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Article

Plasma Gasification of a Simulated Low-Level Radioactive Waste: Co, Cs, Sr, and Ce Retention Efficiency

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Abstract: Thermal plasma is a versatile technology that can be used to treat various types of wastes, including vegetal and mineral oils, solvents, plastics, papers and cardboard, glasses, bricks and rocks, metals, clothes, and mixtures of these materials. In this study, we utilized a commercial plasma cutter as a thermal plasma source to decrease the volume of a simulated low-level radioactive mixed solid waste. The simulated waste included papers, plastics, clothes, gloves, metals and stable Co, Cs, Sr, and Ce additives as surrogates of ⁶⁰Co, ¹³⁷Cs, ⁹⁰Sr, and ¹⁴⁴Ce, the latter typical contaminants in nuclear LLW. As a result of the process two products were obtained, a solid phase in which we focused this work and a gaseous phase. To retain as much as possible surrogates in the solid final phase, crushed glass from broken bottles was included as a vitrification additive to the original waste. After undergoing heat treatment, a dense vitreous slag was produced and ashes. The process resulted in a volume reduction of 70%, indicating the successful gasification of organic excess materials. The surrogate elements were retained in the process and were found in the ashes composition: Co (3.4% w/w), Cs (37.7% w/w), Ce (0.6% w/w) and in the glass matrix composition of Co, Cs, Sr and Ce: 72.4 ± 14.7, 32 ± 18.2, 125.3 ± 31.6, 80 ± 13.1 % w/w respectively. For the actual experimental conditions, retention efficiencies were estimated for Cobalt (Co) at 72.4 ± 14.7%, Cerium (Ce) at 80 ± 13.1%, Strontium (Sr) at 125.3 ± 31.6%, and notably Cesium (Cs) at 32 ± 18.2%.

Keywords: Waste plasma gasification; low-level radioactive waste; volume reduction; vitrification

1. Introduction

The current governments are seeking to generate electricity using methods that are free from the use of fossil fuels and have low rates of greenhouse gas emissions. Nuclear fission is a proven alternative with potential growth for coming years [1,2]. China alone, is planning to build 100 new nuclear power plants (NPPs) by 2030, which illustrates the potential growth of nuclear energy [3].

Radioactive wastes (RAWs) are generated as a by-product of the electric power generation process in nuclear reactors, fuel processing plants, hospitals, and research facilities [4]. RW is defined as: “radioactive material for which no further use is foreseen, and with characteristics that make it unsuitable for authorized discharge, authorized use or clearance from regulatory control” [5]. States are responsible for the safe management of RW to guarantee and protect the health of living creatures and the environment. The International Atomic Energy Agency (IAEA) determines general guidelines for all stages of RW management [6].

RAWs can exist in solid, liquid, gas or mixtures and can be classified as very low, low, intermediate and high level waste based on their activity concentration [7]. This type of waste must be subjected to treatments that improve its characteristics to protect human health and the

environment now and in the future [8]. The goal of the treatment of intermediate and low level waste is to reduce their volume [9, 10, and 11] and transform them into safer forms for storage, transport, and final disposal, such as incorporated into glassy and/or cementitious matrices. Low and intermediate level wastes (LILWs) contain various radionuclides, including: ^{60}Co , ^{90}Sr , ^{134}Cs , ^{137}Cs [8]. In addition, other radionuclides are present in the wastes generated in fuel manufacture such as uranium and its isotopes ^{235}U and ^{238}U [12], and those coming from medical applications (mostly with very short half-lives) [13,14].

Thermal processes, such as flame incineration, pyrolysis and plasma treatment, have been effective in reducing the volume of LILWs and destroying their organic phase [15, 16, 17 and 18]. Plasma treatment is considered the most comprehensive method since it can treat all types of wastes [19], resulting in significant volume reduction and destruction of all hazardous components (chemical and biological) of the wastes [20]. However, during thermal treatment for RWs conditioning, some radionuclides may become volatile and escape from the treatment chamber along with the gaseous effluents [21, 22, 23, 24 and 25]. Therefore, although part of the radionuclides are carried away by gases, maximum retention of the radioactive elements in the solid phase is necessary.

This article explores the vaporization of simulated LLW and the distribution of these radionuclide surrogates within a prototype plasma treatment chamber designed for small-scale mixed waste processing. Additionally, it examines the retention of substitutes in the solid phases, including slag and ash, that are produced. When working with RWs, a compact process is highly desirable as it simplifies operation and enhances safety [26].

