



Review

Thermal plasma technology for the treatment of wastes: A critical review

E. Gomez^{a,b}, D. Amutha Rani^{a,b}, C.R. Cheeseman^b, D. Deegan^c, M. Wise^c, A.R. Boccaccini^{a,*}^a Department of Materials, Imperial College London, South Kensington Campus, London SW7 2AZ, UK^b Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK^c Tetronics Ltd., South Marston Business Park, Swindon, Wiltshire, SN3 4DE, UK

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ABSTRACT

This review describes the current status of waste treatment using thermal plasma technology. A comprehensive analysis of the available scientific and technical literature on waste plasma treatment is presented, including the treatment of a variety of hazardous wastes, such as residues from municipal solid waste incineration, slag and dust from steel production, asbestos-containing wastes, health care wastes and organic liquid wastes. The principles of thermal plasma generation and the technologies available are outlined, together with potential applications for plasma vitrified products. There have been continued advances in the application of plasma technology for waste treatment, and this is now a viable alternative to other potential treatment/disposal options. Regulatory, economic and socio-political drivers are promoting adoption of advanced thermal conversion techniques such as thermal plasma technology and these are expected to become increasingly commercially viable in the future.

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* Corresponding author.

E-mail address: a.boccaccini@imperial.ac.uk (A.R. Boccaccini).

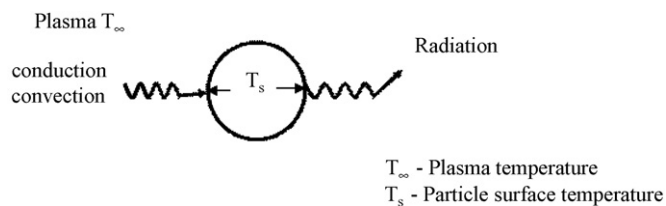


Fig. 1. Basic transfer mechanism involved in the in-flight plasma heating and melting of a particle [5].

1. Introduction

Increasing population, consumerism and industrial development have led to an increase in the quantities of hazardous and municipal solid waste (MSW) generated worldwide. Various thermal processes, including incineration, pyrolysis, melting or vitrification, have been proposed for treating these hazardous wastes prior to disposal; their aim being to destroy the organic fraction and convert the inorganic fraction into an inert silicate slag, or glass, that can either be advantageously reused, or harmlessly disposed of in an inert landfill [1–3]. This paper critically reviews the current status of thermal plasma technology in the treatment of hazardous industrial wastes. The vitrification of high, intermediate and low-level radioactive wastes is not discussed here as this is a specialist topic with different end requirements and it is outside the scope of this review.

2. Plasma technology

2.1. Fundamental background

Plasma is considered to be the fourth state of matter, consisting of a mixture of electrons, ions and neutral particles, although overall it is electrically neutral. The degree of ionisation of a plasma is the proportion of atoms that have lost (or gained) electrons and, in the case of thermal plasmas of interest for this review, this is controlled mostly by temperature. Plasma technology involves the creation of a sustained electrical arc by the passage of electric current through a gas in a process referred to as electrical breakdown. Because of the electrical resistivity across the system, significant heat is generated, which strips away electrons from the gas molecules resulting in an ionised gas stream, or plasma. At 2000 °C gas molecules dissociate into the atomic state and when the temperature is raised to 3000 °C, gas molecules lose electrons and become ionised. In this state, gas has a liquid-like viscosity at atmospheric pressure and the free electric charges confer relatively high electrical conductivities that can approach those of metals [4].

The basic heat transfer mechanism involved when a particle is in contact with a plasma is presented schematically in Fig. 1 [5]. The net energy contributing to heating and melting the particle (Q_n) is the difference between the conductive and convective energy transferred from the plasma to the particle, and the radiative energy loss from the surface of the particle to the surroundings. This is given by

$$Q_n = ha(T_\infty - T_s) - \sigma \varepsilon a(T_s^4 - T_a^4) \quad (1)$$

where h is the plasma-particle heat transfer coefficient, a is the surface area of the particle, T_∞ is the plasma temperature, T_s is the particle surface temperature, T_a is the reactor wall temperature, σ is the Stephan–Boltzmann constant and ε is the particle emissivity. This equation represents a simplistic description of the mechanism occurring in the early stages because the surface vaporises forming a gaseous shroud that inhibits heat transfer and, consequently, the mechanism changes.

Thermal plasmas have numerous advantages including: high temperature; high intensity, non-ionising radiation and high-energy density. The heat source is also directional with sharp interfaces and steep thermal gradients that can be controlled independently of chemistry. Whereas an upper temperature limit of 2000 °C can be achieved by burning fossil fuels, electrically generated thermal plasmas can reach temperatures of 20,000 °C or more. Thermal plasma reactors offer a range of other advantages including:

1. High throughput with compact reactor geometry;
2. High quench rates ($>10^6$ K/s) allowing specific gas and solid material compositions to be obtained;
3. Low gas flow rates (except for non-transferred plasma devices) compared to the combustion of fossil fuels, thereby reducing the requirements for off-gas treatment.

A possible disadvantage, especially from an economic perspective, is the use of electrical power as the energy source [6]. However, a complete comparative cost evaluation often demonstrates the economic viability of plasma-based technologies.

Thermal plasma treatment technologies are used for a wide range of applications including:

- (a) Coating techniques, such as plasma spraying, wire arc spraying and thermal plasma chemical vapor deposition (TPCVD);
- (b) Synthesis of fine powders, in the nanometre size range;
- (c) Metallurgy, including clean melting and re-melting applications in large furnaces;
- (d) Extractive metallurgy including smelting operations;
- (e) Destruction and treatment of hazardous waste materials.

Surface modification and coating is by far the most significant application of thermal plasma in terms of technical maturity and number of installations [7]. Thermal plasmas are used in materials processing because of their high-energy densities and ability to heat, melt and, in some cases, vaporise the material to be treated.

Thermal plasmas have also been used for chemical synthesis, as they are a source of reactive species at high temperatures. This is necessary in the preparation of pigments, high-purity synthetic silica and in the synthesis of high-purity ultra-fine ceramic and inorganic powders [5].

For completeness, it should be mentioned that in fact two basic types of plasma are used for industrial processes: thermal or “equilibrium” plasmas and non-equilibrium plasmas. As mentioned above, the former are characterised by a high-energy density and the equality of temperature of the heavy particles (atoms, molecules and ions) and electrons. Because of their much higher mobility, the energy given to the plasma is captured by the electrons and transferred to the heavy particles by elastic collision. Due to the high electron number density, associated with operation at atmospheric pressure, elastic collision frequencies are very high and thermal equilibrium is reached rapidly. Typical examples of thermal plasmas are those produced by direct current (DC) plasma torches or in radio frequency (RF) inductively coupled discharges [5,7–12].

