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QUANTITATIVE ANALYSIS OF RADIONUCLIDES IN PROCESS AND ENVIRONMENTAL SAMPLES

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Abstract - An analytical method was developed for the radiochemical separation and quantitative recovery of ruthenium, zirconium, niobium, neptunium, cobalt, iron, zinc, strontium, rare earths, chromium and cesium from a wide variety of natural materials. The method is based on the anion exchange properties of the various radionuclides although both ion exchange and precipitation techniques are incorporated. Volatilization is used to eliminate iodine. The recovery of the individual isotopes is greater than 95% with a standard deviation of ±4%. The decontamination factors for the individual radionuclides are greater than 10^4 for all ion exchange separations and greater than 10^3 for gravimetric separations.

Introduction

The analysis of process, stream, and river water along with vegetation, soil and biological samples is complicated by the large number of diverse radionuclides that may be present. In all cases, interfering activities must be reduced by a factor of 10^3 or greater without sacrificing the quantitative yield of the individual radionuclides. In most cases standard analytical-inorganic methods are not directly applicable, because individual isotopes are present in microgram quantities. A scheme of analysis was sought which would separate the common longer-lived isotopes in high yield and simplify routine analysis.

Ion exchange was chosen as it appeared to exploit the maximum differences among elements, offering quantitative separations with minimum cross-contamination. Ion exchange techniques cover concentrations ranging from microgram to gram quantities per milliliter of solvent depending only upon column capacity. Anion exchange is preferred over cation exchange because of its high selectivity for complexes of most of the metals of interest. Additionally the effective operation of the anion exchange resin is not hindered by high acid concentrations needed for sample preparation. Where anion exchange techniques were not feasible gravimetric separations were used (Figure 1).

Experimental

Apparatus

- Millipore Pyrex filter holder.
- Millipore filters, HA type, 047 mm. (Millipore Filter Corp., Watertown, Mass.).
- Ion exchange columns, 17.0 cm. long, 0.9 cm. inside diameter, with stopcock and 50-ml. capacity reservoir.
- Sample vials, Celluplastic Corporation, polystyrene, ½" (ID) × 2" high with friction polyethylene cap.
- Scintillation well counter, 1¾" (D) × 2" thallium activated sodium iodide crystal with a 5/8" (D) × 1½" central well.
- Scaler, Tracerlab Model CC-10.

Reagents

Carrier Solutions. These are not standardized since nearly quantitative recoveries are obtained and gravimetric yield determinations are not required. Chemically pure reagents were used to prepare the following.

Carrier Ion	Solution Concentration, mg/ml.	Solute* and Solvent
Ru^{++++}	25	$RuCl_4 \cdot 5H_2O$ in H_2O
Cr^{+++}	10	$CrCl_3 \cdot 6H_2O$ in 1N HCl
Fe^{+++}	5	$FeCl_3 \cdot 6H_2O$ in H_2O
Co^{++}	10	$CoCl_2 \cdot 6H_2O$ in 1N HCl
Cs^{+}	1	$CsNO_3$ in H_2O
Ce^{+++}	2.5	$Ce(NO_3)_3 \cdot 6H_2O$ in 1N HNO_3
Nb^{+++++}	5	$K_8Nb_6O_{19} \cdot 16H_2O$ in H_2O
Ba^{++}	20	$Ba(NO_3)_2$ in H_2O
Sr^{++}	20	$Sr(NO_3)_2$ in H_2O

* Reagent grade material used whenever possible.

Special Solutions. Details are as follows.

- Zirconium carrier, 20 mg/ml. Weigh 4.7 grams of $Zr(NO_3) \cdot 6H_2O$ on a trip balance. Transfer to a 100-ml. volumetric flask. Add distilled water to dissolve, then dilute to the mark. Mix thoroughly and transfer to a labeled polyethylene bottle.

- Zirconium carrier, 5 mg/ml. Repeat the above procedure for making a 20 mg/ml. zirconium carrier solution using instead 1.8 grams of $ZrOCl_2 \cdot 8H_2O$.

- Thioacetamide, 0.2 g/ml. Weigh 20 grams of thioacetamide on a trip balance. Transfer to a 100-ml. volumetric flask and add approximately 100 ml. of slightly warm distilled water. Mix thoroughly, allow to cool and dilute to the mark. Transfer to a labeled reagent bottle.

- Phosphotungstic acid, 0.05 molar solution. Transfer the contents of a freshly opened 100-gram bottle of phosphotungstic acid (Eastman Kodak), $P_2O_5 \cdot 24WO_3 \cdot 44H_2O$, (mol. wt. = 6500 g.) to a 500-ml. graduated cylinder. Dissolve in distilled water and dilute to 300 ml. Mix thoroughly and transfer to a labeled reagent bottle.

- Fuming nitric acid, ACS reagent grade, 95% nitric acid.

- Boric acid, saturated solution in water.

- Ammonium oxalate, saturated solution in water.

Ion Exchange Column Preparation

The ion exchange column, a 17.0 cm. × 0.9 cm. inside diameter glass tube with a 50-ml. reservoir at the top, is packed to a 13-cm. height with a thick distilled water slurry of Dowex-2×8, chloride form, 200 to 400 mesh anion exchange resin (Dow Chemical Co., Midland, Mich.). The resin is allowed to settle in the column and the excess water is removed leaving only enough water above the resin to prevent dryness.