The plasma torch used in this work is a commercial plasma cutting equipment that we modified and adapted to use in the plasma waste treatment reactor. This fact makes the use of this technology accessible to users that produce small waste quantities and even in developing economies. To simulate the radionuclides commonly found in LILWs, their stable elements are used as surrogates. Specifically, for ^{60}Co , ^{134}Cs , ^{137}Cs , and ^{90}Sr , stable Co, Cs, and Sr are used respectively. For radionuclides such as ^{144}Ce , ^{141}Ce , and others that do not have stable isotopes like ^{238}U and ^{235}U , stable Ce is used. The use of stable elements as surrogates for radionuclides is a common practice in environmental studies. The simulated LLW was prepared from non-radioactive salts; these compounds, however, are recognized as chemically identical to its radioactive counterpart based on the 'critical' ^{60}Co , ^{134}Cs , ^{137}Cs , and ^{90}Sr , isotopes [27, 28, 29 and 30].

2. Materials and Methods

2.1. Experimental Set-Up

The system used here for thermal plasma treatment of the waste, as shown in Figure 1, consists of several components as shown in Figure 1. These include a reactor, a transferred arc plasma torch, a compressed air supply, a copper anode, a cooling water service, and off-gas treatment.

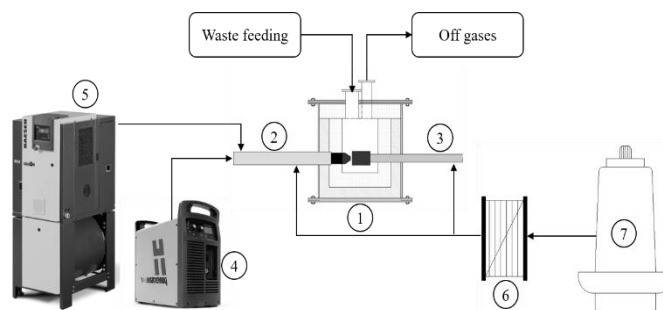


Figure 1. Experimental set-up scheme. 1 Reactor, 2 torch, 3 anode, 4 power source, 5 air compressor, 6 heat exchanger, 7 water cooling tower.

The reaction chamber has a 1.4 L volume and was made of refractory material with a 35 mm wall thickness. The refractory material is composed of 60% Al_2O_3 , 31% SiO_2 , 3% CaO , 1% Fe_2O_3 , and 5% impurities (w/w). The reactor walls, which contain the reactor chamber, consist of two layers: an internal insulating mineral blanket that is 105 mm thick and made of 50% SiO_2 and 50% Al_2O_3 (w/w),

and an external steel structure that is 3 mm thick (Figure 2.a). The torch and the anode are located at the bottom of the reaction chamber, and plasma is generated between them (Figure 1). The wastes are fed through the top lid of the reactor and come into contact with the plasma in the lower part of the reaction volume. The organic and inorganic volatile component fraction of the waste are converted to the gaseous state and move out of the reactor through the upper outlet of gaseous effluents (Figure 2.a). The inorganic and other non-volatile components of the waste remain inside the reactor until the end of the operation, and they are removed from it once the reactor becomes cold. The operating temperature in the reaction volume, which ranges from 1000 to 1400 °C, is monitored by two type S thermocouples (Pt-PtRh) located on the refractory walls.

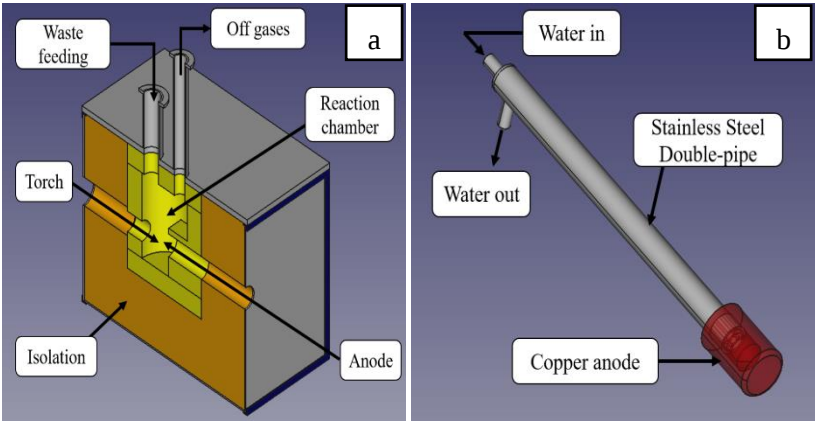


Figure 2. a) Scheme of the plasma treatment reactor. b) Refrigerated copper anode scheme.

