Thermal Plasma Solid Waste and Water Treatments: A Critical Review

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Abstract—In this work, the principle and application of thermal and non-thermal plasma water and solid waste treatments are reviewed. For the solid waste treatment such as incinerator ash and low radiation level nuclear waste treatment, the technology was already commercialized by oxidation principle. However, the potential for the reduction approaches are also introduced. For the drinking and waste water treatments, remote-plasma techniques such as ozone water treatment and indirect-plasma techniques such as UV disinfections are already commercialized but advanced direct –plasma techniques still in the small scale studies and now extended to the pilot test stage. All of these recent developments will be critically reviewed.

Keywords—Solid Waste, Drinking Water, Waste Water, Thermal Plasma, Electrohydraulic Discharge

I. INTRODUCTION

For the solid waste treatment such as incinerator ash and low radiation level nuclear waste treatment, the technology was already commercialized by oxidation principle. However, the potential for the reduction approaches are also introduced. The liquid wastes considered are: 1. Waste oils from automobile, chemical industries; 2. Toxic fluids such as PCBs from electrical industries; 3. Ozone depletion fluids such as CFCs, Halon, etc.; 4. Solvents from chemical and electronic industries. The solid wastes considered are: 1. Industrial wastes such as automobile tires, plastics, petroleum process by-products, etc.; 2. Medical wastes from hospitals and pharmaceutical industries; 3. Municipal wastes; 4. Electronic wastes and semiconductor process by-products Solid waste disposal has become a major concern since there are a limited number of landfill disposal sites. In the past, incineration of solid wastes was considered a solution to the landfill site limitation since solid waste volume can be reduced to 1/6 by conversion to incinerator ash, and heat and electricity recovery from the incineration processes can be attained. The landfill of fly and bottom ashes has been considered a potential environmental hazard due to leaching of heavy metals from the ashes after landfill, hence recycling them as construction material is beneficial not only economically but also is less impacting on the environment in long term. The thermal plasma municipal incinerator ash volume reduction system is a recycle method, which converts bottom and fly ashes from municipal incinerator to usable construction materials and recovery of metals [1-4].

The application of plasma technologies for the treatment of drinking and wastewater is not new. Three categories of plasma treatment technologies exist, including: remote, indirect, and direct. Remote plasma technologies involve plasma generation in a location away from the medium to be treated (e.g., ozone). Indirect plasma technologies generate plasma near to, but not directly within, the medium to be treated (e.g., UV, electron beam). More recently direct plasma technologies (i.e., electrohydraulic discharge) have been developed that generates plasma directly within the medium to be treated thereby increasing treatment efficiency. Three types of electrohydraulic discharge systems (pulsed corona electrohydraulic discharge (PCED), pulsed arc electrohydraulic discharge (PAED) and pulsed power electrohydraulic discharge (PPED)) have been employed in numerous environmental applications, including the removal of foreign objects (e.g., rust, zebra mussels), disinfection, chemical oxidation, and the decontamination of sludge [5].

In this work, all of these thermal plasma recent developments will be critically reviewed.

II. TYPE OF PLASMA

For different types of the plasma are normally categorized as Table 1 based on the gas temperature and operating gas pressure. For the solid waste treatment, due to the melting and evaporation requirements, high gas temperature high gas pressure plasma is used. For water treatments, depending on the target pollutants, low temperature and high gas pressure plasma is used. However, the key effect will be the nature of high electron temperature in plasma status, where the plasma is the mixture of the electron, negative and positive ions, excited species and neutral atoms and molecules as shown in Fig. 1.

In plasmas, atoms can be electronically excited and some of the metastable state atoms can be have a life time of msec order where molecules can be rotationally, vibrationally or electronically excited and some of the metastable molecules also have a few sec life times. Plasma is also chemically active and reactions such as ionization, excitation, dissociation, attachment, detachment, atom and molecule transfer etc. can be coexists. Reaction rate will be higher for radical reactions but with ion and electron involved in reactions, the reaction rates become few order of faster than the most of neutral species reactions as shown in Table 2.

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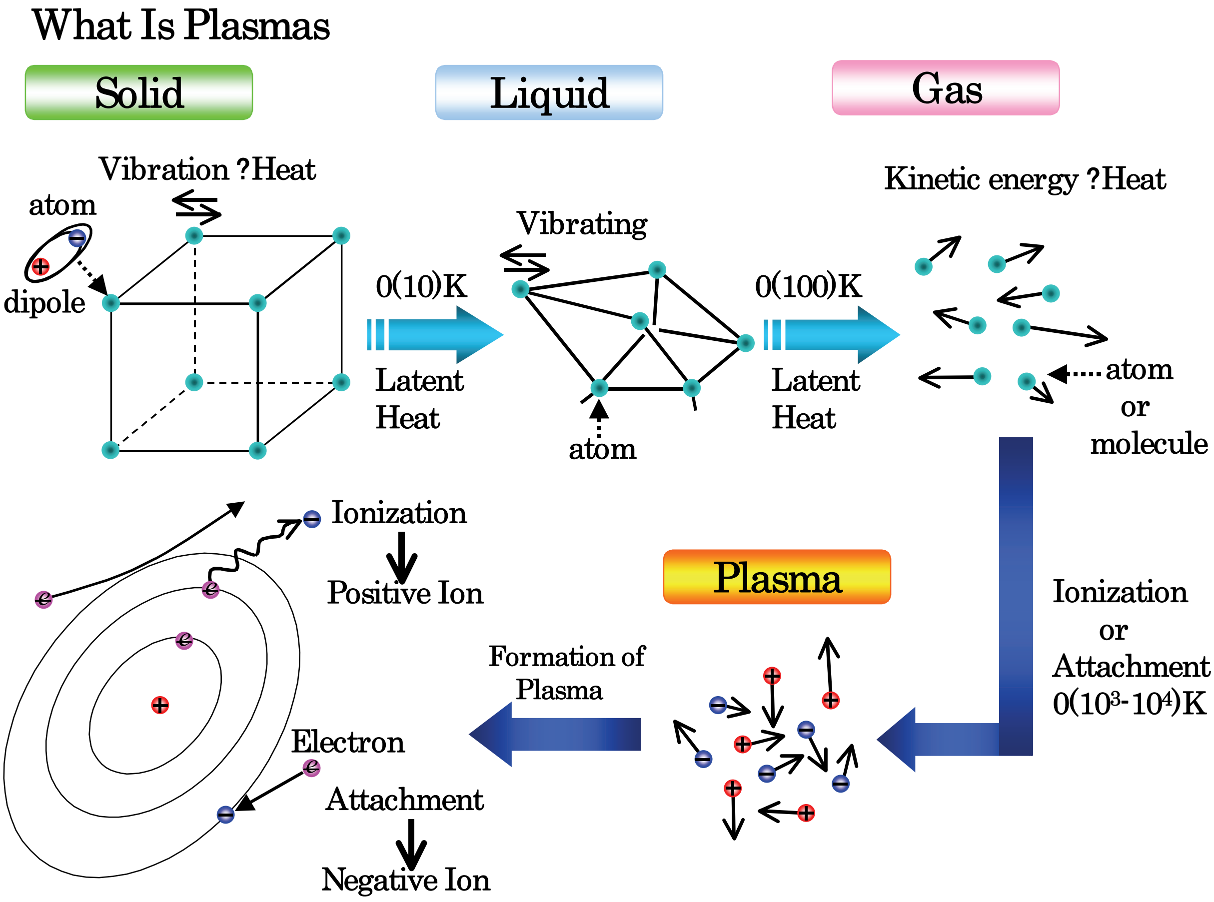
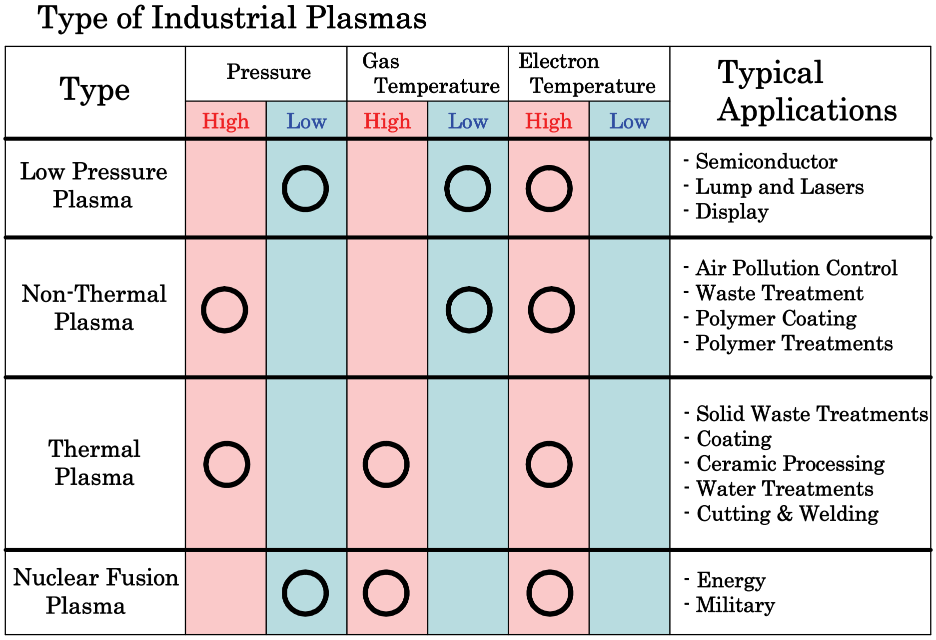


Fig. 1. Solid, liquid, gas and plasma status [6]

TABLE I
TYPE OF INDUSTRIAL PLASMAS [6]



Type of Industrial Plasmas

Type	Pressure		Gas Temperature		Electron Temperature		Typical Applications
	High	Low	High	Low	High	Low	
Low Pressure Plasma		○		○	○		- Semiconductor - Lump and Lasers - Display
Non-Thermal Plasma	○			○	○		- Air Pollution Control - Waste Treatment - Polymer Coating - Polymer Treatments
Thermal Plasma	○		○		○		- Solid Waste Treatments - Coating - Ceramic Processing - Water Treatments - Cutting & Welding
Nuclear Fusion Plasma		○	○		○		- Energy - Military

TABLE II
TYPE OF CHEMICAL REACTIONS AND ORDER OF MAGNITUDE OF REACTION RATES [9, 10]