The resin is previously cleaned and sized by washing with distilled water allowing the resin to settle out. This cycle is repeated several times. Polyethylene shavings are used as a support for the resin bed wherever solutions containing hydrofluoric acid are used. Either pressure or vacuum can be applied to the columns to increase the flow rates of the solutions.

To change the Dowex-2×8 resin column to the hydroxide form, pass 150 ml. of 2M sodium hydroxide through the resin bed followed by 200 ml. of distilled water.

Sample Preparation:

Water samples are evaporated to dryness and dissolved in a solution of 3N hydrochloric acid - 0.1N hydrofluoric acid. If complete solution of the sample is difficult, the sample is digested with 3N hydrochloric acid - 0.1N hydrofluoric acid on a hot plate and evaporated to dryness. The sample is again treated with 3N hydrochloric acid - 0.1N hydrofluoric acid, filtered, and the residue discarded. Mud samples are treated directly as the insoluble residue from water samples. Vegetation and biological samples are first fired in a muffle furnace and then the ash is dissolved or leached with a 3N hydrochloric acid - 0.1N hydrofluoric acid solution as the insoluble residue from water samples.

Radiochemical Procedures

Ruthenium Separation. Transfer a 25-ml. aliquot of the 3N hydrochloric acid - 0.1N hydrofluoric acid solution to a 50-ml. conical centrifuge tube. Dilute the aliquot with 10 ml. of distilled water, add 1 ml. of a 25 mg/ml. ruthenium carrier solution and 1 ml. of a 0.2 g/ml. thioacetamide solution. Heat the sample in a water bath until the black precipitate settles. Filter the solution through an HA Millipore filter using first 3N hydrochloric acid - 0.1N hydrofluoric acid and then 95% ethyl alcohol as a wash. Transfer the filtrate to a 150-ml. beaker and evaporate to dryness.

Ruthenium Estimation. Place the filter in a 50-ml. Erlenmeyer flask with the precipitate side down, and dissolve in 4 ml. of concentrated nitric acid by applying heat slowly. Evaporate the slurry to dryness and ash. Add 5 ml. of concentrated hydrochloric acid and again evaporate to dryness. Dissolve the residue in 25 ml. of 3N hydrochloric acid - 0.1N hydrofluoric acid solution and 10 ml. of distilled water. Add 1 ml. of a 5 mg/ml. solution of zirconium carrier, 5 mg/ml. solution of niobium carrier, 10 mg/ml. solution of chromium carrier, and 2 ml. of a 10 mg/ml. solution of cobalt carrier. Precipitate the ruthenium by adding 1 ml. of a 0.2 g/ml. thioacetamide solution to the sample and heating on a hot plate at 90°C. When the black precipitate settles, filter the solution through an HA Millipore filter using first 3N hydrochloric acid - 0.1N hydrofluoric acid and then 95% ethyl alcohol as a wash. Remove the filter from the filter apparatus and center it on a stainless steel disc. Cover the filter and disc with a 2-inch piece of cellophane tape and obtain a beta count in order to determine ruthenium-103 plus ruthenium-rhodium-106. Discard the filtrate solution.

Strontium Separation. Add 1 ml. of a 20 mg/ml. strontium carrier solution, 1 ml. of a 20 mg/ml. barium carrier solution, 1 ml. of a 1 mg/ml. cesium carrier solution, and 1 ml. of a 2.5 mg/ml. cerium carrier solution to the residue from the ruthenium separation step. After evaporating the solution to dryness, add 2 ml. of concentrated nitric acid to the residue and quantitatively transfer the slurry to a 50-ml. conical centrifuge tube using 25 ml. of fuming nitric acid. Cool the solution under cold tap water and let it stand 15 minutes.

Centrifuge the mixture and quantitatively transfer the supernate to a 50-ml. beaker. After washing the precipitate with 10 ml. of fuming nitric acid, centrifuge the mixture. Combine the wash with the supernate and begin evaporating the solutions to dryness. Dissolve the precipitate with 2 ml. of distilled water, add 1 ml. of a 2.5 mg/ml. cerium carrier solution followed by 25 ml. of fuming nitric acid, and cool the solution under cold tap water. After allowing the sample to stand for 15 minutes, centrifuge, and quantitatively transfer the supernate to the combined supernates of the first precipitation. Wash the precipitate with 10 ml. of fuming nitric acid, centrifuge the mixture, and combine the wash with the previous supernates. (Record the time in order to correct for yttrium buildup.) Evaporate the combined supernates and washes to dryness.

Strontium Estimation. Dissolve the precipitate in 10 ml. of distilled water and add to the solution 1 ml. of a 5 mg/ml. iron carrier solution followed by 1 ml. of concentrated ammonium hydroxide. Centrifuge the mixture and quantitatively transfer the supernate to a 50-ml. conical centrifuge tube. After washing the precipitate with 5 ml. of 3M ammonium hydroxide, centrifuge the slurry and combine the wash with the supernate. Rewash and discard the precipitate. (If barium-140 is suspected to be present, isolate it at this point using a chromate separation.) Heat the combined supernates to boiling and stir in 2 ml. of saturated ammonium oxalate solution. Heat again to boiling and allow to stand while stirring occasionally for 5 minutes without applied heat. Centrifuge and discard the supernate. Quantitatively transfer the strontium precipitate to a flamed stainless steel planchet with 2N nitric acid and count immediately on a Geiger-Mueller counter.