The experiments were conducted using a commercial Hypertherm plasma cutting torch, which was connected to its Powermax 105 model source. The Powermax 105 has an output voltage of 160 VDC and a variable current range of 30 - 105 A. For this work, a fixed current of 30 A and a power of 4.8 kW were used in all the experiments. Air was used as plasmatic gas, and the torch was water-cooled to prevent overheating of the internal wires. The compressed air for the torch was supplied using a Kaesser AirCenter SX8 model compressor. The compressor had a working pressure of 8 bar and a flow rate of 8-9 kg/h. A copper anode with a diameter of 38 mm and a length of 55 mm is utilized to connect the electric arc from the torch. The anode is positioned directly in front of the torch, separated by a distance of 6-9 mm. To extend its useful life, it is connected to a double stainless steel tube that moves cooling water through its internal wall (Figure 2.b). A semi-closed system was used to produce the cooling water, consisting of a cooling tower (number 7 in figure 1), heat exchanger (number 6 in figure 1), buffer tank, and circulation pumps. The refrigeration system is manually controlled using valves and flowmeters and monitored by type K thermocouples that sense the temperature of the inlet and outlet water at each refrigeration point. Effluent gas monitoring was conducted at the reactor outlet using a Horiba PG-350 portable gas detector.

2.2. Sample Preparation

25 gr of simulated non-radioactive waste were prepared for this work. The chemical composition of the SRAWs was taken from Gourvonov et al [31] (Table 1).

Table 1. Composition of a LLWs according to the PLUTON plant and simulant materials used for the preparation.

Original materials	% w/w	Simulant	Mass per 25 g of sample [g]
Paper	70	Paper	17.5
Plastic	12	Plastic containers	3

Cloth	9	Cloth (cotton)	2.25
Gloves	5	Nitrile gloves	1.25
Metal	4	Stainless steel shavings	1

We used the Fritsch brand Pulverisette 25 model to shred the materials and mixed them, taking up a volume of 400 ml (Figure 3). The initial composition was then supplemented with 200 g (125 mL) of crushed commercial glass (bottle glass) (Figure 3). The glass was added as a vitrification additive to capture the waste radionuclides [32].

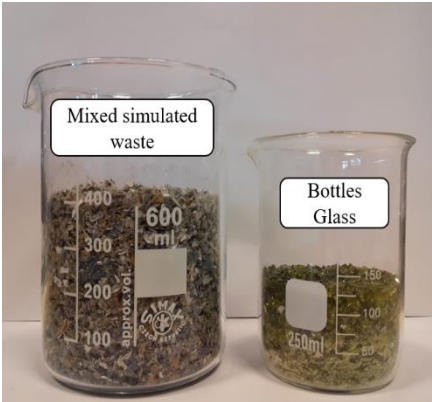


Figure 3. (Left) Mixed simulated shredded waste. (Right) Crushed bottle glass.

To simulate the presence of radionuclides ^{60}Co , ^{137}Cs , ^{134}Cs , ^{90}Sr , ^{144}Ce , and ^{141}Ce in the 25 gr of the simulated LLWs, 3 g of Co and 1 g of each stable isotope of Cs, Sr, and Ce were added. The elements were introduced through the compounds Co_3O_4 , CsNO_3 , $\text{Sr}(\text{NO}_3)_2$, and CeO_2 in the form of solid powders with 99% purity. These quantities are in excess of those found in true LLWs. The surrogate mass oversizing was done to be able to characterize these materials using the instrumental analysis techniques. Finally, the 25 g mixture with 6 g of surrogate compounds was divided into three equal parts and put inside closed paper packets, while the 200 g glass was divided in another 5 equal paper packets. Thus, the 8 packets with a total mass of 231 g and volume of 525 mL were ready for thermal plasma treatment. They were manually fed to the reaction chamber, in the following order: first the 5 glass containing packets and afterwards the 3 containing the simulated waste.

2.3. Plasma Reaction Chamber Operation

The experiment began with the plasma torch being turned on the temperature inside the chamber reaching 600 °C after 60 minutes. At this point, the first package containing glass was fed into the chamber, which caused a slight perturbation of the gasification chamber temperature and in the CO concentration. Once the CO concentration decreased to permissible exposure values, the second glass pack was fed, and this procedure was repeated with the remaining three packages containing glass.

After approximately 120 minutes, the temperature in the chamber reached about 700 °C. At this point, the first package containing simulated LLWs was introduced into the chamber. This caused an increase in temperature and CO concentration due to exothermal chemical reactions, and after 5 minutes, the second package was fed, followed by the third package.

Finally, the temperature in the chamber rose to 800 °C after 195 minutes to complete the heat treatment. The plasma torch was then turned off, causing the temperature to drop to 600 °C.

