

Model analysis of plasma incineration system of radioactive waste: A case in São Paulo, Brazil

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Abstract

Nuclear waste management represents a challenge due to the hazardous characteristics. The most efficient alternative is to prevent improper disposal, thereby avoiding environmental harm and optimizing the resources needed for transport and storage, which in turn minimizes the associated costs. Therefore, the objective of this study is to evaluate the use of plasma technology in waste management for radioactive waste. To understand the impact of implementing a plasma reactor in the radioactive waste management systems, various scenarios were created to analyse the behaviour, particularly in terms of disposal costs for this waste, in this studied case. In light of the present work, the methodology, positive results and analyses may encourage further studies for the development of plasma systems with greater capacity and plasma processes designed to treat low-level radioactive waste. It is essential to acknowledge a limitation in this study, which is the existence of various factors and experimental conditions that can influence the performance of the plasma thermal process. There is also a need for test procedures specifically designed to evaluate the immobilization of radioactive waste.

Keywords

Thermal plasma, radioactive waste, solid waste management, computational modelling, reverse logistics

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Introduction

The rapid urbanization, population growth and industrial expansion have intensified waste generation, creating pressing socio-economic and environmental challenges worldwide (Yu et al., 2020). The generation of waste, which is proportional to the increase in population, affects the daily lives of millions of people in different ways (Dovì et al., 2009).

In Brazil, although technologies are available to meet the requirements of the National Solid Waste Policy, their large-scale application remains limited due to high operational costs. Waste management, particularly for hazardous wastes regulated under NBR 10.004/2024 and by the National Health Surveillance Agency, demands substantial logistical, sanitary and environmental resources (Associação Brasileira de Normas Técnicas, 2024). In addition, the diversification of the Brazilian energy matrix highlights the growing contribution of nuclear power, as evidenced by the significant volumes of radioactive waste generated annually in Angra 1, underscoring the urgency of more efficient solutions for nuclear waste management.

Health services generate hazardous wastes that already have a classification determined by the National Health Surveillance Agency. Such waste comes from exams, surgeries, treatments and other activities in the sector which, in turn, demand

appropriate resources for management and final disposal (Tzeng et al., 1998). These wastes consist of non-hazardous or hazardous waste from hospitals, clinics, among other manufacturing sites in which radiopharmaceuticals or research centres are used as a base.

Given the scenario of the Brazilian energy matrix, which is increasingly diversified, it is possible to note in the National Energy Balance and also in the Statistical Energy Yearbook that there is a growth in the use of nuclear energy, resulting in an increase in nuclear waste generation. A plant in Brazil, Angra 1, for example, has an average generation of radioactive waste of 200 m³ year⁻¹ and can produce over 400 m³ annually, as general data reported by Lakey (1985).

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'Nuclear waste' is normally a by-product of nuclear power generation and other applications of nuclear fission or nuclear technology, such as research, industry, medicine and agriculture (Saleh, 2015). According to the International Atomic Energy Agency (IAEA), nuclear waste, also known as radioactive waste, is any material that contains a concentration of radionuclides greater than those considered safe by national authorities.

Therefore, the most efficient alternative is to avoid improper disposal so as not to harm the environment and optimize the resources needed for transport and storage, thus minimizing the costs inherent to these activities. Accordingly, the objective of this work is to evaluate the use of plasma technology in radioactive waste management.

Conventional treatment and disposal technologies such as incineration, cementation and vitrification are technically mature, yet they face persistent drawbacks including high ash production, secondary waste generation and considerable energy requirements (Internacional Atomic Energy Agency [IAEA], 2014; Pullao et al., 2024). Moreover, recent life-cycle assessment studies in the nuclear sector reveal a systematic lack of consideration for the waste management phase, undermining comprehensive evaluations of sustainability and long-term policy frameworks (Clayton et al., 2025). These limitations emphasize the necessity for innovative waste treatment technologies capable of combining high efficiency with reduced environmental impacts and economic feasibility.

The use of plasma technology is a technically viable technology for mass reduction of waste, which can optimize the space needed in storage and minimize the cost of managing radical waste, for example (Gonçalves et al., 2022).

Plasma is a state of matter referred to as a fully or partially ionized gas consisting of a mixture of electrons, ions and neutral particles. Its degree of ionization is dictated by the proportion of concentrations between charge carriers and neutral particles. Due to its significant number of free charges, long-range forces give it a strong interaction in the form of a collective behaviour, susceptible to internal and external electromagnetic fields (Fridman, 2008; Ma et al., 2024).

Plasma is classified into thermal and non-thermal plasma based on thermodynamical equilibrium (Clayton et al., 2025; Grelier et al., 2023). Plasmas can be classified as high-temperature hot (fully ionized gas as existing in the sun), thermal cold plasmas (partially ionized gas with electron temperature equal to the gas temperature) and non-thermal cold plasmas or plasmas out of thermodynamic equilibrium (partially ionized gas with electron temperature much higher than the gas temperature (Li et al., 2016; Stetsiuk et al., 2025)).