Rare Earth and Yttrium Separation. Add 5 ml. of distilled water to the residue from the strontium separation step and heat to dissolve. (If the residue does not completely dissolve, continue on with the analysis since the addition of the 0.2N sulphuric acid - 0.6N hydrofluoric acid mixture will bring it in solution.) Add 1 ml. of a 20 mg/ml. zirconium carrier solution followed by 5 ml. of a 0.2N sulphuric acid - 0.6N hydrofluoric acid mixture to the sample. After allowing the sample to stand 15 minutes, quantitatively transfer the mixture to a 50-ml. conical centrifuge tube using 5 ml. of a 0.1N sulphuric acid - 0.3N hydrofluoric acid solution. Centrifuge the mixture and pour the supernate directly on a previously prepared Dowex-2 resin column washed with 15 ml. of a 0.1N sulphuric acid - 0.3N hydrofluoric acid solution. Wash the precipitate with 5 ml. of a 0.1N sulphuric acid - 0.3N hydrofluoric acid solution, centrifuge the slurry, and add the supernate directly to the resin column. Rewash the precipitate allowing the combined supernates and washes to pass through the resin column into a 100-ml. beaker.

Rare Earth and Yttrium Estimation. Dissolve the precipitate with 2 ml. of saturated boric acid and 1 ml. of nitric acid. Quantitatively transfer the solution to a 100-ml. lusteroid centrifuge tube using 2 ml. of a 10 mg/ml. zirconium carrier solution and 3 ml. of distilled water. After the addition of 15 ml. of 7N hydrofluoric acid to the sample, let it stand for 15 minutes; then centrifuge the mixture and discard the supernate. After washing the precipitate twice with 5 ml. of 5N hydrofluoric acid, add 2 ml. of 2N nitric acid to the precipitate and quantitatively transfer the slurry to a flamed stainless steel planchet. Count the sample on a Geiger-Mueller counter immediately for rare earths and yttrium.

Zirconium-Niobium Separation. Wash the resin by adding 40 ml. of 0.1N sulphuric acid - 0.3N hydrofluoric acid solution in 5-ml. aliquots to the column and combine the wash effluent with the sample effluent. Cautiously evaporate the combined effluents to dryness.

Zirconium-Niobium Estimation. Elute the zirconium and niobium from the resin with the addition of 50 ml. of a 6N hydrochloric acid - 0.5N hydrofluoric acid solution to the column. Collect the effluent in a 50-ml. beaker, evaporate the solution to a 2-ml. volume and quantitatively transfer it to a ½" (ID) × 2" high polystyrene vial with distilled water. Adjust the volume, seal, and mix thoroughly before counting on a gamma scintillation well counter.

Neptunium, Cobalt, Iron, and Zinc Separation. Dissolve the residue from the zirconium-niobium-95 separation step in a minimum of concentrated hydrochloric acid with the addition of heat. Quantitatively transfer the solution to a previously prepared Dowex-2 resin column, washed with 15 ml. of concentrated hydrochloric acid, and allow the solution to pass through the resin column, collecting the effluent in a 50-ml. beaker. Wash the resin by the addition of 40 ml. of concentrated hydrochloric acid in 5-ml. aliquots, and combine the effluent with that of the sample. Evaporate the combined effluents to dryness.

Neptunium Estimation. Elute the neptunium from the resin with the addition of 40 ml. of 8.5N hydrochloric acid - 0.5N hydrofluoric acid solution to the column. Collect the effluent in a 50-ml. beaker, evaporate the solution to a 2-ml. volume and quantitatively transfer it to a $\frac{1}{2}$" (ID) × 2" high polystyrene vial with distilled water. Adjust the volume, seal, and mix thoroughly before counting on a gamma scintillation well counter.

Cobalt Estimation. Elute the cobalt from the resin with the addition of 30 ml. of 5N hydrochloric acid, and treat the effluent as in the neptunium estimation.

Iron Estimation. Elute the iron from the resin with the addition of 30 ml. of 0.5N hydrochloric acid, and treat the effluent as in the neptunium estimation.

Zinc Estimation. Elute the zinc from the resin with the addition of 50 ml. of 0.005N hydrochloric acid, and treat the effluent as in the neptunium estimation.

Cesium Separation. Dissolve the residue from the neptunium, cobalt, iron, and zinc separation step in 5 ml. of nitric acid, and quantitatively transfer the solution to a 50-ml. conical centrifuge tube with 15 ml. of distilled water. Add 1 ml. of a 0.05M phosphotungstic acid solution to the sample and allow it to stand for 10 minutes. Centrifuge the mixture and save the supernate. Wash the precipitate twice with 4N nitric acid, centrifuge the slurry, and combine the washes with the supernate.

