

INNOVATIVE MOBILE HIGH-VOLUME LIQUID RADIOACTIVE WASTE PROCESSING SYSTEM*

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ABSTRACT

The design of a mobile high-volume liquid radioactive waste (LRW) processing system to extract all radionuclides from low-level, intermediate-level and high-level liquid and sludge nuclear waste and produce industrially clean water is presented. The design is based on innovative and patented methods, the technologies of which have been demonstrated in an industrial-scale prototype plant and are based on the data of relevant experiments. Key features of the prototype plant were presented in the Proceedings of the WM'03 Symposium. This paper presents the full features of an innovative mobile high-volume LRW processing system, to be housed on a standard 40-ft by 7-ft trailer, to process all levels of liquid and sludge nuclear waste, at a rate of 10 tonne/hr, when the concentration of radionuclide salts in the LRW is 5 g/l, at a rate of 5 tonne/hr for those having a salt concentration of 10 g/l and also at a processing rate of 1 tonne/hr for the extreme salt concentration of 50 g/l. The mobile high-volume LRW processing facility is designed to extract and collect entirely all the radionuclides in the form of fine metallic powder, outputting only cleaned water, in which the residual activity is no more than the activity of natural background. The operational features of the mobile facility are also presented. A few such mobile facilities could be used to process large inventories of liquid and sludge radioactive waste, containing high salt concentration of radionuclides that are generated and stored at many nuclear installations. The technologies of the LRW processing system are also extended to partition, chemically separate and selectively extract the long-lived transuranic (TRU) actinides and fission fragments from the post-PUREX raffinate of spent nuclear fuel. Recently, this application has become essential, substantially to reduce the radiotoxic inventory and heat load in geological storage and solve the projected limitation in the next two decades, at Yucca Mountain and at other geological storage facilities, for the disposal of high-level waste and spent nuclear fuel.

INTRODUCTION

The efficient and complete processing of the huge quantity of liquid radioactive waste (LRW) produced at all types of nuclear power installations are a major need, requiring practical, efficient and economical solutions. So far, the conventional methods, which use ion-exchange resins, sorbents or distillation and vitrification processes, are based on technologies that make the overall process expensive and result to large amounts of highly active mass that require long-term storage at additional cost.

Our approach was innovated to overcome these deficiencies in a newly developed technology that permits the more efficient processing of liquid and sludge radioactive waste. The output is cleaned water having the activity of natural background and the complete extraction of all radionuclides in the form of fine metallic powder [1], at high processing rates. In our case, the volume of the isolated highly active solid byproducts is several orders of magnitude smaller [2] than what is produced in the conventional processing methods. Moreover, the minimal volume of all extracted radionuclides from LRW processing, such as ^{137}Cs , ^{90}Sr , ^{60}Co and others, if

desired, can be separated into individual constituents, for further commercial-medical use [3], or could be stored in mixed form in a small vault.

The ability to handle and process sludge radioactive waste (SRW) is a direct consequence of the developed LRW processing technology. Following coarse and fine mechanical filtration and oil filtration, the radioactive sludge that contains radionuclide salts is converted into an electrolytic solution, to enter the same processing stage as the LRW's.

AREV Company's new hydrometallurgical method is based on the coordinated use of electro dialysis (ED) and electrolysis (EL) modules, especially configured to partition, chemically separate and extract the metals of selected radionuclides, individually, in groups of a few or altogether in a mix. This is made possible by processing the aqueous solution of LRW and SRW continuously, in three closed-loop cycles and in a single stage. The starting electrolytic solution containing radionuclide salts is first separated into a base solution and an acid solution, from each of which, respectively, the radionuclide cations and anions are transported via cation-exchange membranes (CEM) and anion-exchange membranes (AEM). This type of separation of functions into three close-loop cycles is also the main reason why very high-volume throughput can be obtained, without scaling the volume of the processing ED and EL modules or the sizes of membranes and electrodes, as a function of increasing processing rates.