Compared with thermal plasmas, non-equilibrium plasmas have lower degree of ionisation and are characterised by lower energy densities and a large difference between the temperatures of the electrons and the heavier particles. These plasmas are also known as “cold” plasmas. Electrons of sufficient energy collide with the background gas resulting in low levels of dissociation, excitation and ionisation without an appreciable increase in the enthalpy of the gas. As a result, the electron temperature exceeds the temperature of the heavy particles by orders of magnitude and it is

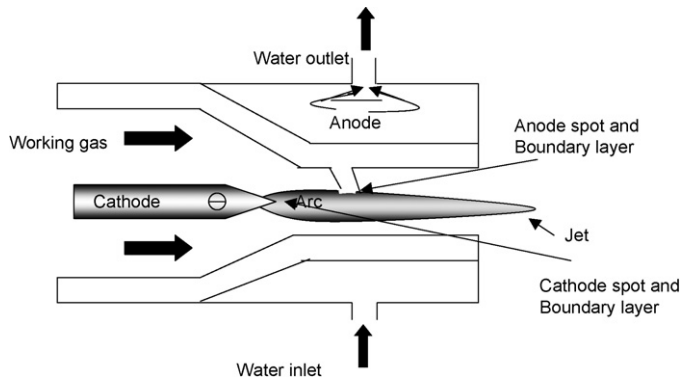


Fig. 2. Schematic diagram of a DC non-transferred arc plasma torch.

possible to maintain a discharge at much lower temperatures, even at room temperature. These plasmas are used for applications such as local surface modification or surface activation, because the ions, atoms and molecules remain relatively cold and do not cause thermal damage to the surfaces with which they come into contact. This enables them to be used for low-temperature chemistry, for plasma etching, deposition and surface modification and for the treatment of heat-sensitive materials, including polymers and biological tissues. These plasmas are produced in various types of glow discharge, low-pressure RF discharges and corona discharges.

2.2. Plasma generation

Thermal plasmas, such as those used in waste treatment, can be generated by many methods including: DC electric discharges at electrical currents up to 1×10^5 A (transferred arcs, or non-transferred arcs); alternating current (AC), or transient arcs (lamps, circuit-breakers or pulsed arcs); RF and microwave discharges at near-atmospheric pressure and laser-induced plasmas.

Plasma production methods used to treat hazardous wastes include: DC plasma torches (transferred and non-transferred configurations), and (RF) inductively coupled plasma devices [11]. Apart from the latter, in these technologies a high energy, high-temperature plasma discharge is generated between two electrodes in the presence of a sufficiently high characterising gas flow and the plasma extends beyond one of the electrodes in the form of a high enthalpy plasma jet. In a transferred arc device, the work-piece is the counter electrode whereas in a non-transferred arc device, the counter electrode is incorporated into the torch and the plasma jet projects beyond it.

The majority of plasma arc generators used in materials processing use DC rather than AC because there is less flicker generation and noise, a more stable operation, better control, a minimum of two electrodes, lower electrode consumption, slightly lower refractory wear and lower power consumption.

2.2.1. DC non-transferred arc plasma torches

DC non-transferred plasma torches are the more commonly used plasma-generating devices in materials processing. They produce a high-temperature plasma arc that interacts with a flowing gas to produce a hot jet into which the material to be processed can be injected for in-flight melting and vaporisation. A schematic diagram of a DC non-transferred arc plasma torch is shown in Fig. 2 [13]. Here, an arc is established between an axial, pointed/tip-type cathode and a toroidal/annular anode. The anode is concentric and parallel to the jet axis; the gas crosses the boundary layer between the arc column and the anode inner surface, and is pushed downstream by the pressure of the gas flow. The arc attachment point of

the anode continuously changes due to the abatement of the anode electrode material, whereas the profile of the cathode generally leads to a fixed plasma arc attachment point. To ensure satisfactory working lives the electrodes are large components, making them tolerant of the gradual abatement and are generally water cooled. However the disadvantages of this type of torch are that they contaminate the product and have very low energy efficiencies, i.e. their power output can be as low as 50% of their power input [9].

Non-transferred DC plasma torches are used with two main electrode configurations:

- *Wall stabilised or constricted arcs with hot electrodes:* Torches with a thoriated tungsten cathode and an annular copper anode are typically used at power levels below 100 kW. The most commonly used gases are Ar, He, N₂, H₂ and mixtures thereof. Oxidising gases cannot be used with this type of torch, since they would oxidise the tungsten cathode. The gas flow rate is generally below 100 l/min and the energy densities in the hot gas may reach 145 MJ/m³ and the plasma temperatures are between 6000 and 15,000 K [4].
- *Wall stabilised or constricted arc with cold electrodes:* Torches with cold, copper electrodes (both cathode and anode) of very high thermal conductivity ($385 \text{ Wm}^{-1} \text{ K}^{-1}$) can be used for plasmas containing oxidising gases. They have two coaxial, tubular electrodes separated by a small gap in which the plasma is generated with a strong vortex motion. This is induced by either a magnetic field, or a swirl in the gas flow. Industrial versions of this type of torch have been operated at power levels ranging from 100 kW to 6 MW with gas flow rates as high as 300 m³/h (5000 l/min) in a 1 MW torch. The plasma temperatures are below 8000 K at atmospheric pressure [7]. These torches are mainly used for ultra-fine powder production or in extractive metallurgy [4].

2.2.2. DC transferred arc plasma torches

In transferred arc torches only one of the plasma forming electrodes is contained within any single torch body and the plasmas are characterised by a relatively large physical separation between the cathode and anode. This can range from a few centimetres to almost 1 m. Torches can be anodic or cathodic; the electrode is concentric with the jet axis and the arc is transferred to the external electrode. This is an electrically conductive material, usually the work piece in a single torch arrangement, as shown schematically in Fig. 3 [9]. Transferred arc torches can produce extremely high thermal fluxes because the plasma arc is formed outside the water-cooled body of the torch. This means they are inherently more efficient than non-transferred arc torches because radiant heat transfer losses to the cold torch body are minimised.

Cathodes are constructed from either a water-cooled metal or more usually a refractory material that is consumed slowly by sublimation, e.g. graphite, tungsten or molybdenum. The gas flow rate requirement is less than 200 l/min and energy densities may reach 2800 MJ/m³ [4]. Anodes are made from metals with high thermal conductivities, such as copper or silver, and are usually in the form of flat ended cylinders to distribute the arc attachment. The key aspect is to provide sufficient water cooling on the back face of the anode to prevent melting, which limits the maximum energy densities to about 750 MJ/m³. Practically, anodes can only be used with inert monatomic gases whereas cathodes can be used with diatomic-monatomic gas mixtures. Anode torches are particularly beneficial in applications where no contamination from the electrode can be tolerated, as in clean metal melting. A typical example is the melting of titanium where tungsten contamination is unacceptable.

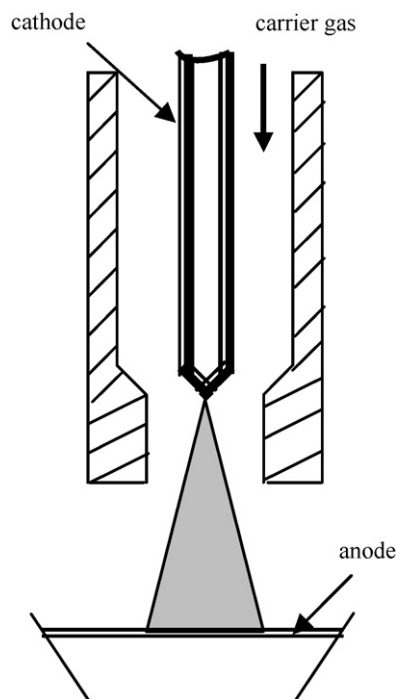


Fig. 3. Schematic diagram of a DC transferred arc plasma torch [9].

Graphite electrodes are a much simpler and cheaper alternative to water-cooled torches in applications where carbon contamination from electrode wear is not a problem, as in most waste processing. Graphite electrodes can be anodic or cathodic and usually comprise a simple graphite rod with a central hole for the plasma gas flow. Being refractory, they do not require water cooling and both anodes and cathodes can be used with diatomic gases, and therefore nitrogen can be used as a cheaper alternative to argon. A typical example from an ash melting plant is the use of a 254 mm diameter electrode to deliver 4.6 MW (13,000 A at 350 V) using nitrogen.