Cesium Estimation. Slurry the precipitate in a minimum amount of distilled water and quantitatively transfer to a flamed stainless steel planchet. Allow 30 minutes for the barium-137 to establish equilibrium with the cesium-137, then count the sample on a Geiger-Mueller counter.

Chromium Estimation. Evaporate the combined supernate and washes from the cesium separation step down to a 2-ml. volume. Quantitatively transfer the 2-ml. volume to a $\frac{1}{2}$" (ID) × 2" high polystyrene vial with distilled water. Adjust the volume, seal, and mix thoroughly before counting on a gamma scintillation well counter.

Discussion

All of the radionuclides discussed could be separated solely by an ion exchange separation scheme. However, the separation of several of the nuclides would involve various chemical solutions difficult to use with the materials sampled, making the separations lengthy. Because of this, gravimetric methods were found more adaptable for the separation of ruthenium, strontium, rare earths (as a group), and cesium. A sequential analysis combining the best separation techniques, either gravimetric or ion exchange, for the radionuclides of concern was then developed.

Sample Preparation

The complete solution of a wide variety of samples is difficult in many instances; therefore, a leaching method was used in the sample preparation. A 3N hydrochloric acid - 0.1N hydrofluoric acid solution with the addition of heat leaches greater than 99.0% of the ruthenium, cesium, zirconium, niobium, neptunium, iron, cobalt, chromium, and zinc from the insoluble residues of water, soil, and ashed vegetation samples.

Radiochemical Procedures

Precipitation of Ruthenium Sulfide. Ruthenium sulfide is quantitatively precipitated by the thermal decomposition of thioacetamide in a 2N hydrochloric acid - 0.08N hydrofluoric acid solution. A second precipitation in a 2N hydrochloric acid - 0.08N hydrofluoric acid solution is sufficient to separate ruthenium from 99.9% of all other interfering activities isolated by the entire scheme. Iodine which carries on the sulfide precipitate is eliminated from the remaining radionuclides by volatilization from a nitric acid solution.

Precipitation of Strontium Nitrate. Strontium is isolated as the nitrate by a double precipitation from a >80% nitric acid solution (8). This method has been frequently used for the separation of barium and strontium from fission products. Barium, if present, can be separated from strontium by the classical method of precipitating barium as the chromate from a hot buffered solution (1). A sizable amount of calcium is carried on the strontium nitrate precipitate causing absorption of the strontium-90 weak beta. For this reason calcium quantities should be less than 100 mg. per sample in order to obtain good results. Further purification of the strontium is necessary when quantities >100 mg. of calcium are present.

Precipitation of Rare Earth Fluorides. Lanthanide rare earths including yttrium are determined by precipitation as the fluorides from a 0.1N sulphuric acid - 0.3N hydrofluoric acid solution. The precipitation is quantitative, and the supernatant solution can be directly used as the medium for the separation of zirconium and niobium from the remaining radionuclides on Dowex-2 resin.

Anion Exchange Separation of Zirconium and Niobium. It is known that both zirconium and neptunium are strongly absorbed on Dowex-2 anion exchange resin at very low concentrations of sulphuric acid (9). It is further known that neptunium can be separated from zirconium by its elution with a combination of both sulphuric and hydrofluoric acids at low concentrations.

Further development of this separation revealed that cobalt, iron, zinc, chromium, and cesium along with neptunium are not absorbed on the Dowex-2 resin when in a solution of 0.1N sulphuric acid - 0.3N hydrofluoric acid.

Both zirconium and niobium remain strongly absorbed on the resin and are quantitatively eluted rapidly with a 6N hydrochloric acid - 0.5N hydrofluoric acid solution. At the same time, zirconium and niobium can also be quantitatively separated by this method depending upon the size of the ion column used. This method provides such a separation with the size ion column described in the preceding paragraphs (see Figure 2).

Since strontium, the rare earths, and yttrium are partially-to-quantitatively precipitated in 0.1N sulphuric acid - 0.3N hydrofluoric acid solution, they are recovered first as previously outlined. Zirconium and niobium can also be separated by passing a solution of 11N hydrochloric acid - 0.5N hydrofluoric acid through Dowex-2 resin, the zirconium eluting first. Niobium which is absorbed more strongly on the resin in this solution can be eluted rapidly, after all the zirconium has been recovered, by passing 6N hydrochloric - 0.5N hydrofluoric acid through the resin (2) (Figure 3).

Chloride Complexes and Anion Exchange. The metals neptunium, cobalt, iron, and zinc are known to be strongly absorbed on Dowex-2 resin in concentrated hydrochloric acid, while chromium and cesium show no absorption (3, 9). Cobalt, iron, and zinc will quantitatively elute at successively lower hydrochloric acid concentrations effecting an excellent quantitative separation of the three metals.

It was observed that the elution curves for neptunium and cobalt using varying concentrations of hydrochloric acid overlap to a great extent. However, neptunium was found to elute specifically with an 8.5N hydrochloric acid - 0.5N hydrofluoric acid solution. Cobalt is then quantitatively eluted with 5N hydrochloric acid, iron with 0.5N hydrochloric acid, and zinc with 0.005N hydrochloric acid (Figure 4).