These desirable features, the resulting compact equipment size at high throughput, make it uniquely possible to apply the developed technology to the design and production of mobile high-volume liquid and sludge radioactive waste processing systems, with ability to handle low, intermediate and high levels of activity. Such mobile facilities would have extensive uses to process the huge inventory of temporarily stored LRW and SRW, at operating or dismantled nuclear reactor installations, both commercial and military, consecutively moving at where such services will be further required. A critical need of such a mobile facility is in the Russian nuclear submarine dismantlement effort, conducted under the US-Norway-Russia Arctic Military Environmental Cooperation Program (AMEC) [4 – 5], in which 71% of the generated and temporarily stored huge inventory of nuclear waste consists of radioactive liquid and sludge.

As will be shown from experimental results, in processing the LRW of Armenia's Metzamor nuclear power plant (NPP), the effectiveness of extraction averaged over all the present radionuclides is extremely high, 6'500:1, or the average extraction efficiency is 99.985%. The very high extraction efficiency of all radionuclides is due uniquely to a recently patented method [1], in which mercury electrodes are used in the electrolysis modules, in a manner that effectively negates the formation of amalgam of mercury, which otherwise would have required the further processing of the amalgam to remove the radionuclides. The net result is the efficient, economical and full extraction of radionuclides in the form of fine metallic powder, which is easy to collect and safely store in a small vault.

The above highly effective and compact hydrometallurgical method is also the reason why an integrated LRW-SRW mobile processing system could be designed that fits on a 40-ft by 7-ft standard trailer, to process the radiotoxic liquid and sludge at a throughput rate of 10 tonne/hr, when the concentration of radionuclide salts is 5 g/l, at a rate of 5 tonne/hr for those having a salt concentration of 10 g/l and also at a processing rate of 1 tonne/hr for the extreme salt concentration of 50 g/l.

Moreover, AREV Company's new hydrometallurgical technology has been extended to partition, chemically separate and selectively extract the long-lived transuranic (TRU) actinides (Np, Am, Cm...) and fission fragments (I, Tc, Sc...) from the post-PUREX raffinate of spent nuclear fuel.

Recently, this application has become essential, substantially to reduce the radiotoxic inventory and heat load in geological storage and solve the projected limitation in the next two decades, at Yucca Mountain and at other geological storage facilities, for the disposal of high-level waste and spent nuclear fuel. The maximum concentration of the radionuclide salts in the post-PUREX raffinate typically is 5 g/l, which in our case would correspond to a high processing rate of 10 tonne/hr.

THE NEW HYDROMETALLURGICAL LRW-SRW PROCESSING METHOD

Figure 1 presents the primary flow diagram of the new hydrometallurgical method, which is designed to perform the complete extraction, and if desired the chemical separation, of all radionuclides present in liquid and sludge radioactive waste. This is done in a single stage and within three closed-loop cycles. In the first closed-loop cycle, the inputted aqueous solution is fed at a fixed rate into a dilution primary holding tank. The solution is sufficiently diluted to manage the handling of specific activities through the electrodiagnosis (ED) stack. The solution is

