RF thermal plasma treatment of dredged sediments: vitrification and silicon extraction

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Abstract. In the present work, dredged polluted sediments with high level of hydrocarbons and heavy metals have been treated by means of a laboratory scale radiofrequency (RF) thermal plasma source inside a graphite crucible. Two different experimental approaches have been utilized (1) to fully decontaminate and vitrify this material, and (2) to study the technical feasibility of metallurgical-grade silicon (MGS) smelting by carbothermal-reduction reactions of carbon with silica (SiO₂) content in these dredged sediments. A two-dimensional model of a commercial inductively coupled RF plasma torch has been used to investigate the effects of plasma flow and temperature distributions of the plasma discharge interacting with the material inside the crucible. Samples of both vitrification and carbothermal reduction processes were characterized by scanning electron microscopy analysis (SEM), energy dispersion spectroscopy (EDS), X-ray fluorescence (XRF) and leaching tests. Results obtained showed a fully decontamination of the dredged sediments, with release values of heavy metals in leachates well below the law limits. Moreover, SEM/EDS analyses suggested that separation of MGS by carbothermal-reduction process is possible.

1. Introduction
The annual volume of dredged sediments in the European Union is roughly estimated between 100M m³—200 Mm³ per year [1]. These sediments are generally contaminated with heavy metals and hydrophobic organic compounds such as Polychlorinated Biphenyl (PCB), Isopropyl Alcohol (IPA) and hydrocarbons, and can be considered as waste under the European Waste Framework Directive (Directive 2008/98/EC). In the past, sediment dredged operations were exclusively aimed at warranting a proper operational functionality of harbours, docks and waterways, and these polluted dredged sediments were usually drained into wastewater systems or sent to landfills. Fortunately, this tendency has been changing in recent years. Conventions for the protection of the marine environment [2-4], and some new European tight regulations concerning waste and water management [5-7], have been introduced (1) to set guidelines for a proper disposal of dredged material into the sea, (2) to establish a framework for water protection, (3) to avoid the traditional perception of these dredged pollutant sediments as waste, considering them as a commercially exploitable resource.

A large group of environmental projects are being currently carried out in the European Union to implement, update and develop the EU environmental policy and legislation, with the financial help of the EU’s funding instrument for the environment, the LIFE+ programme. In particular, the “Recovery of dredged SEDiments of the PORT of Ravenna and SILicon extraction” project (SEDI.PORT.SIL), in which is included this work, represents a highly innovative alternative to the traditional treatment of the dredged polluted sediments. This project is aimed at laying down clear guidelines for the
sustainable management of dredged sediments, establishing the basic pillars for the realization of a treatment plant in the port of Ravenna (Italy), and demonstrating the efficiency of some consolidated technologies for the treatment of sediments, e.g. landfarming for the microbial degradation of hazardous compounds and soil washing for scrubbing soils ex-situ to remove contaminants through particle size separation, coupled with innovative techniques to recycle and increase in value the contaminated sediments.

Among these new innovative techniques thermal plasma technology offers a great number of unique advantages to decontaminate these sediments and to obtain a final recyclable product: (1) the high temperatures (T ≥ 10^4 K) and the high energy densities, ranging from 10 W/cm^3 to above 10 kW/cm^3 [8-9], help to decompose by combustion all organic contaminants presented in these dredged sediments, encapsulating heavy metals and mineral phases into a stable glassy matrix, (2) the use of electric energy to generate the plasma discharge allows decreasing the gas flow rate and the requirements to treat off-gases produced, facilitating control over the chemistry of the process and giving the possibility of generating saleable co-products [10]. One of the most extensively used methods to obtain thermal plasma is by means of radio-frequency (RF) induction discharges [11]. In an Inductively Coupled Plasma (ICP) the discharge is generated by an RF electric field coming from an external coil. This type of device is commonly used as an effective mean to produce a plasma jet with high enthalpy content which can be employed in a wide range of applications and research activities, such as densification and spheroidization of powders, waste treatment, plasma spray deposition of materials, chemical synthesis of nanoparticles, and others [12-16].