Processes that employ plasma technologies encompass waste conversion, material synthesis, assisted combustion processes, coating processes, sintering processes, particle spheroidization processes, metal purification processes, refractory densification, synthesis and nucleation of nanostructures, etc. The disadvantage is its high energy consumption, which entails higher costs, depending on the type of plasma used (Menezes et al., 1999). In

plasma gasification and tailings conversion processes, plasma torches are generally used, which are devices that convert electrical energy into thermal energy transported by a gas, called the working gas. The operating temperatures can vary from 1500°C to 50,000°C, volatilizing the organic matter and melting the inorganic materials, generating in the end, a glassy matrix, containing all the inert material (Ma et al., 2024; Mattos, 2011).

In processes of converting waste into synthesis gas or advanced materials, dedicated plasma torches are generally used in controlled environments of temperature, pressure and nanostructure nucleation catalyst systems (Mountouris et al., 2006; Stetsiuk et al., 2025). In many conversion processes, water vapour torches are used in order to produce a plasma that is more reactive with organic materials and to reduce the production of harmful nitrogen gases (Clayton et al., 2025; Vargaftik et al., 1996).

In this scenario, plasma technology emerges as a new tool to assist physicochemical reaction processes that involve heat, mass and energy exchange, being able to extend the limits of the process parameters that govern such reactions (Stetsiuk et al., 2025). Therefore, new mechanisms and new thermodynamic pathways may arise in plasma-assisted material process reactors. In the most important aspect for the present work, the plasma tailings treatment processes have the effect of substantial percentages of volume and emissions reduction, allowing the separation of hazardous materials from non-hazardous materials with different thermal characteristics.

Kar et al. (2018) claim that plasma technology is probably the most underutilized technology applied to nuclear waste management. In their work, for example, to study the feasibility of putting this technology into practice, a non-thermal atmospheric pressure plasma jet microwave oven was used. However, despite different types of applications, in this research, the thermal plasma of arc transferred with graphite electrodes will be used.

Thermal plasma has traditionally been used to treat a wide variety of wastes (Gomez et al., 2009). The other two types of plasma are classified as non-thermal equilibrium plasma. Two basic types of plasma configurations, transferred and non-transferred arc, can be used in solid waste treatment. In a non-transferred arc torch, the plasma arc is generated in the torch body, whereby a gas is converted to plasma, applied to the waste, producing gas and slag (Kar et al., 2025). In the second case, the substance to be processed is placed in an electrically grounded metallic vessel and acts as an anode; therefore, the reagent material must be an electrically conductive material (Huang and Tang, 2007). The non-transferred arc torch is the most commonly used device for waste disposal.

Thermal waste processing technologies, including incineration, pyrolysis, gasification, promise more efficient treatment and energy recovery from waste. In recent years, interest in using advanced Thermal Plasma Technology, as one of the thermal processing technologies, in waste treatment has increased enormously (Agon et al., 2016; Materazzi et al., 2016; Morrin et al., 2012, 2014; Stetsiuk et al., 2025; Tang et al., 2010), mainly due to

high destruction efficiency and environmental compatibility. By gasifying the combustible parts of solids for heat and power generation and vitrifying the non-combustible parts simultaneously into dense, inert, leach-resistant slag and pollutant emission can be reduced to almost zero (Kar et al., 2025; Li et al, 2016).

As a waste management philosophy, the greatest emphasis is on minimizing waste at all stages of design, operation and maintenance. For effective containment, mass reduction is a key factor in choosing technologies for use in radioactive waste management plants. The development of innovative treatment processes for low and intermediate-level waste in recent times has focused on mass reduction as one of the main objectives. The concentrates obtained in the primary treatment processes are conditioned before disposal. The technology for conditioning in suitable matrices is now quite mature and well established. In the case of high-level liquid waste in China, for example, direct immobilization in a glassy matrix such as borosilicate glass is being practiced using induction-heated metal melters. Still in China, the adoption of melters to improve productivity is at an advanced stage. These vitrification facilities are housed and operated in independently designed and built hot cells with a remote viewing and handling arrangement. Enhanced crystalline matrix development work is also ongoing. Considerable research and development are underway to partition smaller actinides for recycling and transforming. Research is being directed towards the development of advanced technologies for vitrification and better forms of waste (Clayton et al., 2025; Stetsiuk et al., 2025).

Thermal plasma technology has emerged as a promising solution for radioactive waste treatment due to its unique ability to achieve substantial volume reduction while immobilizing hazardous components within vitrified matrices. Recent studies provide encouraging evidence: Pullao et al. (2024) reported up to 71% volume reduction in simulated low-level radioactive waste with effective containment of radionuclides such as Co, Cs, Sr and Ce; Prado et al. (2020) demonstrated volume reduction factors as high as 1:99 for compactable wastes. Additionally, Abu Darda and Gabbar (2023) proposed an innovative atmospheric thermal plasma system for high-level radioactive waste separation, highlighting its potential for safer long-term management.

Disposal of radioactive waste

Tailings disposal is the final step in tailings management and ideally is carried out in a dedicated disposal facility. Discharge of effluents to the environment within permitted limits is also an option. All types of radioactive waste need to be carefully managed to ensure society is safe, as well as protecting the environment and ensuring any accidents. Disposal of radioactive waste in a facility is intended to isolate the waste from both human activity and nature's dynamic processes. It is important to distinguish between disposal (permanent and irreversible removal of tailings) and residential storage with irrecoverable tailings; Ojovan and Lee, 2005).