If zirconium and niobium were absorbed on the column they would elute in this scheme so as to overlap the neptunium elution. The niobium would also "straggle" off the column making the elution time consuming (Figure 5). This is true for higher hydrochloric acid concentrations along with a 0.5N concentration of hydrofluoric acid. Any changes in the hydrofluoric acid concentration other than 0.5N were also found deleterious to the specific elution of each metal.

Precipitation of Cesium. Cesium is precipitated as the phosphotungstate from a 4N nitric acid solution by the addition of phosphotungstic acid (5). The precipitation is quite simple and extremely specific excluding all of the radionuclides of interest here with the exception of zirconium and niobium. However, if zirconium and niobium were not eliminated first as in this sequential analysis, the addition of zirconium carrier would raise the decontamination factor to $>10^3$, making the separation quite satisfactory for a direct analysis of cesium.

Purification of Chromium. Since chromium is the only radionuclide left, the solution is concentrated and counted. If a purification is desired, the chromium is oxidized to the chromate by heating with sodium hydroxide and hydrogen peroxide, and the resulting solution collected on Dowex-2 anion exchange resin in the hydroxide form. Elutriation is quantitative and rapid with a 2M potassium thiocyanate solution (4).

Separation of Radionuclides from Biological Samples. Separation of small quantities of radionuclides from biological samples is complicated by the large amounts of sulphates, phosphates, alkali metals and alkaline earths present after ashing the sample. However, by rearrangement of the scheme of analysis as shown in Figure 6, most of the trace radionuclides are easily and rapidly separated from large quantities of alkali and alkaline earth salts.

After performing the ruthenium separation, the remaining solution is evaporated and brought back in solution with hydrochloric acid. This solution is passed through Dowex-2 anion resin separating neptunium, zirconium, niobium, cobalt, iron, and zinc from chromium, cesium, rare earths, and strontium which are not absorbed on the column but rather appear in the effluent along with the phosphates, sulphates, alkali metals, and alkaline earths.

Of the radionuclides absorbed by the resin, neptunium, zirconium, niobium, and cobalt are eluted quantitatively as a group with a 6N hydrochloric acid - 0.5N hydrofluoric acid solution. Zirconium and niobium are separated from neptunium and cobalt, as shown in Figure 1, using the 0.1N sulphuric acid - 0.3N hydrofluoric acid solution. In turn neptunium is separated from cobalt using the first part of the hydrochloric acid anion exchange step discussed on page 5. Iron and zinc are eluted rapidly by their respective elutriant solutions as shown by Figure 1.

Of the radionuclides contained in the resin column effluent, strontium is precipitated as the nitrate. However, large amounts of calcium may interfere in obtaining a highly accurate answer unless further separation techniques are used (6, 7). The rare earths and yttrium are next precipitated as hydroxides from a 4N sodium hydroxide 3% hydrogen peroxide solution which in turn oxidizes chromium to the chromate preparing it for absorption on Dowex-2 resin in the hydroxide form. Cesium remains in solution. If cesium is the only radionuclide of interest, it is easily precipitated from the chloride column effluent by the phosphotungstate separation as discussed on page 15.

Counting

Special attention must be paid to the types of radiation of the radionuclides as well as to their chemical characteristics if accurate results are to be obtained. The scintillation well counter is suitable for measuring most radionuclides emitting gamma rays or high-energy beta rays, but a thin-window Geiger counter is used where the most accurate results are obtainable by a beta count.

Where activities of daughter products interfere (strontium-90) or the radioactive decay is rapid (yttrium-90), the samples must be counted as soon after they are separated as possible. In some cases the activity is based on parent-daughter equilibrium (cesium-137); therefore, the sample should be stored at least 30 minutes before gamma counting.

Results

The yield and decontamination data presented in Tables I and II illustrate the specificity and accuracy of the analysis scheme. In every case recovery was greater than 95% and precision was within ±4.5% at the 90% confidence limit. Decontamination factors (DF) for individual radionuclides throughout the sequence of analyses were obtained by using spiked samples of 0.2 μc on the average to 2 μc for iodine-131. All decontamination factors were greater than 10^3 and many were greater than 10^4.

The scheme is versatile; it is applicable to many types of samples, and radionuclides may be omitted or new ones added with only minor changes.

WRR:nbb

Table I. Recovery of the Individual Radionuclides

Element	Recovery, %	Standard Deviation, %*
Ruthenium	98.8	±3.4
Strontium	98.9	±2.0
Rare Earths	98.8	±2.0
Zirconium-Niobium	97.0	±3.1
Neptunium	96.6	±3.4
Cobalt	97.0	±2.2
Iron	99.1	±2.5
Zinc	99.0	±2.1
Cesium	96.0	±4.1
Chromium	95.7	±4.4

* 90% confidence level.