In the present work, two different experimental approaches have been investigated by means of a laboratory scale radio-frequency (RF) thermal plasma source to completely decontaminate the dredged polluted sediments and to obtain a saleable end product which enable to defray the high cost of the plasma treatment: 1) carbothermal reduction approach, adding carbon to the untreated sediments, in order to analyse qualitatively the technical feasibility to separate silicon from the silica (SiO_2) content, and 2) vitrification process of the as-received polluted sediments. This plasma source allows reproducing the high temperatures and the high heat exchange conditions of the more widespread arc plasma furnaces. A customized 2-D version of the CFD commercial code FLUENT has been utilized to quickly optimize some of the main parameters of the plasma process and to have a deeper understanding of the different temperature fields inside the reaction chamber during the plasma discharge. Obtained samples of both carbothermal reduction and vitrification processes have been characterized by scanning electron microscopy analysis (SEM), energy dispersion spectroscopy (EDS), and X-ray fluorescence (XRF) to analyse their microstructure and their elemental composition, as well as to determine if the silicon separation is technically possible. Moreover, leaching tests have been carried out to evaluate toxic metals stabilization in the resulting material.

2. Methods and Materials

2.1. Simulation activities

As a consequence of the high temperatures and the aggressive environment inside the reaction chamber where the plasma discharge is generated, direct measurements are extremely complicated. Simulation activities represent an effective and widely used tool to have a deeper understanding of the physical and chemical processes of a plasma system [17, 18]. For the purpose of this study, a two-dimensional model of a commercial ICP torch already developed with commercial code FLUENT® has been used [19]. Numerical modelling results have allowed optimizing the torch operating conditions and understanding the influence on the plasma flow and temperature, as well as the behaviour of the plasma discharge interacting with the material inside the crucible. For the sake of simplicity, this material has been considered all silica (SiO_2) because it is the main compound of the dredged sediments, the effects of silica vapour on plasma have been neglected and the graphite crucible has been included in the heat transfer and fluid dynamics model domain.

2.1.1. Optimization of the distance between the exit nozzle of the plasma torch and the crucible position. The Optimal Zone where the crucible must be placed has been defined to avoid (a) high temperatures that partially evaporate the treated material, and (b) a low crucible position where heat is
not enough to completely melt the material. After the first simulation results, two new distances have been taken into consideration for the laboratory experiments: Optimal_1 (85mm) and Optimal_2 (92mm).

![Fig.1](image1.png)

**Fig.1** Detail of the temperature field inside the torch and in the highest part of the reaction chamber for two different positions of the crucible: LOW (distance 170mm) and HIGH (distance 70mm).

![Fig.2](image2.png)

**Fig.2** Evolution of the highest temperature reached inside the crucible depending on its position inside the reaction chamber; identification of the OPTIMAL ZONE where the crucible must be placed.

2.1.2. *Time-dependent simulations*. These results help to optimize the minimum time necessary to melt the silica undergoing the plasma discharge inside the crucible. This time has been estimated in 5 minutes when a crucible of dimensions 110mm x 25mm (Diameter x Height) is placed in the highest position. On the other hand, when the crucible is in lower positions, the time needed increases drastically up to 13-14 minutes (figure 3).

2.1.3. *Volume of material to treat inside the crucible*. This volume has been reduced from 16 cm$^3$ to 12cm$^3$ because of the low thermal conductivity (1.3 W/m·K) and high specific heat (740 J/Kg·K) of the silica. As a consequence, a more homogeneous temperature profile has been achieved all along the treated material. This effect has been also confirmed in the first laboratory tests filling completely the crucible with the dredged sediments. After these trials, the lower part of the material inside the crucible was completely unreacted after the treatment.
2.2. Experimental set-up

In figure 5 the experimental setup used in this work is shown. The laboratory scale RF thermal plasma source consists of: RF plasma torch, model Tekna PL-35 (with ceramic confinement tube for operation up to 30kW); 35 kW LEVEL unit RF power supply working at 3 MHz; a control console Tekna Plasma Systems (Sherbrooke, Quebec, Canada) RF-CS-30 with gas flow meters for operation with Ar, Ar/H2 or any other auxiliary gas (Air, N2, O2); Tekna Plasma Systems external cooling system; adjustable water-cooled steel manipulator. The manipulator allows regulating the distance between the exit of the torch nozzle and the graphite crucible from 70mm down to 170mm. The importance of modifying this specific parameter has a large influence in the temperature field inside the graphite crucible, and more than 1500K of difference have been measured between the highest temperature in the upper crucible position with respect to the lower one [20].
The off gases produced during the plasma treatment pass through a cyclone to separate the largest particles, and through a dry collector which has a filter bag membrane with minute pores to retain the smallest particles near the filter surface.