Reaction	two body reaction rate [cm^3/s]	three body reaction rate [cm^6/s]
molecule-molecule	10^{-14}-10^{-31}	10^{-30}-10^{-40}
atom/radical-molecule	10^{-11}-10^{-24}	10^{-30}-10^{-36}
ion-atom/molecule	10^{-9}-10^{-13}	10^{-28}-10^{-32}
electron-molecule/molecule	10^{-7}-10^{-11}	10^{-27}-10^{-35}
positive-negative ion	10^{-6}-10^{-8}	10^{-25}-10^{-26}
electron-ion	10^{-6}-10^{-7}	10^{-26}-10^{-28}
molecule/radical-aerosol	(10^{-5}-10^{-10}) Rp (nm)	
	Rp: diameter of aerosol	

comparison of dominant reaction
[reaction rate] x [molecule density] x [reactant density]
(x [third body molecule density])

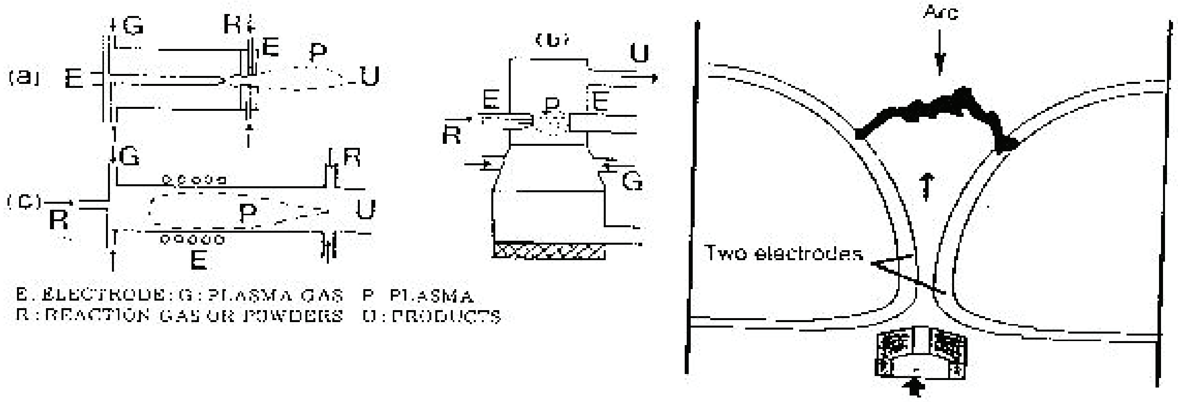


Fig. 2. Typical thermal plasma reactors,
a) dc plasma torch; b) transferred arc plasma; c) inductive coupled RF plasma torch; and d) gliding arc plasma [1,6,8]

III. THERMAL PLASMA REACTORS

Two different types of thermal plasma processes do exist; one based on DC or AC submerged arc discharge inside materials and the other based on self-standing plasma torch [1-3,6] above the material being treated. Thermal plasmas considered are dc and ac arc reactors and dc, rf-inductive, rf-capacitive and microwave plasma torches [1] for solid waste treatments and water treatments. Typical thermal plasma reactor is shown in Fig. 2 and their gas temperature environments are shown in Fig. 3.

Schematics of the 12 t/day plasma torch type ash melting system is similar to the larger commercial system as shown in Fig. 4 [12], where a dc 0.5 MW plasma torch is used as a heat source and both bottom and fly ash is fed, at a rate of 500 kg/h, from the waste incinerator and baghouse filters.

Schematics of the 45 t/day three-phase submerged arc type ash melting system are shown in Fig. 5, where this arc reactor was modified from the scrap metal furnace used in the steel industry [Yahagi Steel Co.]. The MSW incinerator ashes are introduced to a three phase 2 MW submerged arc reactor (3.3 m diameter) and melted above 1500 K in a slightly reducing (coke mixture) environment. The addition of small amounts of cokes is essential to produce CO to reduce PbO_2, CdO_2, etc, and evaporate for trapping in the baghouse filters. The fully melted ash is drained into a container by tapping the reactor to separate metals and slag for recycling after natural air cooling [12].

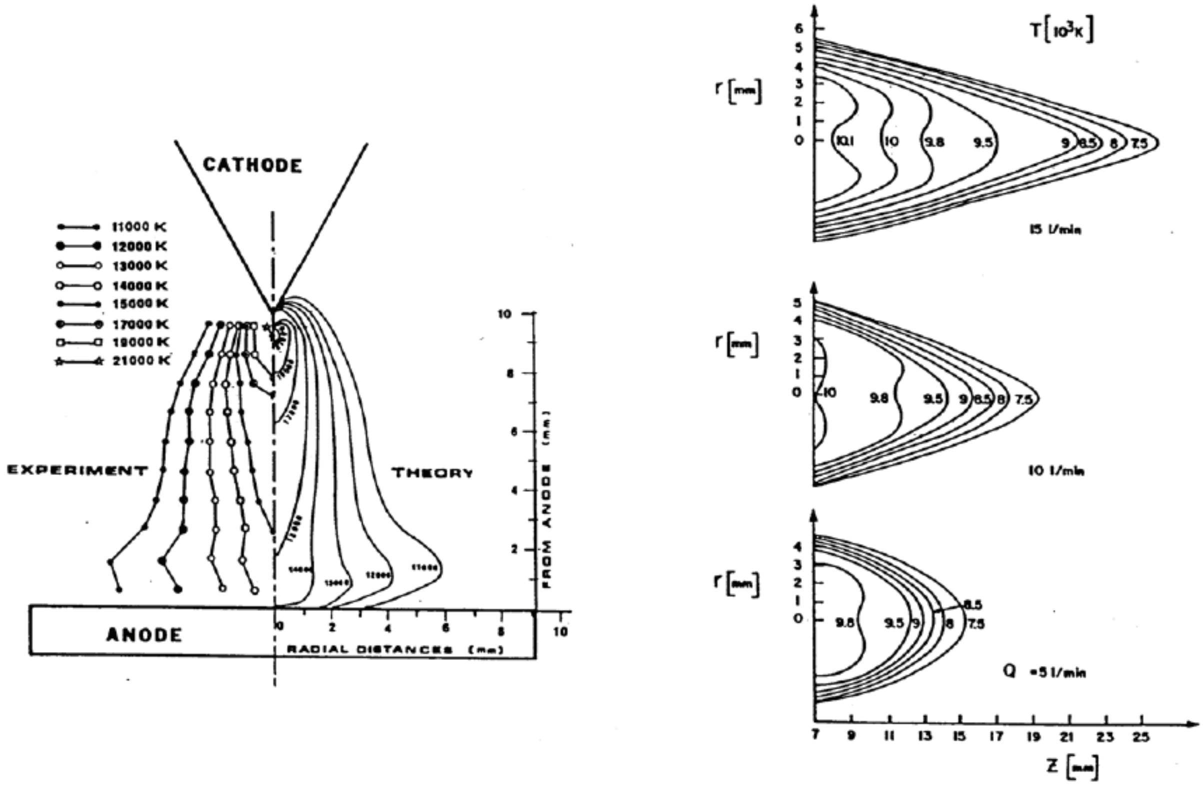


Fig. 3. Typical thermal environment generated by dc arc (adapted from Hau, Etimadi and Pfender [8]) and rf plasma torches (adapted from Donskoi [11]) [8]

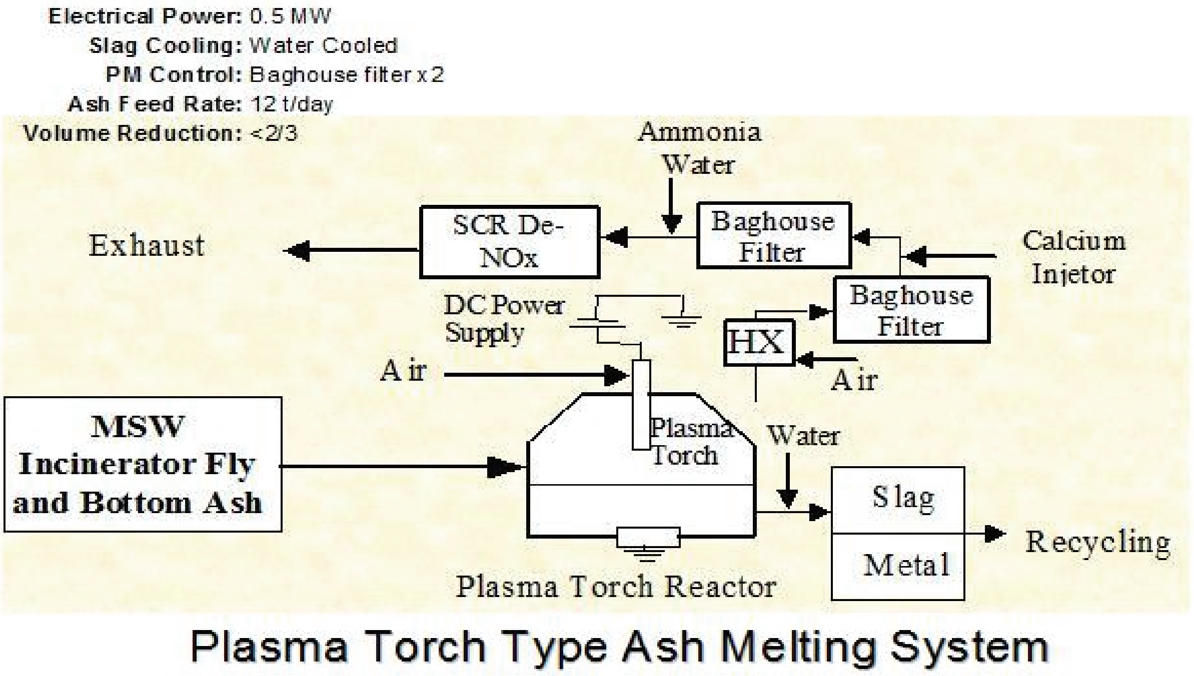


Fig. 4. Plasma torch type municipal waste incineration ashes melting system [12]