Table II. Decontamination Factor Data According to Procedure Sequence

Elements	DF $>1 \times 10^3$	DF $>1 \times 10^4$
Ruthenium	Zr, Nb, Np, Co, Cr	I, Cs, RE, Sr, Fe, Zn
Strontium	Zr, Nb, Np, Co, Fe, Zn, Cs, Cr	RE, Ru, I
Rare Earths	Zr, Nb, Np, Co, Fe, Zn, Cs, Cr, Sr	Ru, I
Zirconium-Niobium	Cr	Cs, Np, Co, Fe, Zn, Sr, Ru, RE
Neptunium	-	Fe, Zn, Cr, Cs, Sr, RE, Ru, Co, Zr, Nb
Cobalt	-	Fe, Zn, Cr, Cs, Sr, RE, Ru, Np, Zr, Nb
Iron	-	Ru, Sr, RE, Zr, Nb, Np, Co, Zn, Cs, Cr
Zinc	-	Ru, Sr, RE, Zr, Nb, Np, Co, Fe, Cs, Cr
Cesium	Cr	Ru, Zr, Nb, RE, Sr, Co, Fe, Zn, Np
Chromium	Cs	Ru, Zr, Nb, RE, Sr, Co, Fe, Zn, Np

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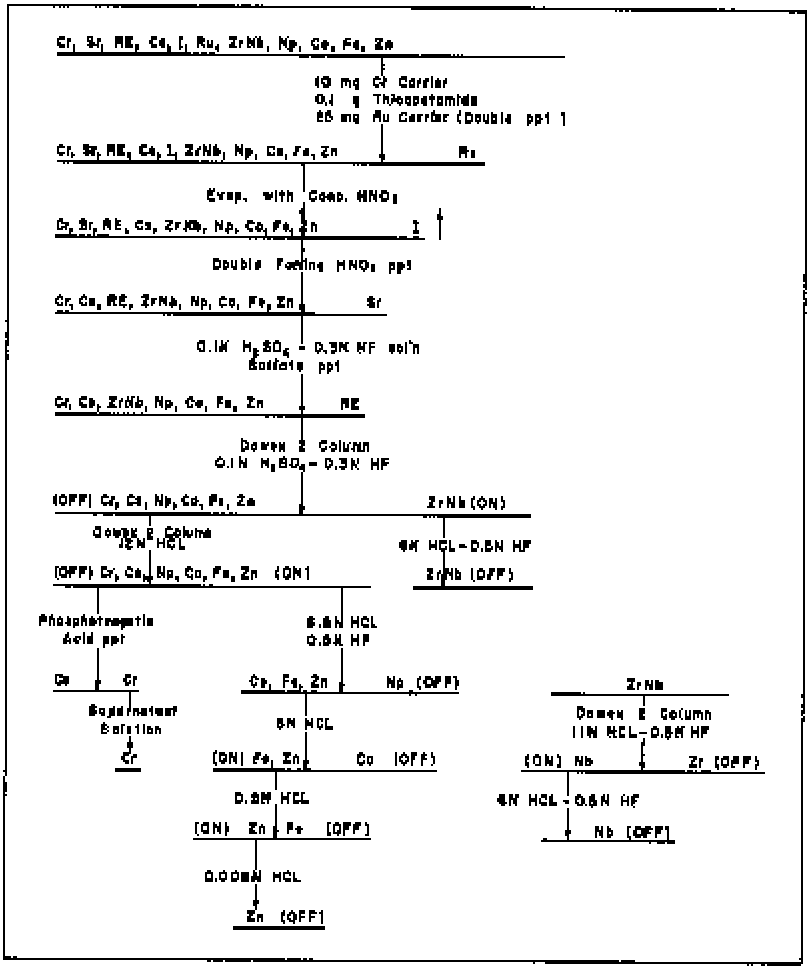

