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Treatment Methods for Radioactive Wastes and Its Electrochemical Applications

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1. Introduction

There are many uses of radioactive materials which improve or facilitate human activities or quality of life of people. These uses are given in different fields of technology, ranging from power generation to supply entire cities or areas, to medical and industrial uses, even the smoke detectors in buildings. All these applications generate radioactive waste that may represent risks to the environment or to human beings, but it is necessary to have special attention to the management of radioactive waste.

In this chapter there are information about the generalities of radioactive wastes, such as its definition, origin, classification and stages of radioactive waste management. In addition, there are information about the current state of research and technologies which have been proposed for the treatment of radioactive waste, with their advantages and disadvantages, in special case of the electrochemical techniques to treat radioactive waste with theoretical considerations and cases of study. At the end of this chapter, there is information about the risk assessment and development of future strategies.

2. Radioactive waste

2.1. Origin of radioactive waste

Radioactive waste are created from all activities that radioactive materials are used, either as part of the process or the use of such materials as a constituent of equipment or instruments that allow the realization of a practice. Due to large differences in the characteristics of the waste generated in the different areas and to a better understanding of these origins, is

convenient to differentiate the activities coming from nuclear fuel cycle of applications coming from medical, research activities and industrial uses (Radiation Safety General Regulations, 1988; Méndez de Vigo, 2000).

2.2. Classification of radioactive wastes

Classification of radioactive waste is in order of any stage from its origin just to their collection, segregation, treatment, conditioning, storage, transportation and final disposal. In this case, in the Figure 1 is the physical classification of radioactive waste (IAEA, 1970 and 1994).

ACTIVITY	HALF-LIVE	SOURCES	FORM
LOW LEVEL WASTE	VERY SHORT LIVE < 100 days	SEALED SOURCES	SOLID <div>COMPACTIBLE</div> <div>NON-COMPACTIBLE</div>
INTERMEDIATE LEVEL WASTE	SHORT LIVE < 30 years		LIQUID <div>AQUEOUS</div> <div>ORGANIC</div>
HIGH LEVEL WASTE	LONG LIVE >30 years	OPEN SOURCES	BIOLOGICAL

Figure 1. Classification of radioactive waste (own creation).

Quantitative values of allowable activity content for each significant radionuclide will be specified on the basis of safety assessments for individual disposal sites, and the radiological classification of radioactive waste is (IAEA, 2009):

- **Exempt waste (EW):** Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes (IAEA, 2004).
- **Very short lived waste (VSLW):** waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primary radionuclides with very short half-lives often used for research and medical purposes.
- **Very low level waste (VLLW):** Waste that does not necessary meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes

soil and rubble with low levels of activity concentration. Concentrations of longer lived radionuclides in VLLW are generally very limited.

- **Low level waste (LLW):** Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration, and also long lived radionuclides, but only at relatively low levels of activity concentration.
- **Intermediate level waste (ILW):** Waste that because of its content, particularly of long lived radionuclides, requires a greater degree of containment and isolation that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of meters to a few hundred meters.
- **High level waste (HLW):** Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred meters or more below the surface is generally recognized option for disposal of HLW.

2.3. Management of radioactive waste

The ultimate goal of waste management lies in its restraint and seclusion of the human environment, for a period of time and under conditions such that any release of radionuclides does not pose unacceptable radiological risk to people or the environment. Management should ensure that all charges are minimal for future generations.

A responsible management of radioactive waste requires the implementation of measures aimed at protecting human health and the environment. The basic steps for effective management of radioactive waste are part of a global system, ranging from waste generation to final disposal are: minimization of radioactive waste, pretreatment, characterization, treatment, conditioning, transport, storage and disposal (IAEA, 1970; Figure 2).

A management system should to be applied in all steps of radioactive waste management, in order to ensure that activities, facilities, equipment and waste products in meeting the overall safety, health, environmental, security, quality and economic requirements, with safety and environmental protection being of primary importance (IAEA-2008, IAEA 2006a, 2006b).

Management system has to contain a description of the processes and supporting information that explain how work is to be prepared, reviewed, carried out, recorded, assessed and improved. In the design of work processes, a detailed sequence of steps in the activities for

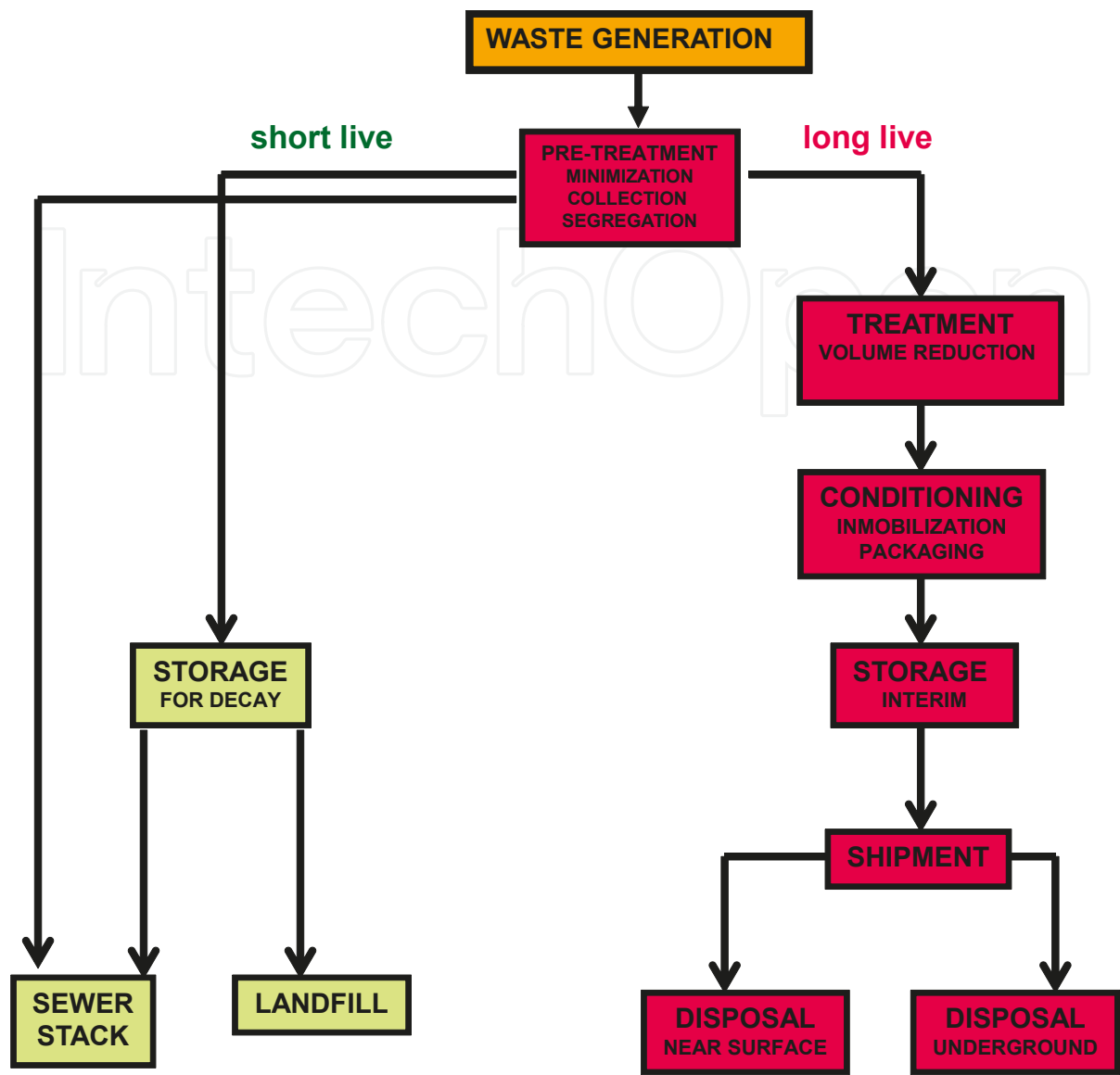


Figure 2. Steps for managing radioactive wastes (IAEA, 2001).

pretreatment, treatment, conditioning and disposal wastes should be considered, such as: (i) characterization of waste at each step in the overall waste management program, (i) analytical methods such as sampling protocols for waste characterization or process control; (iii) monitoring of discharges; (iv) monitoring for clearance purposes; (v) non-destructive examination and testing; (v) heat treatment, (vi) use of special handling tools and techniques, protective clothing or facilities for radiation protection, etc.

