INTRODUCTION

Wastes treatment is a major environmental problem challenging the present generation. As traditional means or ways of disposal of waste such as ocean dumping, landfilling etc. are no longer acceptable or becoming more difficult due to tight regulation introduced in most countries. Therefore, there is the need to eliminate, utilise or properly treat wastes. Incineration has been continuously used for reduction of waste, but its disadvantage of high cost of off-gas clean-up and generation of residue containing hazardous substances such as dioxin, furans and heavy metals makes it non-viable option. Recent times, thermal plasma treatment technology has become a fascinating idea for waste treatment especially hazardous waste prior to disposal. The target is to destroy the organic fraction and convert the inorganic fraction into an inert silicate slag, or glasses, which can either be reused, or harmlessly disposed of in an inert landfill (Gomez et al., 2009).

1.1. Plasma Technology:

Plasma technology basically involves the creation of a sustained electrical arc by passing electric current through a gas in a process referred to as electrical breakdown. Since electrical resistivity exist across the system, significant heat is generated, which strips away electrons from the gas molecules resulting in an ionised gas stream, or plasma. Air is the most common gas used, but several inert gases (N2, He, Ar etc.) have been widely used (Hrabovský, 2002; Watanabe and Shimbara, 2003). In order for air to conduct electricity, it must be subjected to a large differential in electrical potential. This is done between two electrodes which are separated by air. When this potential is large enough, electrons can be pulled from the normally neutral molecules in the air. These electrons then move with the electric field and impact other molecules, releasing more free electrons at an exponential rate. This phenomenon is called an electron cascade and once enough electrons are moving with the electric field, an arc is created between the electrodes. At temperatures of about 3000°C gas molecules lose electrons and become ionised (Aucilippo and Flamm, 1989). Temperatures of 20000 °C and above is attainable with electrically generated plasma (Gomez et al., 2009). With plasma, it is possible to treat waste of varying quality such as waste with a high concentration of inorganic material and a very low heating value. Thermal plasma has the additional advantages of high throughput with compact reactor geometry and high quench rate that allows specific gas and solid material compositions to be obtained. Also when compared with combustion of fossil fuels it has a low gas flow rate which reduces the need for off gas treatment. In the past decade, thermal plasma technology has been extensively used for the treatment of various kind of Toxic or hazardous waste (Bonizzoni and Vassallo, 2002; Karoly et al., 2007; Katou et al., 2001; Liu et al., 2011; Pan et al., 2008; Tu et al., 2008b; Wang et al., 2009).

The exposure of waste to extreme temperatures generated by plasma result in many possible reactions such as combustion, pyrolysis, gasification
and vitrification. The type of the reaction depends on the nature of the material and on the surrounding conditions, such as the amount of oxygen in the atmosphere where the plasma treatment is occurring. Despite the economic disadvantage in the use of electric power as the energy source. A complete cost benefit analysis has demonstrated its economic viability for treatment of wastes. Thermal plasma has a wide range of application that includes synthesis of Nano powders, destruction and treatment of hazardous waste, metallurgy application (smelting operations and remelting application in large furnaces) surface modification and coating, chemical synthesis (Boulos, 1996). In Vitrification process, inorganic components such as silicate are melted into a viscous liquid which traps heavy metals into a solid matrix once solidified. The process converts the inorganic fraction of the waste into a non-leachable material which can be used as construction material. Heavy metals or toxic elements present in the waste are locked in a silicate matrix and are highly resistant to leaching to the environment. Gasification which is a thermal degradation of carbon based organic materials into a gas takes place between high temperatures of 400°C to 1500°C (Min and Yoshikawa, 2004).The process is carried out in an oxygen starved environment, preventing the combustion of carbon to CO₂.

1.2. Types of Plasma:
There are basically two types of plasma for industrial processes: thermal or (equilibrium) plasmas and non-equilibrium plasmas.

1. Thermal “equilibrium” plasma. It is characterised by a high-energy density and the quality of temperature of the heavy particles (atoms, molecules and ions) and electrons. Due to their very high mobility, the energy given to the plasma is captured by the electrons and transferred to the heavy particles by elastic collision (Boulos, 1991; Kogelschatz, 2004). Also, because of the high electron number density, associated with operation at atmospheric pressure, elastic collision frequencies are very high and thermal equilibrium is rapidly reached. Examples of thermal plasma are those produced in radio frequency (RF) inductively coupled discharges and by direct current (DC) plasma torches (Boulos, 1996).

