

# Engineering and Physical Bases of Development and Creation of Plasmochemical Reactors for Mobile Facilities for Medical Waste Disposal

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## Abstract

This paper presents the results of the development and creation of plasma-chemical reactors for mobile and stationary installations for the destruction and disposal of solid, liquid, gaseous and mixed medical waste based on the domestic plasma generator PUN-1, with air as the plasma-forming gas. The design and principle of operation of plasma-chemical reactors installed on mobile experimental and industrial plants “Plazmon-1,2,3”, as well as the main features of the plasma waste disposal process are described.

## Keywords

Medical Waste, Incineration, Plasma Chemical Reactor, Plasma Generator, Mobile Installations

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## 1. Introduction

Plasma-arc technologies and installations that can be implemented in various mobile versions [1] are environmentally friendly industrial technologies that can quickly, in milliseconds, reach and maintain high temperatures, high chemical reactivity and thermal energy density for high-speed thermal treatment, processing

or disposal of medical and other solid, liquid, gaseous and mixed hazardous waste at temperatures of 1150°C - 1350°C.

In this paper, the term “medical waste” (MW) defines the full range of all known categories and types of medical waste, which in Ukraine are classified as hazardous and which critically pose a special environmental hazard [2].

Today, it is quite obvious that environmentally safe and efficient treatment, processing, destruction and disposal of such waste, including radioactive waste [3], requires new high-speed mobile methods, technologies and facilities capable of disposing of all types of medical waste in accordance with medical protocols and the State Sanitary and Epidemiological Rules and Regulations for Medical Waste Management, approved by Order of the Ministry of Health of Ukraine No. 325 of June 8, 2015 [4].

Therefore, it is impossible to study the problems of choosing environmentally friendly technologies for medical waste disposal in Ukraine without taking into account the impact of the war on both its generation and management [5]. However, due to the lack of modern high-speed, high-performance and environmentally friendly technologies for the treatment and disposal of medical waste, up to 95% of medical waste ends up in landfills and dumps.

Unlike smoke and fire technologies, plasma technologies allow maintaining a consistently high temperature level in the reactor zone of a plasma chemical reactor and, through high-temperature molecular destruction processes, almost completely neutralize any hazardous substances contained in medical waste [6] [7]. And, unlike their smoke-emitting counterparts, plasma technologies destroy medical waste without the formation of environmentally hazardous residues [8].

The fuel gas generated in a plasma chemical reactor as a result of the gasification of carbon-containing waste consists of 45% - 55% hydrogen and 25% - 30% CO (monocarbon monoxide), as well as methane, acetylene, and ethylene. The calorific value of the resulting synthesis gas can be up to 30% - 35% of the calorific value of natural gas. This gas, in its untreated state, can be effectively used for the plant's own needs to increase its thermal and economic efficiency.

Mobile plasma installations can also be widely used for the destruction of hazardous military and military waste and substances [9] [10], for the neutralization of poisonous substances and toxic waste, for mercury demercurization, for the final destruction of old pesticides, explosives, such as heptyl, residual products of household and other waste processing in hospitals. The use of the “cryogenic trap” method with high-speed pumping of mercury vapor ensures a low residual concentration of mercury in flue gases.

Therefore, the development and creation of efficient, simple and environmentally friendly mobile installations for plasma high-temperature destruction of medical and other wastes “in the field” and in stationary conditions is an extremely promising area [11].

## 2. Objective

To study domestic and foreign experience in the development, creation and efficient operation of mobile plasma plants for the elimination of the consequences of the accumulation of hazardous medical waste as a result of military operations with chemical and infectious contamination of territories, as well as for the disposal of any hazardous medical waste in other territories of Ukraine in the post-war period of environmental and social restoration of the territories of Ukraine.

## 3. Practical Significance

The results of the analysis of domestic and foreign experience in the creation and operation of mobile plasma plants for the treatment/processing, destruction and disposal of hazardous medical and other wastes have been obtained, which allow to improve the technology and design of plasma facilities in terms of increasing their environmental safety and the rate of final disposal of any categories of hazardous medical and other wastes in military field and emergency/disaster conditions.

