Determination of ^{233}U Using High Resolution ICP-AES After Chemical Separation

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INTRODUCTION

Uranium (U) is the heaviest naturally occurring element on earth and is usually found in very small amounts in rock, soil, air, and water. Its atomic number is 92 with an electron configuration of $[\text{Rn}] 5f^3 6d^1 7s^2$. Uranium is the most commonly used material in the nuclear industry to generate electricity and shows weak radiotoxicity due to its chemical properties and unstable isotope behavior. In nature, uranium consists of three isotopes: ^{234}U , ^{235}U , and ^{238}U with relative isotopic abundances of 0.0054%, 0.720%, and 99.275%, respectively. The half-life of the ^{234}U , ^{235}U , and ^{238}U isotopes is $t_{1/2} \approx 2.5 \times 10^5$ years, $t_{1/2} \approx 7.0 \times 10^8$ years, and $t_{1/2} \approx 4.5 \times 10^9$ years, respectively. Although all three isotopes are radioactive, only ^{235}U is a fissionable material used for nuclear power generation (1). Another fissile isotope, ^{233}U , can be produced from natural thorium and finds important applications in the nuclear technology as a fuel (2). To produce ^{233}U , atoms of ^{232}Th are exposed to neutrons. ^{232}Th has a half-life of about 23.5 minutes and decays into ^{233}Pa through beta decay. ^{233}Pa has a half-life of about 27.4 days and decays into ^{233}U also through beta decay. The stepwise reaction of ^{233}U generation is shown in Equation 1 below:

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ABSTRACT

A ^{233}U -Al alloy sample was dissolved in concentrated HNO_3 by heat treatment under an infrared lamp. The sample was chemically separated using 20% Tri-n-octyl amine (TnOA)/Xylene/4M HNO_3 as the extractant and determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). The spectral profile of the ^{233}U separated from the concomitant elements and the intensity was found to be nearly 50 times greater than the blank reagent. This confirmed the absence of interference and background. The most suitable spectral line was 424.398 nm. The profiles of the ^{235}U and ^{238}U spectral lines were recorded on enriched samples (at various levels) for comparative study. A set of nominally ^{233}U enriched uranium samples was analyzed from 5 to 35 ppm using the calibration curve. The ^{233}U concentration of the uranium sample was determined at levels as low as 5 ppm. There was no significant contribution from the interference and background up to 35 ppm. The observed values of ^{233}U were found to be in close agreement with the added amount. The ^{233}U sample of 10 ppm concentration was analyzed by mass spectrometry for crosscheck. The results of mass spectrometry were in very close agreement with the ICP-AES analysis. The overall precision of the optimized method was 5% RSD with a detection limit of 0.01 ppm. The present method provides a quick analysis of uranium samples for their isotopic constituents.

Uranium is a naturally occurring element whose atom is unstable and decays slowly by emitting alpha particles and energy (3).

Uranium isotopic measurements can be performed either by alpha-spectrometry for ^{234}U , ^{238}U , and to a lesser extent ^{235}U or by a mass spectrometric technique for all three isotopes. However, the ^{234}U isotope is found at very low concentrations in natural uranium. Methods such as inductively coupled plasma mass spectrometry (ICP-MS), electrothermal vaporization (ETV)-ICP-MS, thermal ionization mass spectrometry (TIMS), and extractive electrospray ionization mass spectrometry (EESI-MS) have been used for isotopic measurement of uranium in natural samples (4-7). TIMS provides highest precision with 0.2% at the 95% uncertainty level compared with approximately 1-2% for ICP-MS. The isotopic levels are normally measured using mass spectrometric techniques due to their accuracy and precision. The high sensitivity of ICP-MS allows the determination of ^{235}U and ^{238}U and their isotope ratios in uranium samples. However, it frequently requires a tedious and lengthy sample preparation and is time-consuming, in addition to the high cost of instrumentation and analysis.

In this context, an alternative technique is required ideally suited to estimate all the isotopic/metallic impurities, particularly at ultra-trace levels with regard to the power of detection, precision and accuracy, and the number of elements. In the present study, inductively coupled plasma atomic emission spectrometry (ICP-AES) was used for isotopic determination. The ICP-AES

methodology is very simple and can be adopted for rapid analysis at intermediate stages of a process such as nuclear fuel production. In view of its speed, high sensitivity, good precision, large linear dynamic range, and relative freedom from matrix effects, it provides reasonable detection limits and is generally used for the simultaneous determination of common metallic impurities (8, 9) as well as for rare earth impurities in a uranium/plutonium matrix. The high-resolution spectrometer, with a practical resolution of 0.005 nm, offers higher tolerance for residual amounts of the actinides. The sequential ICP-AES system requires about 10 seconds per analyte line (10). The isotopic effect in the emission spectrum of the same element with different mass numbers can be effectively studied by isotopic assay through resolving the fine structure using a high-resolution ICP spectrometer, which should have the capability to resolve very close analyte peaks.