2. Non equilibrium plasma. They are also referred to as “cold” plasmas. These types of 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 when compared to thermal plasmas. The ions, atoms and molecules remain relatively cold and do not cause thermal damage to the surfaces with which they come into contact. They are used as local surface modification or surface activation. These plasmas are generated in low-pressure RF discharges and various types of glow discharge.

1.3. Plasma generation:
Plasma production methods used to treat hazardous wastes include: DC plasma torches (transferred and non-transferred configurations), and (RF) inductively coupled plasma devices (Gleizes et al., 2005). Figure 1 is a schematic diagram for DC arc plasma (transfer and non-transfer) and RF inductively coupled plasma (Tatarova et al., 2014).

With the exception of (RF) inductively coupled plasma devices, other technologies generate a high energy and high temperature plasma discharge between two electrodes in the presence of a sufficiently high characterising gas flow with the plasma extending beyond one of the electrodes in the form of a high enthalpy plasma jet. Arc plasmas is the most commonly used in term of waste treatment because they are relatively insensitive to changes in process conditions. The generated arc plasma are used in two mode (transfer and non-transfer). It is a transfer arc when one of the electrodes is usually the material to be treated while a non-transfer arc if the arc is contained inside a plasma torch and plasma jet exiting the torch is used for treatment (Heberlein, 1993; Joachim and Anthony, 2008). In the transferred arc configuration, the waste material is exposed to the arc plasma which typically has peak temperatures of 12 000 to over 20,000 K, depending on plasma gas, location in the arc and the cooling of the arc. The plasma exiting the water cooled plasma torch in non-transfer arc plasma torch has peak temperatures of 10000K-14000K (Joachim and Anthony, 2008). Most of the plasma arc generators use direct current rather than alternative current because of its more stable...
operation, power efficiency, longevity of electrode and lower refractory wear. According to Joachim and Anthony (2008) the approach for plasma treatment of different types of waste may consist of the following:

a. Thermal break down of chemical components without oxidation which is called plasma pyrolysis.

b. The incomplete oxidation of organic fraction of waste and generation of syngas and other gases which can be used to generate electric power or drive steam turbines known as plasma gasification.

c. Compaction and verification of solid wastes by gasifying organic material, melting inorganic material eliminating voids and binding hazardous metals in a ceramic matrix (e.g. a silicate).

d. The integration of plasma pyrolysis, compaction and vitrification process or a combination of plasma gasification, compaction and vitrification can be applied for solids with high fractions of organic.

2. Thermal Plasma Waste Treatment:
2.1. Incineration bottom ash, fly ash and air pollution control residue:

Incineration bottom ash (IBA) is primarily a coarse, heterogeneous, non-combustible materials and unburned organic matter collected in a quenching-cooling tank at the outlet of the combustion chamber. Air pollution control (APC) residue is of fine particle size and generally contains high concentrations of heavy metals and soluble/volatile salts. They also contain hazardous organic compounds such as dioxins and furans. Its high alkalinity, high leachability of heavy metals and the high level of soluble anions, such as chlorides, make APC residues difficult to manage. Fly ash consists of finely divided particles that are removed by a combination of precipitators and cyclones before further treatment of the gaseous effluents. Fly ashes from incinerators have high heavy metals, dioxin and furans (Martha et al., 2009; Sukandar et al., 2006; Yang et al., 2007; Zhao et al., 2010; Zhao et al., 2008).

In 2013, a melting process based on a direct current thermal plasma torch has been developed to convert medical waste incineration (MWI) fly ash into harmless slag (Xinchao et al., 2013). Investigation was conducted on the density and micro-structure of the original ash and melted slag to evaluate the performance of the plasma melting process. The effect of the treatment on the destruction of PCDD/Fs and the immobilization of heavy metals was also examined. The working gas of the plasma torch was argon and its flow rate was varied from 12 to 14 L/min. The double arc plasma torch was operated in direct current mode with typically 20–30 V/100 A for the first arc and 50–60 V/100 A for the second arc. The temperature of the argon plasma jet near the torch exit is about 11,000 K, and the heat flux of the plasma jet around 65 kW/m² at 14 cm downstream from the plasma torch exit (Tu et al., 2007; Tu et al., 2008a). Samples were collected from different medical waste incinerator FA1 and FA2. The physicochemical properties of the samples indicate major elements in FA1 were oxygen, calcium and chlorine, while oxygen, carbon, and silicon were the major elements of FA2. Both fly ashes contained high concentrations of heavy metals, especially zinc and lead. Also the ash content (incombustible inorganics) of FA1 was 81.85%, much higher than that of FA2, which was only 34.45%. The experimental results show that the decomposition rate of PCDD/Fs is over 99% in toxic equivalent quantity value and the leaching of heavy metals in the slag decreased significantly after treatment. The produced slag has a compact and homogeneous microstructure with density of up to 2.8 g/cm³ (Xinchao et al., 2013). Previous researches carried out indicates that ashes brought out more than 90% of polychlorinated dibenzo-p-dioxins dibenzofurans (PCDD/Fs, as l-TEQ), polybrominated diphenyl ethers (PBDEs, as TEQs), and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) from an incinerator (Chiu et al., 2011; Lin et al., 2010; Wang et al., 2010).