Organic radioactive waste of low and medium radioactivity represents an important fraction of waste that originates from the

peaceful application of nuclear energy in different fields of our daily life. These tailings are considered a dangerous source of pollution for man and his environment and must be isolated. According to the IAEA, radioactive waste disposal is defined as the disposal of waste in a specific approved facility that is intended to isolate waste from humans and the environment and prevent or limit the release of potentially harmful substances in such a way that human health and the environment are protected (IAEA, 2014). The disposal process represents the last step of the tailings management regime, which must be compacted and stored in a solid form (KekkiI and Titta, 2000).

Different types of tailings packaging are used to ensure protection against radioactivity, especially tailings that can permeate into groundwater. Multiple barrier systems, both natural and/or engineered, have been used to provide adequate storage security. Typically, the geological barrier provides the ultimate long-term protection (KekkiI and Titta, 2000). Disposal using shallow burial or deep underground repositories, such as depleted mines, is widely employed throughout the world with no obvious technical issues. However, many nations view the disposal of low- and medium-level tailings (LILW) as a more pressing tailings management problem, due to the volume of waste involved and the difficulties faced in setting up treatment and storage facilities. The repository for LILW can be broadly categorized into two groups: near-surface placement facility and rock cavity placement (KekkiI and Titta, 2000). However, the safe disposal of radioactive waste is a major concern for those who oppose nuclear technology. Therefore, disposal plays an important role in the public acceptance of civil applications of nuclear technology in different nations. According to the IAEA, radioactive waste generated in hospitals, educational and research institutes in developing countries ranges from 4 to 10 m³ per year for one facility. In Egypt, more than 40 institutes are using radioisotopes in different peaceful applications and 160–400 m³ of waste are generated, mostly low-level organic solid radioactive waste.

Waste incineration is one of the most widespread and effective technologies that significantly reduces the volume of waste. Many industrial plants (up to 100,000 tonnes per year) for incineration of municipal and industrial waste are in operation all over the world. The treatment of radioactive waste requires capacities limited to tens and hundreds of kilograms of waste per hour. Only the combustible components of the tailings after preliminary separation are sent to incineration. The main disadvantage of incinerating radioactive waste is the production of high amounts of ash with concentrated radioactive isotopes – potentially dangerous for transport and unsuitable for a landfill. Several radioactive ash treatment methods have been developed and offered for industrial use: cementation, vitrification in induction furnaces or with metallic thermal mixtures, plasma treatment and others. All of these methods require the construction of additional plants, transport of ash residue for treatment, input of additional materials or, in many cases, expensive energy sources (IAEA, 2014).

At the same time, worldwide interest is growing in methods of direct treatment of radioactive waste to obtain a product suitable for transport and for landfill or long-term storage. In this scope,

among the promising technologies for the treatment of radioactive waste, the plasma technology generated by thermal plasma torches stands out. This technology, intended for the treatment of tailings with low and medium levels of radioactivity, ‘allows you to substantially reduce the volume of tailings after subjecting them to temperatures that can reach temperatures above 1800°C in the process region and temperatures above 2500°C in the plasma regions (plasma jet and arc)’. This processing condition has the property of decomposing the volatile products contained in the processed materials into simpler molecules, reducing emissions and transforming the inorganic fraction of the residue into a glassy matrix with reduced leaching rates obtained by the addition of fluxes (sand, glassware). The limiting factor in the development of plasma technologies for the treatment of radioactive waste is the high degree of production of volatile radionuclides (Filius and Whitworth, 1996). In this aspect, research work should be conducted in the development of plasma technologies aiming at obtaining vitrified slag containing the maximum degree of inclusion of radionuclides with minimum contamination of the exhaust gases.

Given this scenario, assessing the technical and economic feasibility of thermal plasma technology for the treatment of radioactive waste in Brazil becomes essential. The synergistic combination of volumetric reduction, vitrification and the potential for radionuclide separation suggests that plasma systems may offer a more integrated and efficient pathway compared with current practices. Therefore, the objective of this study is to evaluate how the incorporation of thermal plasma torches into a radioactive waste management system could influence waste volumes, treatment performance and overall disposal costs. By modelling different operational scenarios, the study seeks to determine whether plasma-based treatment represents a viable and advantageous option for low-level radioactive waste in the Brazilian context.

Materials and methods

This research was based on the results achieved by Gonçalves et al. (2022) which made possible the feasibility of these analyses. Faced with the need to know the impact of the use of the plasma reactor in the radioactive waste management, scenarios were created to analyze the behaviour mainly of the disposal costs of this waste.