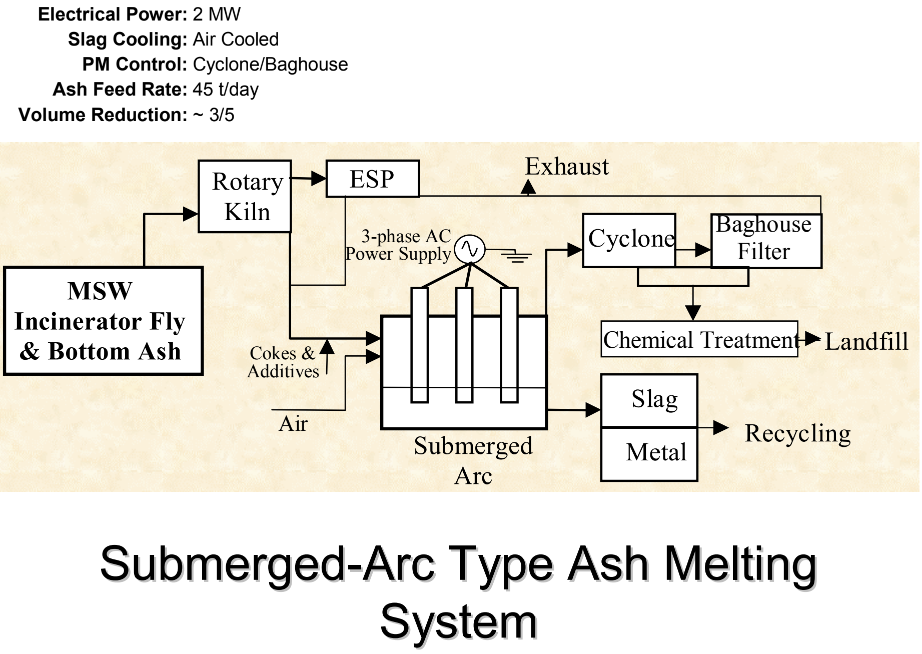


Fig. 5. Three phase ac arc type municipal waste incineration ashes melting system [12]

IV. SOLID WASTE TREATMENT

A. Introduction

Plasma torches are already in commercial use for various industrial processes. Potential benefits are more efficient use of energy, lower capital costs, the substitution of exhaustible fossil fuels and in rendering small capacity plants economically viable, i.e., reversing of the "economies of scale" approach to the construction of mega-projects. The use of plasma technology is also expected to have environmental benefits since total gas flow rate is much smaller compared with conventional heating systems.

In many countries, plasma research and development efforts are being directed towards environmental clean up areas [1-4] such as gasification of municipal wastes [1, 2] and used tires [13] as an alternative energy source, destruction and disposal of toxic and hazardous medical [14], chemicals [1, 2], and nuclear wastes [15, 16] such as baghouse dust from steel making furnaces, power plants, thermal incinerator ashes etc.

In a waste treatment plant, normally three approaches are proposed as follows [4]:

1. Collecting solid wastes for landfill and discharge liquid, and gaseous wastes to water streams or open air with dilutions to accepted levels;
2. Conversion of wastes to harmless product such as water, N_2, CO_2, O_2, unleachable slag, etc., and discharge to air, water streams or landfills;
3. Conversion of wastes to a reusable product such as building materials, agricultural fertilizers, syngases, etc.

The thermal plasma process is one of the most effective methods for solid waste treatment, since only relatively small and controllable amounts of toxic by-products will be discharged. Three types of solid wastes have been treated in plasma reactors: municipal, industrial and special (military/medical) wastes [1¬4, 12-19].

Typically, the municipal solid waste (MSW) contains about 50 percent combustible material, which can be converted to a low calorific value fuel gas. The non-combustible solids in the MSW are melted down to a slag, which may prove to be a saleable by-product. Thus, there is a good potential for relieving the pressure on ever-increasing use of land for municipal landfill sites in urban areas. Thermal plasma processes for these types of wastes have taken two different approaches as follows:

1. Direct thermal plasma gasification of solid waste in a reducing environment and converted to syngas. The significantly reduced volume solid components will be recovered as slag.
2. Using Stoker type or fluidized bed incinerator to incinerate/volume reduction solid waste to bottom and fly ashes then transported to thermal plasma reactor to melting/volume reduction to slag as shown in Figs. 4 and 5. In this case, solid waste is recycled as electricity, steam, hot water, raw metals and construction materials.

For small amount of solid wastes such as low-level nuclear, military or medical wastes, the direct thermal plasma gasification can be effectively applied. However, for large volume municipal and industrial wastes, the incinerator-plasma ash melting system is more practical.

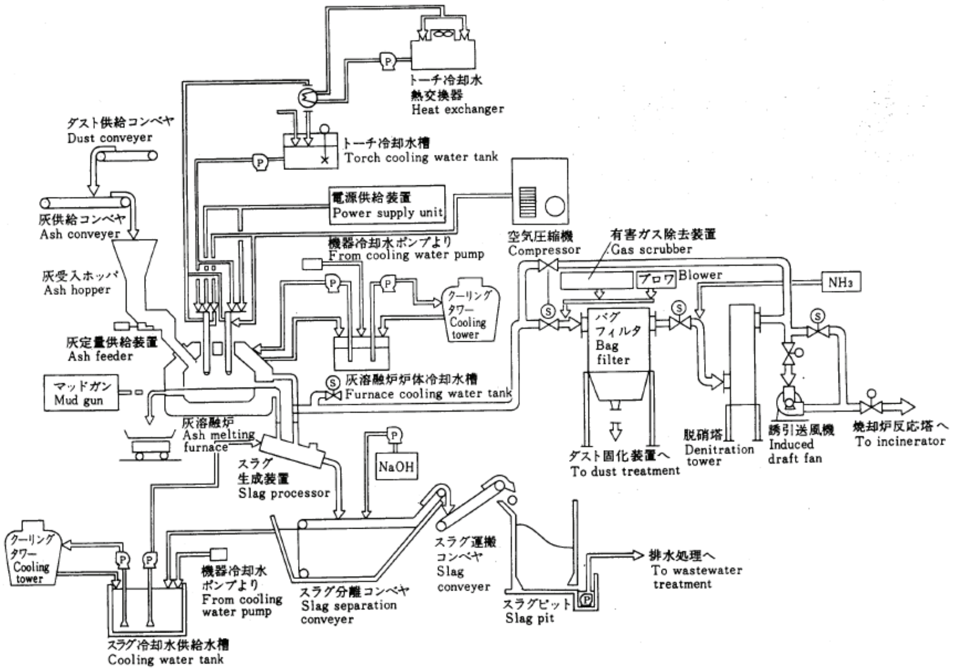


Fig. 6. Flow sheet of plasma ash melting system in Matsuyama [17]

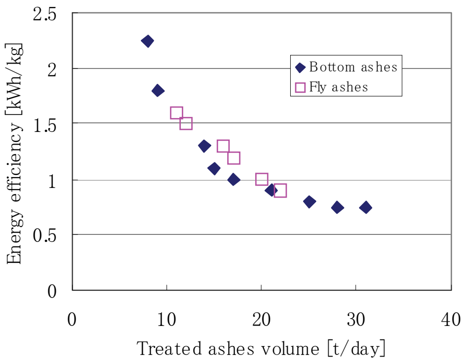


Fig. 7. Energy efficiency of ash melting system [17]

B. Municiple solid waste treatment

In order to reduce bottom and fly ash volumes and detoxicity of ashes, a thermal plasma ash melting volume reduction system was recently developed and the first commercial plants have been constructed at Matsuyama City Minami Clean Center, Japan, to treat 52 tons of ashes per day from 390 tons of municipal waste per day in March 1994, where currently operating/constructing many similar commercial plants. In this work, detoxicity characteristics of thermal plasma ash volume reaction processes are experimentally investigated.

Schematics of the plasma ash melting system is shown in Fig. 6, where two dc 1.5 MW plasma torches are used as a heat source and both bottom and top ashes are automatically fed from the waste incinerator and baghouse filters, respectively. Slag generated from the plasma generated ash melting furnace is water crushed and the fly ashes will be collected by baghouse filters as shown in Figs. 4 and 5 [12, 17-19]. Depending on the ash volume required to treat, the plasma torch was operated from 0.4 to 1.3 MW electricity generated by waste incinerations. Hence, no extra electricity from the external sources is required. Typical plasma melt reactor temperature is 1100 to 1700 °C depending on plasma operating power. The energy efficiency of operation is 0.7~2.2 kWh/kg [ashes] and 0.9~1.6 kWh/kg [ashes] for pure bottom ashes and mixed ashes as shown in Fig. 7.

The size distribution of plasma generated fly ashes collected by baghouse filters are analyzed by scanning electron microscope (SEM), and the multi-element trace species analyses of ashes are analyzed by ICP, chemical and neutron activation analyses (NAA) using the McMaster Nuclear Reactor (5 MW).

B1. Bottom and fly ashes from incinerator

A typical SEM image of bottom and fly ashes from waste incinerator and their size distributions show that the bottom ash geometry is very irregular and mean size is around 150 µm while fly ashes are less irregular with mean diameter around 0.2 µm. Major compositions of bottom and fly ashes from municipal waste incinerators are summarized in Table 3 and the trace composition of bottom and fly ashes measured by NAA analyses are shown in Table 3. For bottom ashes ($SiO_2 > Al_2O_3 > CaO > Na_2O > Fe_2O_3$) are major compositions and ($CaO > SiO_2 > Al_2O_3 > Na_2O > K_2O$) are major compositions

TABLE III
MAJOR OF COMPOSITIONS FROM PLASMA OF TREATED OF MUNICIPAL ASHES [17]

%	Bottom Ashes	Fly Ashes	Plasma Slag	Plasma Fly Ashes	Metal
SiO_2	41.6~56.0	10.1~14.6	42.7~73.9	2.3~10.2	1.27 (Si)
Al_2O_3	7.8~21.6	4.6~6.4	7.2~22.9	0.93~4.9	
CaO	5.1~18.5	27.1~39.1	4.7~16.9	1.1~40.6	
Na_2O	1.3~8.2	4.0~6.2	3.2~7.4	3.6~15.3	
Fe_2O_3	2.0~5.7	0.42~1.4	1.3~9.2	0.33~0.66	81.4 (Fe)
MgO	0.7~2.4	0.84~2.4	1.7~2.1	0.03~1.9	
K_2O	0.3~2.4	2.24~4.3	0.80~2.3	3.4~8.9	
Cu	0.2~2.3	0.05~0.07	0.07~0.60	0.05~1.9	11.2
P_2O_5	0.4~2.0	0.60~1.01	0.41~1.15	0.57~3.7	3.9 (P)
C	0.4~1.9	0.58~1.29	<0.1	0.1~0.79	
Zn	0.3~1.4	0.84~6.8	0.90~0.34	0.62~41.3	0.54
Cl	0.15~0.83	14.6~18.6	0.05~0.35	10.8~23.0	
Ti	0.44~0.77	0.53~0.70	0.06~0.94	0.01~0.08	
SO_4	0.03~0.45	0.15~2.54	0	0.46~7.68	
Pb	0.06~0.39	0.71~0.87	0.02~0.03	0.57~11.5	
S	0.08~0.30	0.78~1.32	0.01	0.70~2.4	
Mn	0.11~0.28	0.06~0.12	0.11~0.21	0.02~0.06	
Ni	0.01~0.04	0.015	0.012	0.011	0.9
Ba	0.047	0.012	0	0.059	