Identification of items should be established and documented on the basis of the importance to safety and environmental protection or waste isolation. Records shall specify: (a) the origin of the waste and the processes that generated it; (b) pretreatment of the waste; (c) clearance of the waste; (d) discharge of the waste; (e) characterization of the waste; (f) treatment of the waste; (g) design of the containers and/or packages and of equipment, structures, systems and components for the pretreatment, treatment of the waste.

Additionally, assessments must perform on work processes used in the waste management. Inspections and measurements have to being performed and the associated records maintained. Consequently, controls to activities, facilities, equipment and waste products will have to be designed, considering factors such as: (a) the quantities and potential hazards (radiological and non-radiological, for example chemical) of the waste, and the necessary degree of isolation; (b) the dispersibility and mobility of the waste forms involved and the necessary degree of containment; (c) the interval before disposal; (d) experience with, and maturity of, the technology and the potential for future advances; (e) the reliability of equipment and its function in relation to safety and environmental protection; (f) the complexity and degree of standardization of the activities; (g) the novelty and maturity of the activities; (h) ease of operation, maintenance of equipment and eventual decommissioning of the facility, etc.

Quality assurance requirements should be established for all phases of the waste management process to ensure that each waste is correctly processed and the final waste form has the required properties. This requires quality assurance parameters to be specified. Performance data must be documented for each parameter in order to demonstrate compliance. The quality assurance program should cover the following aspects: (1) waste characterization, (2) waste management process specification, (3) processing conditions, (4) product specification and (5) storage or disposal (HSEEA 2007; IAEA 2008, IAEA 2006).

2.4. Safety guide

Safety is a top priority in radioactive waste management, because of this, the purpose of this section is to present a brief guideline of recommended procedures for working with radioactive wastes. The safety aspects and environmental protection which need to be considered in the handling and processing of radioactive wastes are mainly associated with: flammability, toxicity, explosion and radioactivity.

Some of the most important aspects to consider regarding safety and environmental protection in the radioactive waste management are (IAEA 2008, IAEA 2006a,2006b):

1. The handling, processing and storage radioactive wastes require a permit which is authorized by a local regulatory agency.
2. The wastes must be adequately characterized; chemically, physically, and radiological as a precursor to waste management. The composition of waste should be known with sufficient accuracy that nuclear and conventional safety and environmental protection are not compromised. Toxic or hazardous constituents should be characterized by analytical means or from knowledge of the processes, so that hazards associated with treatment methods of waste can be identified. The reachability of radionuclides, toxic materials and the generation rates for volatile organic compounds or powders and other hazardous gases should be determined. It is important to know the chemical stability of radioactive waste: flammability, corrosively, reactivity, pyrophoricity, rapid oxidation promotion, biodegradability and the chemically incompatible waste forms should be carefully controlled. The amount of mobilizing agents such as chelating compounds, particularly stable ones, should be kept to a minimum. Waste containing hazardous constituents that

are mobile in the environment, or constituents that enhance the mobility of radionuclides should avoid.

3. Several possible process options have to be identified for treating radioactive wastes and before selecting it should include a safety analyses. To prefer processes the cheapest and simplest to procure and operate. The best practical environmental options should be selected, with radiation doses and discharges as low as reasonably achievable (ALARA).
4. Radioactive liquid and gaseous discharges should be as low as reasonably achievable (ALARA) and meet regulatory and environmental restrictions.
5. It is suggested that cheap simple structures will be adequate for installation.
6. Personnel protection should be used in installation: protective clothing, rubber gloves, face mask, visors and personal dosimeters.
7. It is necessary to assess the radiation exposure of the operators on the site and to estimate the frequency and consequences of possible accidents related to the facility and the materials which it handles;
8. The waste processing area must to have suitable fire protection systems, adequate ventilation, and for the waste contains liquids a collection sump.
9. To ensure that radiation exposure to the workforce is as low as reasonably achievable (ALARA).
10. It is recommended having a central waste management facility.
11. Details of the safety methodology will be given in a planned technical document.

3. Treatment of radioactive waste

The aim of the radioactive waste treatment is to minimize the volume of waste requiring management. Treatment process selection for waste depends upon its radiological and physicochemical properties and the quantity (IAEA, 2001; Adenot et al, 2005; Chang, 2001). The objective of this section is to provide a brief overview of usually techniques applied for the treatment of radioactive waste as Figure 3 shows.

3.1. Treatment of aqueous waste

The processes available for treating aqueous radioactive waste are mainly: ion exchange/sorption, chemical precipitation, evaporation or ultrafiltration/reverse osmosis. However, liquid containing suspended matter must be treated to remove the particulates before primary treatment or after it. Sedimentation, decantation, filtration or centrifugation are treatments used commonly to clear the effluent wastes or to remove miscellaneous debris or insoluble particles (IAEA, 2001; Adenot et al, 2005; Abdel et al, 2011).

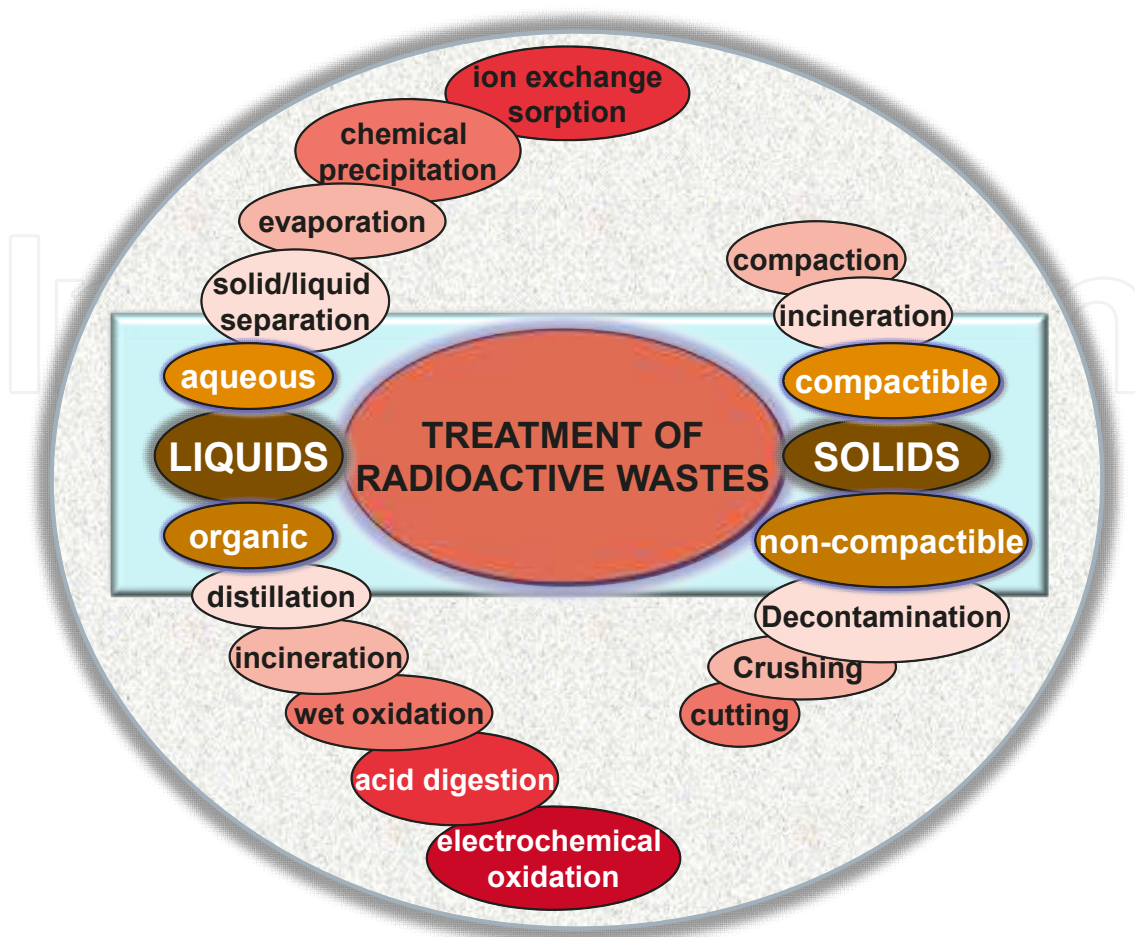


Figure 3. Classification of the treatment process applied to radioactive wastes (authors own creation).