## 4. The main Features of the Plasma Disposal of Medical Waste at Mobile Facilities

Plazmon-2 units use a plasma chemical reactor for liquid medical waste disposal. And Plazmon-3 plants use a reactor for the disposal of solid medical waste. Thanks to this approach, Plazmon-2,3 plants are able to completely destroy and dispose of almost all categories of liquid and solid medical and other hazardous waste and substances. The powerful ultraviolet radiation of the plasma jet completely destroys pathogenic microorganisms and infected biomedical waste, which makes it possible to avoid transportation and dispersal of infected and other potentially hazardous waste in the environment under epidemic conditions. At the same time, all waste is fed into the plasma-chemical reactor of the plant without detailed sorting and without any segregation or pretreatment. The prototype of Plazmon-2, 3 was the Plazmon-1 bench-scale experimental pilot plant [12] for laboratory research and testing (Figure 1).



**Figure 1.** General view of the prototype pilot experimental plasma unit “Plazmon-1”.

One of the main basic principles of the development and creation of mobile plasma plants is to ensure their maximum autonomy with the possibility of power supply from both stationary and autonomous mobile diesel generators. Mobile autonomous plants “Plazmon-2,3” (**Figure 2(a)**, **Figure 2(b)**) are fully mounted in a 20-foot sea container and can be transported directly to the places of generation/accumulation of medical and other hazardous waste.



(a)



(b)

**Figure 2.** (a) Plasmon installation 2. General view; (b) Plasmon installation 2. General view of the mobile container.

The experimental industrial installations “Plazmon-2,3” were created on the basis of the domestic DC plasma generator PUN-1, the general view of which is shown in **Figure 3** and developed at the Eugene Paton Institute of Electric Welding of the National Academy of Sciences of Ukraine.

The modular design of the unit makes it possible to arrange the unit for different process variants in order to adapt it to different types and categories of waste—solid, liquid, gas and aerosol, etc.

The main plasma-forming gas used for the operation of the plasma generator is compressed air. At the same time, for plasma gasification of the initial technological mixture, the quantitative ratio is 4 - 5 kg of air per 12 kg of mixed waste. In the case of air gasification, the maximum concentration of synthesis gas reaches  $\approx 80\%$  ( $\text{CO} \approx 30\%$ ,  $\text{H}_2 \approx 50\%$ ). The concentration of oxidants ( $\text{CO}_2 + \text{H}_2\text{O}$ ) does not exceed  $\sim 0.2\%$ . The concentration of ballast nitrogen ( $\text{N}_2$ ) is  $\sim 20\%$ , which is neutralized by a catalytic filter. The concentration of hydrogen chloride ( $\text{HCl}$ ) is up to 2%.



**Figure 3.** General view of the PUN-1 plasma generator. Plasma generator is modeled on a plasma-chemical reactor for the utilization of solid HLW.

At temperatures above  $\approx 1500^{\circ}\text{C}$ , calcium chloride ( $\text{CaCl}_2$ ), iron (Fe), silicon monoxide ( $\text{SiO}$ ), and chlorine (Cl) appear in the gas phase with a total concentration of less than 2%, which is neutralized by a HEPA filter.

### **5. Some Results of Commissioning Tests of Plazmon-2.3 Units**

At the first stage of the commissioning tests, after checking the functioning of all plant systems, the compliance of the plant's environmental characteristics with environmental standards was determined. This involved direct measurements of the chemical composition of the residual exhaust flue gases at the outlet section of the chimney and laboratory analyses of the sediment samples taken on the inner walls of the chimney. It turned out that solid impurities condensed on the inner wall of the chimney.

According to the test results, the humidity of solid medical waste at the inlet of the plant can be 30% - 40%. The presence of water leads to the formation of its vapor in the reactive combustion zone (RCZ), which in turn causes additional complex chemical reactions and accelerates the combustion rate as a result of the thermal dissociation of water molecules. This is due to the fact that a large number of active centers of atomic hydrogen  $\text{H}^+$  and hydroxyl  $\text{OH}$  which accelerate the combustion process many times over. This increases the intensity of the plasma flame and reduces the intensity of smoke formation.

Toxic residues are condensed in the subsequent elements of the cooling and purification system.