2.4. Characterization

The analysis of the feasibility of the formation of potential reaction products of Co, Cs, Sr, and Ce with the reactive atmosphere and their volatility was done using the calculation program and thermodynamic data from HSC Chemistry 7.0 software [33]. The chemical composition of the

simulated residue LLWs and the final vitrified products were characterized using energy dispersive spectroscopy (EDS). Also a sample of each material was analyzed using a ZEISS Crossbeam 340 FIB-SEM scanning electron microscope simultaneously with an EDS Oxford Instrument 80Max detector. X-ray powder diffraction analyses were performed using a D8 Advance machine (Bruker D8 Advance, Karlsruhe, Germany) operating at 40 kV and 40 mA with CuK α radiation (0.15418 nm) in the 2 θ range from 9 to 70°, with a step size of 0.02° and counting time of 2 s per step. Phase identification was performed using the HighScore Plus V.3.0d software, (PANalytical B.V., Almelo, The Netherlands) with the COD2023 database.

3. Results and Discussions

3.1. Reaction Chamber Thermal Excursion

In Figure 4, the evolution of the measured temperature values from a reference thermocouple in the reaction chamber is clearly depicted during the heating of the chamber, the feeding of glass and waste, and the final cooling phase. Three temperature peaks are shown at time ~ 120 minutes corresponding to the heat liberated during the feeding of the three waste packs.

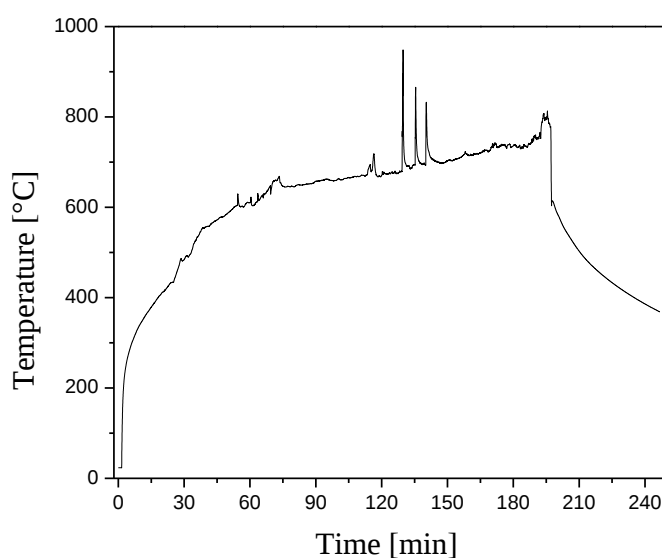


Figure 4. Temperature evolution of the reaction chamber taken at point P in Figure 2a .

3.2. Thermodynamic Analysis

The feasibility of a chemical reaction can be determined by analyzing the change in Gibbs free energy associated with the reaction. In this study, the Gibbs free energies of reactions involving Cl₂ (coming mainly from gloves) and O₂ (coming mainly from the plasmatic gas) were calculated for solid compounds CeO₂, Co₃O₄, CsNO₃, and Sr(NO₃)₂ at temperatures ranging from 100 to 4000 °C. The results of these calculations are represented by equations 1-8 and 9-14.

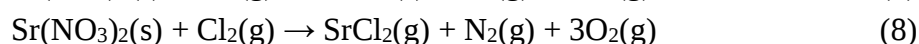
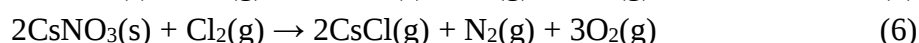
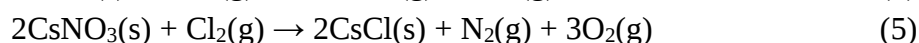
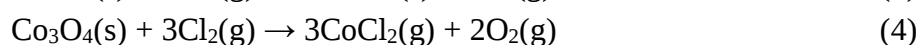
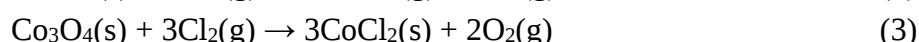
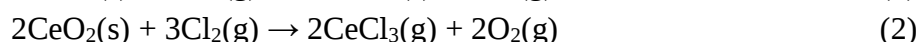
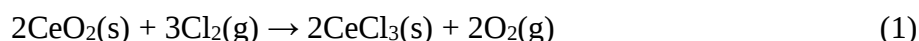


Figure 5 shows the variations of the Gibbs free energies as a function of temperature for reactions 1-8 in a thermal range from 100 to 4000 °C.