TABLE IV
THE TRACE TOXIC COMPOUNDS FOR MUNICIPAL ASHES WITH AND WITHOUT PLASMA TREATMENTS [17]

	Bottom Ashes	Fly Ashes	Plasma Slag	Plasma Fly Ashes
T-Cr (ppm)	73~210	68~220	260~2000	100~1030
Cr^{+6} (ppm)	<1	<1	<1	<1
Cd (ppm)	1.4~14	100~190	0.0~0.5	2~520
As (ppm)	2~81	6.7~38	0.0~5.0	5~480
Pb0 (ppm)	--	0.23	0.04	1.18
T-Hg (ppm)	0.034~460	4–8.70	0.05~0.94	0.05~6
PCB (ppm)	<0.01	<0.01	<0.01	<0.01
CN (ppm)	0.09~2	<0.1	0.1–2	0.1~2
I-TEQ (ng/g)	0.12~0.16		0.00	0.01
PCDDs (ng/g)	3.3~4.9		ND	0.45~1.9
PCDFs (ng/g)	4.4~7.1		ND	0.58~0.85

TABLE V
A TYPICAL LEACHING TEST RESULTS OF PLASMA SLAG [17]

Unit (mg/Li)	T-Hg	Cd	Pb	Cr^{6+}	As	Se
Test Results	<0.0005	<0.005	<0.03	<0.01	<0.01	<0.01
Japanese standard	0.05	0.3	0.3	1.5	0.3	0.3

from fly ashes from municipal waste incinerators. The trace toxic compounds are (Hg > Cr > As > Cd) in ashes are summarized in Table 4. Table 4 also shows several trace dioxins do exist inside ashes from incinerators. Hence, these ashes, especially fly ashes, must be well treated before landfill or even recycling without specific treatments. The results also show that the specific elements are concentrated in a specific size range; hence, we should consider to treat specific sized ashes separately in future.

B2. Water clashed slag and metal layers

A typical optical image and size distribution of water clashed slag generated by high temperatures (20,000 K) thermal plasma show that the size distribution of irregular shaped slag mean size is around 150 to 300 μm. In a plasma slag, the major compositions are (SiO_2 > Al_2O_3 > CaO > Fe_2O_3 > Na_2O) as bottom ashes and Fe and Cu are dominant compositions in metal layers in the bottom of plasma reactor as summarized in Tables 3 and 4, where detail trace compositions measured by NAA is also shown in Fig. 8 for different size groups. However, only significant small amounts of toxic compounds exist in plasma slags especially dioxins are also not observed. Fig. 10 also shows that the particle size difference of trace elements in water-clashed slag is relatively small except some elements such as As, W, Rb, Ti and S. Typical leaching test results for the slags are summarized in Table 5. No significant leachable toxic elements were observed [17].

B3. Plasma generated fly ashes and pollution gases

A typical SEM image of plasma generated fly ashes collected at baghouse filters after $Ca(OH)_2$ powder spraying HCl treatments show the shape of the fly ashes is irregular and chain-like agglomerates, where particle and agglomerate sizes are in the range of submicron and a few microns, respectively. Approximately 21 kg

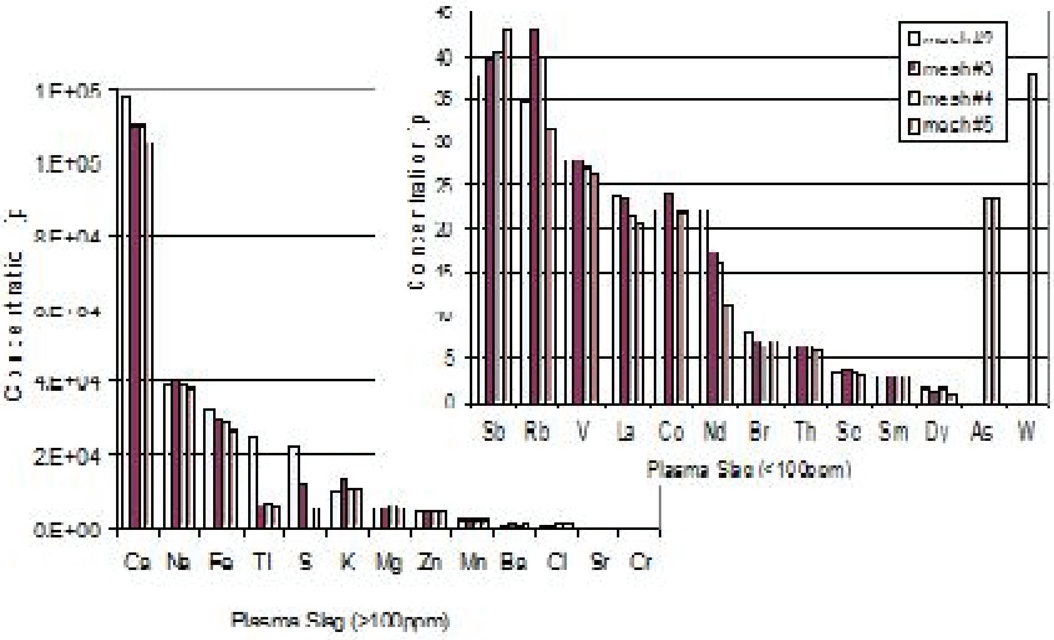


Fig. 8. Typical NAA analyses of plasma slugs for a various particle size [12]

TABLE VI

AMOUNT OF PLASMA FLY ASHES OF GENERATED BASED ON TYPES OF INCINERATION ASH TREATED [17]

[kg/t]	Bottom Ashes	Mixed Ashes
Baghouse Filters	21	37-56
Wall Deposited	1	3-6

TABLE VII

FLUE GAS COMPOSITION AT THE EXIT OF PLASMA REACTOR AND SCR FOR VARIOUS TREATED ASHES (BDL: below detection limit) [17]

	Bottom Ashes	Mixed Ashes	Fly Ashes	
Reactor Temperature [°C]	1500~1550	1469	1529	180-183
Flue Gas Flow Rate [Nm^3/m]	770~830	1450	1260	770-1450
CO [ppm]	14.5~21.4	2	3	BDL
HCl [ppm]	190-450	1300	3480	BDL
SO_x [ppm]	720-4730	820	2010	BDL
NO_x [ppm]	1454~1475	810	290	1~10
Hg [mg/m^3]	0.133~0.115	0.112	0.05	0.018~0.043
PM [g/m^3]	5.56~9.58	14.4	-	BDL

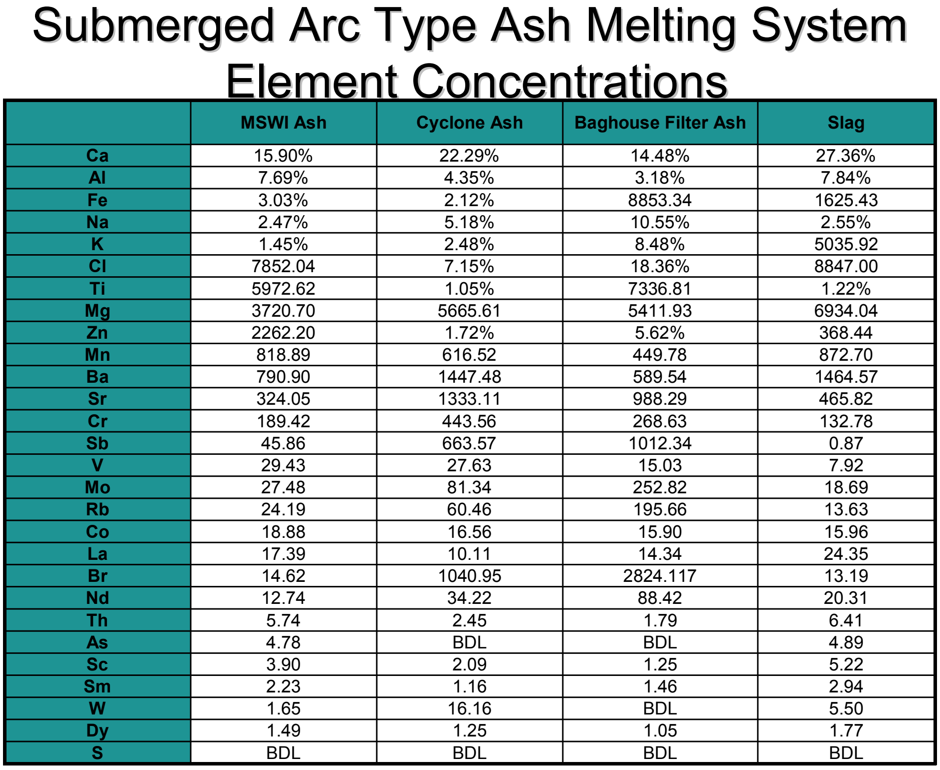
[ashes] were generated by plasma systems from 1 [t] of bottom ashes treated and this amount was increased to 37~56 kg [ashes] when we treated mixed ashes (bottom: fly ashes = 4:1) as summarized in Table 6, where wall deposited plasma fly ashes are less than 5 % [17]

The main composition of bottom and fly ashes from the incinerator are summarized in Table 3. Based on present NAA analyses, the trace composition (above 1000 ppm) observed in fly ashes is Ca > Cl > Zn > Na > K > Mg > Ti > Fe, and in bottom ashes is Ca > Na > Fe > Mg > Ti > Cl > Zn > Mn. However, fly ashes collected from the baghouse filters downstream of the thermal plasma furnaces changed their composition significantly as compared in Table 3. Trace composition (above 1000 ppm) shifted to Zn > Ca > Cl > Na > K > S, where a zinc enrichment factor of 6 times to fly ashes and 60 times to bottom ashes are observed. Beside that trace amounts (below 800 ppm) of Sb > Mg > Ti > Br > Cr > Mn > As > V > Co > La > W > Sw > Dy and Sc are also observed as shown in Fig. 10. The other compositions of incinerator ashes are converted to metals and slag and recycled as building construction materials as summarized in Table 3. Based on Table 3, most toxic trace elements can be concentrated in plasma melt fly ashes and can be trapped by baghouse filters [17].