Krachler et al. (11) suggested a reliable method for the determination of ^{233}U using high resolution ICP optical emission spectrometry (ICP-OES). For quantitative ^{233}U analysis, the development of adequate peak deconvolution strategies were required to separate the individual peaks. The study highlights that the currently employed analytical approach provides potential solutions for a selective and reliable quantification of ^{233}U , ^{235}U , and ^{238}U using high resolution ICP-OES. The method has special relevance in the determination of ^{233}U in the presence of other alpha-emitting radionuclides which otherwise interfere in the ^{233}U analysis by alpha radiometry and in complex matrices. Rameback et al. (12) used inductively coupled plasma mass spectrometry (ICP-MS) and gamma spectrometry for ^{233}U determination. All measurement results were in good agreement, i.e., consistent

within the combined uncertainties. Furthermore, the use of fundamentally different measurement techniques providing the same result can serve as a validation and give confidence in a measurement result. Patwardhan et al. (13) reported results of the isotopic line of ^{233}U which could be adequately resolved from the ^{238}U emission line using ICP-AES. The shift for the 424.431 nm emission line of ^{238}U is found to be of the order of 0.040 nm on the lower wavelength side for ^{233}U . Further, the analysis procedure of ^{233}U at various stages during the recovery and purification of ^{233}U is discussed. The precision of the method is 5% RSD. In another report, ^{233}U as fuel in the form of plates of ^{233}U -Al alloy was used at the Indira Gandhi Centre for Atomic Research at Kalpakkam in 1996 (14).

In a previous study, we reported the determination of ^{235}U and ^{238}U isotopes in a set of uranium samples using an ICP-AES technique (15). In the present work, the development work was continued by (i) the determination of ^{233}U in ^{233}U -Al alloy sample after chemical separation and (ii) the determination of common metallic impurities prior to ^{233}U isotopic analysis. The methods were developed in our laboratory for separation of plutonium, uranium, and thorium using different extractants such as Tri-n-octyl amine (TnOA) and Cyanex-923 (16-17) under a quality control program. The determination of trace levels of ^{233}U in a ^{233}U -Al alloy sample by ICP-AES requires prior separation of the major matrix due to possible spectral interferences. K. Radhakrishnan et al. (18) separated ^{233}U from thorium using the oxalate precipitation method followed by ICP-AES analysis. In another report, DHOA (Di-n-hexyloctanamide) was used as an alternative extractant to TBP (tri-n-butyl phosphate) known for the extraction of uranium from moderate

nitric acid medium without significant extraction of the fission products. A comparison of the analytical performance of DHOA with TBP revealed that its performance is at par with the TBP extractant (19). The studies showed that 5 ppm of common impurities and 1 ppm of critical elements can be determined in a uranium matrix by ICP-AES. Based on these reports, different extractants were studied for the separation of ^{233}U .

TnOA is fairly well known as a solvent that can be used to extract uranium nitrates and other salts from aqueous solution. Therefore, ^{233}U was extracted using 20% TnOA in xylene/4M HNO_3 and was found to be one the best extractants in terms of quantitative recovery (20). Prior to the TnOA extraction step, a ^{233}U -Al alloy sample was dissolved in concentrated HNO_3 and made up to 10 mL volume after adjusting the acidity to 4M HNO_3 . The commercially available ICP atomic emission spectrometer was extensively modified and successfully employed for the analysis of ^{233}U samples up to ppm levels. The design of the ICP enclosure and its installation were mainly governed by criteria such as total containment of radiotoxic materials (21). ICP-AES appears to be a good alternative to α -spectrometry and other methods for the determination of long-lived radionuclides because of its simplicity, accuracy, excellent detection limits, and speed of analysis.