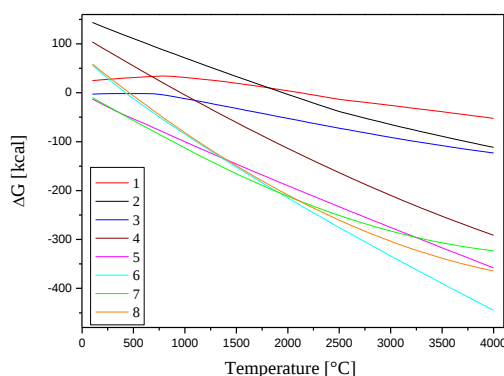
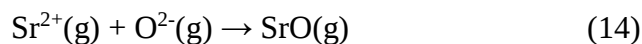
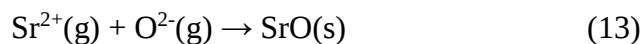
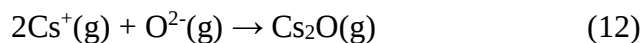
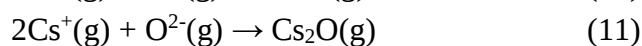


Figure 5. Gibbs free energies for the chemical reactions between the compounds CeO_2 , Co_3O_4 , CsNO_3 and $\text{Sr}(\text{NO}_3)_2$ and Cl_2 .

During the gasification process, $\text{O}_2(\text{g})$ is a highly reactive species that can under the experimental conditions form the $\text{O}^{2-}(\text{g})$ ion. This ion can react with other species in the system to form oxides or superoxides. Additionally, several compounds such as CeO_2 , Co_3O_4 , CsNO_3 , and $\text{Sr}(\text{NO}_3)_2$ can dissociate in the plasma zone to form gaseous ions such as $\text{Ce}^{4+}(\text{g})$, $\text{Co}^{2+}(\text{g})$, $\text{Co}^{3+}(\text{g})$, $\text{Cs}^+(\text{g})$, and $\text{Sr}^{2+}(\text{g})$. As a result, chemical reactions between these species and the $\text{O}^{2-}(\text{g})$ ion can occur (equations 9-14).



Equations 9-14 exclude reactions with $\text{Ce}^{4+}(\text{g})$ due to its interaction with the ion $\text{O}^{2-}(\text{g})$ that would produce CeO_2 , the original species. Chemical reactions with the $\text{Co}^{3+}(\text{g})$ ion were not considered because the HSC Chemistry 7.0 database lacks thermodynamic data on compounds containing this ion. Figure 6 displays the Gibbs free energies variations as a function of temperature for these reactions.

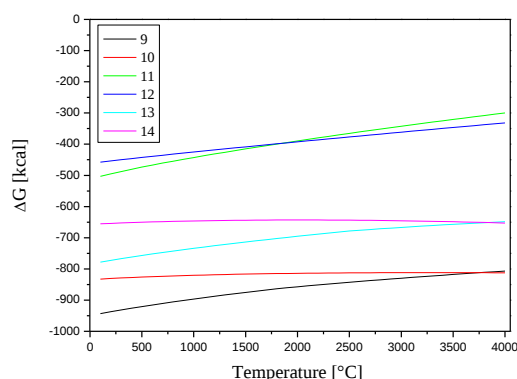


Figure 6. Gibbs free energies for the chemical reactions between $\text{Co}^{2+}(\text{g})$, $\text{Cs}^+(\text{g})$ and $\text{Sr}^{2+}(\text{g})$ ions and $\text{O}^{2-}(\text{g})$.

On the other hand, the wastes have metallic materials that contain Cr and Fe in their composition, thus the following chemical reactions are proposed between these metals in their elemental state, and the O_2 and Cl_2 gases (equations 15-20 and 21-26 respectively). The variations of

the Gibbs free energies as a function of temperature and for the reactions with these gases are shown in Figures 7 and 8 respectively.

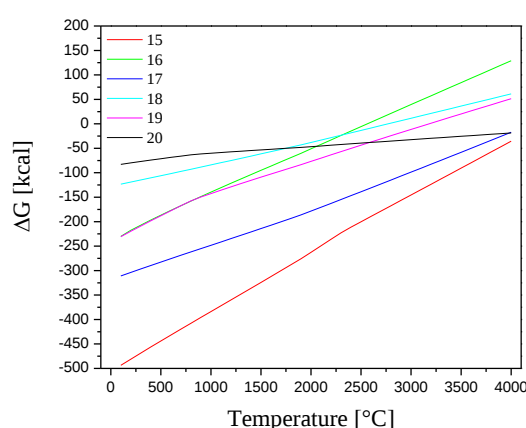


Figure 7. Gibbs free energies for the chemical reactions between elemental Cr with the gaseous species O_2 and Cl_2 .

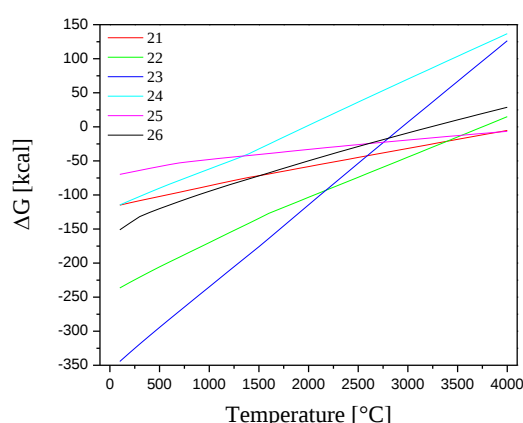


Figure 8. Gibbs free energies for the chemical reactions between elemental Fe with the gaseous species O_2 and Cl_2 .