Another advantage of transferred arc devices is their ability to be used in a coupled twin-torch mode. Inclined anode and cathode torches (or graphite electrodes) each produce plasmas that are initially repulsive close to the devices, but then couple to form a plasma flame in free space. The advantage of this arrangement is that there is no need for the work-piece to form the return electrode so it is ideal for the melting of non-conducting materials and for the in-flight vaporisation of powders.

2.2.3. RF inductively coupled discharges

RF discharges are characterised by the absence of electrodes, which avoids the contamination of the plasma by metallic vapors. A schematic diagram of an RF inductively coupled discharge facility is shown in Fig. 4 [8].

In RF-induction plasma torches, energy coupling to the plasma is accomplished through the electromagnetic field produced by the electrical induction coil. The plasma gas does not come in contact with electrodes, thereby eliminating possible sources of contamination, and allowing for their operation in a wide range of operating conditions including inert, reducing and oxidising, and other corrosive atmospheres. The local power density is lower than that of a DC plasma.

The main industrial applications are in the field of spectrochemical analysis, synthesis of high-purity silicon or titanium dioxide pigments, and ultra-fine and ultra-pure powder synthesis. RF inductively coupled plasma torches are being increasingly

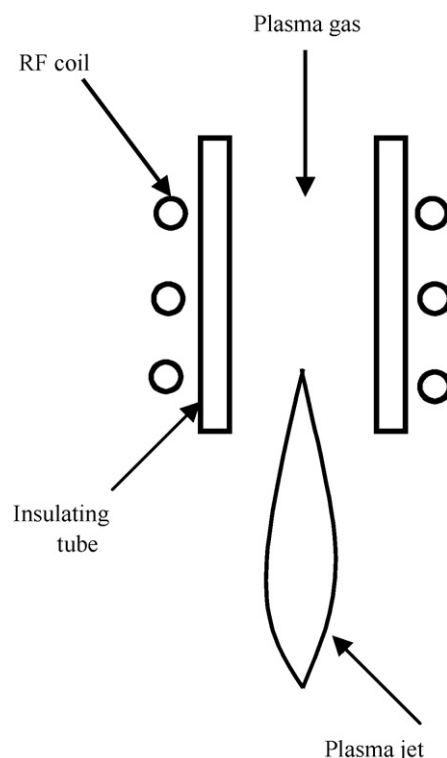


Fig. 4. Schematic diagram of RF inductively coupled discharge device [8].

considered for a wide range of applications in areas of materials processing and for the destruction of hazardous wastes. They are commonly available at power levels of 100 kW which severely limits their application.

3. Thermal plasma treatment of wastes

3.1. General considerations

Thermal plasma reactors offer the following unique advantages for the destruction of hazardous wastes:

1. The high-energy density and temperatures associated with thermal plasmas, and the correspondingly fast reaction times, offer the potential for a large throughput with a small reactor footprint.
2. The steep thermal gradients in the reactor permit species exiting it to be quenched at very rates so allowing the attainment of meta-stable states and non-equilibrium compositions, thereby minimising the reformation of persistent organic pollutants (POPs).
3. Plasmas can be used for the treatment of a wide range of wastes including liquids, solids and gases.
4. The high heat flux densities at the reactor boundaries lead to fast attainment of steady state conditions. This allows rapid start-up and shutdown times, compared with other thermal treatments such as incineration, without compromising refractory performance.
5. Oxidants are not required to produce the process heat source, as no fuel is combusted, therefore, the gas stream volume produced is much smaller than with conventional combustion processes and so is easier and less expensive to manage.
6. The combination of the above characteristics allows plasma treatment to be integrated into a process generating hazardous

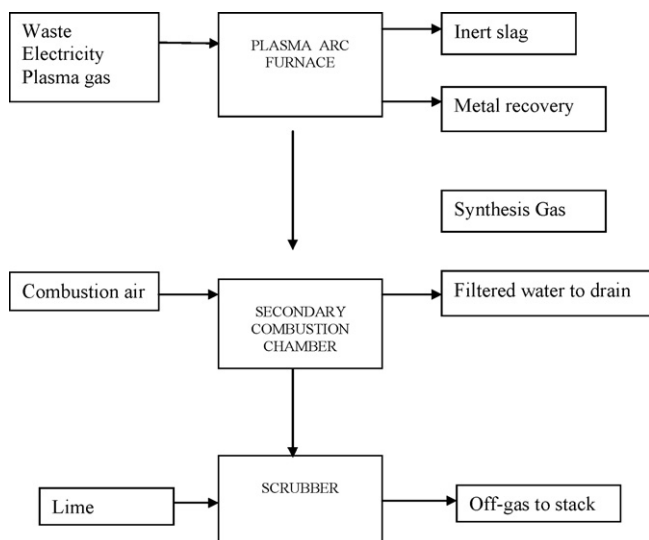


Fig. 5. Process diagram for the plasma gasification and vitrification of hazardous waste.

wastes, thus permitting the destruction of wastes at source and giving a truly proximal solution.

Plasma reactors can be employed to melt, or with the addition of glass formers, to vitrify waste to form a stable, non-leachable, glassy slag product in which hazardous substances are trapped within the glass network. The vitrified product offers the potential for re-use and other products with high added value, such as scrap metals, can be safely recovered. In addition, plasmas can thermally decompose hazardous organic compounds into simpler, benign materials. Alternatively, using gasification or pyrolysis, the organic fraction of waste can be converted into a synthetic gas (syngas) that can substitute for fossil fuels. Fig. 5 shows a simplified process diagram for the plasma gasification/vitrification of hazardous wastes, which is discussed in detail in Ref. [14].

The major disadvantage of the plasma process is the use of electricity which is an expensive energy source. However, it may be economically viable when considered as part of a long-term investment to provide a sustainable waste management solution. Although electricity is expensive, the use of transferred arc devices means that power is used efficiently and there is no parasitic load associated with the heating of air, with its high nitrogen content, to support combustion.

The high process temperatures mean that volatile metals vaporise and are carried out of the unit, together with halogens and other acid gases, in the off-gas stream. However, acid gas output can be reduced by the use of a basic slag with a high halogen ion capacity. The materials of construction of the unit and the air management system must be designed to separate, collect and/or chemically treat the materials entrained in the off-gas. These can then be recycled, reprocessed or disposed of to landfill. A wide range of gas abatement techniques are available for this remedial treatment.

For waste treatment, hollow graphite electrodes are normally used to produce the plasma arc. The electrodes and the lining of the treatment vessel or chamber are slowly abated and/or consumed during waste processing, the consumption rate being typically <5 kg/MWh and, therefore, an order of magnitude lower than conventional arc furnaces.

Recent developments in thermal plasma waste treatment can be classified as

- (1) Pyrolysis or gasification of organic hazardous wastes using reactors with non-transferred plasma torches, or a RF inductively coupled discharge [15,16].
- (2) Treatment of solid materials, or slurries, using a combination of pyrolysis and vitrification of the resulting residues in a transferred arc plasma reactor [17].
- (3) The reclamation of waste products from manufacturing processes, such as baghouse dust from electric arc furnaces (EAF), where both non-transferred and transferred arc reactors are being used [18].