EXPERIMENTAL

Instrumentation

All experiments were carried out using a Jobin Yvon ULTIMA high-resolution inductively coupled plasma atomic emission spectrometer (Jobin Yvon Ultima, France) with a 0.5 M focal length and two concave holographic gratings with 3600 grooves/mm and 4320 grooves/mm. The optical configuration with 4320 grooves/mm grating

gives a practical resolution of <0.005 nm and a continuous coverage of the widest spectral range of 200-800 nm, which is ideally suited for analysis of uranium and plutonium samples. However, the commercially available ICP-AES cannot be readily employed for the analysis of ^{233}U -based nuclear fuel samples due to their inadaptability to handle radiotoxic materials. The ICP-AES instruments have been suitably modified for either glove box or fume-hood containment so as to analyze radiotoxic materials. The high-resolution sequential spectrometer used in the present studies was also extensively modified by incorporating an ICP torch assembly, peristaltic pump, and other sample handling accessories within the glove box to enable the analysis of the radiotoxic samples within an alpha containment facility as mentioned earlier. Details of the instrumentation are discussed elsewhere (22-24). The specifications and operating conditions of the instrument and the plasma source are listed in Tables I and II, respectively.

Preparation of Samples and Standards

All chemicals used were of analytical reagent (AR) grade. Quartz double distilled water and HNO_3 were used for the reagents as well as the preparation of the standards. The multi-element standards containing Al, B, Be, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Na, Ni, Pb, Si, Sn, V, W, and Zn were prepared from single-elemental CertiPUR® solutions (E-Merck, Darmstadt, Germany) diluted with 0.5M HNO_3 . The stock solution of ^{233}U , prepared at the concentration level of 2000 ppm in HNO_3 , was employed to prepare a series of ^{233}U sample concentration ranges (from 5 ppm to 35 ppm) after appropriate dilution with 0.5M HNO_3 . Three synthetic samples of various isotopes with higher concentration levels at

TABLE I
Specifications and Operating Conditions of the ULTIMA HR-ICP-AES

Optical design	1.0 M Czerny Turner
Grating	Holographic, ion-etched original grating
Groove density	4320 g/mm and 2400 g/mm
Grating size	110 x 110 mm
Spectral range	160 to 800 nm
Resolution	0.005 nm in the first order
R.F. Generator	
Operating frequency	40.68±0.02 MHz
Design	Solid state, Crystal control
R.F. power	Computer-Controlled, continuously adjustable from 800-1550 W in the plasma
Automation	Computer programmable R.F. power and shutdown of plasma
Safety interlocks	Argon, water, plasma compartment door, reflected power and exhaust
Introduction of Sample	
Torch design	Completely de-mountable quick-change kits
Plasma geometry	Single view, radial observation
Plasma viewing height	Simultaneous radial observation of entire Normal analytical zone
Patented sheath gas	Computer-controlled, sheath flow of argon around aerosol prior to 3 mm injector tube; optimizes residence time for group I & II elements and allows for analysis of high dissolved solid samples
Pump	Dual channel (nebulizer, drain) 12 roller computer-controlled
Nebulizer	Pneumatic concentric
Spray chamber	Glass Chamber
Detectors	Two patented high dynamic range detectors
Instrument control	The Ultima is equipped with a Spectralink, containing microprocessors controlling all instrument functions and data acquisition. The Spectralink is connected via a serial RS 232 link to the main computer PIII 550 MHz, 128 Mb RAM, 4.3 Gb Hard Disk
Software	V5 for Windows® 95 and Image Navigator for spectrum acquisition and semi-quantitative analysis

TABLE II
ULTIMA HR-ICP-AES Operating Conditions for ^{233}U Determination

Argon gas	Plasma gas flow	12 L/min
	Cooling gas flow	0.2 L/min
	Nebulizer pressure	3 bar
	Nebulizer flow	0.85 L/min
Pressure of manometer	6 bar	
R.F. power	Continuously adjustable between 800-1550 KW in the plasma	

1580 ppm in 0.5M HNO₃ were prepared. Optimization of the ICP-AES experimental parameters was carried out with 20 ppm of ²³³U to obtain maximum S/N response. Initially, studies were conducted for peak search, spectral interferences, and auto-attenuation with 20 ppm concentration of ²³³U. The other experimental parameters such as R.F. power, varying viewing positions of the plasma, argon gas flow rates for coolant, sample and plasma flows and signal integration period were standardized and adopted for ICP-AES analysis. An amount of 0.5M HNO₃ as the lower standard and 20 ppm concentration of ²³³U as a the higher standard was used for the calibration curve. The small quantity of separated ²³³U was used for ²³³U⁵⁺:LiNbO₃ sample preparation by the flux method described by Lewis et al. (25) for carrying out Electron Paramagnetic Resonance measurements.