Figure 1. SCHEMATIC DIAGRAM OF THE METHOD

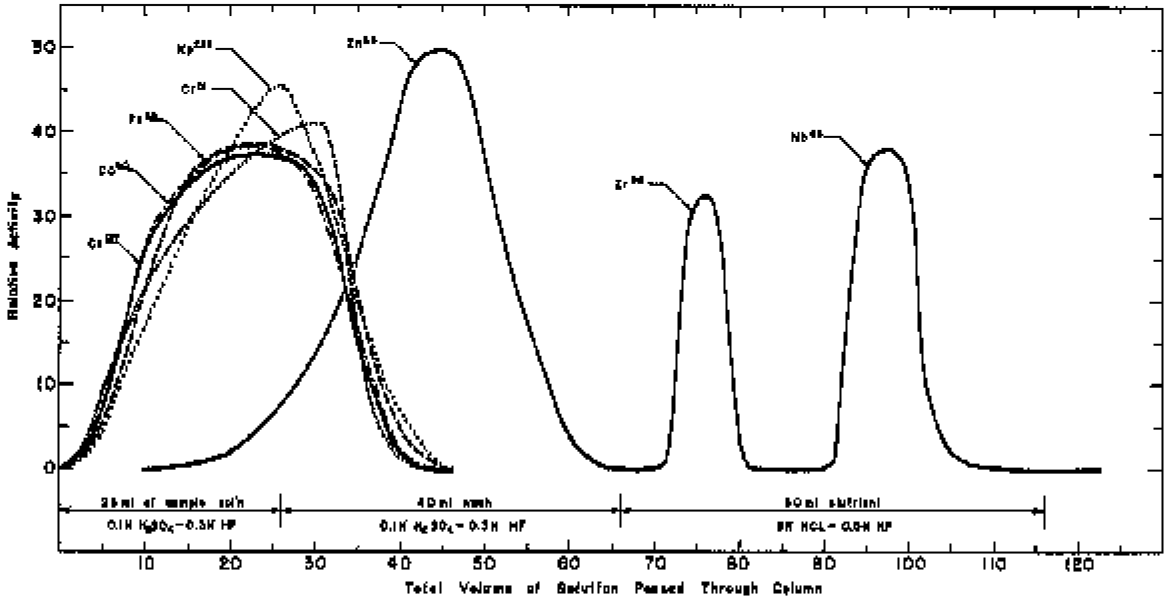

Figure 2. ION EXCHANGE ISOLATION AND SEPARATION OF ZIRCONIUM AND NIOBIUM

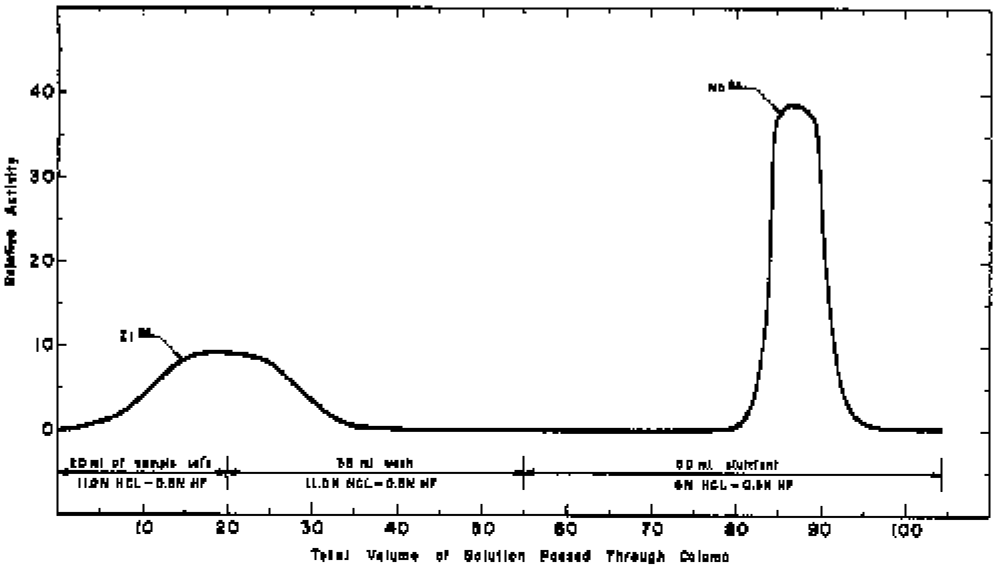

Figure 3. ION EXCHANGE SEPARATION OF ZIRCONIUM AND NIOBIUM

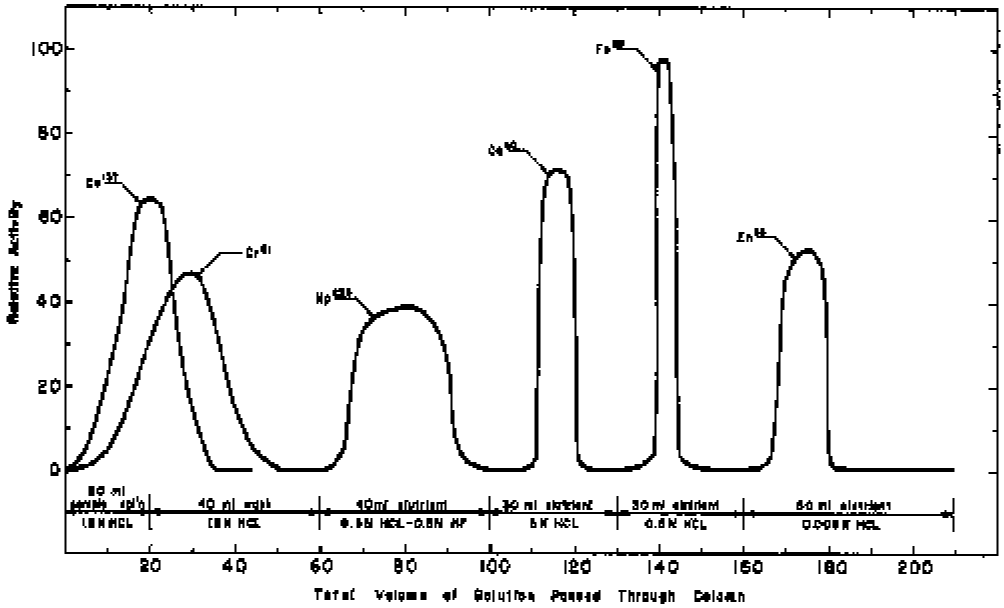