Plasma treatment units consist of several sub-systems besides the thermal plasma source. These components are: a waste feed system, a processing chamber, a solid residue removal and handling system, a gas management system, operational controls and data acquisition and monitoring. A modern plasma system to treat waste incinerator ash is described elsewhere [19]. Briefly, it consists of a DC hollow graphite cathode installed through the roof of a furnace and supported by a vertical manipulator column. Nitrogen is injected down the centre of the cathode to produce a stable plasma arc that is transferred to the furnace melt; the anode consists of conductive elements built into the furnace hearth and the process is capable of handling a wide range of ashes of varying particle size and composition. The furnace operates under controlled reducing conditions and runs at a temperature of approximately 1600 °C. The electrical power supply depends on throughput, but is usually of the order of a few MW and is controlled independently of the other process variables. Remote water cooled elements are deployed at the melt line to form a protective frozen slag layer, ensuring efficient refractory performance [19]. The prepared feed ash-material is metered at a controlled rate into the unit and the plasma power is controlled to maintain the melt temperature at around 1500 °C. The ash is rapidly melted and the molten slag phase overflows continuously from the converter after which it is granulated or cast. The exhaust gas exiting the unit is treated in a thermal oxidiser unit to oxidise fully any residual combustible gas species. A conventional dry or wet scrubbing system is often used to remove acid gases contained in the off-gas prior to removal of the particulates in a fabric filter baghouse. The cleaned gas is vented to atmosphere in compliance with discharge consent thresholds.

Table 1 shows a summary of different types of wastes treated by plasma reported in the literature. The type of plasma equipment used is also indicated. In the following sections key investigations on the plasma vitrification of a number of wastes are described in detail. A list of websites related to specific commercially available plasma technologies is presented in Ref. [20].

3.2. Residues from waste to energy (WtE) facilities

Although landfill continues to account for the majority of municipal solid wastes disposal, many countries and regions have limited landfill capacity and it is increasingly difficult to find new sites [21–23]. Incineration in modern waste to energy plants is a sustainable alternative that results in considerable waste volume reduction with the added ability to reclaim energy [24,25]. A typical modern WtE facility, such as the SELCHP plant in London, is shown schematically in Fig. 6 [25]. WtE plants produce incinerator bottom ash (IBA), fly ash and/or air pollution control (APC) residues. In total these ashes account for 25% (w/w) of the mass input to the plant.

IBA (20%, w/w of the mass input to the incineration plant) consists primarily of coarse, non-combustible materials and unburned organic matter collected in a quenching-cooling tank at the outlet of the combustion chamber. It has a heterogeneous composition and physical character, but it is not currently considered to be haz-

Table 1
Plasma generation devices for the treatment of different wastes

Waste	Plasma generation equipment	Reference
Bottom ash from municipal incinerator	DC transferred arc (Takuma Co. Ltd.)	[35]
Fly ash and sludge from wastewater treatment	DC non-transferred arc (experimental equipment)	[38]
Fly ash from sanitation centre, asbestos	DC non-transferred arc (experimental equipment)	[44]
Bottom ash from hospital incinerator, fly ash from a power plant	DC transferred arc (Technical University of Lodz, Poland)	[49]
Fibre reinforced plastic composites (FRPC), gill net, waste glass	DC non-transferred arc (Institute Energy Research, Taiwan)	[68]
Dried sludge from hot galvanising process and a converter flue dust from steelmaking	RF plasma reactor (Tekna Plasma Systems)	[55]
Zinc oxide from electric arc furnace	AC plasma arc furnace	[54]
Electroplating sludge	DC transferred and non-transferred arc	[58]
Charcoal with NaCl (carbonaceous wastes)	DC plasma torch + RF plasma torch (experimental equipment)	[61]
Chlorine-containing wastes	DC plasma torch with nebulisation system	[67]

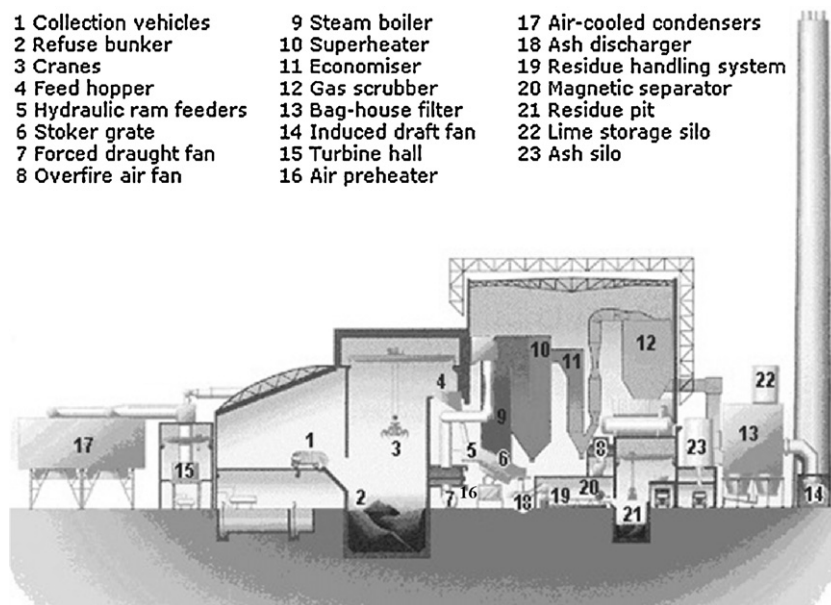


Fig. 6. Schematic diagram of a modern energy from waste (EfW) facility [25].

ardous waste. The concentrations of some heavy metals, such as lead, cadmium and mercury, may be lower than in fly ash or APC residues if these are volatilised during combustion and condense and combine with solid particulate residues.

Fly ash consists of finely divided particles that are removed by a combination of precipitators and cyclones before any further treatment of the gaseous effluents. Fly ash is listed as an absolute hazardous substance in the European Waste Catalogue (19 01 13*).

APC residues include materials derived from processes such as (i) dry and semi-dry scrubber systems involving the injection of an alkaline powder or slurry to remove acid gases, particulates and flue gas condensation/reaction products (scrubber residues); (ii) fabric filters in bag houses, which maybe used downstream of the scrubber systems to remove the fine particulates (bag house filter dust); (iii) the solid phase generated by wet scrubber systems (scrubber sludge).

APC residues are of fine particle size and generally contain high concentrations of heavy metals and soluble/volatile salts. They will also contain hazardous organic compounds such as dioxins and furans. The amount of contaminant in APC residues depends on the characteristics and composition of MSW, the incineration temperature and the removal efficiency of the air pollution control system. The high alkalinity (pH > 12 and above), the high leachability of heavy metals and the high level of soluble anions, such as chlorides, make APC residues a particularly difficult hazardous waste to manage (European Waste Catalogue 19 01 07*) [26–29].

The hazardous classification of fly ash and APC residues means they can only be disposed of at hazardous waste landfill after appropriate pre-treatment. Tables 2 and 3 show the chemical composition of ashes from MSW WtE plants.

Fly ash from the municipal waste incinerator plant in Budapest [30] was melted in a laboratory scale DC plasma furnace at 1600 °C.