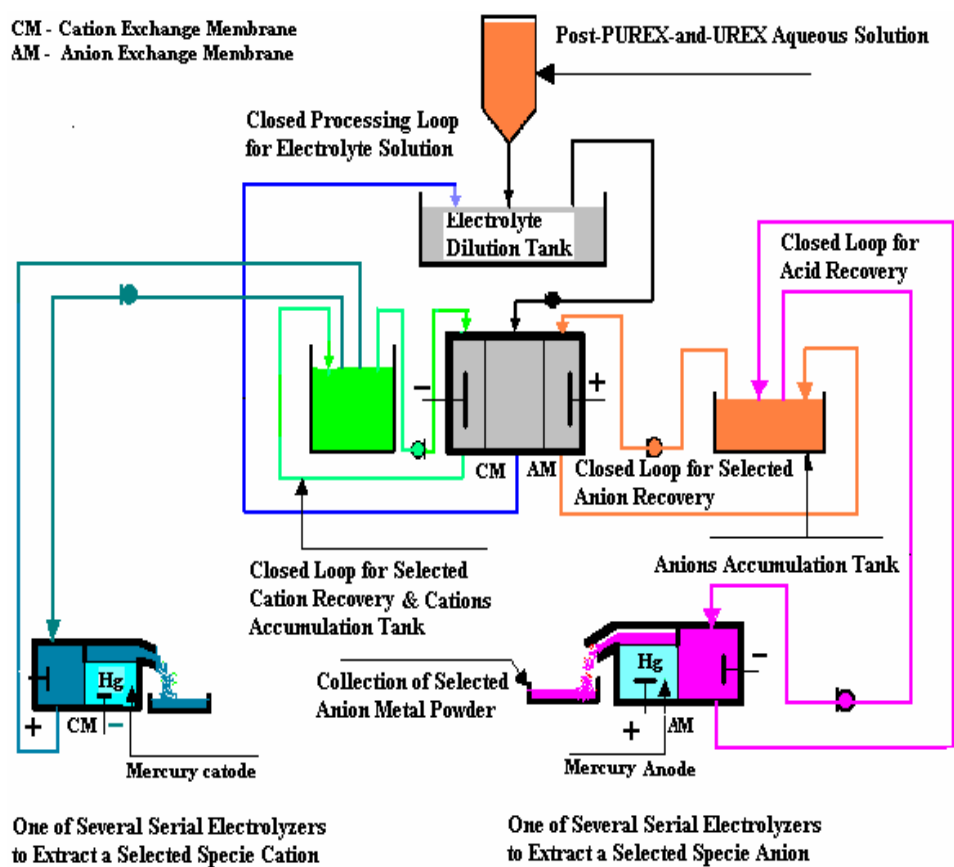


Fig. 1. Schematic flow diagram for the complete extraction of selected radionuclides from liquid and sludge radioactive waste and the post-PUREX raffinate

then pumped into the electrolyte processing cells of the ED stack. The ED module would consist of a stack of numerous cells, made of some 400 anion-exchange membranes (AEM)

and cation-exchange membranes (CEM) and 201 especially designed electrodes. Typically, the area of membranes would be 0.5 m^2 and the electrodes would have an area of 0.4 m^2 .

A similar ED stack currently assembled at AREV Company has the capacity to process the inputted electrolyte at a rate of 5 tonne/hr, if the salt of radionuclides in the aqueous solution has a concentration of 10 g/l, and equivalently, to process at a rate of 1 tonne/hr, if the salt concentration is high, at 50 g/l. Moreover, AREV Company's technology permits to design an ED stack to handle salt concentrations of as high as 200 g/l at a processing rate of at least 0.25 tonne/hr, if such a capability is required. For the extreme salt concentration, this would correspond to a LRW processing rate of 1'500 tonne/yr for 6'000 hr of annual operation.

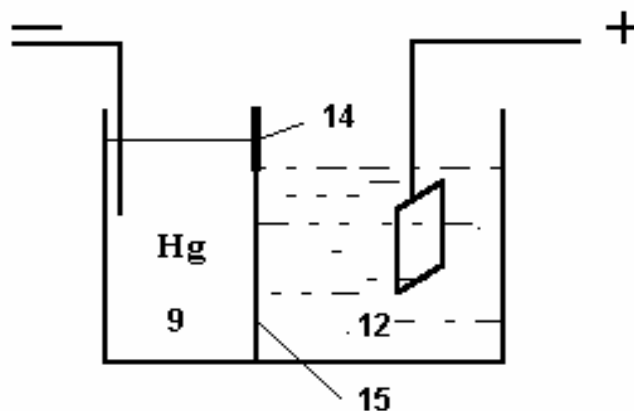
In the first closed-loop cycle the incoming salt solution of radionuclides is separated at a high throughput into a base solution and an acid solution. The geometry of the ED stack consists of anode (A) chambers with CEMs, processing (P) chambers and cathode (C) chambers with AEMs. The stack is arranged in the geometry of C-P-A-P-C-P-A..., in which the flow in all anode chambers are connected in parallel, and similarly, the flow in all cathode chambers and those in processing chambers are connecting in parallel, respectively to produce three circulation loops. In Fig. 1, for simplicity the ED stack is represented as a three-chamber module.

As a result of the continuously circulated processing, the content of salts is depleted in the aqueous solution coming out of the processing chambers, while the concentration of the base solution is increased in the solute coming out of the adjacent cathode cells, which contain the radionuclide cations. Similarly, the concentration of the acid solution is increased in the solute coming out of the adjacent anode cells, which carry the radionuclide anions. The ion concentration in the separated solutions is also kept constant. The radionuclide cations are collected in the concentrated base solution's holding tank (on the left side in Fig. 1), while the radionuclide anions are accumulated in the concentrated acid solution's holding tank (on the right side in Fig. 1). The depleted salt solution is returned to the primary holding tank, to reenter the ED's processing chambers with new inputted electrolyte.