The head of the discharge electrode is made of elemental Cu, which can react with O_2 and Cl_2 gases according to the reactions represented by equations 27-30. Figure 9 shows a diagram with the variations of the Gibbs free energies as a function of temperature for these reactions.

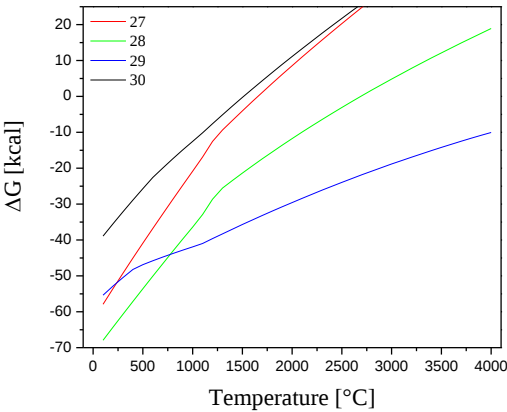


Figure 9. Gibbs free energies for the chemical reactions between elemental Cu with the gaseous species O₂ and Cl₂.

3.3. Solids Characterization: Samples and Products

The simulated LLWs underwent energy dispersive spectroscopy (EDS) analysis before the experiment. This was done to identify its initial chemical composition (refer to Table 2), which was then compared to the composition of the reaction products. Cs, Co, Sr, and Ce were not detected in the materials used to prepare the simulated waste. This implies that the content of these elements found in the solid products is only due to the additives incorporated into the initial sample.

Table 2. EDS analysis of simulated LLWs components prior to gasification.

Element	Paper [% w/w]	Plastic [% w/w]	Gloves [% w/w]	Cloth [% w/w]	Metal [% w/w]	Glass [% w/w]
C	57.3	92.6	69.6	52.8	14.1	-
O	40.5	6.6	15.6	45.7	2.2	47.6
Mg	-	-	-	-	-	0.8
Na	0.3	0.1	0.4	-	-	10.3
Al	0.3	0.2	0.2	-	0.2	0.7
Si	0.4	0.3	0.2	0.3	0.5	33.8
S	-	-	2.0	0.8	-	-
Cl	-	-	7.1	-	-	-
K	-	-	0.5	-	-	0.3
Ca	1.1	0.2	2.5	0.6	0.2	6.7
Cr	-	-	-	-	16.4	-
Ti	-	-	0.7	-	-	-
Fe	-	-	-	-	59.6	0.3
Ni	-	-	-	-	6.8	-
Zn	-	-	0.9	-	-	-

After plasma treatment, Figure 10 shows that the remaining products inside the reaction chamber were a mixture of glassy blocks and particles, ashes, and some scattered small metal

particles. However, the heterogeneity of the obtained products was mainly due to the cold spots inside the reactor and the short operation time. The cold spots are essentially because of the presence of the refrigerated anode inside the reactor, which caused materials in contact with the cold wall of the anode were not be susceptible to heat treatment. Additionally, a part of the ashes generated from the thermal disintegration of the simulated LLWs, stuck to the cold walls of the anode. Short operating times did not promote the total formation of the slag and caused a dispersion of glassy and metallic particulate material that are not integrated into the final mass of the slag.

The glassy products, consisting of particles and blocks, exhibited red, blue, gray, and turquoise hues and spots in contrast to the original green color of the bottle glass. This indicates that the plasma treatment incorporated a new element into the glass, resulting in the change of coloration.

The initial overall composition (called nominal composition) was calculated as the weighed EDS compositions of the initial sample components (metal, glass, simulants). The chemical composition of both, glassy samples and powders deposited on the anode surface after the thermal process were also analyzed by EDS. In Tables 3 and 4 the results are presented together with the nominal composition of the sample previous to the experiment. The analysis revealed that the following elements can be retained by the slag and the remaining ashes after plasma treatment: Cesium, Cobalt and Cerium. Strontium, on the other hand, was only be retained by the vitreous slag.