The mass distribution of metals and the crystalline characteristics of slag during the vitrification of incinerator fly ash from bag house filters of a municipal solid waste incinerator located in southern Taiwan were investigated (Yi-Ming et al., 2012). The premixed powdery specimens were held in graphite crucibles, and then heated in a vitrification furnace (Dengying DFH-30). The specimens were heated from 25 to 1000°C at a heating rate of 6 °C/min, from 1000°C to 1450°C with a heating rate of 4 °C/min, isothermal held at 1450°C for 0.5 h and cooled to room temperature without any convection. The vitrification shows, metals with low boiling points (Cd, Pb, and Zn) vaporized into flue gas as particulate phase. High levels of Pb and Zn of 315,000 mg/kg and 226,000 mg/kg respectively made the particulate phase worth reclaiming. Metals with high boiling points mainly stayed in the slag. Major crystalline phases of the slag were 15.9% Ca,SiO₂ and 12.1% often found in a thermal melting environment with a mass ratio of CaO/SiO₂ ≈1 (Ball et al., 1993; Klein, 2008). In 2010, it was demonstrated that glass derived from DC plasma treatment of APC residues can be used to form high strength geopolymer–glass composites (Ioanna et al., 2010). The research investigated the optimisation and properties of geopolymers prepared from the glass. It also shows that High strength geopolymers can be formed and NaOH concentration of the activating solution significantly affects the properties. A mix prepared with S/L = 3.4, Si/Al = 2.6 and [NaOH] = 6 M in the activating solution, produced high strength geopolymers with compressive strengths of ~130 MPa. This material had high density (2070 kg/m³) and low porosity.
Treated fly ash from municipal solid waste (MSW) incinerator without additives in a DC arc plasma furnace achieved volume-reduction and recycling of vitrified slag (Peng et al., 2010). This process uses extremely high-temperature in an oxygen-starved environment to completely decompose complex waste into very simple molecules. A novel crucible-type plasma furnace was used. The DC plasma arc, plasma gas flow rate and ash through put were 100kw, 12 L/min and 0.0278 kg/s respectively. The heating rates of fly ash were controlled to about 10 K/min. The molten slag was kept above 1700 K for 10 min. The produced granulated slag was less than 1/3 of the original volume of the fly ash and 64% of the weight of the fly ash. The melting process metamorphosed fly ash to granulated slag that was less than 1/3 of the volume of the fly ash, and about 64% of the weight of the fly ash. The slag was subjected to different cooling methods. Water-cooled and composite-cooled slag showed more excellent resistance against the leaching of heavy metals as shown in the table 1.

### Table 1: Leaching test result for fly ash and various slags (Peng et al., 2010)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Toxicity Leachate (mg/l)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash</td>
<td>0.38</td>
<td>0.0013</td>
<td>1.41</td>
<td>12.19</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>Air-cooled slag</td>
<td>0.02626</td>
<td>0.001455</td>
<td>0.002168</td>
<td>0.104</td>
<td>0.0055</td>
<td>&lt;0.0005</td>
</tr>
<tr>
<td>Water-cooled slag</td>
<td>0.02660</td>
<td>0.001134</td>
<td>0.000814</td>
<td>0.0229</td>
<td>0.0006</td>
<td>&lt;0.0005</td>
</tr>
<tr>
<td>Composite-cooled slag</td>
<td>0.03165</td>
<td>0.000197</td>
<td>0.000258</td>
<td>0.0315</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Upper limit by law</td>
<td>100</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note: NA: not available

Heavy metals originated in the incinerated ash are confined in the treated silicate framework, hence yielding very low leachability results (Cheng et al., 2002; Kim and Park, 2004; Wan et al., 2006). It also presented better resistance to the decomposition by an acid than the crystalline structure. Treat incinerated ashes, and slag has the potential to serve as a viable alternative for construction applications (Ecke et al., 2001; Kuo et al., 2007; Park et al., 2005b).