In order to evaluate the effectiveness of the implementation of plasma treatment, a cost function was created that includes the transport, storage, handling and final disposal of the tailings studied. The function was applied to simulate scenarios with different compositions in the waste management. Given the limited predictability of waste generation, logistics planning faces significant management uncertainties, and the development of a cost model helps minimize these uncertainties by systematically estimating the cost components across the waste management chain. Figure 1 presents the conceptual logistics network constructed by the authors as part of the methodological framework. It illustrates

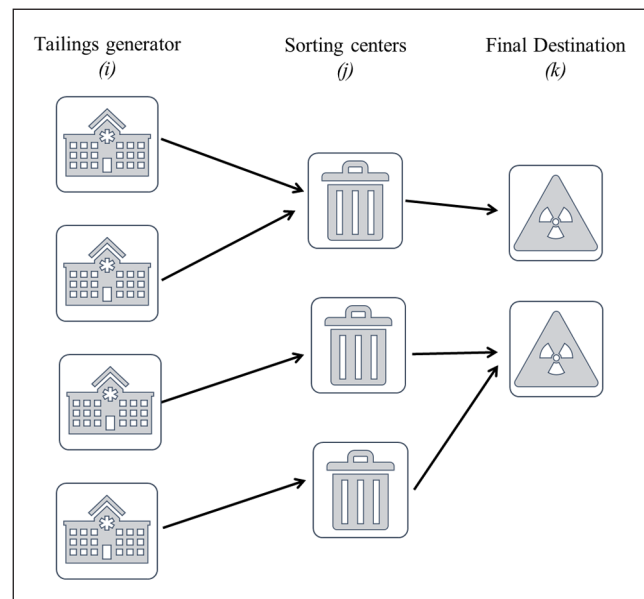


Figure 1. Network logistics of radioactive waste.

Source: By authors.

the stages and flows considered in the modelling approach, rather than depicting an existing operational chain from the case study.

In the model illustrated in Figure 1, the first link of the logistics network corresponds to the waste generators, denoted as i . A total of 200 generating points were simulated in the network, following a standard normal distribution to represent variability in waste generation across different facilities.

The second link, denoted as j , represents the Sorting Centre, which receives the waste, performs the separation procedures, and sends the material to its final destination. For this node, a uniform statistical distribution between 0.45 and 0.65 was adopted to represent the mass reduction achieved by plasma thermal treatment, based on the experimental results obtained in this study. This reduction directly affects the amount of waste forwarded to the subsequent stage of the chain.

From the sorting centre (j) to the final disposal site (k), transportation costs are influenced by the mass of waste after treatment. When the plasma reactor is placed at node j , the mass reduction occurs before transport, thereby decreasing transport cost. Alternatively, if the plasma reactor is allocated to node k , the waste is transported without reduction, and mass reduction occurs only upon arrival. The model therefore evaluates both configurations: plasma treatment at the sorting centre (j) and at the final disposal site (k).

The final disposal site, represented as k , receives all waste originating from the sorting centre. When the plasma reactor is positioned at this link, the same mass-reduction parameters apply, ensuring comparability across scenarios.

The proposed cost function f (equation (1)) integrates installation costs, operational costs, and transportation costs associated with each link of the network. The model computes the total cost of waste management considering the flows between i , j and k ,

and the presence or absence of plasma treatment at different nodes. Through simulation, the behaviour of function f is evaluated by varying inputs such as waste volume, mass-reduction parameters and reactor allocation, enabling comparative analysis of the economic performance of each scenario.

$$f = \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^o q_i co_i ct_{ij} d_{ij} + q_j co_j ct_{jk} d_{jk} + q_k co_k$$

Equation (1): Cost function

Where the decision variables are:

- Number of tailings produced at the generator site (q_i);
- Number of tailings handled in a sorting centre (q_j);
- Number of tailings handled at the place of final disposal, (q_k);

Of which the parameters are:

co_i = operation cost in i , considering handling at the generating site;

ct_{ij} = transport cost from i to j ;

d_{ij} = distance between i and j ;

co_j = operation cost in j ;

ct_{jk} = transport cost from j to k ;

d_{jk} = distance between j and k ;

co_k = operating cost in k .

Composition of simulation scenarios

The scenarios proposed for evaluation in this study consist of contemplating a variation of the mean and its respective standard deviation in order to identify the behaviour of the results as such changes occurred.

The number of Tailings Generators (samples) used in i was 200 for all scenarios proposed in this work, and only one option to send i to j and from j to k . Therefore, in the notation of the sum of i , n varies from 1 to 200, in the notation of the sum of j and k , there is no variation, as it is considered only an option.

The standard deviation considered for the amount of tailings generation was 10% in all scenarios, and the mean values were simulated considering an arithmetic growth to understand the behaviour of the results as the number of tailings generated increases, as a way of following the growth population over the years. All scenarios were simulated 25 times.

For the case of the logistic flow currently practiced for the disposal of tailings, the formula considered the transport and operational costs in full in all links, that is, the percentage of mass reduction in links j and k was not considered. For the calculation considering plasma reactor allocation in the collection and treatment centres (CT), link j , it was considered that the transport of this link to DF (k) would have a reduction in volume and, consequently, a reduction in the total cost. And in the case of assigning the reactor only to the DF (k), a reduction in the amount of tailings to be incinerated was considered, according to the mass

reduction index obtained in the experiments by Gonçalves et al. (2022).

For the cost of handling and segregation in i , U.S.\$ 0.32 adapted from Nogueira and Castilho (2016) was considered, considering inflation, the IGP-M index calculated according to parameters of the Central Bank of Brazil.

