 - 0.100	1.2	2.4	1.2	0.9	5.7	3.0
	0.100 - 0.500	0.6	1.4	0.9	0.7	2.8	1.9
	0.500 - 3.000	0.3	0.7	0.5	0.5	1.4	1.2
	3.000 and above	0.3	0.6	0.4	0.4	1.2	0.9

Conclusion

Methodologies for the measurement of uranium enrichment and plutonium isotopic composition have been developed and attested for use by Rostekhnadzor inspectors utilizing Canberra U/Pu Inspector with NaI and HPGe detectors, and the IMCA and MGAU analysis software. These methodologies also can be used for verification measurements by operators at Rosatom facilities that utilize these instruments. Accuracy and precision values for a variety of material compositions and container types have been attested at the state level by UNIIM. Major limitations of the methodologies are container thickness (especially for MGA and MGAU analyses), presence of U-232 from reprocessing (especially for MGAU analysis), and the presence of Np-237 in mass fractions above 2.5% (for MGA analysis).