Again, fly ash without additives was melted in a DC thermal plasma reactor (Wang et al., 2009). The core of the reactor used is a DC double anode plasma torch. Vitrification of the fly ash shows an obvious change in the microstructural and the mineralogical characterization, an excellent resistance against leaching of heavy metal ions and a significant decomposition rate (99.95%) of PCDD/Fs in TEQ in the produced slag. These results indicate that the thermal plasma vitrification is an alternative technology with high efficiency and energy to dispose MSWI fly ash. APC residues from waste to energy (WtE) plant in London UK were blended with silica (21.9 wt %) and alumina (8.3 wt %), and treated in a DC plasma transferred arc furnace. 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). (Amutha Rani et al., 2008). A non-transferred plasma torch with a tungsten cathode and copper anode treated mixes of fly ash and sludge in Korea to determine the reduction in volume and removal of hazardous elements in fly ash and sludge from wastewater treatment on a laboratory scale. The leaching test on the vitrified slag showed that heavy metals leached below the regulatory limits. (Kim and Park, 2004).

The incinerated ash from a MSW incinerator in Taipei was melted in a 100kW non-transferred arc plasma laboratory-scale torch at the Institute of Nuclear Energy Research (INER) in Taiwan (Cheng et al., 2002; Cheng et al., 2011). Argon was used for ignition of the plasma, and nitrogen 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. Wet IBA from a MSW incinerator in Japan was treated in a DC graphite-electrode plasma melting furnace with nitrogen as the plasma gas (Katou et al., 2001; Sakai and Hiaraoka, 2000). The concentration of lead, cadmium and Cr$^{6+}$ in the slag was very low (Pb and Cd: 0.01mg/l) and 99.9% of dioxins and furans was destroyed. Jimbo (1996), treated IBA and fly ash mixes in a DC transfer arc plasma furnace for over 28 months. The slag obtained had a lead content of less than 0.01mg/l with no traces of dioxin. Fly ash from the municipal waste incinerator plant in Budapest was melted in a laboratory scale DC plasma furnace at 1600°C (Karoly et al., 2007). Single-stage crystallisation heat treatments were performed on bulky samples in chamber furnaces at different temperatures. The microstructure of the vitrified product was investigated. The main crystalline phases obtained were wollastonite (CaSiO$_3$) (the majority) and anorthite (CaAl$_2$Si$_2$O$_8$). Also, Researches on the vaporisation behaviour of heavy metals produced by plasma treatment of incinerated ashes has been carried out (Cerqueira et al., 2004).

### 2.2. Wastes from metal smelting and steelmaking:

The steel making industry generates large quantity of waste from Basic oxygen furnace and electric arc furnaces. The waste contains metals such as a viable alternative for construction applications.
as iron, lead, chromium and other heavy metals which prevent it from being landfilled without treatment. Thermal plasma has been employed to vitrify and recover metals from the waste. Recently, an attempt has been made to study the effect of reductant and type of plasma forming gas on reduction of blue dust and characterization of final product. Blue dust collected from Dalmia Institute of Scientific & Industrial Research, Odisha, India was treated in 35 KW DC transferred arc plasma. Transferred arc plasma was used to convert blue dust to industrially useful product like metallic iron. Carbon percentage and type of plasma gas was varied to study its effect on recovery rate and degree of metallization. Three different phases; ferrite, pearlite and cohenite were identified (Samal et al., 2015).

Red Mud, a by-product generated from the caustic leaching of bauxite to produce alumina in the Bayer Process, causes serious environmental problems and is considered as a hazardous industrial waste. A novel process has been developed for production of Pig Iron from NALCO Red Mud by employing Plasma Smelting Technology. The Red Mud containing 15-40 % Fe₂O₃ was subjected to Thermal Plasma Smelting by use of Extended Arc Plasma Reactor at a temperature of 1600°C for a period of 30 minutes and to obtain high quality Pig Iron. Effect of various process parameters e.g. basicity, amount of reductant, plasmagen gas, input electric power and reduction time for recovery of Pig Iron has been studied and optimized. Basicity of 0.3, reduction time of 25 minutes at 12.5 kW power was found to be optimum for maximum recovery of pig iron (70%) from Red Mud in 1kg scale (Mukherjee et al., 2012). The carbothermic reduction of dust from steelmaking using transfer arc plasma furnace resulted in non-toxic slag and metallic zinc as product. In 2003, Ye et al study the slag reduction for the recovery of valuable metals and oxide materials using a DC plasma furnace and zinc oxide from electric arc furnace dust under a carbon monoxide atmosphere was reduced in an AC plasma reactor (Ye et al., 2003). 97% recovery of Zinc and lead was achieved (Best and Pickles, 2001). Radio frequency plasma has been used to synthesize special ceramic powders. A precipitated dried sludge from hot galvanising process and converter flue dust from steelmaking were also treated in RF plasma reactor (Kikukawa et al., 2002; Szepvolgyi et al., 2004).