For the cost of operation in j , U.S.\$ 1.52 kg⁻¹ was considered, as studied by Nogueira and Castilho (2016), with adaptation to inflation, IGP-M index calculated according to parameters of the Central Bank of Brazil.

The transport cost between the links of this chain was set at U.S.\$ 6.18 (kg × km)⁻¹ based on Yu et al. (2020) from i to j and also from j to k .

The distance between the generating site (i) and the sorting centre (j) is 20 km and between the sorting centre (j) and the final disposal site (k) is 50 km.

To calculate the electric energy tariff, the report of the Decision Support System of average tariffs by region, company and monthly and annual consumption class was considered (Brasil, Agência Nacional de Energia Elétrica, 2017). For industrial collection, it costs an average of U.S.\$ 0.30 kWh⁻¹, and for incineration, it is necessary to consider inputs such as the graphite electrode and equipment maintenance. However, the cost of plasma incineration was fixed at the Final Disposal site k , it was fixed at U.S.\$ 1.40 kg⁻¹, if the logistic flow with plasma reactor is calculated. For this value, the possibility of generating energy from incineration was not considered.

The value for DF currently practiced, that is, for the SR (without reactor) situation – without reactor, is approximately U.S.\$ 1.86 based on Teske et al. (2018), applying accumulated inflation since the reference period.

The amount of waste generated in a hospital (generator site i) can exceed 142 kg month⁻¹ in the Brazilian Midwest (Bastos, 2016). Therefore, considering the São Paulo region, that is, a region with higher population density, the amount of 150 kg month⁻¹ was considered in the first scenario, with an arithmetic increase in the following scenarios until reaching 400 kg month⁻¹. The data referring to the sample (n) of i were created randomly using the formula [INV.NORM.N_RANDOM; mean, deviation] of MsExcel, which implies generating random data obeying a normal distribution, with standard deviation. Data referring to the random assignment of mass reduction were obtained using the formula [RANDOMBETWEEN; 0.45; 0.65] obeying a uniform distribution.

A mass reduction rate (between 45% and 65%, based on the results of the experiments in this study) was considered when allocating the reactor in the CT, which, in principle, tends to reduce the cost of transport from this level of the logistics network.

Results and discussion

The presented results referring to the simulation contemplate different scenarios that represent situations that include the

Table 1. Simulation results.

Scenario	Waste generator (sample n)	Mass waste (average value)	Standard deviation (10%)	Result SR (without reactor) (U.S.\$)	Result R-CT (with reactor) (U.S.\$)	Result R-DF (final destination) (U.S.\$)
1	200	150	15	13,143,728.51	8,915,284.12	13,087,147.40
2	200	200	20	17,492,756.03	11,865,194.11	17,448,974.12
3	200	250	25	21,886,134.44	14,845,186.94	21,831,356.52
4	200	300	30	26,310,226.05	17,846,012.29	26,244,375.25
5	200	350	35	30,708,167.57	20,829,100.25	30,631,309.34
6	200	400	40	34,941,678.82	23,700,656.49	34,854,224.70

Source: By authors.

CT: collection and treatment centres.

alteration of the installation site of the reactor for the treatment of tailings by plasma.

As for the results, Table 1 has three types, located in the last three columns:

- Result SR – total cost without using a plasma reactor;
- R-CT result – total cost with the use of a plasma reactor in CT;
- R-DF result – total cost with the use of a plasma reactor in DF;

In order to explain the application of the formula associating the results obtained in Table 1, the following is a description of what was considered for the scenarios, using the data from scenario 1 as an example.

1. The amount of waste generated (150 kg month^{-1}) in each of the 200 generating sites was multiplied by the handling cost ($co_k = \text{U.S.}\$ 0.32$);
2. The value obtained in 1 was added by multiplying the amount of tailings q_{ij} ($\text{U.S.}\$ 26.30\text{ kg}^{-1}\text{ month}^{-1}$) to be transported with the transport cost from i to j $ct_{ij} = \text{U.S.}\$ 6.18 (\text{km} \times \text{kg})^{-1}$ with $d_{ij} = 20\text{ km}$;
3. Added the value obtained in 2 with the multiplication of the amount of tailings received in j (150 kg month^{-1}) by the cost of operation $co_j = (\text{U.S.}\$ 1.52\text{ kg}^{-1})$;
4. Added the value obtained in 3 by multiplying the amount of tailings to be transported by the transport cost from j to k $ct_{jk} = (\text{U.S.}\$ 6.18 (\text{km} \times \text{kg})^{-1}$ with $d_{jk} = 50\text{ km}$). In this step, the mass reduction was not considered for result SR, only for result R-CT;
5. Added the value obtained in 4 to add to the multiplication of the amount of tailings received in k , that is, DF with the cost of incineration. In this step, the reduction was considered only when the reactor is allocated to this link in the chain, generating a difference in the R-DF result.

Table 1 presents the results referring to the simulation, which was carried out in 6 scenarios for 25 times, obtaining the average of the averages, varying q_i based on the normal distribution and the mass conversion factor by the uniform distribution.