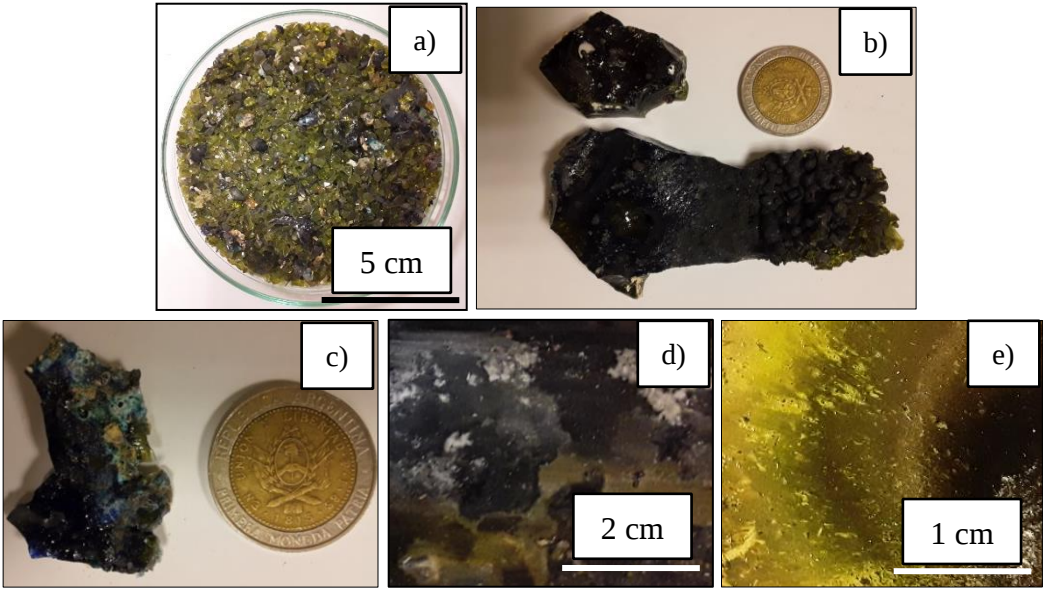


Figure 10. Products of the plasma gasification process. a) Glass and metal particles. b) Slag block. c) Slag block. d) Ashes stuck on anode (lateral part). e) Ashes stuck on anode (front part).

Table 3. Nominal composition of the glass and ashes obtained.

Composition (% w/w)			
Element	Nominal (simulated waste + glass + surrogates before plasma treatment)	Bulk Glass (slag product)	Ashes (powder product)
C	22.7	5.6	34.7
O	41.6	47.2	21
Mg	0.5	0.4	0.2
Na	6.3	8.4	0
Al	0.5	1.7	1.0
Si	20.6	26.2	4.2
S	0.1	0	0.2

Cl	0.1	0	0.3
K	0.2	0.4	0.1
Ca	4.4	6.8	2.8
Cr	0.2	0.2	0
Ti	0.0	0.1	0
Fe	1.1	0.6	0.2
Ni	0.1	0	0
Zn	0	0	0.2
Co	0.9	1.1	7.1
Cs	0.3	0.2	5.8
Sr	0.3	0.6	1.4
Ce	0.3	0.4	1.5
Cu	0.0	0.2	19.3

Table 4. EDS of vitreous (V1, V2, V3 and V4) and ashes (S) products after treatment

Other colored remaining wastes recovered after the experiment [% w/w]					
Element	V1 (Red)	V2 (Blue)	V3 (Grey)	V4 (Turquoise)	S
C	10.3	9.5	9.0	-	25.2
O	44.8	48.9	37.2	48.4	15.8
Si	28.9	26.8	19.4	38.6	0.5
Cl	-	-	-	-	7.3
Ca	5.5	3.7	8.0	4.4	2.1
Cu	2.0	0.8	12.7	1.7	6.7
Na	6.5	6.6	4.8	5.1	1.2
Mg	0.3	0.2	0.3	-	-
Al	1.1	1.4	0.7	1.0	0.5
Ti	-	-	-	-	-
Cr	-	0.1	-	-	1.4
Pb	-	-	-	-	-
Co	-	0.6	3.5	-	3.4
Cs	-	0.4	0.7	-	33.7
Ce	-	-	0.4	-	0.6
Sr	-	-	1.3	-	-
Fe	0.2	0.6	0.2	0.5	0.1
Zn	-	-	-	-	0.3
S	-	-	-	-	0.4
K	0.3	0.3	0	0.3	0.5

Ashes analyzed by XRD (Figure 11a) showed the presence of CoO [34], CsCl [35], CrCl₂ [36] and CuCl [37] as reaction products.

Slag was also analyzed by XRD (Figure 11b), recognizing the presence of a large portion of amorphous phase with incipient diffraction peaks corresponding probably to the crystalline CeO₂ [38] and Co₃O₄ [39] phases.