### **6. Analysis of Foreign Developments of Plasma Installations for Various Purposes**

The well-known company Westinghouse (USA) has created a mobile plasma chemical plant [13] based on a cargo trailer with an electric generator, gas and

water supply system, grinder and sprayer, control system, etc. The plant can process chemical waste up to 4 l/min, with 99.99% destruction of hazardous pollutants.

E. S. T. Ecological Systems Ltd., together with Plasmaktor LLC, has manufactured and put into operation a mobile pilot plasma unit for the disposal of toxic chemical waste [13] mounted in a 20-foot container. This unit is designed for the disposal of organic and inorganic waste, and can be easily adapted to the disposal of various categories of waste.

There is also experience in the creation and operation of mobile plasma plants for the disposal of medical and biological waste in emergency conditions [14]. Plasma equipment from other companies, such as RCL (Canada) and Europlasma (France), has similar performance.

SolenaGroup (USA) has developed equipment for plasma gasification of solid waste on board cruise ships.

The E.O. Paton Institute of Electric Welding of the National Academy of Sciences of Ukraine and the Gas Institute of the National Academy of Sciences of Ukraine have developed plasma technology and equipment for environmentally safe disposal and neutralization of medical waste with a capacity of 50 kg/hour [15].

UKRPLASMA Co. has developed a plasma utilization technology by means of high-temperature plasma-chemical exposure to toxic substances for their decomposition using microwave plasma [16].

SolenaGroup (USA) has developed a plant for plasma gasification of solid waste on cruise ships.

Thus, despite the fact that today plasma technologies for medical waste processing have passed the experimental stage and are ready for industrial implementation, such machines still exist only in single experimental copies or are in testing mode. This situation is confirmed by the data of the Cayman Registered Corporation [17].

The main constraint to the practical widespread use of plasma technologies for processing various wastes is the high cost of electricity consumed by them. Therefore, plasma technologies are advisable for the destruction of hazardous waste with high tariffs for their processing, as well as for the production and use of untreated synthesis gas produced by the plants for the own needs of the plants themselves in order to improve their thermal and economic performance. The correctness of this conclusion is confirmed experimentally at the Plazmon-1,2,3 plants.

## **7. Design of the Plazmon-2 Plasma Chemical Reactor**

The detailed design of each plasma-chemical reactor is developed depending on the category and state of waste—liquid, solid, gaseous, mixed, etc. Depending on the purpose of the plant, the reactor may have thermal insulation made of refractory material, a waste feed inlet with an exhaust outlet, and a slag accumulator and unloader [18]. The upper part of the reactor has a flue gas outlet for exhaust flue

gases. An auxiliary afterburner is located at the exhaust outlet, where another gas burner can also be placed to circulate and heat the exhaust gases in the afterburner.

However, the system proposed in this patent has a rather high inertia due to the need for a long process of heating the heat-insulating walls of the reactor and the same long time to cool the reactor walls in the event of a scheduled or emergency shutdown of the reactor, which leads to significant heat losses and, as a result, to an increase in the cost of processing substances. And insufficient and uneven heating of the plasma reactor vessel leads to the formation of a significant amount of nitrogen oxides (NOX), which requires the use of auxiliary gas burners for their afterburning, as well as expensive and large-sized and material-intensive structures for hazardous gas residue treatment systems, and as a result, high capital and operating costs.

Another example is the technical solution of the reactor in the device for ash gasification using a plasma arc [19], in which the reactor is a furnace shaft in the form of a heat-insulated cylindrical reactor with a feeder on its upper cover for introducing controlled portions of waste into the reactor. The upper part of the reactor sidewall is equipped with a nozzle for removing residual exhaust gases. In the lower part of the reactor there is a discharger for the removal of molten slag.

Air and water vapor are blown into the heating zone in a ratio that is optimized to minimize the required amount of electricity input and improve the quality of the fuel product gas. In this case, the gasification process (flow rate, composition of the product gas, the degree of carbon extraction with the organic component, slag vitrification) is determined by the composition of the loaded waste and the temperature in the reactive combustion zone. However, all analyzed known devices do not provide: rapid heating of the reactor and the reaction mixture, complete gasification of the input and complete filtration of the output exhaust products. In addition, the prototype reactor has large dimensions and high capital and operating costs.