3.1.1. Chemical precipitation

Chemical precipitation processes are regularly used for removing radioactivity from low and intermediate level aqueous wastes at fuel reprocessing facilities, research laboratories and power stations. Precipitation processes are greatly versatile, relatively low investment and operational costs; and may treat from large volumes of liquid effluents containing relatively low concentrations of active species to those containing large amounts of particulates or high concentrations of inactive salts. However, in some cases, a pretreatment stage, such as oxidization of organic contaminants, decomposition of complexed species, pH adjustment, change of the valency state or adjust the ionic species, should be applied prior to the formation of precipitate in order to improve the process. Radionuclides can be removed by precipitation, co-precipitation with a carrier or sorption on to particulates present in the waste (IAEA, 2001; Adenot et al, 2005).

3.1.2. Ion exchange/sorption

Ion exchange methods have extensive applications to remove soluble radionuclides from liquid waste produced in nuclear fuel cycle operations, radioisotope production and research

facilities. It is very effective at transferring the radioactive content of a large volume of liquid into a small volume of solid.

Ion exchange process involves the replacement of cations or anions between an insoluble solid matrix containing ionizable polar groups and a liquid solution. When the ionic groups are negatives the exchange will involve cations and when they are positively charged they involve anions. The process is selective, stoichiometric and, as a rule, reversible; therefore ion exchangers can be “regenerated” and radioactive liquid waste recovered with high activity content or if the exchangers become “exhausted” they are removed and treated as radioactive wastes.

A wide range of materials is available for the ion exchange treatment of radioactive liquids: (a) natural ion exchangers (clays, zeolites, cellulose, charcoals, collagen) and (b) synthetic materials such as zeolites, hydrous oxide gels of metals or organic resins formed by highly polymerized cross-linked hydrocarbons containing ionic groups (sulfonic acid, carboxylic acid, amino groups, etc.).

Ion exchange processes can be operated in batch or continuous modes and if the wastes contain high concentrations of salts, suspended solids, organic contaminants or the radionuclide ionic form not suitable, the liquid wastes will have to be pre-treated before exchange process (IAEA, 2001 and 2002; Adenot et al, 2005).

3.1.3. *Evaporation*

Evaporation process is effective for concentrating or removing salts, heavy metals and a variety of hazardous materials from waste effluent, reducing large volumes of liquid wastes with high factor decontaminations. The process is commonly used for the treatment of high, intermediate and low level waste effluents; in particular for the treatment of small volumes of highly active effluents and may be carried out through the use of commercially available evaporation equipment. However, evaporation has some important limitations: unsuitable for waste effluents containing large concentrations of inactive salts, expensive because its large energy requirement and the presence of some organic compounds can produce explosions during evaporation (IAEA, 2001; Adenot et al, 2005).

3.2. **Treatment of radioactive organic liquid**

Liquid scintillation, solvents, oils and diverse biological fluids, generated in nuclear research centers, medical centers or industries are considered as radioactive organic liquid wastes. These wastes may present radioactive and chemical or biochemical hazards requiring treatments to remove or destroy chemically or biochemically hazardous components. The objective is to reduce the volume of radioactive waste which requires storage, transport, conditioning and land disposal, eliminating the organic components to enhance compatibility of the treated waste with secondary conditioning processes.

Processes such as incineration, wet oxidation, acid digestion, electrochemical oxidation and distillation, can be applied for treating radioactive organic liquid (IAEA, 1992 and 2001).

3.2.1. Incineration

Incineration is used for reduction of solid and liquid radioactive waste volume, downscaling land requirements for disposal. Incineration combusts or oxidizes wastes at high temperatures, generating as end products of the complete incineration: CO₂, H₂O, SO₂, NO, and HCl gases. Emission control equipments for particulates, SO₂, NO_x and products of incomplete oxidation are needed to control emissions of regulated air pollutants.

The disadvantages of radioactive waste treatment with incineration are: off-gas filtering system are required to control radioactive discharges, thickening and dewatering wastes pretreatment may be required, is not economical for small solid waste plants and secondary waste volumes may be large (Chang, 2001; IAEA, 1992, 2001 and 2006; NEA, 1999).

3.2.2. Wet oxidation

The organic components of radioactive wastes such as ion exchange resins, foams, cellulosic waste and liquid scintillation can be transformed, degraded, or immobilized using wet oxidation.

Wet oxidation remedial process involves injecting an oxidizing agent, such as hydrogen peroxide, activated sodium persulfate, ozone, Fenton's Reagent (hydrogen peroxide with an iron catalyst) or other oxidant into the subsurface to destroy organic compounds.

The complete mineralization of carbon-based compound wastes by most chemical oxidizers produces carbon dioxide, water, and oxygen as well as minor concentrations of nontoxic ions, salts, and acids. Wet oxidation is thus a process analogous to incineration, with the advantage of using low temperatures (Twissel and Holt, 1996; IAEA, 1992; Chang, 2001).

3.2.3. Acid digestion

Acid digestion is an oxidative destruction technology for some liquid organic wastes (hexane, TBP) and organic constituents of mixed waste such as cellulose (paper), polyethylene, latex rubber, Tyvek™, neoprene, polyvinylchloride, polystyrene ion exchange resins, filters, plastics, and/or chlorinated cutting oils organic, that may reduce the waste volume of 20 to 100 times. Acid digestion process uses a mixed of nitric acid in a phosphoric acid carrier solution at temperatures below 200°C and at atmospheric or moderate pressures (< 20 psig). The principal organic portion of the waste is broken down and mineralized by the acid solution producing: inorganic constituents in solution, which can be immobilized easily in a glass or ceramic, and gases (CO₂, CO, O₂ and NO_x) that can be treated in an off-gas scrubbing system, to convert NO_x to reusable nitric acid (Report OST, 1999; IAEA, 1992 and 2001; Adenot et al, 2005).

3.2.4. Distillation

Distillation is a radioactive waste volume reduction technique used for pretreating liquid scintillation and miscellaneous solvent waste in conventional equipment. The process is

simple, known, and cost effective if the valuable solvent is recycled or reused. The active residue could be either immobilized or destroyed by incineration (IAEA, 2001).

3.3. Treatment of solid waste

Solid wastes are produced by all applications and uses of radioactive materials, in normal operations and maintenance activities. Solid, low and intermediate level wastes are generally segregated into combustible, compactible and non-compactible forms.

Treatments for solid waste are used to reduce the waste volume and/or convert the waste into a form suitable for handling, storage and disposal (IAEA, 2001 and 2002; Chang, 2001; Adenot et al, 2005; NEA, 1999).