Table 2
Chemical composition of solid residues from municipal waste incinerators (major oxides wt%)

Elements	Fly ash from Budapest [30] incinerator plant (wt%)	Incinerated ash from Taipei [37] incinerator plant (wt%)	IBA and fly ash mix from Japan [34] incinerator plant (wt%)	Bottom ash [73] from Taiwan incinerator plant (wt%)
CaO	15.3	32.96	14.4	17.83
SiO ₂	56.7	12.41	53.7	22.9
Al ₂ O ₃	7.5	8.06	21.6	0.19
TiO ₂	0.8	2.18	–	–
Fe ₂ O ₃	1.6	2.35	3.1	11.4
MgO	1.5	2.23	1.9	1.05
Na ₂ O	1.5	5.15	8.2	3.69
K ₂ O	1.8	1.92	2.1	–
ZnO	0.3	–	–	–
Cl ⁻	–	–	0.43	–
S	–	–	0.08	–

Table 3

APC residue composition data and range of concentrations typically leached using the L/S = 10 EU compliance leaching test for granular wastes BS EN 12457-3 [29]

APC residues composition data	Aqua regia total metals/water soluble ions (mg/kg)
Al	10,000–24,000
As	10–210
Ba	70–400
Ca	30–35% (w/w)
Cd	100–150
Co	9–14
Cr	12–200
Cu	350–600
Fe	3000–5200
Hg	<1–16
K	9000–24,000
Mg	4000–6000
Mn	350–500
Mo	2–13
Na	13,500–20,500
Ni	15–35
P	1500–3000
Pb	2500–3500
Sb	200–500
Se	0.1–6
Sj ^a	Nd
Sn	200–800
Ti	900–4000
Tl	0.5–0.8
V	<30
Zn	4000–8500
Water extractions	
Br	1000–2000
F	100–1500
Cl	16 wt%
Water soluble ^b SO ₄ CO ₃ as CaCO ₃	0.8–3 wt%
CO ₃ as CaCO ₃	10,000–45,000
Water soluble alkalinity as CaCO ₃	–
Water soluble OH as CaCO ₃	–
NH ₃ –N	<5
NO ₃ –N	–
Total N	–
pH	12.0–12.6
Sulphite	200–600
Free lime %w/w CaO	150,000–200,000
Insoluble matter %w/w	–
%w/w Ca(OH) ₂	–
Total phenols (ng/g)	<0.03
Total PAHs (ng/g)	–
PCDD/DF (ITEQ ng/g)	0.5–1.3
Total carbon	10,000–250,000
Total organic carbon	10,000–250,000
VM (%) (LOI)	1.5–2.7

^a Nd: not determined.

^b NB: high SO₄ values may have been calculated from S determinations on digests (i.e. include other S forms).

Single-stage crystallisation heat treatments were performed on bulky samples in chamber furnaces at different temperatures with the objective of comparing the vitrified products in terms of microstructure. The main crystalline phases obtained were wollastonite (CaSiO₃) (the majority) and anorthite (CaAl₂Si₂O₈) [30].

The vaporisation behaviour of heavy metals in the melt produced by plasma treatment of incinerated ashes has been determined [31,32]. The results showed that the operational conditions play an important role in optimising the thermal treatment of ashes. A high partial pressure in the carrier gas, or a low waste chlorine content resulted in an improvement of the retention of heavy metals in the slag. A washing pre-treatment was proposed to reduce the chlorine content in the waste [33], although this would give rise to additional problems including larger volumes of liquid effluent and

higher plasma energy requirements due to the wet character of the as-washed ash.

The effectiveness of slag encapsulation, the degradation of dioxins and the possible reuse of the generated slag and metal products have been investigated for IBA and fly ash mixes in Japan [34]. A DC transferred arc plasma furnace was run for over 28 months. Tests on the water-cooled slag indicated a lead content of no more than 0.01 mg/l with no traces of dioxins. The slag had suitable physical properties for use in combination with other materials for the fabrication of interlocking building blocks.

Similar tests have been conducted using wet IBA from a MSW incinerator in Japan using a DC graphite-electrode plasma melting furnace with nitrogen as the plasma gas [35,36]. Molten iron and copper present in the IBA were discharged in the bottom of the furnace. The concentration of lead, cadmium and Cr⁺⁶ in the slag was very low (Pb and Cd: 0.01 mg/l) and 99.9% of dioxins and furans was destroyed [35,36].

The incinerated ash from a MSW incinerator in Taipei was melted in a 100 kW non-transferred arc plasma laboratory-scale torch at the Institute of Nuclear Energy Research (INER) in Taiwan [37]. Argon was used for ignition of the plasma, and nitrogen was used as the carrier gas during treatment. Heavy metals originally in the incinerated ash were encapsulated in the vitrified silica network, resulting in very low leachability. A one-stage heat treatment process applied to a plasma vitrified slag formed a glass-ceramic which consisted predominantly of a melilite Ca₂(Mg_{0.5}Al_{0.5})(Si_{1.5}Al_{0.5}O₂) group solid solution, gehlenite (Ca₂Al₂SiO₇) and akermanite (Ca₂MgSi₂O₇) [37].

A non-transferred plasma torch with a tungsten cathode and copper anode was used in Korea to evaluate the reduction in volume and removal of hazardous elements in fly ash and sludge from wastewater treatment on a laboratory scale [38]. The leaching test on the vitrified slag showed that metals, such as copper, zinc and lead and other heavy metals leached below the regulatory limits. Plasma treated mixes of fly ash and sludge also had leachabilities below the regulatory limit.

Recently, APC residues from a major WtE plant in London, UK have been plasma treated. APC residues were blended with silica (21.9 wt%) and alumina (8.3 wt%), and the mix melted using a DC plasma transferred arc furnace. Waste acceptance criteria (WAC) leach testing demonstrated that the APC residue derived glass released only trace levels of chloride (0.2 mg/kg) and metals (lead (0.007 mg/kg) and zinc (0.02 mg/kg) [39].

3.3. Asbestos-containing residues

Fatal pulmonary disease can be caused by the presence of even very low concentrations of asbestos fibres in the lungs [40]. The chemical and physical properties of asbestos are shown in Table 4. Asbestos-containing wastes can be immobilised by solidification using cement [41] or polymeric resins [42], but plasma processing offers a complete destruction capability.

A number of different kinds of asbestos were tested in an experimental plasma facility using argon gas. It was possible to produce slag having a hard surface, inhibiting the formation of dust, although the interior was much more brittle than the surface due to the low thermal conductivity of asbestos. Additional experiments concluded that it was possible to convert asbestos into a rocklike structure (hardness of 6 Mohs) by reducing the sample thickness and melting [43,44]. Plasma treatment of asbestos resulted in a volume and weight reduction of 51% and 70%, respectively. This effect was reported to be due to the removal of water of crystallisation accumulated from the wet removal process and suggests that this was only a partial treatment.

Table 4
Chemical and physical properties of six kinds of asbestos [44]

	Chrysolite	Anthophyllite	Amosite	Tremolite	Actinolite	Crocidolite
Hardness (Hv) (GPa)	2.5–4.0	5.5–6.0	5.5–6.0	5.5	6.0	4.0
Specific density (g/cc)	2.4–2.6	2.85–3.1	3.1–3.25	2.9–3.2	3.0–3.2	3.2–3.3
Specific heat (J kg ⁻¹ K ⁻¹)	0.266	0.210	0.198	0.212	0.217	0.201
Tensile strength (kg/cm ²)	30,000	2,800	25,000	70–560	70	35,000
Temperature of maximum weight reduction (°C)	982	982	871–982	982		649
Filtration ability	Slow	Medium	Fast	Medium	Medium	Fast
Electrical charge	Positive	Negative	Negative	Negative	Negative	Negative
Melting point (°C)	1521	1468	1399	1316	1393	1193
Spinnability	Good	Poor	Good	Poor	Poor	Good
Flexibility	High	Poor	Good	Poor	Poor	Good
Heat resistance	Good. Brittle at high temperature	Excellent	Good. Brittle at high temperature	Good		Poor. Melts at high temperature
Acid resistance	Weak	Medium	Medium	Very strong	Strong	Strong
Alkali resistance	Very strong	Strong	Strong	Very strong	Strong	Strong
Decomposition temperature (°C)	450–700	620–960	600–800	600–850	950–1040	400–600

A commercial facility in France (INERTAM) provides asbestos waste treatment using high-temperature plasma vitrification with air as the plasma gas. This enables the transformation without prior selection of wastes contaminated with asbestos into an inert, non-leachable, fibre-free product [40].