The design of the ED stack can be optimized to process a radionuclide salt concentration of up to 200 g/l at a rate of at least 0.25 tonne/hr. In this case, the ED system parameters to be optimized for the safe handling of the very high activity are: (a) the dilution level of the inputted highly radioactive electrolytic solution, (b) its feeding rate into the primary holding tank, and (c) the processing throughput in the ED stack as set by the area of the membranes and the number of cells in the stack.

The second closed-loop cycle continues with the concentrated base solution holding tank, containing the radionuclide cations; it enters a loop of a single or a number of serially placed and especially featured electrolysis modules [1], such as the one shown in Fig. 2.

Similarly, the third closed-loop cycle continues with the concentrated acid solution holding tank, containing the radionuclide anions; it enters a loop of a single or a number of serially placed electrolyzers, similar to the one shown in Fig. 2.



9—Mercury electrode in cathode chamber of electrolysis module	12—Processing chamber and anode of electrolysis module
14—Dielectric isolation barrier	15—Cation exchange membrane (CEM) to transport selected radionuclide cations

Fig. 2. Electrolysis module with mercury cathode to completely extract the metal of selected radionuclide cations; a symmetric arrangement with AEM is for the radionuclide anions

The innovative use of the mercury electrodes in a specified geometry of the electrolyzers [1], for the base and acid solutions shown in Figs. 1 and 2, is the main reason for the complete extraction of all selected radionuclides. The one-way extraction of selected ions from these solutions exploits the skin currents induced on the surfaces of the mercury electrodes. In Fig. 2, under the influence of the applied electric field, cations are transported through the CEM and, due to the skin currents on the mercury surface, are driven up to the top layer of the mercury cathode. The placement of the dielectric isolation barrier excludes the possibility of ions to diffusion back into the processing chamber of the electrolyzer.

The speed of the skin-current driven ions is typically 25 m/s, which many times exceeds the speed of ions to dissolve into the mercury cathode. That is, the ions are driven and collected at the top of the mercury much faster than they could be dissolved to form an amalgam of mercury. An insignificant amount of amalgam of mercury is formed, which requires processing after many hours of operation. This is demonstrated in processing the LRW aqueous solution from the operation of Armenia's Metzamor NPP. Experimental results presented below, show that extraction of selected radionuclides in the form of fine metallic powder has a very high effectiveness of 6'500 : 1, which corresponds to an average extraction efficiency of 99.985%.

Moreover, the new hydrometallurgical method has been tested at AREV Company with electrolytes formed from the aqueous solution of different metal ore concentrates, partitioning Mg, Ce, Mo, Cu, Au, Ag, and fully extracting large masses of the selected metals at a refinement level of 99.99%. For this application, large-scale equipment for the industrial production of highly refined metals is now being assembled, the designs of which are also based on AREV Company's recently granted patent [1]. This is to produce daily 10's of tonnes of highly refined metals of the stated types. The new hydrometallurgical method has also been applied in a prototype industrial-scale plant, to fully process large volumes of liquid radioactive waste produced at nuclear power plants. In particular, AREV Company has designed,

assembled and operated such a prototype industrial system [2], to process over 6'000 tonnes of LRW that has been produced and stored at Armenia's Metzamor NPP.

A laboratory-scale three-chamber electro dialysis-separator having the following characteristics was used to perform a LRW processing experiment:

Voltage between electrodes	10 V
Type of membranes used	MK-40 & MA-40 for cathode & anode sides
Membrane surface area	500 cm ²
Number of membranes	3 of each type (a total of 6)
Separation of membranes	0.3 cm
Type of electrodes used	Stainless steel plates

together with the electrolysis extractor-concentrator that had the following features:

Current density in electrolysis extractor-concentrator (11)	mA/ cm ²
Type of membrane used	MK-40
Membrane surface area	100 cm ²
Volume of chambers (9 and 12) with electrodes, each	30 cm ³

Table I lists in order of measured specific activity the radionuclides to be extracted in the LRW's aqueous solution. The salt concentration of radionuclides in the LRW was 3 g/l. In processing the LRW, washing the mercury cathode's top surface with a weak jet of water, collecting the extracted radionuclides in the form of fine metallic powder, and measuring the residual specific activities in the cleaned liquid, the entries listed in the third column were produced. The demonstrated single-pass extraction effectiveness averaged over the selected radionuclides was 6'500 : 1, or the averaged separation and extraction efficiency was 99.985%.