3.3.1. Decontamination

Decontamination is defined as the removal of contamination from areas or surfaces of facilities or equipment by washing, heating, chemical or electrochemical action, mechanical cleaning or by other means. The decontamination objectives are mainly: to reduce the volume of equipment and materials requiring storage and disposal in licensed disposal facilities, to remove contamination from components or systems, to reduce dose levels in the installations and to restore sites and facilities to an unconditional-use condition. Decontamination processes may divide into chemical, electrochemical and mechanical processes:

- **Chemical decontamination.** In the chemical decontamination are used concentrated or dilute chemical reagents in contact with the contaminated item, to dissolve the contamination layer, covering the base metal and eventually a part of the base metal.
- **Decontamination by melting** presents the particular advantage of homogenising a number of radionuclides in the ingots and concentrating other radionuclides in the slag and filter dust resulting from the melting process, thus decontaminating the primary material. The problem with inaccessible surfaces or complex geometries is eliminated and the remaining radioactivity content is homogenised over the total mass of the ingot.
- **Mechanical and manual decontamination** included wet or dry abrasive blasting, grinding of surfaces and removal of concrete by spalling or scarifying, washing, swabbing, foaming agents, and latex-peelable coatings. These techniques are most applicable to the decontamination of structural surfaces which may be cleaned by sweeping, wiping, scrubbing or removed by grit blasting, scarifying, drilling and spalling.

A wet abrasive-blasting system uses a combination of water, abrasive media and compressed air, and is normally applied in a self-contained, leaktight, stainless steel enclosure. The dry abrasive-blasting technique, commonly called sandblasting or abrasive jetting, uses abrasive materials suspended in a medium that is projected onto the surface being treated, resulting in a uniform removal of surface contamination. The scarification process removes the top layers of a contaminated surface down to the depth of the sound, uncontaminated surface.

There are two basic disadvantages with the mechanical methods: the surface of the workpiece has to be accessible and many methods may produce airborne dust (IAEA, 2001 and 2002; Chang, 2001; Adenot et al, 2005; NEA, 1999).

3.3.2. *Compaction*

Compaction is performed in order to reduce the waste volume and concentrates the radionuclides. Plastics, paper, absorbent material, and cloth are compatible in conventional compactors. Metal pipe, valves, conduit, wood, and other like items are compatible in super compactors. Compactors can range from low-force compaction systems (~5 tons or more) through to presses with a compaction force over 1000 tons (super compactors). Volume reduction factors are typically between 3 and 10, depending on the waste material being treated (IAEA, 2001 and 2002).

3.3.3. *Cutting*

Cutting and sawing operations are carried out mainly on large items which consist usually of metals or plastics. This waste has to be reduced in size to make it fit into packaging containers or to submit it to treatment such as incineration. The cutting is carried out either in the dry state in cells, using remote control when necessary and with conventional tools, or underwater. The cutting may also be done with plasma-jets, laser torches, or explosive fuses.

3.3.4. *Crushing*

Crushing techniques may be used for size reduction of friable solids (glass, concrete, ceramics). In principle, all types of mill, grinder, and crushing machines of conventional technology can be used.

3.3.5. *Shredding*

Shredding reduces void space and is particularly effective when plastics are compacted. Air, which is trapped between the folds of bulk plastic and in plastic bags and sleeving, takes up storage space. When the plastic is shredded, better use is made of the waste container space.

3.3.6. *Incineration*

The size reduction, mixing and blending of the solid wastes is necessary for successful combustion operation.

4. **Electrochemical treatment of radioactive waste**

4.1. **Electroremediation**

The electrochemical treatment, electroremediation, also known as electrokinetic remediation (EKR) process is classified as a physicochemical technology by the electrochemical transfor-

mation or destruction of organic and inorganic wastes, which offers many advantages such as the capacity to remove organic and inorganic pollutants by applying direct electric current into the soil. The EKR is easy to operate and involves the installation of electrodes into the organic or inorganic waste and the application of a low voltage gradient or direct current through them (Vazquez et al, 2007). This process is capable of mineralizing the organics into carbon dioxide and water completely, without emission of any toxic materials like dioxins. Several metal oxidizing agents like Ag(II)/Ag(I), Ce(IV)/Ce(III), Co(III)/Co(II), etc., have been tested with this process in pilot and commercial scale systems (Adenot et al, 2005; Chang, 2001; Prabhakaran et al, 2009; Farmer et al, 1991).

This technology requires having humid waste into which electrodes are inserted, the electrodes' terminals are connected to a power supply, and an electric current or potential gradient is applied to generate an electrical field. During this process, electrode reactions take place on its surface, generating protons (H^+) and hydroxyl (OH^-) at the anode and the cathode, respectively. The concentration of these ions near the electrodes creates an acid front that moves from anode to cathode and a basic front that moves from cathode to anode. These species interact with the soil to carry pollutants out into the pore solution. Some transport phenomena occur in the liquid phase of soil when direct current or voltage gradient is passed through the electrodes, such as ion migration (electromigration), electroosmosis and electrophoresis (Murillo – Rivera et al, 2009; Alcántara et al, 2008), inducing complex and coupled electrochemical and properties of matrix. In this case, the transport phenomenon depends on the chemistry of the pollutant (Pamuku and White, 1992; Reddy and Chinthamreddy, 2003; Braud et al, 1998).

If the pollutant is inorganic, as metals, these can be removed by electromigration, because the compounds are dissociated in ions. If the ions have negative charge (anions) they will move toward the anode, and if they have positive charge (cations) they will move toward the cathode, an important characteristic which can determine where the metal, in ionic form, can be recovered (Virkutytea et al, 2002; Figure 4). Non-polar pollutants or organic pollutants can be removed by electroosmosis, attributed to the excess charges on the soil surface. There occurs the net ionic migration that represents the bulk movement along pore fluid through the electrical double layer of charge at the solid–liquid interface (Al-Shahrani and Roberts, 2005). And finally, electrophoresis is the movement of charged solid particles, including clay particles and bacterial cells with size less than 20 μm , in response to the electrostatic potential gradient. As in electromigration, positively charged particles migrate towards the cathode, and negatively charged particles migrate towards the anode, or they both simply move by a mechanical transport (Hamed et al, 1991; Méndez et al, 2012).

On other hand, many different soil remediation technologies are available to clean polluted waste, and most of them remove pollutants from the soil–water complex for further treatment or disposal in a more concentrated form. However, when the pollutants are persistent, toxic or simply have low solubility and a strong adsorption to soil surfaces and organic matter, the traditional remediation technologies are used, such as washing, and land-farming, amongst others. In these cases, electroremediation, also known as electrokinetic remediation (EKR) process is classified as a physicochemical technology, which offers many advantages such as

the capacity to remove organic and inorganic pollutants by applying direct electric current into the soil, even in clays (Virkutytea et al, 2002). The EKR is easy to operate and involves the installation of electrodes into the soil or waste and the application of a low voltage gradient or direct current through them. This technology has the capacity to removed heavy metals (Pb^0 , Hg^0 , Cd^0 , Ni^0 , Cu^0 , Zn^0 , Cr^0); toxic anions (NO_3^- , SO_4^{2-}); mixtures of organic and ionic pollutants; cyanide; explosive compounds; hydrocarbons (gasoline, diesel, oil, BTEX: benzene, toluene, ethyl benzene and xylene); polychlorinated biphenyls (PCBs) and radioactive species (^{137}Cs , ^{90}Sr , ^{60}Co , ^{238}Ur); from both saturated and unsaturated soils, sludges and sediments (Virkutytea et al, 2002; Hamed et al, 1991).