**2.3. Aluminium dross and electroplating wastes:**

Aluminium dross is classified as hazardous waste because of the content of leachable chlorides and fluorides. It is inhomogeneous and releases gases such as ammonia and methane on contact with moisture. It contains up to 10 wt.% free aluminium (Kos, 1994). Thermal plasma have been applied to dissolve the dross. Electroplating sludge with a particle size < 45µm was subjected to treatment in a DC non-transferred arc plasma using different plasma gas environment. Chromium, nickel and zinc were identified in the form of ferrite/chromite [(Ni, Zn, Fe) (Fe, Cr)₃O₄] from powder/deposit collected from top, bottom, wall of the reactor and deposits in the furnace (Ramachandran and Kikukawa, 2002).

**2.4. E-Wastes:**

Thermal plasma technology offers a very promising alternative for waste electrical and electronic equipment (WEEE) treatment. Recently, Jakub (2014) treated and recover energy from waste Printed circuit boards (PCB) widely used in all kinds of electric and electronic equipment in plasma reactor with three sources of heat i.e. 20kw arc plasmatrons. The working gas is compressed air. The thermal plasma processing of waste printed circuit board consumes 2kWh/kg and allows simultaneous recovery of metals, neutralisation of waste and energy recovery. Cell phone waste samples 7-9g were placed into a 99.8 % pure alumina reactor with maximum operating temperature of 1950°C in reducing atmosphere and treated for 30 minutes (Beuthe and Chang, 1997; Chang et al., 2008). The thermal plasma was generated by a DC 10 kW plasma torch and was ejected vertically through the top of the environmental chamber. The power was limited to 1.5 kW. Pure argon gas with a fixed flow rate of 35 L/min was used in order to produce a reducing atmosphere. The system provides energy recovery with volume reduction of cell phone waste, reduction of toxic gases and potential recovery of metals (Biswajit, 2012).

Direct current (DC) plasma torch which was designed and built at the Centre for Advanced Coating Technology (CACT), University of Toronto was used to investigate Cu recovery from circuit boards simulated by Cu-clad plates after thermal plasma treatment. A mixture of the CH₄ and CO₂ was used as a plasma gas while the low power torch was kept constant at 30 kW. Cu recovery was analysed by measuring the thickness of the Cu layer in the simulated circuit boards before and after the treatment. Thermogravimetric analysis (TGA), scanning electron microscopy (SEM), and energy dispersive spectrometry (EDS) analyses were conducted on samples inside the circuit boards and on its edges before and after thermal plasma treatment (Mitrasinovic et al., 2011). Complete decomposition of organic materials and formation of high caloric syngas immediately after critical temperature was attained. This can be deduced from the TGA analysis presented in Figure 2, showing sharp decrease in sample weight after the first decomposition reaction began.

91 wt. % of Cu was recovered after the treatment. It shows that valuable metals with a similar or higher melting point like Cu can be recovered after thermal plasma treatment. A 20 kW plasma torch system based on a non-transferred
direct current arc discharge with air as a medium gas treated electronic waste. The batch system was able to convert electronic waste into combustible gas and inert solid residue and achieved high mass loss rate of bulk electronic waste (Tippayawong and Khongkrapan, 2009). More than 50% reduction in solid electronic waste was achieved in less than 120s as indicated in figure 3 showing mass loss with respect to time.

2.5. Medical wastes:
Performances of different Plasma torch system N1 and N2 with power rating of 40-45kw and 65-85kw respectively for treatment of medical waste in Korea has been investigated using various surrogate model waste mixtures and excellent results obtained (Park et al., 2005a). When operated, furnace temperature in the bath region did not exceed 1250–1300°C and 1500°C for N1 and N2 respectively. N1 formed melt that is highly viscous and did not flow while N2 Produced vitreous compound that flow out into the slag collector. The slag had a density of 2.6~2.8g/sm³ and brown colour with inclusion of dull grey and shining colours.