2.3. Dredged sediments characterization

Sediments from the Port of Ravenna have been fully characterized, in accordance with the existing Ministerial Decree DM 471/99, to establish an accurate quantification of their different levels of pollution. As a consequence, sediments have been subdivided in three different categories depending on their degree of contamination: Green (no polluted sediments), Yellow (mean polluted sediments) and Red (highly polluted sediments, mainly due to the high content of hydrocarbons, HC). Composition data of heavy metals and hydrocarbons for each category measured in mg/kg on a dry basis is shown in table 1.

Both yellow and red sediments represent the most polluted fractions, especially because of the high hydrocarbons concentration. Nevertheless, thermal plasma technology is a well-established and efficient technology for destruction of organic contaminants [21], and it can be assumed that slight differences in the resulting material for each of these fractions of sediments will be found after plasma treatment. Also common to the main purpose of the project, these categories of sediments have been further subdivided after a sorting and soil washing process into two additional categories, depending on their grain size: sandy fraction (particle size > 75μm) and silty fraction (particle size < 75μm). Both fractions present marked differences, especially related to their chemical composition.

From the first XRF analyses to characterize the different categories of sand and silt fractions, it was determined that the percentage of silica was about 43%-53% depending on the polluted grade (green, yellow and red) and grain size (sandy and silty fractions) of the sediments (table 2). To determine the volatile substances in the each sample, a Loss On Ignition (LOI) test have been carried out: sediments have undergone a temperature of 1223K for 12 hours, losing between 10%-15% in weight after the test.

Table 1. Metal and hydrocarbon concentration in dredged sediments with respect to maximum acceptable limits (APAT, Agenzia per la Protezione dell’Ambiente e per i Servizi Tecnici)

|          | Cd | Ni | Pb | Cu | Zn | Hg | As | V | Cr | Se | HC>12 | HC<12 |
|----------|----|----|----|----|----|----|----|---|----|----|-------|-------|
| VALUE LIMIT REUSE IN INDUSTRIAL AREAS | 15 | 500 | 1000 | 600 | 1500 | 5 | 50 | 250 | 800 | 15 | 750 | 250 |
| VALUE LIMIT REUSE IN PUBLIC PARKS | 2 | 120 | 120 | 150 | 1 | 20 | 90 | 150 | 3 | 50 | 10 |
| GREEN | 0,1 | 71,5 | 21,5 | 31,5 | 71,5 | 0,2 | 6,6 | 25,9 | 41,0 | 0,4 | 1,0 | 0,2 |
| YELLOW | 0,2 | 59,5 | 30,0 | 41,5 | 280 | 3,1 | 7,7 | 24,0 | 47,5 | 0 | 190,4 | 0,6 |
| RED | 0,1 | 73,5 | 64,0 | 34,0 | 66,5 | 0,7 | 38,7 | 20,2 | 43,5 | 0,2 | 764,0 | 8,7 |

* Values which exceed the limits of law for the reuse of the material are underlined

Table 2. XRF analyses for the various categories of sediments

| SAMPLE DESCRIPTION | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MgO | CaO | Na₂O | K₂O | LOI¹ | Tot. |
|--------------------|------|------|-------|-------|-----|-----|------|-----|------|-----|
| Sand - GREEN | 49,5 | 0,5 | 11,1 | 3,9 | 3,8 | 17,1 | 1,7 | 2,1 | 10,2 | 99,7 |
| Sand - YELLOW | 49,9 | 0,5 | 11,0 | 3,6 | 4,1 | 16,0 | 1,8 | 1,9 | 11,3 | 100,0 |
| Sand - RED | 53,0 | 0,5 | 10,7 | 3,8 | 4,0 | 14,2 | 1,8 | 1,8 | 10,0 | 99,8 |
| Silt - GREEN | 44,6 | 0,6 | 14,0 | 5,5 | 4,1 | 11,3 | 1,2 | 2,3 | 16,2 | 99,7 |
| Silt - YELLOW | 45,2 | 0,6 | 14,0 | 5,5 | 4,3 | 11,3 | 1,3 | 2,2 | 15,5 | 99,8 |
| Silt - RED | 43,6 | 0,6 | 13,6 | 6,0 | 4,4 | 12,6 | 1,2 | 2,1 | 15,5 | 99,7 |

¹ Loss On Ignition
3. Results and Discussion
Material treatment in an ICP torch is commonly performed with a powder feeder equipment, which injects powders from the top of the plasma torch, along its axis and into the plasma region by means of a water cooled injection probe. However, because of the unexpected low flowability of the dredged sediments, constant blockages in the feed pipe were experimented with this technique. Therefore, in all these experimental activities, sediments have been treated directly in a graphite crucible inside the reaction chamber, where they have been exposed to the high temperatures and the high heat flux of plasma discharge in controlled atmosphere, resulting in a completely melted batch after the treatment.
For the purpose of this work, two different experimental tests have been performed depending on whether carbon was added or not to the dredged sediments: 1) carbothermal reduction process for the Metallurgical-Grade Silicon (MG-Si) smelting, and 2) vitrification of the as-received sediments.