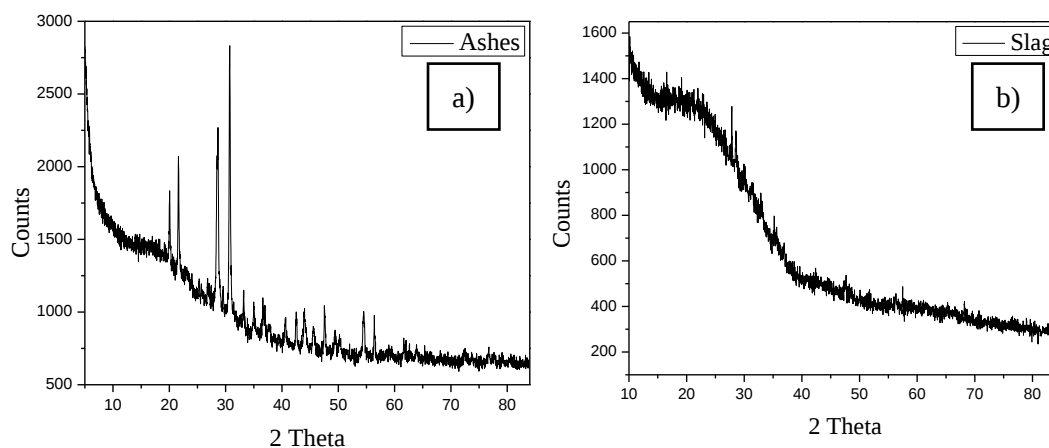


Figure 11. XRD diffraction pattern of a) Sample ash. b) Sample slag.

Here is a breakdown of the key results found after plasma treatment on the simulated LLWs materials:

- The cold zone of the anode retains CoO formed by the decomposition of the Co_3O_4 fed and following an oxidation reaction of the Co in the air plasma atmosphere.
- Chlorine from waste materials in the reactor atmosphere reacts with the Cs added as a surrogate, to form CsCl which is deposited on the anode.
- Stainless steel metallic particles present in the simulated waste materials react in the presence of Cl and the oxidizing atmosphere of the reaction volume at high temperatures to favor the formation of CrCl_2 .
- Chlorine also attacks the copper of the anode to form CuCl , which is undesirable and could have negative effects on its lifespan.
- None of the original salts added as additives to the simulated LLWs were identified by XRD of the ash after plasma treatment.

3.4. Volume Reduction

According to this study, the average volume of solid waste remaining in the reactor after plasma treatment was 150 ml, which represents a volume reduction of 71% from the initial volume of 525 ml. This value is consistent with the results found in the bibliography for this type of waste. This study also demonstrates the viability of using a thermal plasma process for the reduction of a simulated LLWs volume.

4. Conclusions

The findings presented within this study establish the viability of constructing and operating a small-scale simulated radioactive waste plasma treatment system. This system harnesses commercially available plasma cutting equipment, which proves well-suited for managing waste produced by modest generators. In the context of our experimental conditions, the process yields a remarkable 71% reduction in waste volume for Low-Level Wastes (LLWs). Moreover, within the actual experimental conditions it yields a consolidated glassy solid matrix, hosting surrogate radioactive elements analogous to the initial waste. Including as percentage of each surrogate total mass put in the simulated waste: Cobalt (Co) at $72.4 \pm 14.7\%$, Cerium (Ce) at $80 \pm 13.1\%$, Strontium (Sr) at $125.3 \pm 31.6\%$, and notably Cesium (Cs) at $32 \pm 18.2\%$ —a volatile element of particular concern within LLWs.

In the process of crafting a vitrified waste as the final product, the regions of lower temperature in the reactor yield both adverse and beneficial impacts. Detrimentally, these regions partially hinder the formation of a compact glassy end product, leading to the dispersion of metal and glass particles throughout the final material. Such issues could be mitigated by extending treatment durations to reach the uniform temperature along the reactor. However, positively, these cooler sections facilitate the retention of Cobalt (Co) and Cesium (Cs) from the simulated LLWs. Thus, a decision must be

made between prioritizing a more uniformly solid outcome and a higher retention of Co and Cs—a compromise that needs careful consideration.

The presence of chlorine within the waste, introduced to the plasma atmosphere of the reactor, undergoes gaseous transformation. This chlorine reacts with the copper anode, resulting in heightened erosion beyond the normal wear attributed to the plasma's electric discharge. Consequently, this interaction forms the crystalline phase CuCl. Additionally, the gaseous chlorine reacts with Cesium (Cs) and Chromium (Cr) within the system, yielding solid compounds CsCl and CrCl₂. Simultaneously, oxygen in the reaction chamber environment reacts with Cobalt (Co), culminating in the formation of CoO. Thermodynamic analyses conducted in this study support the feasibility of these compound formation during the thermal treatment of the simulated LLWs. However, an in-depth exploration of the reaction kinetics is warranted to elucidate the mechanisms underpinning the creation of each compound.

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