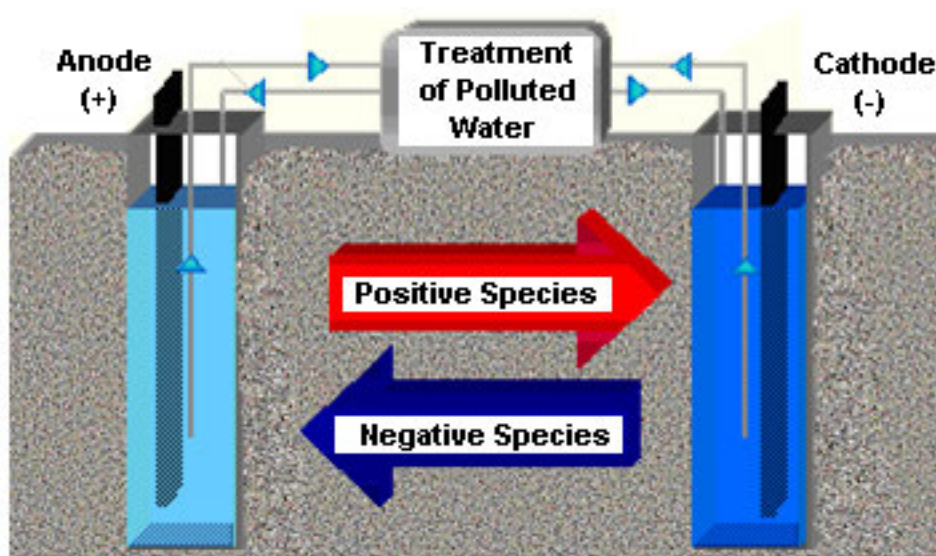


Figure 4. Electromigration of ions in an electrochemical arrangement to remove pollutant from the matrix (authors own creation).

Some researchers have published (Pamuku et al, 1990 and 1992; Reddy et al, 2003; Hamed and Bhadra, 1997; Reed et al, 1999; Khan and Alam, 1994) that the EKR application was better in clayed soils that had low concentration of heavy metal than even expensive regular mining procedures. However, a disadvantage was the time required to achieve over 90 % metal removal.

In order to improve the EKR process and diminish the removal time, some efforts have been focused on changing some operational parameters. For example, some researcher have modified the pH and the current density, introducing chemical compounds on electrolyte chambers (Yeung et al, 1996; Cox et al, 1996), or have added complexing and chelating agents to desorb the pollutant from soils (Cundy and Hopkinson, 2005; Ruiz et al, 2011; Colleta et al, 1997), or have modified the system, placing reactive barriers into the soil matrix (Ribeiro et al, 2005; Gómez et al, 2009) or simply they have tested different electrode material.

Thus, the efficiency of pollutant removal using EKR depends of many factors. However, it is important to select a good electrode material, especially when electrochemical technologies are used. Their selection can be according the thermodynamic and kinetic reactions carried out on their surfaces or by their mechanical, thermal and corrosion resistance.

4.2. Electrodes during the electrokinetic remediation of wastes

In that sense, some materials, as the case of titanium (Vázquez et al, 2004), platinum, gold, silver, stainless steel, among others used in EKR, suffer a kind of passivation, generating an oxide film on their surfaces which cover the active sites. This behavior occurs during the experimental conditions, which increases the electrical resistances in the system. For that reason, it is necessary to pre-treat or pre-activate the material before using, to increase roughness or surface active sites. Also, carbon electrodes have been used in EKR processes because of their low cost and accessibility (Saichek and Reddy, 2003; Hu et al, 2002) and because they are inert. However, these kinds of materials commonly form bonds with the species in solution or form oxide film. As well, they can adsorb some species on their surface.

In order to increase the active sites, eliminate the passivation phenomenon, increase electrode life and improve the oxidant activity, it is necessary to modify electrode surfaces to obtain high overpotentials. Consequently, some electrode materials have been modified with metallic oxide, forming a thin layer on a base metal (usually titanium), i.e. $\text{Ti}|\text{SnO}_2\text{-Sb}_2\text{O}_3$, $\text{Ti}|\text{IrO}_2\text{-Ta}_2\text{O}_5$, $\text{Ti}|\text{IrO}_2$, $\text{Ti}|\text{RuO}_2$, and carbon $|\text{TiO}_2$, among others (Hu et al, 2002; Méndez et al, 2012). These kinds of electrodes can be used as anodes in order to promote electrochemical oxidation. For that reason, the name “Dimensionally Stable Anodes” (DSA) was proposed by Comninellis and Pulgarin (Comninellis and Pulgarin, 1991) who demonstrated the high reactive surface of iridium DSA. These are able to degrade organic compounds by the presence of hydroxyl radicals on their surface, while being mechanically resistant to this reactive species and to pH changes (Comninellis, 1994).

4.3. Configuration of electrodes during an electrokinetic remediation of wastes

Furthermore, most conventional *in situ* methods have trouble managing the remediation of fine-grained soils with one or more of the following conditions: high water content, high organic matter content, high metal concentration; whereas electroremediation is suitable for wastes (Saichek and Reddy, 2005). Although, there are some aspects of electroremediation that require attention before the technology can be successfully implemented in the field, such as: soil characterization, type and concentration of pollutant and electrode material, as well as electrode array configuration and spacing.

In the last three decades, different research groups have been working in the electrokinetic treatment at different levels: laboratory, pilot system and directly in the site pursuing to remove organic pollutants (Gilbon, 2001), inorganic pollutants and radioactive wastes, among others (Hamed et al, 1991). Also, there are reports about the successful implementation of electrokinetic treatment *in situ*; one example is reported by Monsanto, DuPont and General Electric, who used the LasagnaTM remediation treatment *in situ* to remove trichloroethylene

with 98 % of efficiency (USEPA, 1997). Another practical example was developed by Sandia National Laboratories, who removed chromium *in situ* using Iridium/Titanium electrodes protected with a porous ceramic coating (Fernández, 2012).

Previous research has been focused on maximize electrokinetic extraction efficiency. Most laboratory or pilot electroremediation studies have been carried out in one dimension (1D) array, having only one anode (+) and one cathode (-), separated by the polluted soil. For field applications, the system must be effective and efficient; therefore it is required an appropriate electrode configuration, in order to accomplish this goal EKR treatment should be implemented in a bidimensional system (2D), this means that electrode array must be set up in respect to the *x-y* axis; however, there are few reports evaluating the performance of electrode configurations in the *x-y* plane, and there is no experimental data about performance of electrokinetic treatment with different electrode arrays (Méndez et al, 2012; Pérez – Corona et al, 2013; Reddy et al, 2001).

In addition, several flushing solutions have been investigated, such as water, acids, bases, chelating agents, alcohol, and other additives (Chaiyaraksa and Sriwiriyanuphap, 2004). In practice, acid washing and chelator soil washing are the two most prevalent removal methods (Giannis et al, 2007; Rampley and Ogden, 1988). Also, most of the electrokinetic equipment has been manufactured as a horizontal type. Laboratory-scale electrokinetic remediation has been performed for TRIGA soil during the past 5 years, but in this time, a study related to pilot-scale electrokinetic remediation was performed (Kim et al, 2002 and 2003).

4.4. Destruction of radioactive organic wastes

The process developed for the removal of organic contaminants from bulk water using graphite based adsorbents with electrochemical regeneration at the University of Manchester (Brown and Roberts, 2007), was adjusted for the destruction of radioactive organic wastes, specifically oils contaminated with alpha radioactivity produced at Magnox Ltd nuclear decommissioning site in UK (Wickenden, 2001). This approach comprises four stages:

1. *Emulsification*: the oils contaminated are emulsified in water using CLAX 200S as organic emulsifying agent to give a stable emulsion.
2. *Adsorption*: the emulsion is vigorous mixing with the graphitic adsorbent (Nyex™ 1000 supplied by Arvia Technology Ltd) by fluidizing the adsorbent using air sparging. A quick adsorption is produce by the non-porous nature of the Nyex™.
3. *Sedimentation*: when the fluidising air is turn off, Nyex™ particles precipitate to form a bed in the anode compartment of the electrochemical cell.
4. *Electrochemical destruction*: two electrodes are placed either side of the bed and a direct electric current is passed through the bed which destroys the pollutant through anodic oxidation of the organic matter. Oxidation of the organic matter may produce soluble breakdown products or off gases (CO, CO₂) and small amounts of H₂ and Cl₂ at the electrodes. After electrochemical treatment, the regenerated adsorbent is ready for immediate reuse and the whole cycle is repeated (Brown et al, 2013).