Table I. Specific activities in the experimental aqueous solution, before and after the extraction of selected radionuclides

Radionuclides in Aqueous Solution ^a in Order of Their Specific Activities	Specific Activities of Radionuclides in Initial Electrolyte [Bq/l]	Post-processed Residual Activities of Extracted Radionuclides [Bq/l]	Demonstrated Single-Pass Extraction Effectiveness of Selected Radionuclides
¹³⁷ Cs	15'000	1.70	8'820 : 1
⁹⁰ Sr	6'000	1.30	4'620 : 1
¹³⁴ Cs	5'000	0.60	8'330 : 1
⁶⁰ Co	1'200	0.70	1'710 : 1
⁵⁴ Mn	600	-	-
²⁴ Na	200	-	-
Total [Bq/l]	28'000	4.30	6'500 : 1

^aDensity is 1.003 (g/cm³); also contains boric acid at a concentration of ~ 1.2 (g/l) and other chemicals, such as synthetic radioactive materials, detergents and inorganic compounds

MOBILE HIGH-VOLUME LRW-SRW PROCESSING SYSTEM

Based on the above hydrometallurgical developments, the conceptual design of a mobile high-volume LRW-SRW processing facility is presented, to extract all radionuclides from low-level, intermediate-level and high-level liquid and sludge nuclear waste and produce only industrially clean water. The full features of the mobile high-volume processing system are displayed in Fig. 4. The design is based on the newly developed hydrometallurgical technologies, the experience gained in the industrial-scale prototype plant and the above experimental data.

In particular, our unique technology permits to have compact equipment size for high throughput processing, so that all desired features of a mobile high-volume system could be housed on a standard 40-ft by 7-ft trailer. The mobile equipment is designed to process all levels of liquid and sludge nuclear waste, at a rate of 10 tonne/hr, when the concentration of radionuclide salts in the LRW is 5 g/l, at a rate of 5 tonne/hr for those having a salt concentration of 10 g/l and also at a processing rate of 1 tonne/hr for the extreme salt concentration of 50 g/l.

Such a mobile facility would have extensive uses to process the huge inventory of temporarily stored LRW and SRW, at operating or dismantled nuclear reactor installations, both commercial and military, consecutively moving at where such services are further required. A critical need of this mobile facility is in the Russian nuclear submarine dismantlement effort, which is being performed under the US-Norway-Russia Arctic Military Environmental Cooperation Program (AMEC) [4 – 5], in which 71% of the generated and temporarily stored radiotoxic inventory of nuclear waste consists of radioactive liquid and sludge.