3.1. Carbothermal reduction process
This process has been aimed at separating silicon from the silica content presented in the sediments. It is well-known that this process proceeds through more steps [22, 23], especially because of the different temperature distribution along the reaction chamber. Only considering a Si-C-O system, the intermediate reactions of this process with their respective temperature would be:

\[
\begin{align*}
\text{T} & \approx 1500 - 1800 \text{ K} & \text{SiO}_2 (\text{s}) + \text{C} (\text{s}) & \rightarrow \text{SiO} (\text{g}) + \text{CO} (\text{g}) & (1.1) \\
\text{T} & > 1800 \text{ K} & \text{SiO} (\text{g}) + 2\text{C} (\text{s}) & \rightarrow \text{SiC} (\text{s}) + \text{CO} (\text{g}) & (1.2) \\
& & 2\text{SiO}_2 (\text{g}) + \text{SiC} (\text{s}) & \rightarrow 3\text{SiO} (\text{g}) + \text{CO} (\text{g}) & (1.3) \\
\text{T} & \approx 2100 \text{ K} & \text{SiO} (\text{g}) + \text{SiC} (\text{s}) & \rightarrow 2\text{Si} (\text{s,l}) + \text{CO} (\text{g}) & (1.4) \\
& & \text{SiO}_2 (\text{g}) + \text{Si} (\text{l}) & \rightarrow 2\text{SiO} (\text{g}) & (1.5)
\end{align*}
\]

Moreover, all the various types of dredged sediments contain a great number of other compounds, such as Hematite (Fe₂O₃), Aluminium Oxide (Al₂O₃), Calcium Oxide (CaO) or Magnesia (MgO), which will undoubtedly modify the progress of the global reaction for the silicon separation. Consequently, the overall reduction reaction can be simplified as follows in order to estimate the amount of carbon necessary for the total reaction of silica:

\[
\text{SiO}_2 (\text{s}) + 2\text{C} (\text{s}) \rightarrow \text{Si} (\text{s,l}) + 2\text{CO} (\text{g})
\]

Operating conditions of an optimized carbothermal reduction test are shown in table 3. Argon has been used as plasma and carrier gas, whereas a proportional mixture of argon and hydrogen has been utilized as sheath gas because the high thermal conductivity and specific heat of the hydrogen results in a higher plasma enthalpy and in a higher heat flux to the particles. The crucible has been placed in the Optimal 2 position, included in the Optimal Zone previously determined with the simulation activities. A high concentration of minute metallic spheres has been visibly observed, and later analysed with SEM/EDS microscopy. The remaining material is roughly 60% of the total, mainly because of a partial evaporation of some volatile elements and other compounds formed as a consequence of the high temperatures of the plasma discharge.

3.2. Vitrification process
The other group of tests have been aimed at treating directly with the thermal plasma source the as-received sediments in order to vitrify them, analysing the resulting material to check out the leaching properties. This is a well-known technology and just few tests were enough to prove the feasibility of this technology to obtain a homogeneous glass, with a partial separation of metallic spheres which are formed in the surface of the final material. As it was expected, the percentage of the resulting material after the thermal treatment is higher with respect to the carbothermal reduction tests, approximately 74%.
3.3. Characterization of plasma treated sediments

Material resulting from plasma treatment of carbothermal reduction and vitrification processes have been analysed with different characterization techniques: (1) X-Ray Fluorescence (XRF) to determine the main compounds of the sediments after the thermal treatment, (2) SEM/EDS to check out the silicon extraction from all the other compounds, and (3) leaching tests to predict whether these treated sediments are likely to leach contaminants, generally metals, at levels of concern for their possible reuses. The most relevant results are presented.