The treatment of radioactive oils by adsorption and electrochemical regeneration systems has been achieved at pilot scale 200 L. The latter consisted of three bipolar stacks of six electrochemical cells of each with an electrode area of 2 500 cm². Graphite plate bipolar electrodes were used and a micro-porous polyethylene membrane (Daramic, Grace GMBH) separated the adsorbent bed from the cathode. The catholyte solution, 0.3 wt % NaCl solution acidified to a pH of less than 2, was stored in a small tank and pumped through the cathode compartments of the six cells. The distribution of the radioactivity after the process was examined in the samples of the adsorbent and electrolyte after each regeneration cycle or after each destruction cycle for 1.5 L of contaminated oil using high-resolution gamma spectrometry for ²⁴¹Am, ¹⁵⁴Eu, ¹⁵⁵Eu, ¹³⁷Cs and ⁶⁰Co, liquid beta scintillation counting for ³H, ¹⁴C, ⁵⁵Fe, ⁶³Ni, ⁹⁰Sr, ²⁴¹Pu and ³⁶Cl, and alpha spectrometry for plutonium isotopes (^{239/240}Pu, Pu) and ²⁴¹Am (Brown et al, 2013).

The process was achieved with a specific treatment rate of 0.63 μL cm⁻² h⁻¹ using a current density of 10 mA cm⁻². Regeneration was carried out a current of 1 A (20 mA cm⁻²) for 25 h L⁻¹ of oil with a regeneration energy of 48 kWh L⁻¹ of oil. And the oil loading on the adsorbent was less than 25 wt % on the adsorbent to avoid excessive cell voltage.

The process of adsorption coupled with electrochemical regeneration can remove and destroy around 95 % radioactive oils in the first cycle, and over 99 % of the emulsified oil. Around 80 – 90 % of the majority of the radioactive species are transferred to the aqueous phase with a negligible discharges of tritium gaseous; hence no off-gas treatment before direct discharge to atmosphere is necessary (Brown et al, 2013).

Electrochemical oxidation using a boron-doped diamond (BDD) anode coupled with sonication is a promising method to oxidise (Low Level Waste) LLW or Intermediate Level Wastes (ILW) oils to carbon dioxide and water. The boron-doped diamond (BDD) electrodes contain non-aggressive and non-corrosive chemicals, are ease of disposal of the spent electrolyte and allow simple electrochemical cell configuration. Electro-oxidation tests were performed into an electrochemical cell which comprised a 250 mL beaker fitted with a rubber bung that held a BDD (DIAFILM PE TM) anode and a stainless steel cathode applied 0.1 A, a cell potential of 5 – 15 V and sonication. The electrolyte contained oil, sodium sulphate and sodium hydroxide added at the start of the test to maintain an alkaline pH in order to trap the carbon dioxide as carbonate. The method was effective for unused hydraulic oil, vacuum pump oil and a waste used machine tool oil (Taylor et al, 2009).

Mediated Electrochemical Oxidation (MEO) process has been used by destroying the organic components of combustible mixed wastes and for dissolving radioactive materials, such as transuranic oxides (PuO₂). The radioactive components of the wastes dissolved in the electrolyte, can be recovered or immobilized for disposal (Chiba et al, 1995). The destroying organic process is accomplished via a mediator (oxidizing agent).

Several metal oxidizing agents like Ag(II)/Ag(I), Ce(IV)/Ce(III), Co(III)/Co(II), Fe(IV)/Fe(III) etc., in nitric or sulfuric acids have been tested (Chiba et al, 1995; Farmer et al, 1995). In particular, the Ag(II)/Ag(I) based MEO system is capable of destroying cutting oil, cellulose (paper and cloth), rubber (latex), plastics (Tyvek, polyethylene and polyvinyl chloride),

biomass (bacteria) and ion exchange resins, attaining high destruction efficiencies at reasonable coulombic efficiencies (Chiba et al, 1995).

Ag(II) in a nitric acid solution produces highly reactive OH and NO₃ radicals which attack organic compounds converting most of them to CO₂, water, and inorganic ions. The resulting Ag(I) is recycled to Ag(II) at the anode of an electrochemical cell to maintain a supply of oxidant and minimize consumption of Ag. The Ag(II) migrates back into the bulk electrolyte to continue the oxidation process. A microporous membrane is usually placed between the electrodes to prevent the oxidizer produced at the anode from being reduced at the cathode. Ag(II) is a very effective oxidizing agent for the destruction of nonhalogenated organic compounds. Unfortunately, halide ions liberated during the destruction of halogenated organics react with Ag(II) to form insoluble precipitates. Therefore systems tolerant to halide anions such as Ce(IV)/Ce(III), Co(III)/Co(II) and Fe(IV)/Fe(III) have been tested. Tests at Pacific Northwest Laboratory with the Cerium/HNO₃ system has shown that cerium provides the same or better oxidation rates for cutting oils that silver system (Schwinkendorf and Hart, 1995).

4.5. Examples of electrochemical treatments of radioactive waste

4.5.1. ¹³⁷Cs and ¹³⁴Cs removal from radioactive ash

Combustible waste contaminated with ¹³⁷Cs and ¹³⁴Cs, generated by the tsunami within Fukushima, was incinerated, producing a large quantity of radioactive ash. A washing-electrokinetic decontamination method was developed by Kim and collaborators to decontaminate these radioactive ashes (Kim et al, 2002 y 2003). The process consists in a washing of contaminated ash with HNO₃ in three cycles using pH of 0 and ash (1g) – nitric acid (1 mL) mixture; the waste solution generated is precipitated with CaO and reused only those produced in the third washing. If the residual radioactivity of the washed ash is higher than the clearance concentration level, the washed ash is treated by electrokinetic equipment for decontamination. The removal efficiency of ¹³⁷Cs from radioactive ash is inversely proportional to an increase in the mixing ratio of ash weight (g) / solution volume (mL) and directly proportional to the increase in the concentration of HNO₃.

A pilot-sized washing-electrokinetic equipment was manufactured to remove cesium from lots of radioactive ash. The equipment consisted of 200 L washing equipment, 50 L electrokinetic equipment, and 150 L precipitation equipment. The electrokinetic equipment consisted of a couple of anode rooms, electrokinetic ash cells, cathode rooms and metal oxide separators. Cesium from radioactive ashes moves to the cathode room through electro-migration and electro-osmosis. 87 – 89 % of ¹³⁴Cs and ¹³⁷Cs in the radioactive ashes were removed in three washings and around 98 – 100 % from the waste solution after precipitation with CaO. If the radioactive ashes contain more than 30 – 40 Bq g⁻¹ of ¹³⁴Cs and ¹³⁷Cs the electrokinetic process requires between 8 – 10 days after three washings to reach below 2.0 Bq g⁻¹ (Kim et al, 2013).

4.5.2. Sodium recovery from alkaline nuclear waste

An electrochemical salt-splitting process has been developed to recover and recycle NaOH from radioactive wastes containing large amounts of sodium salts. Sodium separation process can save costs by reducing the disposal volume of wastes and by producing NaOH for recycle into waste treatment processes such as sludge leaching, regenerating ion exchange resins, inhibiting corrosion in carbon-steel tanks, or retrieving tank wastes (Fontain et al, 2009). The process is based on a two-compartment cell separated by a cation selective membrane. The waste enters into the anolyte electrodes, sodium ions migrate across membrane into the catholyte, under the influence of an applied electrical potential. Hydroxides form at the cathode by the reduction of water producing thus a sodium hydroxide solution (Kurath et al, 1997; Hobbs, 1999; Ambashta and Sillanpää, 2012; Fountain et al, 2009).

Platinized titanium (Pt/Ti) anodes and cathodes, and a Ceramtec® NASD membrane were tested by Hobb, applying a current density of 300 A m^{-2} and a voltage of 5 - 5.6 V during a run time of 70 - 104 h. This approach allows retain anionic species such as nitrate, aluminate or sulfate in the compartment anolyte of the electrochemical cell, and can produce caustic from radioactive wastes with low levels of gamma radioactivity, which could be released for off-site use without further treatment (Hobbs, 1999).