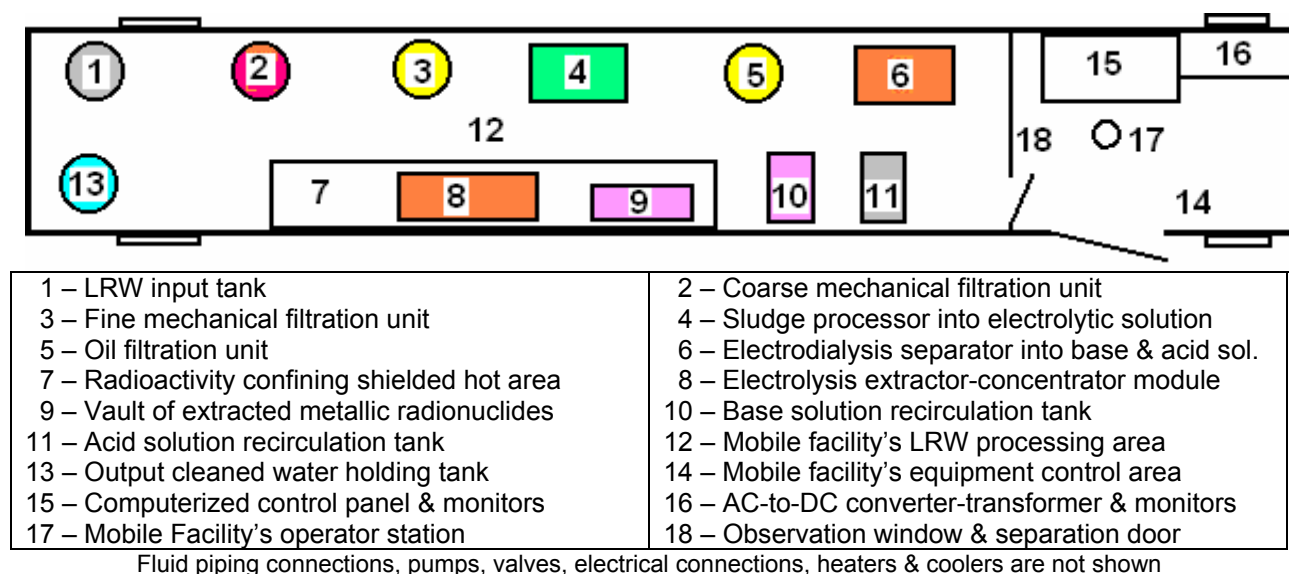


Fig. 3. Mobile modular high-volume LRW-SRW-processing facility mounted on a standard 40-ft by 7-ft trailer to be driven by a heavy-duty truck

Moreover, the LRW produced in the operation and maintenance of Russian nuclear submarines is known to contain 5 – 10 g/l concentration of radionuclide salts, which places this LRW in the high throughput range of the mobile system's processing capability of between 10 – 5 tonne/hr, respectively. The SRW inventory may have as much as 50 g/l of radionuclide salts that would be processed in the mobile facility at a rate of 1 tonne/hr. Data from Russian naval nuclear

operations also show that the radiotoxicity in the huge LRW inventory would consist of 70 – 80% of ^{137}Cs and ^{134}Cs , 10 – 20% of ^{90}Sr and 5 – 10% of ^{93}Zr , ^{95}Nb , ^{60}Co and lanthanides. The long-lived radionuclides in the LRW, in order of their specific activity, are ^{60}Co , ^{137}Cs , ^{134}Cs , ^{90}Sr , ^{63}Ni , ^{14}C , ^{125}Sb and ^{129}I .

Figure 4 shows the equipment layout of the mobile high-volume LRW-SRW processing facility. The equipment will be anchored on a standard 40-ft by 7-ft trailer's bed. Not shown in the Figure are the fluid-piping and electrical connections, pumps, valves and the various services.

The equipment layout is grouped in three areas: a) The radioactivity confining shielded hot area that houses the electrolysis extractor-concentrator module and the vault of the extracted radionuclides in the form of fine metallic powder; b) The LRW-SRW main processing area, containing the LRW input tank, the coarse and fine filtration units, the sludge converter into an electrolytic solution, the oil filtration unit, the ED stack separating the aqueous solution into a base and an acid solution, and the recirculation tanks for the base and acid solutions; And c) the operational and equipment control area of the mobile facility, containing the computerized control system and monitors, the AC-to-DC power converter and transformer and the single operator's station.

Essentially, the input to the mobile system is AC power and the LRW to be processed, pumped into a holding tank, while the output is industrially clean water pumped out of the corresponding holding tank, which would have an activity no more than the natural background activity of the particular location, that is, it would be a few Bq/l. The fully extracted inventory of the medium- and long-lived radionuclides from this facility would have a relatively insignificant volume, when compared with the output from the other conventional LRW processing methods.

Moreover, as shown in the next section, the mobile facility can be reconfigured easily to also partition and chemically separate the transuranic actinides and fission fragments from the post-PUREX raffinate, should the spent nuclear fuel be reprocessed at a different installation and the mobile facility be moved to such a plant. This would be a means of also considerably reducing the huge radiotoxic solid waste inventory, to have a much-reduced mass and volume for geological storage.

THE NEW METHOD EXTENDED TO PARTITION & SEPARATE TRU ACTINIDES & FISSION FRAGMENTS IN POST-PUREX RAFFINATES

AREV Company's proven hydrometallurgical technology [1 – 2] has also been extended to address the extraction, partitioning and chemical separation of the long-lived transuranic actinides (Np, Am, Cm...) and fission fragments (I, Tc, Sc...), found in the post-PUREX raffinate [3] of spent nuclear fuel. This includes 14 or more of the most offensive long-lived radionuclides, which can be separated and extracted in the same single stage and the three closed-loop processing cycles. But, in this application, the use of additional electrolyzer modules is required. Recently, this application has become essential, to reduce substantially the radiotoxic inventory and heat load in geological storage and solve the projected limitation in the next two decades, at Yucca Mountain and at other geological storage facilities, for the disposal of high-level waste and spent nuclear fuel.