Thus, the existing reactors for plasma-chemical gasification of carbon-containing materials in the solid state with subsequent production of a fuel gas product have industrial, economic, and especially environmental and technological imperfections.

During the development and creation of plasma-chemical reactors for the Plazmon-2,3) plants, the task was set to improve the plasma-chemical, environmentally safe destruction of any solid, liquid, gaseous and mixed waste by using two plasma-chemical reactors for separate high-temperature plasma-chemical destruction of solid and liquid or gaseous medical waste [20].

In the lower part of both reactors, a Lavalier nozzle is installed, the lower nozzle of which is connected to a high-temperature catalytic ceramic filter. After passing through the Lavalier nozzle and the catalytic filter, the residual exhaust products pass through a special cooling filter fluid of a two-chamber cylindrical labyrinth liquid filter with one upper and one lower cylindrical partition. After passing

through the labyrinth filter, the purified gas and aerosol residue enters the ventilation filter system through special openings with strainers, at the inlet of which bag filters and an exhaust pipe are installed.

The liquid, gaseous and gas-aerosol waste is fed into the destructive plasma-chemical chamber into the plasma jet zone by a high-pressure pump through special high-pressure nozzles, which ensures rapid heating of the reaction plasma-chemical mixture, as well as further rapid destruction of the input products due to the high plasma temperature of more than 1200°C.

A vertical cylindrical plasma chemical reactor has cylindrical coaxial walls with outer and inner walls, between which coolant or air circulates. The lower part of the outer wall of the plasma-chemical reactor has a welded-in coolant inlet pipe, and the upper part of the outer wall has a similarly welded-in pipe for the heated coolant outlet to the circulation system. Air is used for additional rapid cooling of the outer walls of the destruction chamber.

To cool the anode-cathode system of the plasma generator, a special automatic cooling unit was designed and manufactured. The cylindrical labyrinth system has vertical lower and upper cylindrical partitions forming cylindrical concentric compartments for circulation of special cooling and neutralizing liquids A1 and A2 for neutralization and additional cooling of the gas and aerosol component and cooling of the solid residue, if any. The residual gas and aerosol component, after cooling and neutralization, passes through a system of bag or other filters at its outlet.

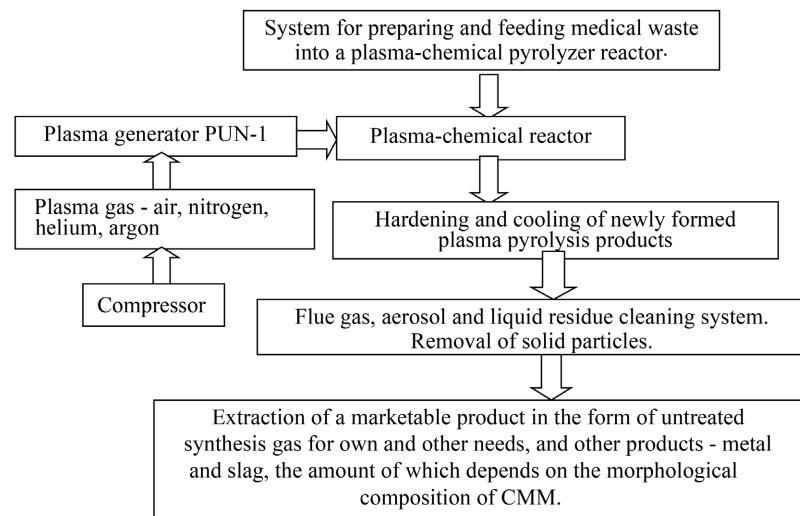
**Figure 4** shows a general view of the plasma-chemical reactor of the Plasmon-2 facility for liquid medical waste disposal. The technological flowchart of this plant is shown in **Figure 5**.



**Figure 4.** General view of the plasma-chemical reactor of the Plasmon-2 mobile unit for liquid medical waste treatment.