Typical flue gas trace pollution gas measured at exit of plasma reactors with different treated ashes are summarized in Table 7. Due to the high temperature operations, significant N, Cl and S components in ashes will be converted to NO_x, HCl and SO_x. Hence, plasma flue gas was cooling/diluted to 16 to 30 times by fresh air and treated by $Ca(OH)_2$ powder spraying in first stage and SCR in second stage to allowable levels at exhaust as shown in Table 7 [17].

Detoxicity characteristics of thermal plasma municipal incinerator ash volume reduction system are experimentally investigated and the following concluding remarks are obtained [17]:

TABLE VIII
SUBMERGED ARC TYPE ASH MELTING SYSTEM ELEMENT CONCENTRATION [12]



Submerged Arc Type Ash Melting System Element Concentrations

	MSWI Ash	Cyclone Ash	Baghouse Filter Ash	Slag
Ca	15.90%	22.29%	14.48%	27.36%
Al	7.69%	4.35%	3.18%	7.84%
Fe	3.03%	2.12%	8853.34	1625.43
Na	2.47%	5.18%	10.55%	2.55%
K	1.45%	2.48%	8.48%	5035.92
Cl	7852.04	7.15%	18.36%	8847.00
Ti	5972.62	1.05%	7336.81	1.22%
Mg	3720.70	5665.61	5411.93	6934.04
Zn	2262.20	1.72%	5.62%	368.44
Mn	818.89	616.52	449.78	872.70
Ba	790.90	1447.48	589.54	1464.57
Sr	324.05	1333.11	988.29	465.82
Cr	189.42	443.56	268.63	132.78
Sb	45.86	663.57	1012.34	0.87
V	29.43	27.63	15.03	7.92
Mo	27.48	81.34	252.82	18.69
Rb	24.19	60.46	195.66	13.63
Co	18.88	16.56	15.90	15.96
La	17.39	10.11	14.34	24.35
Br	14.62	1040.95	2824.117	13.19
Nd	12.74	34.22	88.42	20.31
Th	5.74	2.45	1.79	6.41
As	4.78	BDL	BDL	4.89
Sc	3.90	2.09	1.25	5.22
Sm	2.23	1.16	1.46	2.94
W	1.65	16.16	BDL	5.50
Dy	1.49	1.25	1.05	1.77
S	BDL	BDL	BDL	BDL

1. Municipal waste volume can be reduced up to one-thirtieth by the combination of municipal waste incinerator with thermal plasma ash volume reduction system;
2. Major compositions of fly and bottom ashes from incinerators can be confined in plasma slags and metal layers generated by thermal plasmas and can be recycled into construction materials and re-sale for iron production respectively;
3. Trace toxic compounds in fly and bottom ashes can be decomposed or confined to unleachable plasma slags and plasma melt fly ashes by the thermal plasma reactors;
4. Energy efficiency for ash treatment decreases with increasing ash amount/reactor and the maximum efficiency can be achieved for 2.2 kWh/kg for bottom ashes and 1.6 kWh/kg for mixed ashes; and
5. Thermal process generates higher concentration acid gases due to the higher gas temperature operation. However, all acid gas emissions can be removed by optimum operations of SCR.

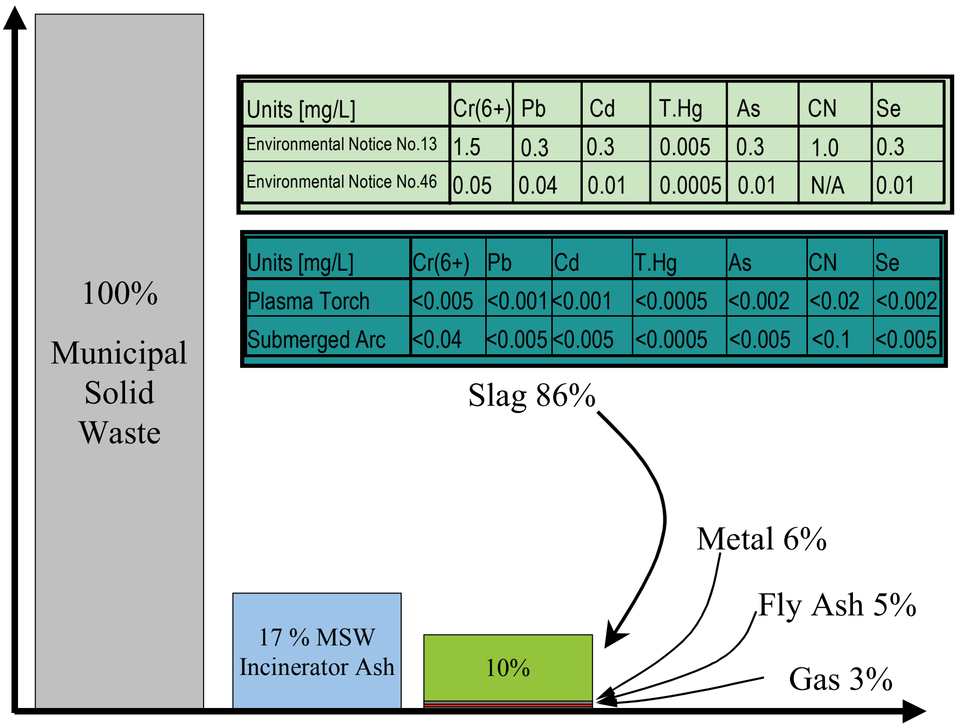
B4. Air cooled slag from the submerged arc type processes

The submerged arc generated slag is composed primarily of Ca > Al > Na > Ti > Cl > Mg > K > Fe > Ba by NAA analysis. Fe compounds are more abundant in the plasma torch type process compared with the submerged arc type process. Table 8 shows the results of the chemical analysis by XRF and ICP-MS that was also performed on the submerged arc generated slag, where, when compared with Table 3, the major elements analysis agree with NAA analysis.

Typical leaching test results observed for the slags are summarized in Fig.10. No significant leaching of toxic elements occurs, however, plasma torch process generated water crushed slag shows better leaching characteristics than that of the submerged arc process generated air-cooled slag. Fig. 10 also shows that the over all system can be reduced waste volume to below 10 % [12].

B5. Fry ashes from the submerged arc type processes

The particle distribution of the submerged arc reactor fly ash shows that the maximum particle size for the baghouse and cyclone collected fly ashes are below 2 μm and around 4-6 μm respectively. The major components (> 1000 ppm) of the ash by-products of the arc plasma process, in decreasing concentration order, are Ca> Cl> Na> Al> K> Fe> Zn> Ti> Mg> Ba> Sr> Br for the cyclone collected ashes, and Cl> Ca> Na> K> Zn> Al> Fe> Ti> Mg> Br> Sb for the baghouse filter collected ashes. As expected the presence of major elements is similar to those of the incinerator ash, however, in different concentrations as shown in Table 9. The main component, Ca is 1.3 times enriched in the cyclone-collected ashes but almost unchanged in the baghouse filter collected ashes. Concentration of some elements



Units [mg/L]	Cr(6+)	Pb	Cd	T.Hg	As	CN	Se
Environmental Notice No.13	1.5	0.3	0.3	0.005	0.3	1.0	0.3
Environmental Notice No.46	0.05	0.04	0.01	0.0005	0.01	N/A	0.01

Units [mg/L]	Cr(6+)	Pb	Cd	T.Hg	As	CN	Se
Plasma Torch	<0.005	<0.001	<0.001	<0.0005	<0.002	<0.02	<0.002
Submerged Arc	<0.04	<0.005	<0.005	<0.0005	<0.005	<0.1	<0.005

Fig. 9. Leaching characteristics of arc system and the percentage of volume reduced during the processes [12]

such as Cl and Zn are enriched significantly in the fly ashes. Cl is enriched 9 and 22 times for cyclone and baghouse filter ashes respectively (where it becomes the major component). Zinc increases 8 and 25 times respectively to 1.72 % in cyclone and 5.62 % in baghouse filters. Br follows a similar trend as Zn, though its final concentrations are not as high. Other elements such as As are separated into the slag and its concentration decreases below detection limits for the treated ashes. If a process could be developed to extract some of the high concentration metals from the ashes, some of the by-product would also prove to be valuable; however, currently they are land filled after special chemical treatments [12].

B5. Arc vs plasma torch processes

Detoxicity characteristics of thermal plasma municipal incinerator ash melting system are experimentally investigated and the following concluding remarks are obtained [12]:

1. Municipal waste volume can be reduced up to one-tenth by the combination of municipal waste incinerator with thermal plasma ash melting system;
2. Major components of fly and bottom ashes from MSW incinerator can be confined to plasma generated slags since the toxic elements are not leachable and can be recycled to construction materials. The metal layers generated by thermal plasmas are mainly composed of iron products and can be reused after processing, however, the plasma torch type process shows better iron confinement in the metal product than the submerged arc type process;
3. Trace toxic compounds in MSW incinerator fly and bottom ashes can be confined to unleachable plasma generated slag, however, plasma torch type process generated water crushed slag is less leachable than the submerged arc type process air-cooled slag. The modification of submerged arc type processes from air cooled to water crushed slag is highly recommended.
4. Both plasma torch type and submerged arc type ash melting systems yield small amounts of fly ashes with highly concentrated reusable elements such as Zn, Ti, Mg, etc, for submerged arc type process and Zn for plasma torch type process. Recovery of these elements may enhance economic benefit in the long term; and
5. Energy efficiency of the plasma torch type process is much higher than the submerged arc type process. However, NO_x generation from air plasma must be minimized for better economic process

C. Used tire waste treatment

The disposal of used tires represents an environmental problem. As the heat content of the rubber tires is even higher than that of coal, it might be an opportunity to be a source of alternate fuel for power generation. There have been attempts to burn old tires directly in coal-fired boilers for production of electricity [20, 21]. However, there are several environmental concerns, since the combustion flue gas may contain acid gases, such as NO_x, CH_x and SO_x, and heavy metals such as Hg, Zn, Cd, etc. One of the techniques being developed is to pyrolyse rubber tires in a 700 °C nitrogen atmosphere to produce combustible gases [22], where the scrap tires produced approximately 55 % oil, 10 % gas and 35 % char. Other techniques, such as hot ceramic balls, vertical cross flow reactor, whole tire semi-fluidized-bed reactor, oxidative, steam atmosphere and melted salt processes, have also been studied in pyrolysing waste rubber tires.