A modern PUREX reprocessing plant for spent nuclear fuel would have a recovery yield of 99.89% for plutonium (Pu) and a similar recovery of the uranium (U) that would also contain up to 1.1% of ^{235}U . The maximum concentration of the radionuclide salts in the post-PUREX

raffinate is 5 g/l, which in the mobile facility would correspond to the high processing rate of 10 tonne/hr.

The task at hand is therefore to partition, chemically separate and extract the 14 or more of the most offensive long-lived radionuclides in the post-PUREX raffinate. This includes the residual U and Pu, the main TRU actinides, Np, Am and Cm, the medium-level and excessively active fission fragments (FF), ^{137}Cs and ^{90}Sr , and the important long-lived FFs, ^{99}Tc , ^{129}I , ^{93}Zr , ^{135}Cs , ^{63}Ni , ^{126}Sn , ^{79}Se and ^{36}Cl , which are given in order of their abundance.

Table II. Anions and cations of the 14 long-lived TRU actinides and fission fragments, selected for partitioning and chemical separation and listed in increasing order of their electrochemical potential [6]

Element or Radionuclide for Partitioning in Post-PUREX Raffinate	Equilibrium Electro-Chemical Reactions in Base & Acid Solutions	Electro-Chemical Potential of Radionuclides [V]
ACID SOLUTION	ANIONS	U_{ai}
^{79}Se	$\text{Se} + 2e^- \leftrightarrow \text{Se}^{2-}$	- 0.670
^{129}I	$\text{I}_2 + 2e^- \leftrightarrow 2\text{I}^-$	+ 0.621
^{36}Cl	$\text{Cl}_2(\text{aq}) + 2e^- \leftrightarrow 2\text{Cl}^-$	+ 1.396
BASE SOLUTION	CATIONS	U_{ci}
^{90}Sr	$\text{Sr}^{2+} + 2e^- \leftrightarrow \text{Sr}$	- 2.890
Americium	$\text{Am}^{3+} + 3e^- \leftrightarrow \text{Am}$	- 2.070
Curium	$\text{Cm}^{3+} + 3e^- \leftrightarrow \text{Cm}$	- 2.060
Plutonium	$\text{Pu}^{3+} + 3e^- \leftrightarrow \text{Pu}$	- 2.030
Neptunium	$\text{Np}^{3+} + 3e^- \leftrightarrow \text{Np}$	- 1.790
Uranium	$\text{U}^{3+} + 3e^- \leftrightarrow \text{U}$	- 1.660
^{93}Zr	$\text{Zr}^{4+} + 4e^- \leftrightarrow \text{Zr}$	- 1.550
^{63}Ni	$\text{Ni}^{2+} + 2e^- \leftrightarrow \text{Ni}$	- 0.257
^{126}Sn	$\text{Sn}^{2+} + 2e^- \leftrightarrow \text{Sn}$	- 0.140
^{99}Tc	$\text{Tc}^{2+} + 2e^- \leftrightarrow \text{Tc}$	+ 0.400
Cesium	$\text{Cs}^+ + e^- \leftrightarrow \text{Cs}$	+ 2.923

Table II lists the 14 long-lived TRU and FF radionuclides to be partitioned. These are grouped as anions in the acid solution and cations in the base solution, and entered in increasing order of their electrochemical potential [6]. The equilibrium electrochemical reaction [6] of each is also presented.

In this application, the second closed-loop cycle starts with the concentrated base solution holding tank in Fig. 1, containing the radionuclide cations, and enters a loop of serially placed and especially featured electrolysis modules, a number of which consecutively partition and completely extract the selected radionuclide cations. The serially placed electrolyzers in the loop have voltage settings in increasing order of the electrochemical potential of the selected radionuclide cations, as shown in Fig. 4, to partition, separate and extract the ^{90}Sr , Am, Cm, Pu, Np, U, ^{93}Zr , ^{63}Ni , ^{126}Sn , ^{99}Tc and Cs.