The results, which are divided into three columns, highlight the ‘Result R-CT’, which has an average reduction in all six scenarios of 33% when compared to the result of the flow currently practiced (SR). However, the result considering the reactor at the final destination site (DF), does not exceed 0.3%.

The mass reduction taking place in the CT, that is, installing the plasma reactor to incinerate the tailings in the CT, appears to be a more viable option when compared to the option of installing the reactor only at the final disposal site, DF. Considering the average mass reduction between 45% and 65% obtained in the experiments of this research, the reduction in the amount to be transported for storage at the final disposal site is significant. Installing the reactor only in the DF means that the tailings would have to be transported approximately 20 km from the generating site for sorting, and another 50 km to reach the final disposal site, resulting in 70 km to be incinerated only in this link of the chain.

The variable that most impacts the total cost of the logistics network is the cost of transport. The conditions required in the legislation for collection, handling and transport are strict to maintain safety, which implies an increase in costs. However, when multiplying by the distance and volume to be transported, it yields considerable values.

It is important to note that the total cost is not paid by just one link in the chain. The purpose of this function is to know the cost without assigning responsibilities to the links, as each contract can be prepared and conducted in different ways. But it is necessary to recognize the influence of the cost factor on the logistics activity for this type of tailings.

For scenario 1, for example, the SR result in BRL, means that each of the 200 tailings generators (sample n), would have a monthly cost of approximately U.S.\$ 65,718.64 for final disposal of tailings, considering the collection on site until disposal Final. The R-CT Result, U.S.\$ 8,915,284.13 implies a cost of U.S.\$ 44,576.42 for each generator. For these situations, it is important to point out that the total cost of disposal is not necessarily paid by the generator. Mechanisms can be created to apply shared responsibility that would enable a better distribution of responsibilities. It is still possible to claim a partnership via a sectoral agreement or even government subsidies to minimize environmental damage, also considering the possibility of generating energy from the incineration process.

Table 2. Incineration time.

Scenario	Average waste (kg month ⁻¹)	1. Reactor			2. Reactor		
		RO-A (kg h ⁻¹)	RO-B (kg h ⁻¹)	RO-C (kg h ⁻¹)	RO-D (kg h ⁻¹)	RO-E (kg h ⁻¹)	RO-F (kg h ⁻¹)
1	30176.89	188.61	94.30	62.87	94.30	47.15	31.43
2	40212.75	251.33	125.66	83.78	125.66	62.83	41.89
3	50268.16	314.18	157.09	104.73	157.09	78.54	52.36
4	60269.48	376.68	188.34	125.56	188.34	94.17	62.78
5	70278.84	439.24	219.62	146.41	219.62	109.81	73.21
6	80269.49	501.68	250.84	167.23	250.84	125.42	83.61

Source: By authors.

Table 2 was created to present an operational perception of the reactor. The first column refers to the scenarios used in Table 1.

The other columns represent the tailings target to be incinerated, considering the following operating regimes:

RO-A: operating regime A – one reactor operating in one shift of 8 hours day⁻¹ = 160 hours month⁻¹;

RO-B: operating regime B – one reactor operating in two shifts of 8 hours day⁻¹ = 320 hours month⁻¹;

RO-C: operating regime C – one reactor operating in three shifts of 8 hours day⁻¹ = 480 hours month⁻¹;

RO-D: operating regime D – two reactors operating in one shift of 8 hours day⁻¹ = 320 hours month⁻¹;

RO-E: operating regime E – two reactors operating in two shifts of 8 hours day⁻¹ = 640 hours month⁻¹;

RO-F: operating regime F – two reactors operating in three shifts of 8 hours day⁻¹ = 960 hours month⁻¹;

The values contained in the ‘RO’ columns correspond to the amount of tailings to be incinerated, considering the operating conditions of operating time and reactor (one or two) to burn the tailings for each scenario.

In column RO-A, to incinerate the amount of tailings received in just one 8-hour shift, a reactor with greater installed capacity and electrical power would be needed.

In the RO-B column, operating with a reactor in two 8-hour shifts, the need for a more powerful reactor is no longer a priority, since there is a 50% reduction in the mass to be incinerated per hour, however, it is important to observe the costs for keeping two shifts in operation.

In the RO-C column, using one reactor in three 8-hour shifts, there is a reduction of approximately 33% of the tailings mass to be incinerated when compared to the operating time of the RO-B column, but the cost to maintain the third shift is more onerous to maintain night shift work rights.

In column RO-D, there are two reactors operating in an 8 hours shift, resulting in 16 hours per day, with results similar to those contained in column RO-B, which refers to one reactor operating two shifts of 8 hours, also resulting in 16 hours day⁻¹. The acquisition and maintenance cost of two reactors should be evaluated in comparison to the two-shift regime using only one reactor.

In column RO-E, there are two reactors operating in two shifts of 8 hours, resulting in 32 hours day⁻¹ of work. In this condition, despite the high operating cost, there is a 75% reduction in the amount of tailings to be incinerated when compared to the RO-A column, which could require two reactors of lower capacity, which could balance the incineration process.