Pacific Northwest National Laboratory (PNNL) and Ceramtec Inc. tested a NaSelect® (sodium super ionic conductor) ceramic membrane to separate sodium from Low Activity Waste (LAW) streams at Hanford site (Fountain et al, 2009; Pendleton et al, 2011). A pilot scale system was designed, built and operated to process 7 L h^{-1} of LAW. The process selectively removed up to 80 % of sodium hydroxide from LAW and produced up to 50 % concentrated caustic for reuse in removal aluminum during sludge washing as a pretreatment step in the vitrification of radioactive waste; reducing about 39 % the waste volume. NaSelect® ceramic membrane prevents migration of mono valent and multi valent elements and other radionuclides to the sodium hydroxide stream (Pendleton et al, 2011; Figure 5).

Electrolytic decontamination is accomplished by applying a low dc voltage through an electrolyte to induce a chemical reaction. Contamination is removed at the anode the working electrode and goes into solution. The cathode (counter electrode) can be constructed from stainless steel. Electrolyte solutions such as phosphoric or sulfuric acid, used normally in electropolished, have to be changed after a few articles decontaminated, resulting in large quantities of radioactive toxic waste that must be treated and/or disposed. Due to this, electrolytes with a very low toxicity from which the radioactive materials can be easily separated and recycled, are investigated and applied. Sodium nitrate has been chosen as electrolyte to decontaminate metals contained Pu and Am (Wedman et al, 1996). In this medium, both actinides can be precipitated or entrained in the ferric hydroxide formed as surface metal is removed, resulting a clean surface, free of contamination, and the separation of the radioactive waste from the solution. Thus, the electrolyte solution can be recycled, greatly reducing waste.

For this process, the appropriate current densities appear to be in the range of 0.1 to 0.2 A cm^{-2} . Higher current densities result in higher metal removal rates, but adversely affect the

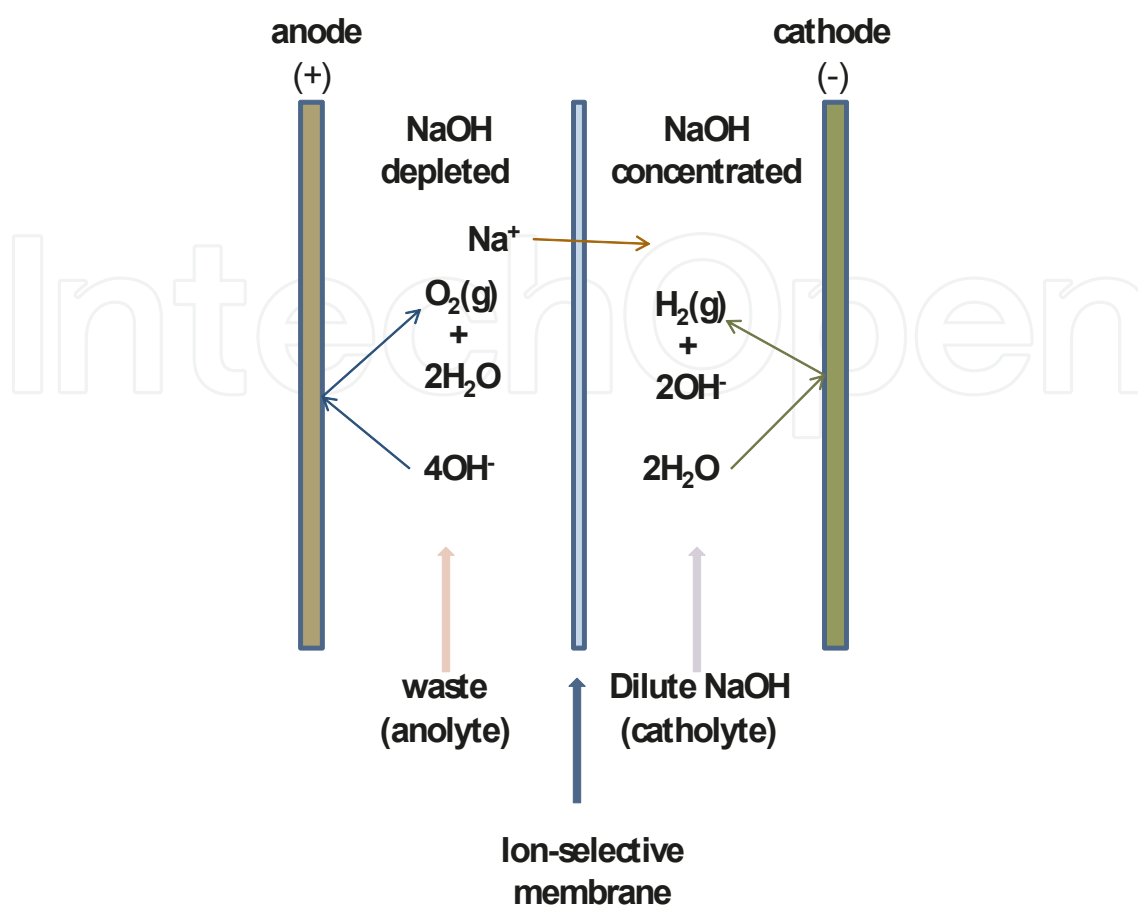


Figure 5. Electrochemical cell for the recovery of sodium hydroxide from alkaline salt solutions (Hobbs, 1999).

surface morphology by causing roughening, pitting, or burning. Optimum situation for the electrolytic decontamination process is the treatment of metal surfaces that have been electro-polished before contamination (Wedman et al, 1996).

NaOH solutions have been used as electrolytes to decontaminate metal surface contaminated by tritium. In this approach, the metal to be decontaminated is submerge in the electrolyte, connected to the negative pole, and the anode (polytetrafluoroethylene wax-impregnated graphite), to positive pole; applying a current densities in the range of 10 - 50 mA cm⁻². The tritium adsorbed on the cathode surface is replaced by the hydrogen and ejected to the electrolytic solution. This process is proper to small metallic parts of complex geometry or large pieces with simple geometry; and does not modify the surface metal, thus the objet can be reused (Bellanger, 1992).

Other decontamination process for contaminated stainless steel equipment is accomplished by dissolution of the metal surface that is being decontaminated when it is in contact with a solution composed by an inorganic reduction-oxidation systems such as Ce(IV)/Ce(III), Cr(VI)-Cr(III), Ag(II)-Ag(I) or Co(III)-Co(II) in nitric acid. This solution is subsequently reoxidized by electrolysis (Lerch et al, 1980).

4.5.3. Remotion of ^{137}Cs from soil

The thick-target PIXE analysis was successfully applied at least to the analysis of the electrokinetic behavior of cesium mixed with the soil as CsBr. By using cesium as a test pollutant, we could clearly observe the effect of the electrolysis without taking into account complicated interactions between the contaminant and the soil, such as dissolution of soil particles and adsorption phenomena.

The water supply to the anode well was effective to enhance the removal rate. From the observed fast migration of the pore water, as well as from the result of a simple calculation on the electrophoretic flow velocity, it was concluded that the migration of cesium observed was due mainly to the electroosmotic flow. Remediation performance by increasing the electric conductivity of the soil by mixing NaCl was possible. This result was consistent with the reduction of the electroosmotic flow velocity due to the elevated ionic strength. It was found that the addition of NaCl makes no sense also from the viewpoint of the potential hazard due to toxic gas emission as well as the cost of electricity. Owing to the interference by major metallic elements in the soil, the detection sensitivity of the present method based on the simple LX-ray measurement was not enough to investigate behavior of the trace level Cs contaminants. In order to attenuate only Ti-K α but to allow high transmission of Cs-L α radiation, a thin foil of a single element having an absorption edge at an appropriate energy.