Although many experiments have been done, tire pyrolysis processes are far from satisfactory in both economic and environmental aspects. Pyrolysing used tires in a thermal plasma to produce syngas may be an attractive option for power plant applications. Syngas can be used to substitute ignition oils in coal-fired power plant boilers [13,23,24]. In the thermal plasma pyrolysis [13], the tire particles are dissociated into atoms and charged particles. With the proper quenching process, it is possible to "freeze" the chemical reaction before unexpected substances are formed. Therefore, plasma pyrolysis may be a better alternative to get economic and "cleaner fuel" from old tires. Chang *et al.* [13] conducted preliminary study of thermal plasma pyrolysis of used tires, and up to 4 to 7 MJ/m^3 heating valve syngas was produced with trace NO_x, SO_x and H_2S emissions (<100 ppm).

The treatment system is consisted of DC plasma torch with the powder and steam injection segment, plasma reactor, and the quenching chamber [13]. The pure argon or argon-hydrogen mixture gas was injected into the torch as a working gas. The gas sampling system included a 0.5 micron, ceramic-made high-temperature and steel-made low temperature filters, gaseous pollutant detection sensors, and solenoid valves to control the sampling processes. A fluidized bed powder feeder was used to inject the tire powder into the plasma torch. Argon was used as the carrier gas to transport the solid particles. At the same axial location of the powder injection port, the steam vapor was injected into the plasma torch from the steam generator. The superheated, pressurized steam was produced and stored in a pressure vessel. The gas produced was analyzed by FTIR and GC (gas chromatography) techniques. The ash particles were analyzed by the neutron activation analysis (NAA) and ICP-ES (Inductive Coupling Plasma-Emission Analysis). PCB and PAH were analyzed by the solvent extracted-gas chromatography/mass spectrometer method. Typical downstream region gas temperature profiles inside the reaction chamber shows that the gasified tires will be rapidly quenched inside the reaction chamber to form hydrocarbon and ash aerosol particles.

C1. Tire analyses

In order to obtain a better heat and mass transfer, size distribution of shredded tires must be as small as possible. Hence, the shredded tire mean size used in the present investigation is approximately near 200 μm which is much smaller compared with earlier investigation of Chang *et al.* [13], i.e., R_p = 500 μm. A typical microscopic view of shredded tire powders.shows that the shape of the tire powders is irregular and many glass fibre particles coexist with tire powders.

C2. Ash analyses

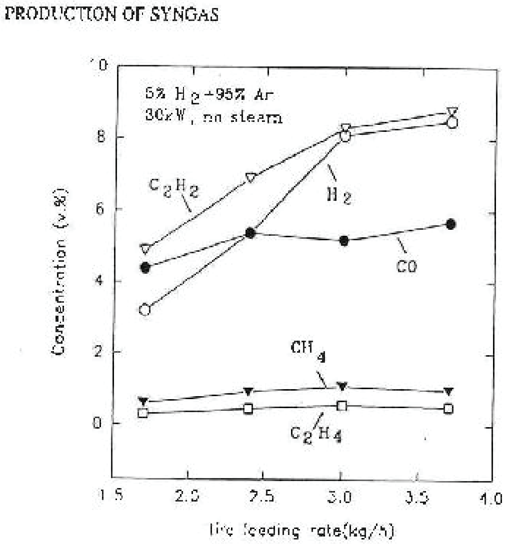


Fig. 11. Plasma generated tire treated by-products gas as a function of tire feeding rate [13]

A typical NAA of ash particles shows that except for S, most of the compounds can be concentrated up to 50 % to the factor of 8 times in ash particles [13].

C3. Gaseous products analyses

The sampling gases were analyzed by FTIR and gas chromatography (GC) techniques. The IR spectra can identify most of the hydrocarbon gases, carbon dioxide and carbon monoxide. The experimental results show a large quantity of combustible gases, such as H_2, CO, C_2H_2, CH_4, NH_3 and C_2H_4, were produced during the tire pyrolysis process. No significant pollution gases, such as SO_2 and NO_2, were observed. The relative concentration of gaseous products as a function of plasma torch operating power for various tire feed rates is shown in Fig. 11. The concentration of C_2H_2, NH_3, CO and CO_2 increase with increasing input power while CH_4 and C_2H_4 concentrations decrease for lower tire feed rates. For higher tire feed rates, CO_2 decreases with increasing input power, while CO increases. C_2H_2, NH_3, C_2H_4 and CH_4 concentrations increase non-monotonically with increasing input power, but CH_4 and C_2H_4 become minimal when NH_3 and C_2H_2 become maximum. If tire is pyrolysed in Ar-H_2 thermal plasmas, no significant C_2H_4 and NH_3 are observed and the formation of CO and CO_2 are reduced. CH_4 and C_2H_2 become major components of syngas as well as hydrogen.

C4. Concluding remarks for reduction processes

The effect of plasma gas and powder on the thermal plasma pyrolysis of used tires is experimentally investigated and the following concluding remarks are obtained [13]:

(1) A composition of syngas produced by a thermal plasma pyrolysis consisted of CO_2, CO, CH_4, C_2H_2, C_2H_4, H_2 and NH_3;
(2) No significant pollutant gas such as H_2S, SO_2 and NO_x are observed;
(3) Metal compounds in tire powders such as Zn, Fe, W, Mg, As, Ti and Cr can be confined and concentrated in ash particles during the pyrolysis processes;
(4) The other compounds such as Ba, Br, Cl, K, Na, Ca, etc., in tire powders can also be confined and concentrated in ash particles during the present processes. However, compounds such as S did not oxidize during the process but may vapourize as elementary atoms;
(5) Depending on the operating plasma gas and tire feed rates, hydrocarbon concentrations nonmonotonically increase with increasing operating plasma power. Hence, the optimum plasma tire pyrolysis operating conditions significantly depend on the operating power, tire feed rate, plasma gas compositions and steam flow rates.

V. THERMAL PLASMA WATER TREATMENT

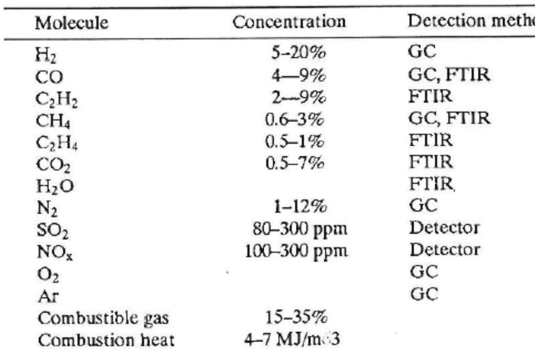
A. Introduction

The application of plasma technologies for the treatment of drinking and wastewater is not new. Three categories of plasma treatment technologies exist, including: remote, indirect, and direct. Remote plasma technologies involve plasma generation in a location away from the medium to be treated (e.g., ozone). Indirect plasma technologies generate plasma near to, but not directly within, the medium to be treated (e.g., UV, electron beam). More recently direct plasma technologies (i.e., electrohydraulic discharge) have been developed that generates plasma directly within the medium to be treated thereby increasing treatment efficiency [4, 25]. Three types of electrohydraulic discharge systems (pulsed corona electrohydraulic discharge (PCED), pulsed arc electrohydraulic discharge (PAED) and pulsed power electrohydraulic discharge (PPED)) have been employed in numerous environmental applications, including the removal of foreign objects (e.g., rust, zebra mussels) [26], disinfection [25, 27-29], chemical oxidation [30-34], and the decontamination of sludge [35]. This section will compare the characteristics of the pulsed corona, pulsed arc and pulsed power electrohydraulic discharge systems, discuss the treatment mechanisms generated by electrohydraulic discharge technologies, review the literature investigating the application of these technologies to water treatment, and discuss the issues and research needs associated with these technologories.

B. Characterristics of electrohydraulic discharge system

The types of electrohydraulic discharge systems differ in several operational characteristics, as summarized in Table 10, due to their different configurations as well as the different amounts of energy injected into each type of system. The PCED system employs discharges in the range of 1 J/pulse, while the PAED and PPED systems use discharges in the range of 1 kJ/pulse and larger. The pulsed corona system operates at a frequency of 10^2 to 10^3 Hz with the peak current below 100 A, and the voltage rise occurring on the order of nanoseconds. A streamer-like corona is generated within the liquid to be treated, weak shock waves are formed, and a moderate number of bubbles are observed [35, 36]. This system also generates weak UV radiation [36, 53] and forms radicals and reactive species in the narrow region near the discharge electrodes.

TABLE IX
GAS CONCENTRATION OF TIRE PYROLYSIS PRODUCTS [13]



Molecule	Concentration	Detection meth
H_2	5-20%	GC
CO	4—9%	GC, FTIR
C_2H_2	2—9%	FTIR
CH_4	0.6–3%	GC, FTIR
C_2H_4	0.5–1%	FTIR
CO_2	0.5–7%	FTIR
H_2O		FTIR
N_2	1–12%	GC
SO_2	80–300 ppm	Detector
NO_x	100–300 ppm	Detector
O_2		GC
Ar		GC
Combustible gas	15–35%	
Combustion heat	4–7 MJ/m3	

TABLE X
CHARCTERISTICS OF ELECTROHYDRAULIC DISCHARGE SYSTEMS [42]

Property	Pulsed Corona (PCED)	Pulsed Arc (PAED)	Pulsed Power (PPED)
Operating Frequency [Hz]	10^2 - 10^3	10^{-2} – 10^2	10^{-3} – 10^1
Current [A]	10^1 – 10^2	10^3 – 10^4	10^2 – 10^5
Voltage [V]	10^4 – 10^6	10^3 – 10^4	10^5 – 10^7
Voltage Rise [sec]	10^{-7} – 10^{-9}	10^{-5} – 10^{-6}	10^{-7} – 10^{-9}
Pressure wave generation	Weak	Strong	Strong
UV generation	Weak	Strong	Weak

PAED employs the rapid discharge of stored electrical charge across a pair of submerged electrodes to generate electrohydraulic discharges forming a local plasma region. The PAED system operates at a frequency of 10^{-2} – 10^2 Hz with the peak current above 10^3 A and the voltage rise occurring on the order of microseconds [31-38]. An arc channel generates strong shock waves with a cavitation zone [36-38] containing plasma bubbles [5] and transient supercritical water conditions [39]. This system generates strong UV radiation and high radical densities, which have been observed to be short-lived in the cavitation zone [40]. Pulsed spark electrohydraulic

TABLE XI
COMPARISON OF PLASMA AND CONVENTIONAL WATER TREATMENT PROCESSES [25, 42]

TARGET COMPOUNDS	CL/CLO$_2$	OZONE	ELECTRON BEAM	PCED	PAED	UV-C
MICROORGANISMS	ADEQUATE	GOOD	ADEQUATE	GOOD	GOOD	GOOD
ALGAE	NONE	PARTIAL	NONE	PARTIAL	GOOD	ADEQUATE
URINE COMPONENTS	ADEQUATE	GOOD	GOOD	GOOD	GOOD	NONE
VOCS	NONE	ADEQUATE	GOOD	GOOD	ADEQUATE	NONE
INORGANICS	NONE	PARTIAL	PARTIAL	ADEQUATE	ADEQUATE	NONE

discharge (PSED) system [41] characteristics are similar to those of PCED, with a few characteristics falling between those of PCED and PAED.