At column RO-F, there are two reactors in operation for three shifts of 8 hours, totalling 48 hours day⁻¹ of work dedicated to the incineration of tailings. Again, it is important to assess the need to maintain two reactors operating in three shifts of 8 hours day⁻¹, that is, 24 hours day⁻¹, considering labour and electricity costs.

Figure 2 represents in a compiled way the results of Table 2, where it is possible to notice the division of RO by column, and each colour represents a scenario, evaluated at each of the times, that is, incineration conditions. The higher-level means that more weight needs to be burned in the estimated time in each column. Low levels mean that there is a need to incinerate fewer tailings in the studied condition.

In Figure 2, however, the A times stand out, which is the condition with the shortest operating time, resulting in an intense volume to be incinerated in just 8 hours, which would require a reactor with greater installed capacity and greater power. Time F also stands out, with two reactors 24 hours day⁻¹, which can accommodate two reactors of lower capacity, while minimizing the risk of process interruption, since if there is a need for maintenance on one piece of equipment, the other can maintain operation. This dynamism of not interrupting the incineration process can lead to high costs (of acquisition, maintenance and consumption) in addition to the 24-hour operating regime.

It is feasible to consider the option of operation with two shifts of 8 hours operating only one reactor, that is, RO-D. In this way, the possibility of interruption due to a lack of tailings is lower, but there is also no limitation of operating capacity, and it is possible to incinerate the amount to be received. The RO-E option is still advantageous in scenarios of high amount of tailings generation, and there is still no need to pay for a night shift for not operating in three shifts per day.

Considering the possibility of applying improvements, the use of new technologies to optimize the plasma incineration process, an analysis was performed using the cost in DF (*k*) reduced by 50%, as presented in Table 3. One of the technologies available for application would be the plasma torch, which has already

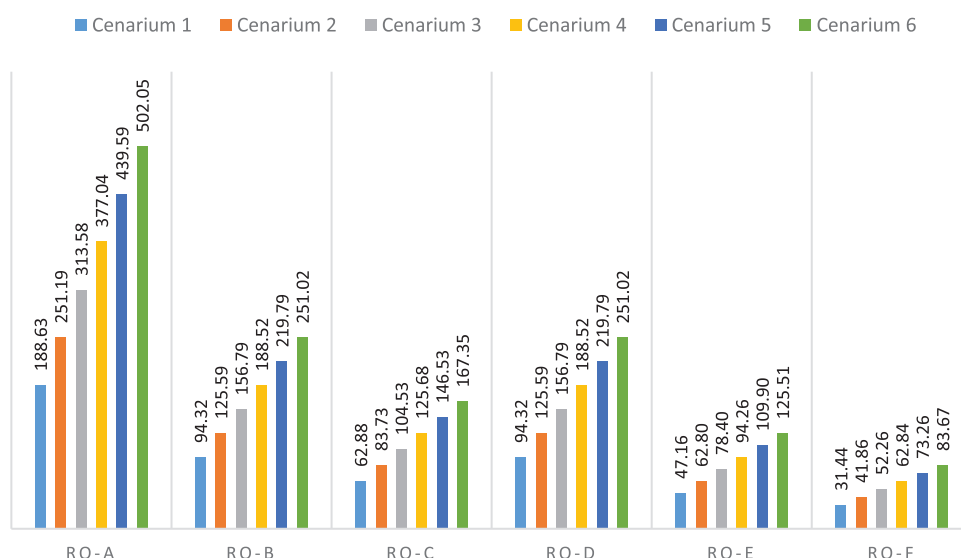


Figure 2. Incineration time.

Source: By authors.

Table 3. Optimization process simulation results.

Scenario	Reject generator (sample n)	Reject mass (average value)	Deviation	Result SR (without reactor) (U.S.\$)	Result R-CT (with reactor) (U.S.\$)	Result R-DF (final destination) (U.S.\$)
1	200	150	15	13,121,871.86	7,888,379.26	13,075,404.78
2	200	200	20	17,423,285.82	10,424,181.85	17,437,317.87
3	200	250	25	21,870,506.36	13,184,937.51	21,830,305.48
4	200	300	30	26,174,385.99	15,910,020.38	26,171,168.63
5	200	350	35	30,601,722.97	18,626,100.49	30,500,843.77
6	200	400	40	34,966,115.43	21,391,803.86	34,905,589.35

Source: By authors.

CT: collection and treatment centres.

been shown to be efficient in processes of converting biomass into synthetic gas (Grigaitienė et al., 2011).

It is possible to notice that, even reducing the cost of DF (k) by 50%, the total cost for the disposal of the tailings does not present a significant reduction, since the variable that most influences the function is the cost of transport. When comparing costs individually, studies and investments should be focused on transport, significantly minimizing the total cost.

It is also important to point out that to carry out the transport of tailings of this classification, the company must apply for licensing with government agencies, keep the record active and audited to ensure quality and safety control. There is still a need to provide specific safety equipment and training of the team responsible for activities related to collection, handling and transport. The implications for non-compliance with the rules established for the regulation of the activity are fines with a financial penalty.