The treatment of asbestos-containing materials by plasma technology has also been successfully undertaken in the UK by Tetronics Limited. A transferred arc plasma furnace operating at 1600 °C, in a negative pressure tented enclosure was used to melt a variety of asbestos-containing materials. This treatment was effective in destroying all the asbestos polymorphs and converting them into a monolith comprising a gehlenite-akermanite solid solution. Analyses completed by an independent government laboratory detected no asbestos fibres in the final wasteform, in the reactor, or in the downstream duct work. This work showed that high-temperature plasma treatment was successful in completely destroying asbestos in a safe manner [45].

3.4. Healthcare wastes

The number of healthcare facilities and with them the amount of wastes they generate are increasing. Hospitals, medical and dental surgeries, maternity units, nursing homes and medical research facilities produce large quantities of hazardous healthcare wastes [46]. This is a major issue and significant changes are expected in the future of healthcare waste management and disposal to meet progressively more stringent regulatory requirements and increasing public concerns about communicable diseases [47].

Healthcare waste is classified into two categories: (i) general waste, which is not potentially dangerous and does not require special handling and disposal, and (ii) hazardous waste, which requires special handling, treatment and disposal. This is primarily due to infectious waste, which can be contaminated by pathogenic micro-organisms. This class of waste is further sub-classified into prescription-only medicines (POMs), sharps, etc.

Healthcare wastes can include anatomical wastes (tissues, organs), blood and body fluids, pathological and highly infectious wastes, and discarded medicines. The high temperatures and ultraviolet radiation associated with thermal plasmas can kill all bacteria and micro-organisms. They can also destroy drug structures, the active ingredients of which are only a small fraction of the actual mass, e.g. cytostatic and cytotoxic drugs [46,47].

Hospital fly ashes have been treated in a DC thermal plasma reactor at the Technical University of Lodz in Poland [49]. The furnace was water cooled and the transferred arc-plasma system had a maximum output power of 150 kW. The molten waste was kept

at 1550–1600 °C for 30 min, and then air cooled to room temperature. Glass-ceramics were prepared by controlled crystallisation of the plasma treated glass. As a result of the heat treatment, different crystalline phases were obtained. Wollastonite (CaSiO₃) was observed to be the major crystalline phase present in materials treated using the optimum thermal treatment and this is associated with high mechanical resistance [49].

The same plasma furnace was used to treat bottom ash from a hospital incinerator. This was mixed at different ratios with fly ash from a coal fired power plant. The chemical composition of the ashes is indicated in Table 5. The product obtained was homogeneous and vitreous in nature. Leach testing was undertaken using demineralised water with the concentrations of ions in the leachate determined by anodic stripping and the final product appeared to be resistant to leaching. The Vickers hardness of the vitrified samples was shown to depend on the mixture composition and varied between 480 and 520 Hv [49].

An indirect plasma heating system was used by the Institute of Nuclear Research in Taiwan for the thermal vitrification of mixed medical waste surrogates [47]. The heat source was a 100 kW non-transferred arc generated plasma torch, using argon as the plasma gas for ignition. After ignition, air was used during the treatment. The waste surrogates were categorised into two groups: combustibles (pork ribs, tongue presses, gauzes, swabs and absorbents) and non-combustibles (glass, stainless steel, sharps, needles and syringes). Processing lasted for 15 min at 1550 °C and the product obtained was a dispersed, metal-bearing second phase embedded

Table 5
Chemical analysis of the hospital incineration bottom ash and coal power plant fly ash [49]

Oxide	Content (wt%)	
	Hospital incinerator bottom ash	Coal power plant fly ash
SiO ₂	47.35	50.02
Al ₂ O ₃	3.05	23.20
Fe ₂ O ₃	7.35	9.25
Mn ₃ O ₄	^a	0.15
TiO ₂	^a	0.96
CaO	16.25	4.08
Na ₂ O	^a	0.96
MgO	2.45	2.48
K ₂ O	^a	3.40
P ₂ O ₅	0.30	0.32
SO ₃	0.48	0.52
Organic compounds	^a	4.25

^a Contents not measured.

Table 6
Quantities of solid waste generated worldwide annually in the steel industry [51]

	World (Mtons)	Major concerns
BOF slag	90	Free lime, heavy metals
EAF slag	25	Leaching of heavy metals
BOF dust	15	Too low Zn for recovery
EAF dust	4	Too high Zn for recycling Hazardous wastes

within the matrix of vitrified glassy slag. The products were subjected to the toxicity characteristic leaching procedure (TCLP), with leachate analysis undertaken by atomic absorption spectrometry (AAS). This showed low leachability [47].

The performance of plasma torch systems for treating medical wastes has been tested in Korea using various surrogate model waste mixtures [50]. Two main plasma torches were used in the experiments denoted N1 and N2. Plasma torch N1 had a power of 40–45 kW, an air flow rate of 4–6 g/s and a plasma jet temperature of 3000–4000 K. Plasma torch N2 had a power of 65–85 kW, an air flow of 7–9 g/s and a jet temperature of 2500–4000 K. The heating time was 2–3 h. When operating with plasma torch N1, the furnace temperature in the bath region did not exceed 1250–1300 °C. The melt was shown to have a high viscosity and did not flow out of the bath. When operating with plasma torch N2, the temperature exceeded 1500 °C and the accumulated slag flowed out into the slag collector. The slag obtained was vitreous and chemically resistant, did not contain any organic components and had a density of 2600–2800 kg/m³ [50].

Plasma technologies have been compared with conventional waste treatment in experiments with simulated hospital wastes, at the Institute for Plasma Research in India, using a 50 kW DC transferred arc plasma reactor [46]. The simulated medical waste consisted of a 2:1 mix of cotton and plastic. The results showed that the gases obtained after pyrolysis were rich in hydrogen and carbon monoxide, with some lower molecular weight hydrocarbons, and that they could be used to recover energy. After combustion in a second chamber, in the presence of excess air, negligible quantities of toxic gases were present. It was also observed that *B. subtilis* and *B. stearothermophilus* bacteria (spores) were completely destroyed when they were exposed to the reactive environment of plasma due to the high temperatures [46].

3.5. Wastes from steelmaking

The steelmaking industry generates large quantities of dust and sludge-containing metals such as iron, zinc, lead, chromium, nickel and molybdenum. The metal content in these wastes is sometimes very high and it is, therefore, economically viable to extract and recycle them due to their value as a process credit. Moreover, these wastes are regarded as hazardous because of the leachability of hazardous components.

Large quantities of slag and dust arise worldwide from basic oxygen furnaces (BOF) and electric arc furnaces as shown in Table 6. In addition to those wastes listed, considerable amounts of blast furnace (BF) slag, millscale, oily millscale and hydroxide sludge are produced [51].