Dissolution and Separation of ²³³U

A ²³³U-Al alloy sample was dissolved in concentrated HNO₃ (AR grade) under an IR lamp. The dissolved uranyl nitrate solution was evaporated to near dryness. 4M HNO₃ was again added to the residual solution. This step was repeated three times to ensure complete dissolution of the sample. The final residue was made up of 4M HNO₃ in 10 mL ²³³U and was separated using 20% tri-n-octylamine (TnOA) in xylene/4M HNO₃. Extraction of uranium from the sample solution was accomplished by using five separate aliquots of equal volumes of 20% TnOA in xylene, followed by two aliquots of pure xylene. The organic phase was scrubbed with dilute 5M HClO₄ acid to recover the uranium. The precipitation was carried out with 5M NaOH by adding part by part with continual stirring. The uranyl hydroxide was washed with quartz double distilled water, followed by

alcohol. Subsequently, it was filtered using the proper size of filter paper and heated under an IR lamp for one hour. The final residue was converted into oxide form by heating in a muffle furnace at 900 °C for two hours (26). For preparation of the stock solution, U₃O₈ (²³³U) was dissolved in 4M HNO₃. The dissolution work was done in a glove box especially made for handling radioactive materials. The solution was further diluted by 0.5M HNO₃ to obtain 20 ppm, which was used as the higher standard. A schematic of the dissolution and separation procedure of ²³³U is shown in Figure 1.

Characterization of ²³³U Sample

A ²³³U nitrate solution was analyzed by ICP-AES for impurity content. Among the spectroscopic methods routinely employed for trace metal characterization of nuclear fuels, ICP-AES is the most established and preferred. The concentrations of the metallic impurities in the fuel must be below the maximum permissible levels specified to obtain the required density for the pellets and also to reduce the loss of neutrons due to the presence of elements with a high neutron absorption cross section. Quantitative determination of these elements in nuclear-grade uranium is therefore necessary prior to its

use as a nuclear fuel. Uranium has a line-rich emission spectrum and is expected to interfere during the determination of the analytes at the trace levels due to its multi-electronic nature. Spectral interference caused by the line-rich spectrum of actinides, especially uranium, is a well-known problem in the determination of trace metal impurities and rare earths (REEs) in nuclear fuels using AES methods (27). ICP-AES analysis of the ²³³U sample was carried out prior to ²³³U determination. The reference samples were analyzed using the two-point standardization procedure. A measure of high accuracy of determinations could be inferred from the close agreement obtained between the analyte concentrations and their certified values. The results of the emission spectrometric analysis of the ²³³U sample are listed in Table III.

RESULTS AND DISCUSSION

Peak Search and Profile of ²³³U Spectral Line

The spectral scan of the ²³³U lines ranging from 250-500 nm was carried out by aspirating a well-characterized stock solution of a ²³³U nitrate solution diluted to 20 ppm into the plasma. As discussed earlier, the instrumental parameters such as forward power, flow rate of

Fig. 1. Schematic flowchart of dissolution and separation of ²³³U.

the argon gas, and signal integration time were optimized to obtain the optimum signal-to-noise ratio. Uranium has a multi-electron configuration and severe spectral interferences caused by the line-rich spectrum require the use of a high-resolution sequential spectrometer to resolve the spectral lines. Matrix and spectral interferences can occur in the radiochemical analysis. Spectral interferences can be avoided by selecting proper sensitivity lines. The elimination of an undesirable sample matrix such as Na and U has been demonstrated by Pretty et al. (28) using a brief cell wash time for detection by ICP-AES and ICP-MS. For this study, the instrumental parameters were suitably optimized to select analytical spectral lines free from the normal interfering elements (29-30). The

TABLE III
ICP-AES Analysis of the
²³³U Sample for Common
Metallic Impurities

Sr. No.	Elements	Wavelength (nm)	Conc. (ppm)
1	Al	309.271	35
2	B	249.773	<0.2
3	Be	313.042	0.3
4	Ca	393.366	<10
5	Cd	228.802	<0.2
6	Co	228.616	<10
7	Cr	383.563	<10
8	Cu	324.754	<4
9	Fe	259.940	<20
10	Mg	279.553	<10
11	Mn	257.610	<4
12	Mo	202.030	<20
13	Na	588.995	160
14	Ni	221.647	<10
15	Pb	220.353	<10
16	Si	251.611	120
17	Sn	242.949	<2
18	V	309.311	<10
19	W	207.911	<80
20	Zn	213.856	<20

spectral line at 424.398 nm was found to be the most suitable and interference-free. Figure 2 shows the profile of the emission spectral line of ²³³U at 424.398 nm. For comparison, the profile of a reagent blank is also shown in Figure 2.