Table 3. Operating conditions of a carbothermal reduction test

| CARBOTHERMAL REDUCTION | FINAL RESULT |
|------------------------|--------------|
| Plasma gas             | Ar 15 slpm   |
| Sheath gas             | Ar 30 slpm + H2 30 slpm |
| Carrier gas            | Ar 3 slpm   |
| Crucible position      | Optimal_2 (92mm) |
| Dredged sediment       | Red sediments |
| Sediments/carbon       | 20g / 5g = 25g |
| Resulting material     | 15.2g        |
| Percentage             | 60.8%        |
| Plate power            | 27.30 kW     |
| Chamber pressure       | 14 kPa       |
| Exposure time          | 5 minutes    |

Table 4. Operating conditions of a vitrification test

| VITRIFICATION | FINAL RESULT |
|---------------|--------------|
| Plasma gas    | Ar 15 slpm   |
| Sheath gas    | Ar 30 slpm + H2 30 slpm |
| Carrier gas   | Ar 3 slpm   |
| Crucible position | Optimal_2 (92mm) |
| Dredged sediment | Silt-red fraction |
| Sediments     | 40g          |
| Resulting material | 29.6g      |
| Percentage    | 74%          |
| Plate power   | 29.23 kW     |
| Chamber pressure | 14 kPa     |
| Exposure time | 5 minutes    |

3.3.1. XRF. Plasma treated powders of 10 tests (8 carbothermal reductions and 2 vitrifications) carried out with similar operating conditions have been analysed by wave-length dispersive XRF to characterize every single sample after plasma treatment. The SiO2 percentage varies from 42% up to 67%, slightly higher with respect to the untreated sediments. In particular, in sand-red fraction tests, the %SiO2 has increased from 53% (table 2) up to 66%-67% (table 5). Moreover, in both silt-fraction tests the silica percentage has increased of about 9%-11%. These significant results are probably a result of a partial evaporation of some volatile elements and other compounds formed as a consequence of the high temperatures of the plasma discharge.
Table 5. Percentage of the different compounds measured in the final samples

| Sample | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MgO | CaO | Na₂O | K₂O | Sample description             |
|--------|------|------|-------|-------|-----|-----|------|-----|-------------------------------|
| 1      | 52.7 | 0.8  | 16.5  | 5.7   | 4.2 | 15.9| 2.1  | 1.9 | Yellow sediment               |
| 2      | 52.7 | 0.9  | 15.4  | 5.8   | 4.9 | 15.5| 2.3  | 2.4 | Yellow sediment               |
| 3      | 54.9 | 0.8  | 14.3  | 4.6   | 3.7 | 17.6| 2.1  | 1.8 | Red sediment                 |
| 4      | 42.1 | 1.1  | 20.7  | 6.3   | 3.0 | 24.7| 1.0  | 0.8 | Red sediment                 |
| 5      | 66.6 | 0.5  | 10.0  | 3.4   | 3.3 | 12.6| 1.8  | 1.7 | Sand-red fraction             |
| 6      | 65.4 | 0.5  | 10.6  | 3.4   | 3.3 | 12.7| 2.0  | 1.8 | Sand-red fraction             |
| 7      | 53.5 | 0.8  | 15.8  | 6.0   | 5.1 | 14.4| 1.5  | 2.5 | Silt-yellow fraction          |
| 8      | 53.9 | 0.8  | 15.3  | 4.9   | 5.2 | 16.1| 1.3  | 2.1 | Silt-red fraction             |
| 9      | 53.8 | 0.6  | 13.1  | 5.1   | 4.6 | 11.3| 7.9  | 3.4 | Vitrification                 |
| 10     | 55.5 | 0.8  | 15.0  | 5.1   | 5.1 | 15.0| 1.3  | 2.0 | Vitrification                 |

3.3.2. SEM/EDS. Chemical analysis and imaging on a variety of zones of the different analysed tests have been performed using a Scanning Electron Microscope (SEM). The Scanning Electron Microscope is equipped with an Energy Dispersive Spectrometer (EDS), which provides chemical analysis of the field of view or spot analyses of minute particles. This kind of micro-chemical analysis is a non-destructive test. A couple of micrographs from two different carbothermal reductions tests are shown in figure 6. Results of SEM/EDS analyses evidence that, despite the significant percentage of carbon which remains probably unreacted within the sediments, a significant percentage of silicon is still present in the material. Moreover, some metallic spheres have been separated from the inert matrix. Most of them are ferrosilicon alloys with different percentages of silicon, from 10% up to 35%. In addition, some EDS analyses showed that some of these metallic particles have a very high percentage of silicon (85-90%), very close to the MG-Si.