The PPED system operates at a frequency of 10^{-3} to 10^1 Hz with the peak current in the range of $10^2 – 10^5$ A [33]. The voltage rise occurs on the order of nanoseconds [33]. This type of system generates strong shock waves and weak UV radiation.

C. Treatment mechanism generated by electrohydraulic discharge

Traditional water and wastewater treatment technologies can be broadly classified into three categories: biological, chemical and physical processes. Biological methods are typically used to treat both municipal and industrial wastewaters, and are generally not successful at degrading many toxic organic compounds. Chemical processes typically involve the addition of a chemical to the system to initiate a transformation; some chemicals commonly added, such as chlorine, are often associated with negative effects on both human and environmental health. Regulations governing the use of many of these chemicals are becoming increasingly stringent. Physical processes do not involve chemical transformation, and therefore generally serve to remove contaminants from the bulk fluid phase through concentrating them in a liquid or sludge phase. Many drinking water systems are challenged with difficult to treat target compounds such as organics (e.g., NDMA) and pathogens (e.g., Cryptosporidium, viruses, etc.). To be effectively removed from drinking water supplies, many of these recalcitrant compounds require specialized, and often target specific treatment technologies. The necessity of multiple treatment technologies can be quite costly, especially for small systems. In order to meet the challenges presented by continuously emerging contaminants and increasingly stringent regulations, new and promising treatment technologies, such as electrohydraulic discharge, must be developed.

Depending on the technology, the treatment mechanisms generated by plasma technologies include 1) high electric fields; 2) radical reactions (e.g., ozone, hydrogen peroxide); 3) UV irradiation; 4) thermal reactions; 5) pressure waves; 6) electronic and ionic reactions; and 7) electromagnetic pulses (EMP). In general, both electron and ion densities are proportional to the discharge current, while UV intensity, radical densities and the strength of the pressure waves generated are proportional to the discharge power. Direct plasma technologies (i.e., electrohydraulic discharge) have the potential to be more efficient than either indirect or remote plasma technologies as they capitalize, to some degree, on all of these mechanisms due to the direct application [25, 42]. Fig. 11 shows the treatment mechanisms initiated by PAED.

Because electrohydraulic discharge systems do exploit all of the treatment mechanisms generated by the plasma reaction, both chemical and physical, these technologies have the ability to effectively treat a range of contaminants broader than that of other conventional and emerging technologies [25]. Preliminary research has indicated that PAED offers advantages over indirect plasma methods in that it can provide comparable or superior treatment of microorganisms, algae, volatile organics, nitrogenous municipal waste compounds, and some inorganics [38-44]; these observations are qualitatively summarized in Table 11 [25, 42]. Moreover, these benefits are available concurrently from one technology as opposed to a series of treatment technologies. In addition, preliminary investigations conducted with a limited number of target compounds have indicated that effective water treatment with PAED utilizes less than 50 % of the kilowatt-hours required by other plasma technologies (e.g., UV) for equivalent levels of treatment [25, 42].

D. Treatment of chemical contaminants by electrohydraulic discharge

Several studies have demonstrated that electrohydraulic discharge can effectively treat aqueous chemical contaminants such as atrazine [34], paraquinone [31, 34], 4-chlorophenol [33], 3, 4 dichloroanaline [34], phenol [45-47], dyes [48], urine compounds [44], MTBE [50], and 2, 4, 6-trinitrotoluene [33, 52]. Several investigations employing pulsed streamer corona discharge (PCED) have been conducted [44-48, 51], however, it has been observed that organic compound treatment by PCED requires the addition of activated carbon, a photocatalyst, or the superimposition

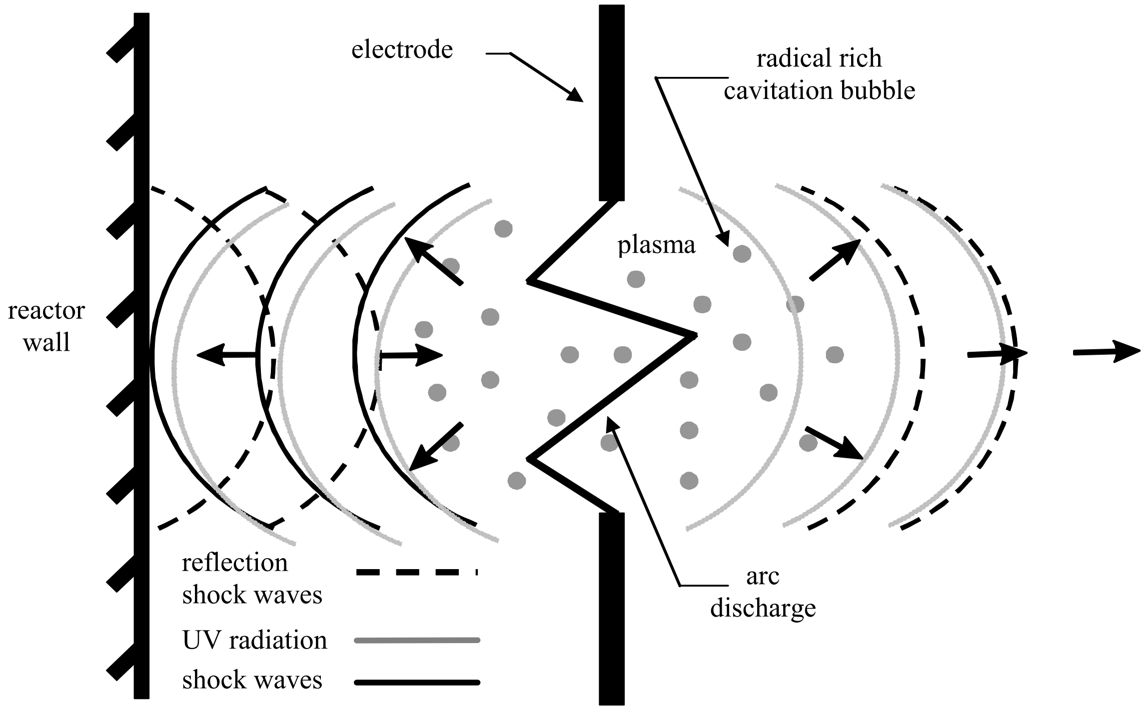


Fig. 11. Water treatment mechanisms initiated by PAED [25, 31]

of glow corona above the liquid surface [6, 39, 40]. Willberg *et al.* [33] investigated the removal of 4-chlorophenol [4-CP], 3, 4-dichloroanaline [3,4-DCA] and 2, 4, 6-trinitrotoluene [TNT] by PPED. A 4.0 L vessel was employed in batch mode as the reaction chamber, and connected to a PPED power supply with a discharge energy of 7 kJ/pulse. The results show that a 35 % conversion of 4-CP was obtained after a cumulative energy input of 69.4 kWh/m^3 (250 kJ/L) at an applied voltage of 10.2 kV and after a cumulative input energy of 126.4 kWh/m^3 (455 kJ/L). This conversion rate is significantly larger than that accomplished by PPED alone on the 4-CP, however it is unclear if the increased conversion can be attributed to ozone addition due to the fact that the reaction pathways for 4-CP and TNT are not the same. They concluded that their results demonstrated the potential application of the electrohydraulic discharge process to the treatment of hazardous wastes.

. The result also shows the production of p-benzoquinone and chloride as a function of cumulative power input. Stoichiometrically, the chloride production can be attributed entirely to the 4-CP degradation, however only 45 % of the 4-CP degraded is present for in the form of p-benzoquinone. Experiments investigating the degradation of TNT through a combination of PPED and ozone were also conducted. Greater than 99 % TNT degradation was achieved [33].

Lang *et al.* [51] investigated the kinetics of TNT removal by PPED as a function of aqueous phase ozone concentration, pH, discharge energy, and water gap distance. A 4.0 L vessel was employed in batch mode as the reaction chamber, and connected to the PPED power supply. It was observed that the rate of TNT degradation increased with increasing aqueous phase ozone concentrations (to 150 μM), increasing pH (from 3.0 to 7.9) increasing discharge energy (from 5.5 kJ to 9 kJ), and decreasing water gap distance (from 10 mm to 6 mm). Several intermediate degradation products (nitrate, 2, 4, 6-trinitrobenzoic acid (TNBA)) were detected over the course of these experiments, however effective mineralization of over 90 % of the initial TNT present was achieved.

Karpel Vel Leitner *et al.* [31] identified various reaction mechanisms initiated by PAED by treating various molecules with known degradation pathways. Their experiments employed a 5 L reaction chamber operated in batch mode connected to a spark gap type power supply (0.5 kJ/pulse) with rod-to-rod electrodes in water. They employed both maleic and fumaric acids, which are known to photoisomerize by UV radiation, to confirm the presence of UV radiation in PAED systems. Approximately 35 % of the maleate and fumarate ions removed in their experiments were converted to fumarate and maleate ions respectively. It was therefore concluded that PAED does induce photochemical reactions, but that photolysis is not the only phenomenon responsible for the abatement of these molecules. Karpel Vel Leitner *et al.* [31] also treated solutions of nitrate ions to demonstrate reduction reactions. They observed that 75 – 86 % of the nitrate ions removed were converted to nitrites, and concluded that reducing species played a significant role in the transformation, as photolysis alone could not account for the observed nitrite production. Karpel Vel Leitner *et al.* [31] investigated the presence of oxidizing species on aqueous solutions of hydroquinone. Although the hydroquinone was oxidized, the study was not able to identify the mechanism responsible for the oxidation reaction. The authors concluded that oxidizing species are present, but that further investigation is required to identify and quantify these species.