ICP-AES Analysis of ²³³U Sample

Separation of atomic emission peak maxima in the emission spectrum of the same element with different mass numbers can be effectively used for the isotopic assay by resolving the fine structure using high-resolution ICP-AES. Since the ICP is an extremely high temperature source, Doppler broadening is prevalent which leads to reduced separation of the analytical lines. This is all the more problematic in the context of isotopic shifts, which are very small. The theoretical line separation between the ²³³U, ²³⁵U, and ²³⁸U lines is thus difficult to achieve in practice, unless the resolution of the optical spectrometer is extremely good. Exactly this aspect is in the present studies, since the practical resolution offered by the present spectrometer optics is <0.005 nm with the available 4320 grooves/mm holographic grating. In addition, due to the high temperature of the plasma and matching of the samples and standards, the physical interferences can be mini-

Fig. 2. Emission profile of ²³³U spectral line.

mized but spectral interference plays a significant role. In view of this, ²³³U determination was carried out after chemical separation from ²³³U-Al alloy by ICP-AES. All measurements are made in the peak intensity mode. Figures 3 (a & b) show the profiles of the spectral lines of different uranium isotopes, such as ²³³U, ²³⁵U, and ²³⁸U. The profiles of the ²³³U and ²³⁸U spectral lines were recorded on 10% enriched ²³³U with 20 ppm concentration and are shown in Figure 3a. The background-free and mutually interference-free lines of 424.398 nm and 424.437 nm for ²³³U and ²³⁸U, respectively, were identified. These spectral lines were recorded by keeping the centering line position at 424.412 nm. The observation window was used of 51 divisions and an increment rate of 0.002.

Figure 3b shows the profiles of the ²³³U, ²³⁵U, and ²³⁸U spectral lines recorded with 25 ppm and the center line position at 424.412 nm on 2% enriched ²³³U + 10% enriched ²³⁵U in the ²³⁸U sample. The observation window of 51 divisions with 0.002 increments was used which was found to be most suitable. The intensity of the ²³³U, ²³⁵U, and ²³⁸U isotopes were clearly observed according to their respective percentages. The well-separated and intense resolved spectral lines of ²³³U and ²³⁵U are shown in the inset box of Figure 3b. Michael et al. (31-32) also reported that the emission signals of ²³³U, ²³⁵U, and ²³⁸U could be separated from each other without difficulty at ~ 411.6 nm (but also at ~ 424.4 nm) using commercial HR-ICP-OES instruments. In the present case, the determination of uranium has been carried out specifically for the ²³³U isotope at 424.398 nm, since the isotopic line could be adequately resolved from the ²³⁵U emission line enabling quantitative analysis. A two-point calibration procedure was adopted using 20

ppm of ^{233}U nitrate solution and 0.5M HNO_3 as the high and low standards, respectively. ^{233}U samples in the range of 5 to 35 ppm were analyzed using the working curve. The analytical line of ^{233}U could be successfully utilized for the determination of ^{233}U by ICP-AES. The lower level of ^{233}U concentration could be determined at 5 ppm. The results revealed that for higher levels up to 35 $\mu\text{g/mL}$ of ^{233}U , there is no significant contribution from the matrix. ^{233}U can be determined from ppm to % levels by proper dilution with 0.5M HNO_3

with the appropriate sample size. Synthetic samples were analyzed and the values found were in good agreement with the added amounts. The detection limit of the uranium analytical line at 424.398 nm was evaluated based on 10 measurements of the concentration corresponding to the intensity of the absolute value of the blank at that specified wavelength plus three times the standard deviation of the measurements ($x + 3\sigma$). The detection limit of uranium at 424.398 nm was calculated. The precision of the determination, as calculated from the

repetitive analyses of an intermediate range concentration of ^{233}U (10% value), was found to be 5% RSD with the detection limit of 0.01 ppm. Table IV lists the analytical results of ^{233}U synthetic samples.

Figure 4 shows the emission spectrum obtained from 424.375 to 424.450 nm. It clearly exhibited spectral lines due to ^{233}U , ^{235}U , and ^{238}U at 424.398 nm, 424.412, and 424.437 nm, respectively.