Fig. 2: TGA Curve of electronic circuit board (Mitrasinovic et al., 2011).

Fig. 3: CPU board mass loss with time when exposed to 20 kW air plasma flame (Tippayawong and Khongkrapan, 2009).

Also the treatment of combustible and non-combustible medical waste surrogate for 15min at 1550°C produced a disperse, metal bearing second phase embedded within the matrix of vitrified glassy slag. Simulated Medical waste consisting of 2:1mix of cotton and plastic was pyrolysed in a 50 kW DC transfer arc plasma reactor. *B.subtilis* and *B. stearothermophilus* bacteria (spores) were completely destroyed and gases obtained can be used to recover energy (Nema and Ganeshprasad, 2002). Arc plasma system with a maximum output of 150 kW treated hospital fly ashes and mixtures of fly ashes from a coal fired power plant and bottom ash. Molten waste (hospital fly ash) was kept at 1550–1600°C for 30 min, and air cooled to room temperature. Different phases were obtained but wollastonite (CaSiO₃) was the major crystalline phase present in materials treated using the optimum thermal treatment. Thermal plasma treated Mixtures (at different ratios) of fly ashes from a coal fired power plant and bottom ash produced a vitrified, homogeneous and resistant to leaching material (Cedzynska et al., 1999; Chu.J.P. et al., 1998).

2.6. Asbestos containing wastes:
Hard surface slag has been produced in an experimental argon plasma facility from different kind of asbestos (Inaba et al., 1999). Researches has indicated the possibility of converting asbestos to rocklike structure by thermal plasma treatment (Inaba and Iwao, 2000; Poiroux and Rollin, 1996). Asbestos waste treated in a commercial plasma treatment facility (INERTAM) with air as plasma gas produced an inert, non-leachable fibre free product. Complete destruction of asbestos has been achieved with high temperature thermal plasma. Variety of asbestos containing materials were melted at 1600°C in a transfer arc furnace at negative pressure tented enclosure. No asbestos fibre was found in the final
2.7. Carbonaceous and chlorine containing wastes:

Cubas et al. investigated the destruction of CCl₄ in graphite electrode argon plasma torch with an integrated pneumatic nebulizer (Cubas et al., 2005). The compounds formed by thermal pyrolysis were identified using gas chromatography with flame ionization detection (GC-FID) and gas chromatography coupled with mass spectrometry (GC-MS). 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 indicated high efficiency of destruction and removal of carbon tetrachloride. Experiment using hybrid plasma system (RF plasma and DC plasma) under three different conditions (treatment by argon thermal plasma, argon thermal plasma and oxygen and by argon thermal plasma and steam) reveal that the treatment of thermal plasma with steam and oxygen can reduce the weight of charcoal and produce hydrogen from the charcoal. Combustion reaction occurred when O₂ was used while pyrolysis and gasification resulted in weight loss from 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 (Nishikawa et al., 2004). Weight reduction has been achieved when graphite representing carbonaceous waste was plasma thermal treated using argon and argon/steam plasma (Nishikawa et al., 2006).

A 100kw non transfer DC steam plasma treated PCB mixture waste. Total toxic equivalent concentration of PCDD/PCDF from the mixture of 27% PCB and 73% CCl₄ was about 0.056 ng TEQ/Nm³. The study indicated that the formation of PCDFs from steam plasma with proper H/Cl ratio was lower than that from air plasma with steam injection (Seok-Wan et al., 2003). Steam plasma torch was more efficient in decomposing higher concentration of PCB in waste mixtures compared to air plasma and conventional incineration processes. Table 2 is showing emission distribution of dioxins and furans in plasma system for PCBs (Test 1 and 2 used steam plasma and air plasma with steam injection at 1570 K).