EAF dust from carbon steel and stainless steel making has been classified as hazardous waste because of its high alkalinity and high content of heavy metals. The dust typically contains significant amounts of zinc and lead, which prevent it from being landfilled without pre-treatment. At present most steel plants have to pay for external treatment and disposal. Mill-scale is usually recycled back to the primary furnaces such as sinter plants, BFs or EAFs. Oily mill-scale and hydroxide sludge need to be dis-

posed of because there are no appropriate treatment technologies [51].

The solid wastes generated from the steel industry mainly consist of [51]

- stable oxides such as calcia, silica and alumina;
- oxides of iron, chromium, nickel, manganese and phosphorus;
- volatile metals such as zinc, lead and cadmium.

There are several possibilities for the treatment of these wastes including vitrification into a glassy slag, recovery of metals by oxide reduction, or a combination of both. Plasma can be successfully employed for all of these processes. The reduction of the oxides can be performed with a reducing plasma gas or with reducing additives (e.g. carbon). Metals such as zinc and lead can be collected as a melt or condensed from the vapor phase. The high temperature of the plasma also allows vitrification of the residuals after the recycling step [52].

PLASMADUST technology [53], which combines a plasma gas heater with a coke-filled shaft furnace, produces alloyed molten iron, metallic zinc and lead vapor from steelmaking dust. More recently, plasma arc centrifugal technology has been developed to process hazardous metallurgical and military wastes. The carbothermic reduction of steelmaking dust containing mainly iron and zinc has been undertaken using a transferred arc plasma furnace, resulting in a non-toxic slag and metallic zinc as products.

Ye et al. [51] have summarised the plasma treatment of some steelmaking wastes in a research study on slag reduction for the recovery of valuable metals and oxide materials using a DC plasma furnace. The chosen reactor for the tests was a DC furnace with a hollow electrode for the simultaneous treatment of slags and dusts including volatile metals such as zinc and lead. Besides the steel slags, EAF dust, millscale, oily millscale, BOF dust, BF dust, hydroxide sludge and scrap residue were also treated. The reductants used included coke breeze, anthracite and petroleum coke. Other materials used were slag formers, such as sand and bauxite, for slag modification. On average, the chromium recovery was over 90% and nickel recovery close to 100%. The leaching of chromium from the reduced slag was 10–100 times lower than that of the untreated reference slag. It was demonstrated that, at pilot plant scale, a DC plasma furnace with a hollow electrode is a flexible and efficient reactor for the treatment of steel slag and for most other solid wastes generated within a steel plant. Metals such as iron, vanadium, chromium and nickel were recovered in a metal alloy phase and the stable oxides were transferred into various slag products [51].

The feasibility of reducing the zinc oxide from EAF dust under a carbon monoxide atmosphere was studied in an AC plasma reactor. Zinc recovery up to 97% was obtained and the degree of lead removal was similar [54].

Contrary to the above technologies, which are based on arc plasma furnaces, a radio frequency plasma system can process fine powders without granulation in a continuous operation. This possibility, together with the advantageous features of thermal plasma (see Section 2.2), offers great potential for the synthesis of special ceramic powders, such as spinel ferrites [55,56].

Two wastes of different origin and composition, a precipitated, dried sludge from the hot galvanizing process and a converter flue dust from steelmaking, were treated in a RF thermal plasma reactor. The components were mixed in a ratio to give the optimum iron/zinc ratio for a zinc ferrite and other compositions [55].

3.6. Electroplating waste

Many industrial components are electroplated to avoid structural degradation due to wear and corrosion. The wastewater from

the electroplating industry contains metals such as zinc, chromium and nickel which are hazardous to the environment. In many countries, environmental protection authorities are imposing laws to prevent the discarding of electroplating wastewater without first removing the hazardous components.

Electroplating sludge has been treated by a DC non-transferred arc process with a number of different plasma gas environments at reduced pressure [57]. Electroplating sludge with a particle size <45 μm , was fed into the plasma using different plasma gas environments. After plasma treatment, powders were collected from the top, bottom and wall of the reactor and deposits in the furnace were also analysed. Chromium, nickel and zinc were identified in the form of ferrite/chromite $[(\text{Ni,Zn,Fe})(\text{Fe,Cr})_2\text{O}_4]$ in the powders and deposits [57,58].

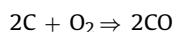
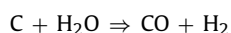
3.7. Aluminium dross

In aluminium recycling dross is produced when the surface of the molten metal reacts with the furnace atmosphere. In general, this waste represents 1–5 wt% of the melt, depending on the process and contains up to 10 wt% free aluminium [59]. It is classified as hazardous waste because of the content of leachable chlorides and fluorides. It is inhomogeneous and unstable releasing gases such as ammonia and methane on contact with moisture. Moreover, since aluminium production is highly energy intensive, dross recycling is very attractive. Thermal plasma processes have been applied to dissolve the dross, and the experimental results of plasma arc treatment have been described in the literature [60].

3.8. Carbon-containing wastes

Several studies have been conducted to determine whether thermal plasma processes can be used for the gasification of carbonaceous wastes in order to reduce their weight and volume and to produce synthesis gas (hydrogen + carbon monoxide + hydrocarbon fractions) [15,61,62].

Nishikawa et al. [61] studied the feasibility of using thermal plasma with steam for the treatment of carbonaceous wastes. The experiment was carried out in a hybrid plasma system (DC plasma torch + RF plasma torch), a gas control system, a steam generator, an exhaust system and a reaction chamber. Argon was used as the plasma gas and carrier gas and oxygen and steam were used as oxidants. Charcoal with sodium chloride was used as a test piece instead of carbonaceous wastes. Three different conditions were tested. The first was treatment by argon thermal plasma alone, the second with argon thermal plasma and oxygen and the third by argon thermal plasma and steam. The results showed that the charcoal experienced a large weight loss when treated by thermal plasma with oxygen and by thermal plasma with steam. In the first case the reaction was as a result of the combustion and in the second case it occurred as a result of pyrolysis and gasification. The gasification of carbon with water is as follows:



It was concluded that the gasification of carbon by thermal plasma with steam is very effective for the disposal of carbonaceous wastes.

The same system was used to investigate the gasification of carbonaceous wastes using graphite as a test piece [63]. The test was carried out using two different experimental conditions: argon plasma and argon/steam plasma which was generated by adding steam to argon plasma. The results showed a larger weight reduc-

tion in the case of steam plasma than in the case of the argon plasma. The weight reduction was due to the pyrolysis and gasification of graphite and more detail of the interaction of the steam plasma with carbon is given in Ref. [63].

3.9. Chlorine-containing wastes

Incineration is not an effective solution for treating chloride compounds because dioxins and furans, produced by incomplete oxidation, remain in the off-gases as thermally persistent species. Undesirably, the waste heat recovery zone of WtE plants is an ideal location for the reformation of dioxins and furans. Pyrolysis followed by gasification by thermal plasma is a very attractive solution for these kinds of wastes because of the possibility of incorporating a dwell of at least 4 s at 1200 °C and rapid cooling from this temperature to minimise the possibility of forming dioxins or furans [64–66].

Dioxin formation is favoured by low oxygen, high carbon monoxide concentration, high dust particulate levels, the presence of catalytic metals, such as copper, on the surface of the particulates and a temperature regime between ~250 and 350 °C.

The destruction of carbon tetrachloride was investigated using a plasma torch consisting of two graphite electrodes coupled with a pneumatic nebuliser [67]. Argon was used to form the plasma and another auxiliary argon stream was used to carry and nebulise liquid materials into the plasma. The gases produced were analysed by a solid-phase micro-extraction system (SPME). The efficiency of destruction of carbon tetrachloride was calculated as the ratio between the carbon tetrachloride chromatography signal obtained with the thermal plasma turned off and the carbon tetrachloride chromatography signal with the thermal plasma turned on. When the aspiration rate of the sample for maintaining equilibrium between the aerosols formed and the plasma was the optimum for complete pyrolysis, the destruction and removal efficiency of carbon tetrachloride was very high.