Figure 4. ION EXCHANGE ISOLATION AND SEPARATION OF Np, Co, Fe, AND Zn

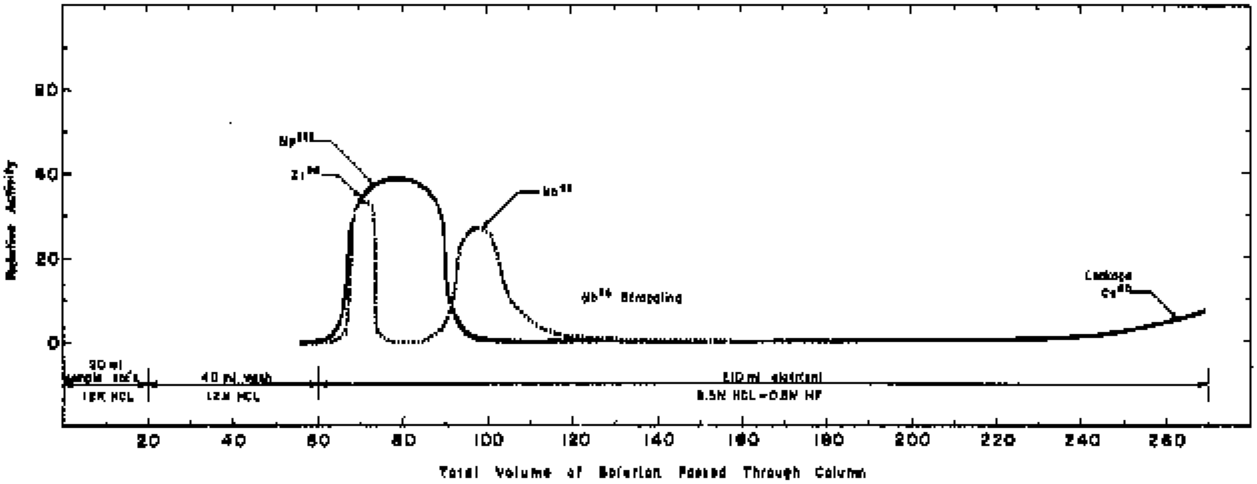

Figure 5. THE ELUTION FOR ZIRCONIUM AND NIOBIUM FROM A CHLORIDE COLUMN

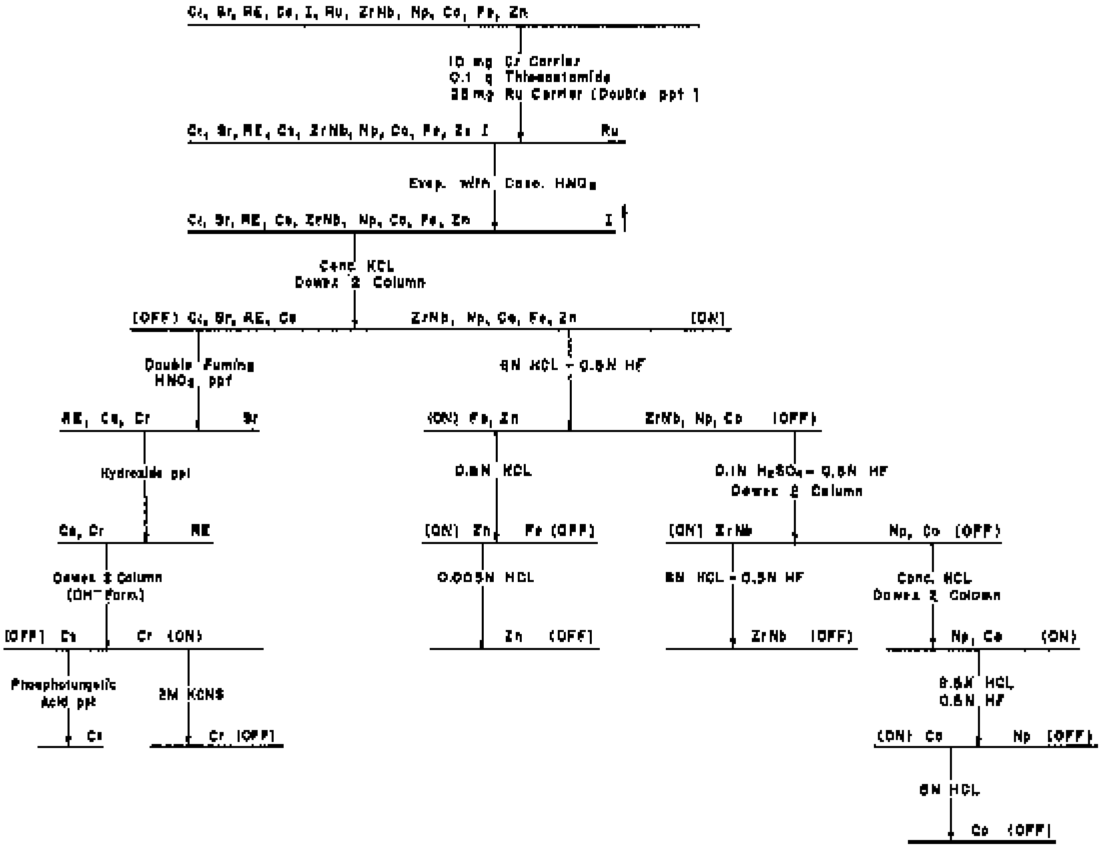

Figure 6. SCHEMATIC DIAGRAM OF METHOD MODIFIED TO INCLUDE BIOLOGICAL SAMPLES