<table>
<thead>
<tr>
<th>Native Isomer</th>
<th>Toxic equivalent quantity (ng TEQ/Nm³, ND, not detected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
</tr>
<tr>
<td>2,3,7,8-TCDF</td>
<td>0.0462</td>
</tr>
<tr>
<td>Other TCDF</td>
<td>0.0053</td>
</tr>
<tr>
<td>1,2,3,7,8-PCDF</td>
<td>0.0032</td>
</tr>
<tr>
<td>2,3,4,7,8-PCDF</td>
<td>0.0026</td>
</tr>
<tr>
<td>Other- PeCDF</td>
<td>0.0004</td>
</tr>
<tr>
<td>1,2,3,4,6,7,8-HCDF</td>
<td>N.D</td>
</tr>
<tr>
<td>Other- HLCDF</td>
<td>N.D</td>
</tr>
<tr>
<td>1,2,3,4,6,7,8-HpCDF</td>
<td>N.D</td>
</tr>
<tr>
<td>Other HpCDF</td>
<td>N.D</td>
</tr>
<tr>
<td>Experimental conditions</td>
<td></td>
</tr>
<tr>
<td>Power of torch (Kw)</td>
<td>75</td>
</tr>
<tr>
<td>Type of plasma gas</td>
<td>Steam</td>
</tr>
<tr>
<td>Feeding rate (g/s)</td>
<td>2.6-2.8</td>
</tr>
<tr>
<td>PCB feeding rate (g/s)</td>
<td>19</td>
</tr>
<tr>
<td>Steam injection as a reaction additive (g/s)</td>
<td>-</td>
</tr>
</tbody>
</table>

2.8. Other kinds of wastes treated by thermal plasma:

Thermal plasma technology is recently applied to treat storm water sediment contaminated by heavy metals, phosphorus, trace organic and hydrocarbons etc. (Li et al., 2015). Also, the recovery of valuable metals might be possible. Two different modes of plasma thermal plasma were studied; a non-transfer direct current DC mode and a partial DC transferred mode with power inputs of 1kw and 10kw respectively. The reductions of total organic carbon (TOC) achieved for non-transferred and partially transferred plasma were 25% and 80%. Most of the toxic organic compounds were converted majorly to CₓHᵧ and solid analysis shows that the concentrations of Ca and Fe were enriched by 500% and 40%, respectively. New chemical compositions such as KAlSi₃O₈, Fe₂O₃, NaCl and CaSO₄ were formed after treatment in partially DC-transferred mode. The feasibility study and operational performance of thermal plasma treatment of wet paper sludge (WPS) and forestry wood waste (FWW) blends (WFB) was conducted by Je-Lueng et al using DC transfer torch plasma (Je-Lueng et al., 2014). The experiments were performed using carrier gas of N₂ injected at temperature of 873 K. The treatment was performed using a pilot-scale torch plasma system in nitrogen atmosphere with 10 kW power capacities. Residue from the treatment was converted into non-hazardous and non-leachable vitrified lava (Je-Lueng et al., 2014). Thermal treatment can be applied to remove mercury from sludges or mercury containing waste. Old dumps of mercury waste sludges from chlor-alkaline industry treated for 1hr at 800°C removed mercury. It reduces the total mercury content close (100%). Leachability
(TCLP leaching) test decreases below the threshold value of 0.2mg Hg/l after treatment at a temperature of 400 °C or higher (Bustoa et al., 2011).

The pyrolysis of waste tires with emphasis for power generation and carbon black recovery was investigated in an 100kw DC arc plasma reactor with a tungsten cathode and a water-cooled copper anode (Chang et al., 1996; Tang et al., 2009). Some other experiments have shown that tire waste can be treated in a plasma reactor to produce combustible gas, such as C_{2}H_{6}, CH_{4}, C_{2}H_{4}, H_{2}, CO. The combustion heat value of the produced gas is about 4–7 MJ/m^{3}, which is higher than that of blast furnace gas and reforming gas from coals. Neither polychlorinated biphenyls (PCBs) nor p-aminobenzoic acid (PAH) were detected in the ashes (Chang et al., 1996). A pilot scale transfer DC thermal plasma torch system treated pulp waste liquor (black liquor) at 1200°C and recovered chemicals (Feng and Tian, 2009). The working gas is nitrogen provided through a pressure reduction valve. The pressure inside the furnace was kept at ~2kPa. Series of chemical reaction (plasma-chemical reactions) produced combustible gas and solid powder. The composition of black liquor and solid powder were the same, an indication that both plasma treatment and chemical pulp recovery was feasible. Composition of the combustible gas (Table 3) shows no possibility of secondary pollution because there isn't any SO_{2}, SO_{3} or H_{2}S and can be reutilized (Feng and Tian, 2009).