![Fig. 6 SEM images and EDS spectra of two sections of different carbothermal reduction tests](image-url)
3.3.3 Leaching test. The same tests analysed with the XRF have been further characterized to measure the amount of metals released into the leachate, simulating the environmental conditions of which the waste would become part. Table 6 shows that concentrations of all the metals analysed were well below the law limits for every sample. In addition, a Gas Chromatography-Mass Spectrometry (GC-MS) technique has been used to detect possible organic pollutants in the samples. The screening with the GC-MS showed that no hydrocarbons were found in every single test (“Organics screening”). Therefore, decontamination of dredged sediments with a thermal plasma source, of both carbothermal reduction and vitrification processes has been demonstrated, and these materials can be all considered inert.

Table 6. Compliance leaching test for different carbothermal reduction and vitrification tests

| LEACHING TEST | Limits DM 27/09/2010 Tab. 5 Non-hazardous Waste | Limits DM 27/09/2010 Tab. 2 Inert Waste | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Test 8 | Test 9 | Test 10 |
|---------------|------------------------------------------------|----------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Al b          | -                                              | 0.006                                  | 0.032 | 0.044 | 0.018 | 0.024 | 0.030 | 0.040 | 0.024 | 0.016 |
| As b          | 0.2                                            | 0.05                                   | 0.025 | 0.033 | 0.028 | 0.001 | 0.001 | 0.002 | 0.004 | 0.021 | 0.035 |
| Ba b          | 10                                             | 2                                      | 1.355 | 0.012 | 0.064 | 1.000 | 0.036 | 0.048 | 0.060 | 0.080 | 0.047 | 0.032 |
| B b           | -                                              | -                                      | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Cd b          | 0.1                                            | 0.004                                  | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Cr tot b      | 1                                              | 0.05                                   | 0.0003 | 0.0000 | 0.0013 | 0.0008 | 0.0002 | 0.0003 | 0.0000 | 0.0004 | 0.0002 |
| Fe b          | -                                              | 0.0109                                 | 0.0083 | 0.0025 | 0.0067 | 0.0065 | 0.0059 | 0.0037 | 0.0024 | 0.0054 | 0.0083 |
| Mn b          | -                                              | 0.0004                                 | 0.0003 | 0.0007 | 0.0007 | 0.0006 | 0.0009 | 0.0003 | 0.0004 | 0.0003 | 0.0010 |
| Hg b          | 0.02                                           | 0.001                                  | 0.0004 | 0.0002 | 0.0001 | 0.0002 | 0.0001 | 0.0001 | 0.0005 | 0.0002 | 0.0004 | 0.0001 |
| Ni b          | 1                                              | 0.04                                   | 0.0001 | 0.0005 | <0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| Pb b          | 1                                              | 0.05                                   | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0002 | 0.0003 |
| Cu b          | 5                                              | 0.2                                    | 0.0007 | 0.0004 | 0.0005 | 0.0005 | 0.0004 | 0.0004 | 0.0008 | 0.0012 | 0.0003 | 0.0002 |
| Se b          | 0.05                                           | 0.01                                   | 0.0007 | 0.0012 | 0.0037 | 0.0044 | 0.0003 | 0.0003 | 0.0026 | 0.0030 | 0.0012 | 0.0030 |
| Sn b          | -                                              | 0.0001                                 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Zn b          | 5                                              | 0.4                                    | 0.0017 | <0.0001 | 0.0007 | 0.0027 | 0.0002 | 0.0016 | 0.0001 | 0.0018 | 0.0012 | 0.0007 |
| Total HC b    | -                                              | -                                      | <10    | <10    | <10    | <10    | <10    | <10    | <10    | <10    | <10    |
| Organics screening |       | -                                      | <10    | <10    | <10    | <10    | <10    | <10    | <10    | <10    | <10    |

a Hydrocarbons
b Unit of measurement mg/L

4. Conclusions
A new and innovative approach has been accomplished to treat polluted dredged sediments with a thermal plasma source. A two-dimensional model of a commercial inductively coupled RF plasma torch with customized CFD commercial code FLUENT© has been used to investigate in the early stages of the project the effects of plasma flow and temperature distributions of the plasma discharge interacting with the material inside the crucible.

Despite the few scientific publications available related to this topic, some important obtained results highlight the great potential of thermal plasmas to decontaminate and vitrify dredged sediments. All the different categories of sediments have been successfully decontaminated, and from the leaching test it was concluded that the resulting material of both carbothermal reduction and vitrification processes were completely inert. Moreover, the first positive results to estimate qualitatively the possibility to extract MGS from marine sediments could represent a major opportunity to the SEDI.PORT.SIL project to become economically sustainable.
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