4.5.4. Remotion of ^{60}Co and ^{137}Cs from soil

The pilot-scale electrokinetic remediation equipment suitable for the geological characteristics of a South Korean nuclear facility site was developed for the remediation of radioactive soil. The optimal experimental conditions were obtained with 50 L electrokinetic remediation equipment and the results are as follows: the removal efficiencies Co^{2+} and Cs^+ from the artificially contaminated soil after 15 days were 98.4 % and 94.9 % respectively, and the generated effluent volume was 3.4 mL g $^{-1}$. The removal efficiencies of ^{60}Co and ^{137}Cs by nitric acid were increased by 3.1 % and 2.0 % more than those by acetic acid. The removal efficiencies of ^{60}Co and ^{137}Cs from the soil of high concentrations (1 320 Bq kg $^{-1}$ and 1 720 Bq kg $^{-1}$) were increased by 14.4 % and 3.8 % more than those from the soil of low concentrations (110 Bq kg $^{-1}$ and 120 Bq kg $^{-1}$).

The removal efficiency of ^{137}Cs from the soil of average 1.4 mm particle size was increased by about 2.3 % more than that from the soil of an average 0.7 mm particle size. The removal efficiencies of ^{60}Co and ^{137}Cs by the application of an electric current of 15 mA cm $^{-2}$ were increased by 1.4 % and 4.4 % more than those by the application of 10 mA cm $^{-2}$. A total removal efficiency of ^{60}Co and ^{137}Cs from the radioactive soil of about 2 000 Bq kg $^{-1}$ was 95.8 % during electrokinetic remediation by the application of an electric current of 15 mA cm $^{-2}$ for 55 days (Gye – Nam et al, 2013).

On other hand, a soil washing system with a hydro-cyclone was very effective for decontaminating the radionuclides in the TRIGA (Training, Research, Isotope, General Atomic) soil in Korea. The size of the contaminated TRIGA soil ranged from very fine to more than 1.0 mm. The volume of soil particles larger than 1.0 mm was 28 - 52 %, and the volume of soil particles smaller than 0.06 mm was less than 4 - 10.5 %, but the volume of

medium-sized soil particle was 43 - 61 %. The radioactive concentration was strongest in the soil particle smaller than 0.063 mm, as predicted. Oxalic acid was the best chemical agent for washing, especially for cobalt. A scrubbing time of 4 h was the optimum time to obtain a removal efficiency of more than 75 % for ^{137}Cs and ^{60}Co . A mixing ratio of the soil weight to the volume of the oxalic acid solution of 1:10 was the best for washing; two scrubbing cycles with 1.0 M oxalic acid avoided the generation of a considerable amount of waste solution. The removal efficiency with a hydro-cyclone was 30 % higher than that without. Vertical plates and alum had important roles in reducing the sedimentation time. The waste solution could be reused up to five times after passage through a column of a strong acid resin (Gye – Nam et al, 2007).

4.5.5. Remotion of ^{238}U , ^{137}Cs and ^{85}Sr from soil

Experimental study seems to demonstrate that the feasibility of electrokinetic soil remediation for the removal of radionuclide contaminants from soils. The experimental results indicate that the technique is effective in radionuclide contaminants from soils with a relatively small amount of energy. Uranium and strontium were efficiently removed from kaolinite by electrokinetic remediation. In the case of cesium, the removal rate may be significantly slower than those of uranium and strontium. This is due to the lower ionic mobility and the affinity of cesium onto kaolinite. Acetic acid was effective as enhancing agent for buffering hydroxide ions produced by the cathode reaction, and prevented the precipitation of uranium ions in the cathode region.

Accordingly, the acetic acid increased the removal efficiency and decreased energy consumption. The use of citric acid was not efficient in removing uranium from kaolinite, because the direction of electromigration was opposite to that of electroosmosis. Since most metal–citrate chelates were negatively charged, they were transported toward the anode by electromigration while electroosmosis flowed toward the cathode. Therefore, removal efficiency significantly decreased. This result indicates that the selection of enhancement agent should be considered with respect to contaminant type and site characteristics. The electrokinetic removal of uranium from the soil weathered from uraniferous black shale was not efficient. This was due to the low proportion of the mobile fraction, since most uranium exists as residual fractions derived from enriched uraniferous parent rocks (Kyeong-Hee et al, 2003).

5. Risk assessment and development of future strategies

Nuclear site operations and successful site restoration depend on the availability of suitable waste management routes and facilities. Effective management of both radioactive and non-radioactive waste is essential to the delivery is a significant part of the process.

Strategic decisions about waste management are informed by the following key principles: risk reduction is a priority, centralised and multi-site approaches should be considered where it may be advantageous, waste should be minimised and the waste hierarchy should be used as a framework for waste management decision making and enables an effective balance of

priorities including value for money, affordability, technical maturity and the protection of health, safety, security and the environment.

For Low Level Waste, disposal will be in fit for purpose facilities that reflect the nature of the wastes to be managed. Within this overall framework our priority is to achieve risk reduction by dealing with waste in ageing storage facilities and placing it into safer modern storage conditions. Diverse radioactive waste management and disposal solutions will be pursued where these offer benefits over previous arrangements. New waste management approaches will often require different transport arrangements and will be a matter of great interest to planning authorities and people living close to the sites involved.

Some general ideas about the underpinning strategies are showed in Figure 2, the basic steps for effective management of radioactive waste are part of a global system, ranging from waste generation to final disposal are: minimization of radioactive waste, pretreatment, characterization, treatment, conditioning, transport, storage and disposal (IAEA, 1970). All of these ideas with the intention to reduce the volume of radioactive wastes.

6. Conclusions

Radioactive materials are extensively used in industrial and research activities into medical, agricultural and environmental applications, and in various other areas. During the production and use of these materials, radioactive waste will inevitably arise; this must be managed with particular care owing to its inherent radiological, biological, chemical and physical hazards.

Producers and users of radioactive materials must be sure that a waste management strategy exists prior to the start of waste generation. A well-developed waste management strategy should consider the entire sequence of waste management operations, from the waste's production until its final disposal, including the various regulatory, sociopolitical and economic issues. The identified goal of radioactive waste management can be met with reasonable cost and resource use by implementing a carefully planned waste management strategy using appropriate technologies.

Waste containing long lived radionuclides must be treated, conditioned, stored and disposed of at a repository specifically designed for this purpose. Sample storage capacity is needed for the decay of short lived radionuclides and for storing long lived waste prior to, and after, the treatment and conditioning steps. Decay is the only natural way of reducing radioactivity (the process of transmutation of some long lived radionuclides is not considered viable at this time).

Since radionuclides have decay rates ranging from days to thousands of years, proper segregation of wastes depending on their half-lives, and separate treatment and conditioning of these wastes, is an important factor in the overall scheme of radioactive waste management. Treatment of waste involves operations intended to benefit safety and/or economy by changing the characteristics of the waste. There are different procedures to the treatment of radioactive waste, like:

1. *Treatment of aqueous waste:* ion exchange/sorption, chemical precipitation, evaporation, ultrafiltration / reverse osmosis (UF/RO), incineration, solid / liquid separation (sedimentation, filtration), centrifugation, hydrocyclone techniques, chemical precipitation (coprecipitation or isomorphous precipitation with the carrier, adsorption on to the floc or on added absorbers, flocculation, sedimentation, pH adjustment, chemical oxidation and reduction, ion exchange / sorption, evaporation and reverse osmosis.
2. *Treatment of radioactive organic liquid:* incineration, wet oxidation, electrochemical oxidation, acid digestion, distillation, phase separation by adduct formation and biological digestion.
3. *Treatment of solid waste:* decontamination, compaction, incineration and electroremediation.

In the case of electroremediation treatment of radioactive wastes offers many advantages such as the capacity to remove organic and inorganic pollutants by applying direct electric current into the soil, even in clays, it is easy to operate and involves the installation of electrodes into the soil or waste and the application of a low voltage gradient or direct current through them. In consequence, the EKR is a very good technological alternative to remove radioactive species as ^{22}Na , ^{137}Cs , ^{134}Cs , ^{85}Sr , ^{90}Sr , ^{60}Co and ^{238}U from both saturated and unsaturated radioactive soils, sludges, ash and sediments, with less time and high efficiencies of removal in comparison of the other alternatives to remove radioactive wastes.

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