Similarly, the third closed-loop cycle starts with the concentrated acid solution holding tank in Fig. 1, containing the radionuclide anions, and enters the loop of serially placed electrolyzers as indicated in Fig. 4, to partition, separate and extract the ^{79}Se , ^{129}I and ^{36}Cl .

The voltage of each electrolyzer-extractor is set to partition an individual element or a group of elements that have nearby values of electrochemical potentials. To extract the selected elements the actual voltage setting of successive electrolyzers, in the loop for cations or the one for anions, will be determined experimentally. This will be slightly different from the values entered in Table II.

The empirical values will depend on the type of acids used to form the inputted aqueous solution, on the design geometry of the electrolysis modules and the types of employed AEMs, CEMs and electrodes. However, once the voltage setting of each is determined experimentally for the partitioning and chemical separation system, the presented hydrometallurgical process

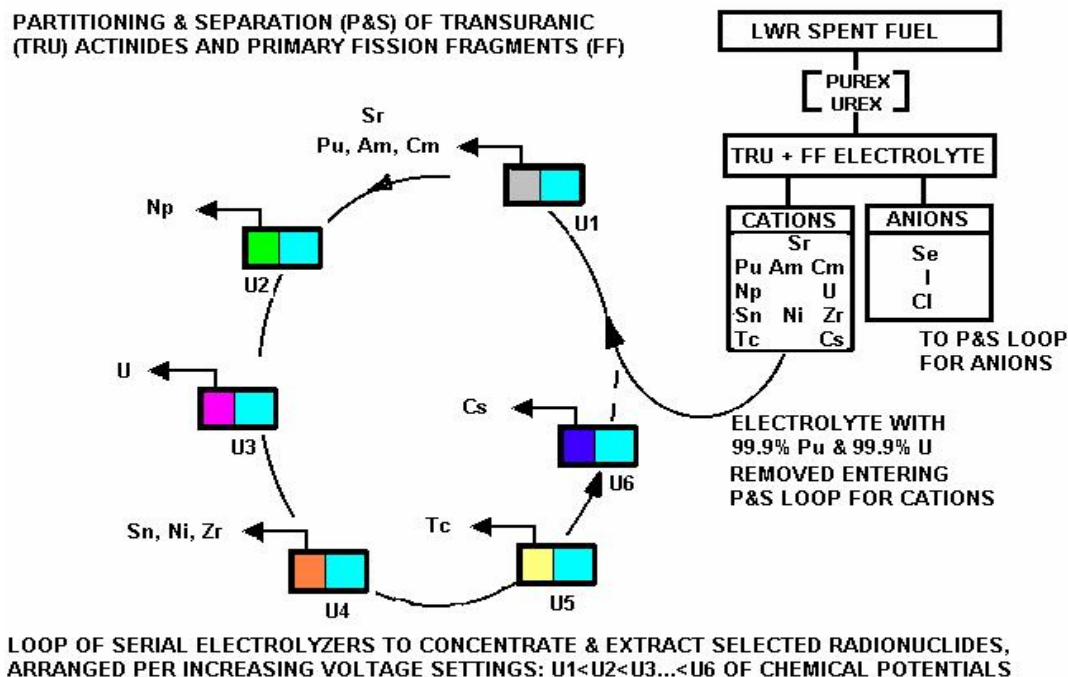


Fig. 4. Single stage extraction, partitioning and chemical separation of selected TRU and fission fragment radionuclides from the post-PUREX raffinate

will be very exact, in terms of completely extracting the selected radionuclide's metal. This is demonstrated by the experimental results shown in Table I, based on processing a radioactive aqueous solution from the Metzamor NPP.

CONCLUSION

The conceptual design of a mobile high-volume LRW-SRW processing system is produced, based on fully developed technologies, the experience gained from an industrial-scale prototype plant and the data of performed relevant experiments. The mobile facility is especially suitable to process the huge inventory of liquid and sludge radioactive waste, accumulated at nuclear power installations; and especially, to completely process the excessively large LRW-SRW accumulated and temporarily stored at Russian nuclear submarine dismantlement shipyards. Moreover, the mobile high-volume processing facility can easily be modified to also separate and extract the transuranic actinides and fission fragments in the post-PUREX raffinate, which is

essential to substantially reduce the radiotoxic inventory of solid nuclear waste of spent fuel that are designated for geological storage.

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