Fig. 3 (a & b). The graphs show the resolved emission spectral profiles of lines (a) ^{233}U and ^{238}U , and (b) ^{233}U , ^{235}U , and ^{238}U .

TABLE IV
Typical Analysis Results of Synthetic Samples

Sr. No.	Samples	Expected Amount (ppm)	^{233}U at 424.398 nm (ppm)
1	Reagent Blank	0	0.10
2	Sample 1	5	5.10
3	Sample 2	10	10.51
4	Sample 3	20	20.56
5	Sample 4	20	20.42
6	Sample 5	20	20.99
7	Sample 6	35	35.79

Fig. 4. The graph shows the resolved emission spectral profile of ^{233}U , ^{235}U , and ^{238}U .

Table V lists the concentrations of the ^{233}U , ^{235}U , and ^{238}U isotopes of the recovered uranium sample from analytical waste. The determined values well matched the expected amount. The radioactive waste, such as unused charges used for d.c. arc-AES analysis and active washings generated during AES analysis of nuclear fuel materials, is required to be processed for ^{233}U , Pu, and Am. Radioactive elements must be recovered before disposal of analytical waste due to their toxicity and hazardous nature. Radiochemical procedures such as precipitation, liquid-liquid extraction, and ion exchange are available for the separation and concentration of these elements. In our analytical work program, a lot of liquid waste is generated during analysis of ^{233}U , Pu, and Am. This analytical waste usually mainly contains uranium along with concomitant analytes, such as trace metal impurities and 5% Ag added for the internal standard. During various stages of the recovery and separation procedures, different types of solutions are encountered requiring the determination of ^{233}U . In the present work, the recovered sample was further dissolved in 0.5M HNO_3 and was subsequently used for spectral studies using ICP-AES.

Analysis of Real Sample

A thermal ionization mass spectrometer (TIMS) (Finigan Mat-261 Instrument, Bremen, Germany), equipped with nine Faraday cup detectors, was used for an independent cross-check of the ICP-AES

results. A small portion of the ^{233}U -enriched sample (10 ppm) was used for mass spectrometric analysis. The data acquisition was evaluated using the static mode of the ion beam collection in the multi-Faraday cup detector system. The estimate obtained for ^{233}U after applying the appropriate multiplication factors was found to be similar to that obtained by ICP-AES, confirming the validity of the method developed in this study. The concentration of ^{233}U sample was determined at 10.10 ppm in 0.5 M HNO_3 .

In brief, ^{233}U -Al alloy samples were analyzed after chemical separation by 20% TnOA / Xylene/ 4M HNO_3 using ICP-AES. The emission spectra of the samples showed the presence of ^{233}U , ^{235}U , and ^{238}U isotopes. A number of enriched ^{233}U samples were analyzed using the calibration curve. The results of the ^{233}U samples were found to be in good agreement between the added and expected amounts.

CONCLUSION

A commercially available high-resolution ICP sequential spectrometer assembly, which was modified extensively and used for analysis of radiotoxic samples with an alpha containment facility. The work was specifically carried out on ^{233}U , since the isotopic line could be adequately resolved from the ^{235}U and ^{238}U emission lines and enabling quantitative analysis. The lowest level of concentration for ^{233}U was 5 ppm. No significant contribution

from the interference and background was observed even at the higher side of ^{233}U samples (up to 35 ppm). The ICP-AES results of enriched uranium samples were found to be in close agreement between added and observed amounts. The simplicity of the precipitate separation of uranium and the quantitative recoveries obtained for the analytes investigated shows that the developed method is fast, accurate, and an effective method for the routine recovery of ^{233}U from ^{233}U -Al alloy samples from the remnant waste solutions originating in the chemical process. In comparison to the mass spectrometric method, the precision may, however, be poor. However, the developed method has the advantage of offering high speed of analysis and using a simple sample preparation process which makes it easily applicable to real samples.

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TABLE V
Typical Analysis Results of ^{233}U , ^{235}U , and ^{238}U in ppm

Sr. No.	Samples	^{233}U (424.398 nm)		^{235}U (424.412 nm)		^{238}U (424.437 nm)	
		Expected	Obtained	Expected	Obtained	Expected	Obtained
1	Sample 7	1580	1586.37	10	9.67	0.40	0.47
2	Sample 8	1580	1581.47	10	9.20	0.40	0.45
3	Sample 9	1580	1586.44	10	9.03	0.40	0.43

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