The simulation results demonstrated that the installation of plasma reactors at CT led to an average cost reduction of approximately 33% across all scenarios when compared to the status quo (SR). This finding aligns with previous studies showing that the

greatest economic leverage in radioactive waste management is obtained when treatment occurs closer to the source, minimizing transportation volumes and associated costs (Prado et al., 2020; Pullao et al., 2024). In contrast, locating the reactor only at the final destination facility (DF) yielded reductions of less than 0.3%, underscoring the critical role of early-stage volume reduction. Similar conclusions have been reported in international evaluations of plasma-based logistics systems, where localized incineration or vitrification has been shown to improve cost-effectiveness while ensuring regulatory compliance (Abu Darda and Gabbar, 2023).

The model clearly highlighted transport as the most influential cost component in the waste management and logistics network, consistent with observations in both Brazilian and international contexts. The strict safety, handling, and licensing requirements governing the transport of radioactive materials amplify costs significantly (IAEA, 2014). Recent system-level assessments of nuclear waste management emphasize that transport distances, rather than incineration or conditioning costs, dominate the overall economic profile of reverse logistics networks (Clayton et al., 2025). By reducing the waste mass by

45–65% before long-distance transport, plasma technology directly mitigates this critical bottleneck, a result consistent with the findings of Gomez et al. (2009) and more recent process-level modelling studies.

The operational scenarios (RO-A to RO-F) revealed the inherent trade-offs between installed reactor capacity, operating shifts and overall system flexibility. While one-reactor, multi-shift regimes (e.g. RO-B and RO-C) offer balanced throughput and capital efficiency, dual-reactor systems (RO-D to RO-F) provide redundancy that reduces the risk of process interruptions. This finding is consistent with international reports on plasma-based incineration of hazardous and radioactive waste, which emphasize the importance of modular and redundant configurations to enhance system resilience (Kar et al., 2018; Li et al., 2016). Furthermore, studies on plasma vitrification plants in Asia and Europe confirm that hybrid reactor regimes – combining moderate capacity with extended operating hours – represent the most viable compromise between operational cost and waste throughput (Materazzi et al., 2016).

Even under optimization scenarios where final disposal (DF) costs were halved, total system costs remained largely unaffected due to the overwhelming influence of transport. These results reinforce the need for targeted investments in transport efficiency, such as decentralized treatment nodes, optimized routing and integration of plasma reactors with existing hospital and research waste management infrastructures. Moreover, the potential for plasma technologies to produce vitrified, leach-resistant by-products suitable for long-term storage or even partial reuse highlights their alignment with global sustainability goals (Ojovan & Lee, 2005; Pullao et al., 2024). Future work should also address the coupling of plasma reactors with renewable energy sources, as suggested by recent investigations into plasma-assisted biomass and waste-to-energy systems (Grigaitienė et al., 2011), thereby reducing both operating costs and environmental footprint.

Recent studies have demonstrated important advances in the application of thermal plasma technology to radioactive waste treatment. Prado et al. (2020) present a comprehensive review of plasma-based processes applied to different categories of radioactive waste, highlighting their potential to produce conditioned outputs free of organic materials and suitable for safe storage. However, the authors also note persistent challenges, such as sensitivity to operational parameters and the lack of standardized vitrification procedures, which still limit the scalability of plasma systems for industrial use.

Similarly, Gonçalves et al. (2022) experimentally evaluated a thermal plasma process for simulated solid radioactive waste, reporting significant reductions in mass and volume. Despite these promising results, the study emphasizes the absence of standardized testing protocols that ensure reproducibility and comparability across investigations. These findings indicate that, although plasma treatment has demonstrated technical feasibility, further research is needed to integrate this technology within broader waste management systems.

In contrast to previous work, which has focused primarily on experimental performance or technical reviews of the plasma

process, the present study advances the discussion by adopting a system-level approach. Here, plasma technology is analyzed not only as a treatment method but also as a component of a broader radioactive waste management network. By modelling alternative reactor allocation scenarios, transportation flows, mass-reduction effects and total system costs, this study addresses a gap identified in the literature and contributes a more integrated assessment of the feasibility and potential advantages of plasma treatment for low-level radioactive waste in the Brazilian context.

Final considerations

The objective of evaluating the application of thermal plasma technology within a radioactive waste management system was achieved. The modelling results demonstrate that plasma treatment is a technically feasible and economically advantageous option for low-level radioactive waste, particularly due to the significant mass-reduction effect and the associated decrease in transportation and disposal costs.

The findings of this study indicate that incorporating a plasma reactor into the waste management network can substantially improve system performance. Among the scenarios analyzed, allocating the reactor at the final disposal site produced the most favourable outcomes, offering greater cost reductions compared with installation at the sorting centre. These results suggest that current waste management configurations may benefit from reassessment, especially in contexts where high operational and logistical costs limit system efficiency.

Nevertheless, the study presents limitations that must be considered. The performance of thermal plasma systems is influenced by operational conditions and characteristics of the waste stream, and the lack of standardized procedures for evaluating immobilization performance introduces uncertainties into comparative assessments. These factors highlight the need for further research to validate operational parameters and expand the modelling framework.

Overall, the methodological approach and the positive results obtained here may support future efforts to develop higher-capacity plasma systems and to advance plasma-based solutions for low-level radioactive waste treatment in Brazil.

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