3.10. Other wastes treated by plasma technology

Fibre reinforced polymeric matrix composite (FRPC) materials have widespread use in maritime applications, such as boat hulls and superstructures, chemical tanks, aircraft and specialist cars. Because the matrices of FRPCs are usually thermosetting or aramid polymers they are a non-combustible waste. Thermal plasma treatment of a mixture of FRPC, gill net and waste glass has been investigated [68]. The plasma furnace was a DC non-transferred arc type. Argon was used initially for generating the plasma and air was then used as the main ambient gas during the vitrification process [68]. The process was carried out for 1 h at 1250 °C. Different compositions of FRPC, gill net and waste glass were added to the plasma and all the slags obtained were amorphous. The vitrified slag was further heat treated to form a glass-ceramic by a heat treatment using additives. Leaching of iron and aluminium was tested and resulted in low values (<1 mg/l). The results suggested that these elements were present either as network forming oxides or as network modifiers as the data indicate their incorporation into the glassy network [68].

4. Applications of vitrified products and viability

Vitrified slags produced from a variety of waste materials have been shown to have low leachabilities. If so, they may meet the waste acceptance criteria enforced in the EU, and be classified as inert waste, in which case they are acceptable for landfill or other applications. The physical properties of some slags are shown in Table 7. Granulated slag has mainly been reused for roadbed

Table 7
Physical properties of slag produced from incinerator ashes in different plasma systems

Properties	Granular slag from a mix of bottom ash and fly ash [34]		Slag from fly ash [36]		Water cooled from a mix of bottom ash and fly ash (75:25) [69]	Aggregate standard	Crush stone standard
	Water cooled	Air cooled	Water cooled	Air cooled			
Specific gravity (g/cc)	2.967	3.026	2.65	2.65	2.665	Over 2.5	Over 2.5
Optimum moisture (%)			3.6	2.8	11		
Absorption rate (%)	1.93	0.2	0.75	0.12	1.774	Under 2.0	Under 2.0
Stability (%)	6.0	1.1	<1	<1	10.7	Under 12	Under 20
Abrasion loss (%)	43.4	20.4	50–60	30–35	14.7	Under 30	Under 40

Table 8
Properties of glass–ceramics obtained after heat treatment of the vitrified product of plasma treatment (slag)

Properties	Vitrified fly ash (heat treated at 1050 °C) [30]	Vitrified ash incinerator (one step heat treatment at 850 °C) [37]	Fiber reinforced plastic, grill net, glass (4/1/1) + 13.2 wt% (Ca(OH) ₂) [68]
Main crystalline phases	Wollastonite anorthite	Albita, anorthite, wollastonite cristobalite	Gehlenite akermanite
Density (g/cm ³)	–	2.99	2.6
Thermal expansion coefficient ($\times 10^6$ C ⁻¹)	–	9.85	–
Four-point bending strength (MPa)	–	–	82
Compressive strength (MPa)	–	–	297
Water adsorption (%)	–	0.28	0
Knoop hardness (GPa)	–	4.84	–
Mohs' hardness	7	7.0	–
Chemical	20 wt% HCl	–	1 wt% H ₂ SO ₄
Resistance (wt%)	0.45	–	1.79
	20 wt% NaOH	–	1 wt% NaOH
	2.67	–	0.12

(asphalt mixtures) and concrete aggregates, but cast slag can also be reused as a secondary product (e.g. interlocking blocks, tiles and bricks).

Water-permeable blocks and pavement bricks have been made from slag produced by a commercial plasma melting plant in Japan [35,69]. The end result satisfied the required product standards and showed limited leaching of heavy metals. An interlocking block, pavement brick, and a decorative permeable brick were made from granular slag in combination with other materials, such as cement or gravel. It was shown that the products had sufficient strength to meet the performance standards for this kind of product [34,35].

Vitrification, followed by appropriate heat treatment, can result in the production of glass–ceramics, a product with enhanced properties and added value [70,71]. Table 8 shows the various properties of glass–ceramic materials obtained by crystallisation of the vitrified products from the plasma treatment of incinerator wastes.

The ultimate success of a technology will be determined not only by technical performance, but also by cost. The major disadvantage of the plasma process is the use of electricity as the energy source which influences the process economics unfavourably. The main economic advantage of plasma vitrification of wastes lies in the cost savings associated with landfill tax avoidance and the added value of the potentially reusable by-products and the end product, i.e. within a regulatory context, it is regarded as a recovery, as opposed to a disposal, technology.

Indeed the cost of the plant (including off-gas treatment), energy, the cost of labour, flexibility in terms of waste composition accepted, economic incentives from local government agencies and the existence of local laws regulating the handling/recycling of hazardous wastes, must all be considered for complete appreciation of the economics of the technology. Only few estimates of the cost of treatment by plasma arc technology have been made [72]. These estimates are made at early stage development of a technology and they tend to be highly inaccurate. It is, therefore, important to begin to collect accurate cost data in a way that can be compared to other technologies and to other applications of the same technology.

As an example, based on local UK conditions, e.g. electrical power costs, plasma treatment of APC residue (see Section 3.2) has operational costs of circa £ G60 per tonne of APC residue. When the equipment capital costs, project preliminaries and financing charges are included within the calculation the specific treatment costs are circa £ G100 per tonne of APC residue. This is economically advantaged when compared to current integrated disposal cost of APC residues using landfill technology, i.e. haulage, pre-treatment, gate fees and landfill tax. This advantage will increase as the landfill tax escalator takes effect; providing a “future-proof” solution character for plasma technology. In a demographic context this equates to a centralised treatment solution addressing the mass arising from two to three large EFW plants. The technology is therefore a ‘proximal’ solution, minimising waste miles and the impacts of hazardous waste transport and management addressing the socio-political requirements of regional development plans and policy. In the case of APC residues, these are one of only a few remaining hazardous wastes that are not recovered and therefore they are subject to increasing political attention. Furthermore, the direct comparison with landfill is not totally appropriate as the landfill solution is a disposal technique, whereas the plasma-based solution is a recovery technique, i.e. only 5% (w/w) of the input ends up as secondary waste. All other material values are categorised as recovered products at the point they are produced, as discussed in the previous sections.

5. Conclusions

In reviewing the applications of thermal plasma generating technologies applied to the treatment of a broad variety of wastes, it is clear that there have been continued advances towards the further development of the plasma technology in the environmental field. The analysis of the published investigations indicates that thermal plasma is a promising alternative to conventional and industrially mature thermal processes and the regulatory, economic and socio-political drivers favour the adoption of advanced thermal conversion techniques such as plasma for waste treatment.

Although the technical feasibility of plasma vitrification technology has been demonstrated for several hazardous wastes, it is not clear that the plasma treatment of wastes on a large scale is economically viable. The lack of sufficient control combined with economic drawbacks in some cases, have been the main obstacles to the growth of thermal plasma technology. It is clear, however, that the avoidance of landfill charges, the added value of the reuse of the vitrified product, the energy production from syngas and the recovery of metals, together improve the commercial viability of the process.

In addition, social issues associated with the use of materials produced from wastes must be tackled because this is still an impediment to the broad use of waste materials in new products, affecting not only plasma technology but also other waste treatment processes.

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