The design of the Plasmon-2 unit works as follows. For spraying, liquid waste is fed through special nozzles to spray nozzles and in the sprayed form is fed into a high-temperature plasma chemical combustion reactor zone around the flare, where plasma chemical molecular destruction of the sprayed liquid waste takes place (**Figure 5**). The plasma-chemical combustion products formed in this zone continue to move along the central axis of the reactor and move to the zone of their cooling (quenching). For the first phase of gas-dynamic cooling, a specially

designed Laval nozzle is used, which is installed in the middle part of the reactor height. After the plasma-chemical combustion products pass through the Laval nozzle, they enter a liquid labyrinth filter-cooler with a solution of lime milk. This unit is made in the form of a coaxial cylindrical labyrinth on the principle of pipe within pipe. The liquid filter also removes inorganic products of plasma-chemical combustion from the gas-aerosol mixture, which are then fed to special millstones for grinding and discharging into the storage tank. And the gas-aerosol mixture partially purified in the liquid filter then enters the external cleaning system consisting of a scrubber, smoke and bag filters, a final condensation system and a horizontal exhaust pipe.



**Figure 5.** Principal process flow diagram of the Plazmon-2 plasma-chemical plant for liquid medical waste treatment and disposal.

In order to convert Plazmon-2 into Plazmon-3, it is only necessary to replace the liquid waste reactor with a solid waste reactor (**Figure 6**).



**Figure 6.** General view of the plasma-chemical reactor of the mobile unit “Plazmon-3” for the treatment of solid medical waste with a plasma generator PUN-1 installed on it.

Solid medical waste is fed into the reactor by a screw mechanism installed together with a plasma-chemical combustion reactor chamber on the upper flange of the reactor with a plasma generator on its upper flange.

## 8. Conclusions

To date, mobile plasma technologies for medical waste treatment and disposal have passed the experimental stage and are ready for industrial implementation, but they still exist only in single experimental copies or are in the process of experimental research and testing.

The main disadvantage of plasma technology, which hinders its practical dissemination, is its provision of expensive electricity. Therefore, plasma technology should be used for the destruction of hazardous waste, the processing of which is quite expensive. Plasma processing and utilization of other types of technogenic waste becomes economically viable when tariffs increase or when the generated untreated synthesis gas is used for the plasma unit's own needs to improve its thermal, technological and economic characteristics.

The experience of development and creation of prototype foreign and domestic experimental and industrial plasma plants "Plazmon-1,2,3" shows their high efficiency in the utilization and destruction of various medical waste of any category. The productivity of the Plazmon-3 unit is 1-3 tons of MW per shift, depending on the composition of the waste and its moisture content, and the morphological and physicochemical composition of which has unpredictable seasonal changes.

The use of the domestic plasma generator PUN-1 in the Plazmon-1,2,3,4 plants allows changing the power and, accordingly, the productivity of the plant in a wide range from several kW to 90 kW. At the same time, the optimal consumption of plasma impingement air is 4 - 5 kg of air per 10 kg of solid medical waste.

For water cooling of the plasma generator, a closed cycle of water supply and recycling is used. The temperature of the plasma jet at the outlet of the plasma generator is 4500°C - 6000°C. The efficiency is ≈65% - 75%.

For maximum afterburning of the residual gas-aerosol smoke mixture, a secondary afterburner chamber can be used, which is installed in front of the Laval nozzle.

Plazmon-2.3 units have been certified and can be mass-produced. The plants are effective for the destruction of all categories of medical waste, as well as for the destruction of chemical munitions by the "hot detonation" method, for compacting for the disposal of liquid and solid radioactive waste, for demercurization with the exclusion of risks of environmental contamination during transportation of various hazardous waste.

The cold incineration method is effective for the disposal of toxic industrial waste, expired pesticides, military chemical agents, explosives such as heptyl and other products, and chemical and biological munitions, including those on tankers—"hot detonation", liquid and solid radioactive waste treatment, and demercurization.

The design of the Plazmon-2,3 plants and plasma-chemical reactors installed on them proposed in this paper allows solving the task of ensuring rapid reactor heating and the required temperature regime in the working plasma-chemical reaction zone around the reactor torch due to the concentration of energy from the

plasma generator, which ensures the required stable temperature regime in the destruction zone and in the cooling and filtration systems. This ultimately improves the environmental performance of the plant.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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