### Table 3: Composition of combustible gas from thermal plasma treatment of black liquor.

<table>
<thead>
<tr>
<th>Composition</th>
<th>N&lt;sub&gt;2&lt;/sub&gt;</th>
<th>CO</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt;</th>
<th>O&lt;sub&gt;2&lt;/sub&gt;</th>
<th>H&lt;sub&gt;2&lt;/sub&gt;</th>
<th>H&lt;sub&gt;2&lt;/sub&gt;O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>15.33</td>
<td>43.00</td>
<td>13.07</td>
<td>0.20</td>
<td>25.90</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Mixture of fibre reinforced polymeric matrix composite (FRPC), gill net and waste glass has been treated in a DC non transfer arc furnace using argon to generate plasma and air as the main ambient gas during vitrification process (Chu et al., 2006). Different compositions of FRPC, gill net and waste glass was treated for 1hr at 1250°C and amorphous slag obtained. Further heat treating of vitrified slag formed a glass-ceramic.

### 3. Applicability Of Thermal Plasma Treated Wastes:

The pozzolanic activity of MSW residues have been investigated by (Lin, 2005; Lin et al., 2008; Lin et al., 2003; Lin et al., 2004; Wang et al., 2001). Ioanna et al demonstrated that APC residues treated at 1600°C in DC plasma produced a glass that can be used in the development of blended Portland cement products (Ioanna et al., 2013). The glass produced is pozzolanic and has the potential to be used in blended cements. More specifically, Portland cement pastes with fritted APC glass have similar or higher strengths than Portland cement at substitutions levels up to 40 wt %. Fritted glass is a more active pozzolan than air cooled glass due to higher Gibbs free energy. The optimum mix achieved was 20 wt % fritted glass and 80 wt % Portland cement which developed a dense structure with high compressive strength. Unreacted APC glass particles are embedded in the binder phase and act as filler in the system improving the strength of the material (Ioanna et al., 2013).

Table 4 and 5 are showing samples of DC plasma treated APC Residue glass powder and particle size distribution respectively.

### Table 4: Different samples of DC plasma treated APC Residue glass powder.

<table>
<thead>
<tr>
<th>Sample</th>
<th>APC residue glass type</th>
<th>Crushing/milling method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fritted glass</td>
<td>Hammer milled to &lt; 250µm</td>
</tr>
<tr>
<td>2</td>
<td>Fritted glass</td>
<td>TEMA milled 2 min</td>
</tr>
<tr>
<td>3</td>
<td>Fritted glass</td>
<td>Ball milled for 2 h (wet milling)</td>
</tr>
<tr>
<td>4</td>
<td>Fritted glass</td>
<td>Ball milled for 8 h (wet milling)</td>
</tr>
<tr>
<td>5</td>
<td>Air-cooled glass</td>
<td>Hammer milled to &lt; 250µm</td>
</tr>
<tr>
<td>6</td>
<td>Air-cooled glass</td>
<td>TEMA milled 2 min</td>
</tr>
<tr>
<td>7</td>
<td>Air-cooled glass</td>
<td>TEMA milled 4 min</td>
</tr>
<tr>
<td>8</td>
<td>Air-cooled glass</td>
<td>TEMA milled 6 min</td>
</tr>
</tbody>
</table>

Fritted=quenched in water to form a granular product

### Table 5: Particle size distribution of APC glass powders.

<table>
<thead>
<tr>
<th>Volume (%)</th>
<th>Particle diameter µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fritted-hammer milled &lt;250µm</td>
</tr>
<tr>
<td>10</td>
<td>138.4</td>
</tr>
<tr>
<td>25</td>
<td>83.35</td>
</tr>
<tr>
<td>50</td>
<td>33.29</td>
</tr>
<tr>
<td>75</td>
<td>9.87</td>
</tr>
<tr>
<td>90</td>
<td>1.37</td>
</tr>
</tbody>
</table>
Construction materials such as Pavement bricks and water permeable blocks have been produced from slag by commercial thermal plasma plants. Granular slag in combination with other materials such as cement or gravel has been used to produce interlocking blocks and decorative permeable bricks. These processes satisfy performance standards for such kinds of products. It is possible to integrate the end product from thermal plasma treatment of fly ash in the production of flag stones to produce a natural granite substitute.

4. Conclusion:
Review on thermal plasma treatment of waste has shown its wide application for immobilisation/vitrification of incinerator ashes (IBA, FA, APC Residues). It has successfully produced inert, harmless and vitrified slag that can be dispose safely or reutilised. The vitrified slags are used for roadbed, concrete aggregate, interlocking blocks and tiles. The recent application of thermal plasma treatment for wet paper sludge, storm water sediment, printed circuit board, blue dust to recover metals/chemicals, produce combustible gases and useful products indicates that it will continue to be one of the most viable option to treat broad variety of wastes.

REFERENCES


presented at the 23rd International Conference on Incineration and Thermal Treatment Technologies, Phoenix, Arizona.