The final objective of the Karpel Vel Leitner *et al.* [31] study was to investigate the effect of various additives, initial concentration, and operating conditions on the degradation of atrazine by PAED. Several additives were considered, including: 5 mmol/L of bicarbonate, 5 mmol/L of dihydrogenphosphate, and 500 μmol/L of hydrogen peroxide; PAED alone, with no additives, constituted the reference case. The result shows that hydrogen peroxide had no significant effect on degradation of atrazine by PAED, and that both bicarbonate and dihydrogenphosphate addition inhibited the removal of atrazine by PAED. Initial atrazine concentrations were also found to be a factor in removal by PAED, with the percentage of atrazine removal increasing with decreasing initial concentrations [34]. Increasing the gap distance between the electrodes in the aqueous solution from 1.5 mm to 4 mm increased removal rates from approximately 50 % to greater than 95 %, with a cumulative input energy of approximately 12.5 kWh/m^3 (45 kJ/L) in each case. Additionally, this increase in gap distance resulted in a decrease in the formation of the by-product, deethylatrazine (DEA) [34]. The increased efficiency with larger gap distances was attributed to an increase in the size of the spurs induced by the plasma.

Angeloni *et al.* [49] investigated the effects of initial solution pH (6 – 8.5), charging voltage (2 – 3 kV), detention time (5 – 30 min) (i.e., cumulative input energy) and water-arc-electrode gap (1 – 3 mm) on the removal of 10 mg/L of methyl-tert butyl ether (MTBE) from an aqueous solution by PAED. A spark gap-type power supply (0.3 kJ/pulse) with rod-to-rod type electrodes in the aqueous solution was employed together with a 3 L flow-through reactor. The result shows that greater than 99 % removal was observed with a cumulative input energy of 12.5 kWh/m^3 (45 kJ/L) (which corresponded to a detention time of 30 minutes), an initial solution pH of 7, a charging voltage of 3 kV, and a water-arc-electrode gap of 1 mm. The experimental investigation indicated that the initial solution pH did not have a significant effect on MTBE removal, however the MTBE decomposition increased with increasing charging voltage and increasing detention times. The result shows that MTBE decomposition decreased with increasing water-arc gap distances; this was attributed to the fact that PAED discharges weaken with increasing water-arc gap distances. UV photolysis was not considered to be a mechanism of MTBE decomposition in these experiments; however the author indicated that further research was required to determine which mechanism(s) were responsible for MTBE decomposition. No significant liquid MTBE decomposition by-products were observed; however the author concluded that further research was required to examine potential by-product formation.

E . Disinfection of pathogenic contaminants by paed

The relative ease of disinfection of *E. coli*, as compared to protozoan pathogens such as *Cryptosporidium parvum*, is commonly recognized. *E. coli* disinfection has been achieved with several treatment technologies, including UV irradiation. Many strains of *E. coli* have demonstrated an ability to repair after irradiation with low- and medium-pressure UV. *E. coli* inactivation by electrohydraulic discharge was reported by Ching *et al.* [29], who employed PPED with discharges of 7 kJ/pulse at 5.5 kV.

Subsequently, Lee *et al.* [54] investigated the disinfection of 0.7 L of a 4.0×10^7 cfu/mL *E. coli* or *B. subtilis* suspension in 0.01 M PBS at pH 7.4 by PAED with 0.3 kJ/pulse at 2.2 kV and a water gap of 1 mm. Figure 5.6 shows the log10 inactivation of *E. coli* cells and *B. subtilis* in PBS as a function of the cumulative power input per liter of solution treated. This figure clearly indicates average *E. coli* inactivation of 2.6-, 3.3-, and 3.6-log after the respective application of 5.6, 13.9 and 25 kWh/m^3 (20, 50 and 90 kJ/L) (corresponding to detention times of approximately 0.8, 1.5, and 5.8 minutes respectively). Slightly larger removals were obtained for inactivation of *B. subtilis*. A logit plot of these data was not constructed because of the relatively small number of data points and the high level of disinfection achieved within the first data point 9.4 kWh/m^3 or (2.6 kJ/L power input).

It is noteworthy that the pattern of *E. coli* inactivation observed by Lee *et al.* [54] is similar to that observed by Ching *et al.* [29], in that the rate of inactivation is initially high, and decreases as the cumulative power input increases. The observations made by Lee *et al.* [54] differ from those of Ching *et al.* [29]; however, as the Lee *et al.* [54] experiments achieved a slightly higher level of *E. coli* inactivation for significantly lower cumulative energy inputs. This difference is likely due to the fact that the Li *et al.* [27] experiments employed a PAED system, while Ching *et al.* [29] used a PPED system. While both systems fall under the category of direct plasma technologies, they operate slightly differently, and as a result the UV radiation generated by PPED is weaker than that generated by PAED [5, 25, 28, 53].

F. Municipal sludge treatment

Conventional municipal wastewater treatment consists of preliminary processes (screening and grit removal), primary settling to remove heavy solids and floatable materials, and secondary biological aeration to metabolize and flocculate colloidal and dissolved organics. Waste sludge drawn from these unit operations is thickened and processed for ultimate disposal. Current

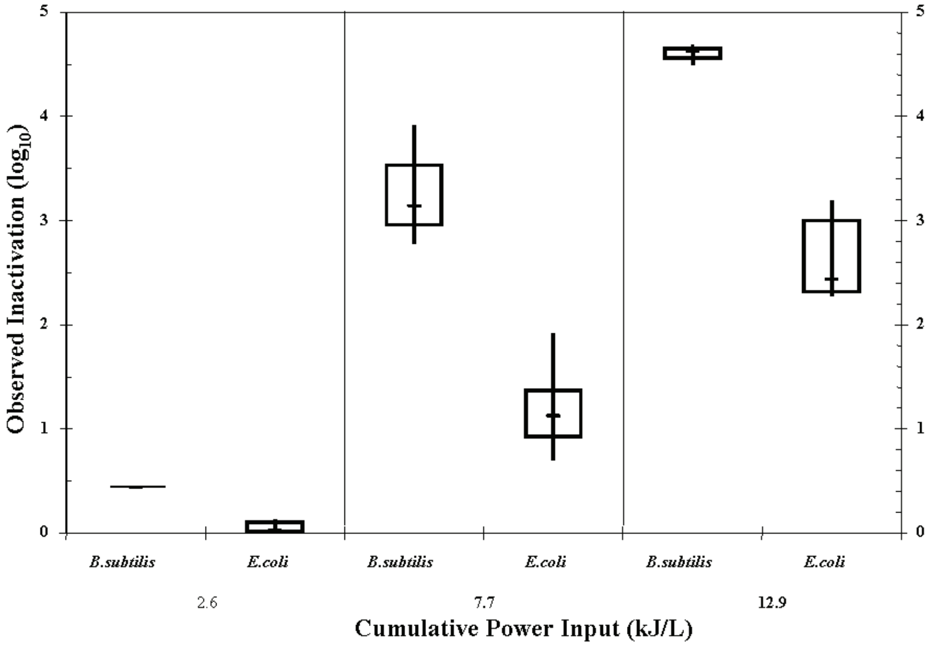


Fig. 12. Box and whisker plots of *E. coli* and *B. subtilis* (suspended in 0.01 M PBS) inactivation by PAED. V = 2.2 kV, E = 0.3 kJ/pulse, pH 7.4, water gap = 1 mm. After Lee *et al.* [54]

TABLE XII
TYPICAL METAL CONTENT IN MUNICIPAL SLUDGE (DRY SOLIDS, mg/kg) [25]

Metal	Arsenic	Cadmium	Chromium	Cobalt	Copper	Iron	Lead
RANGE	1.1-230	1-3410	10-99,000	11.3-2490	84-17,000	1000-154,000	13-26,000
MEDIAN	10	10	500	30	800	17,000	500

METAL	MANGANESE	MERCURY	MOLYBDENUM	NICKEL	SELENIUM	TIN	ZINC
RANGE	32-9780	0.6-56	0.1-214	2-5300	1.7-17.2	2.6-329	101-49,000
MEDIAN	260	6	4	80	5	14	1700

options for ultimate disposal include land application, incineration, or landfill disposal. The characteristics of municipal sludge that affect its suitability for application to land include organic content (about 40 % of total solids if measured as volatile solids), nutrients, pathogens, metals, and toxic organics [25]. The concentration of metals and toxic organics in municipal sludge vary widely. The typical metal concentrations in municipal sludge are shown in Table 12.

Because of the presence of toxic metals and organics, land application of municipal sludge is under greater scrutiny now. For large metropolitan areas, landfill disposal is getting more and more costly. Cost and air pollution concerns also limit the use of incineration as an option for ultimate disposal of municipal sludge. Due to the high organic content of much sludge, however, PAED may be used for sludge volume reduction, i.e. conversion of organics to hydrocarbon gases [42].

G. Concluding remarks for plasma water treatments

This paper conducted a review of the application of direct plasma technologies to the removal/inactivation of chemical and microbial contaminants in water. The result shows that electrohydraulic discharge technologies generate a range of treatment mechanisms, both chemical and mechanical, suitable for removing/inactivating both chemical and microbial contaminants. Furthermore, the results of experiments completed to date indicate that electrohydraulic discharge technologies have the potential to treat these contaminants as effectively, and more economically, than conventional treatment technologies. Although the results to date are very promising, many questions and issues must still be resolved before these technologies will become commonplace in treatment facilities. These issues include, but are not limited to: optimization of the reactor for a range of operating conditions, a more complete understanding of the reactions initiated by this technology and therefore the range and types of contaminants that could be treated effectively, potential additives and catalysts to the reactions initiated, possible hazardous by-product formation, a more complete understanding of the economics of these systems as compared to more conventional treatment technologies, and the effectiveness of electrohydraulic discharge at various points within the conventional treatment process More recently, a plasma injection of radicals was also investigated and review given by Yasuoka *et al.* [55] for detail discussions.

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