NATIONAL TECHNICAL UNIVERSITY of ATHENS
School of Chemical Engineering
Laboratory of Thermodynamics & Trasport Phenomena

Treatment and energy utilization of municipal and industrial solid wastes with the plasma arc gasification technology

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OUTLINE

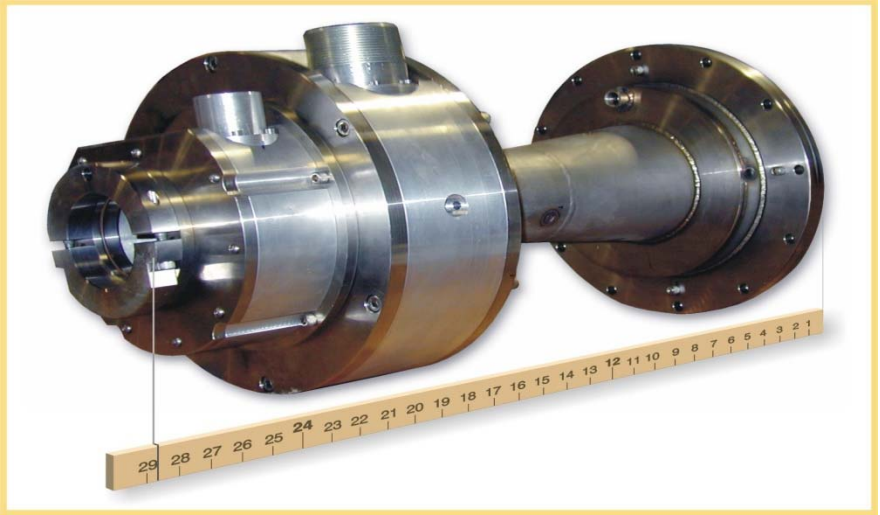
- Introduction
  - ✓ Methods for thermal treatment of MSW
  - ✓ Plasma Arc Gasification Technology
- The Gasification Equilibrium (GasifEq) model
- Results for a case study
- Summary

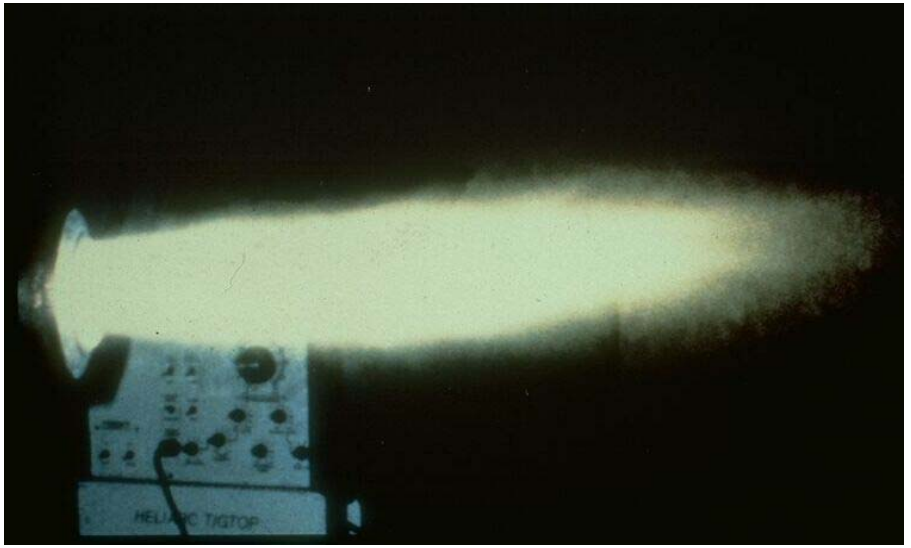
Methods for thermal treatment and energy recovery from MSW

- Incineration (energy recovery through complete oxidation)
- Pyrolysis (absence of oxygen)
- Gasification
  - Partial oxidation process using air, pure oxygen, oxygen enriched air or steam.
  - A process for converting carbonaceous materials to a combustible or synthetic gas (H_2, CO, CO_2, CH_4).
- Plasma arc gasification

Characteristics of the Plasma Arc Gasification Technology

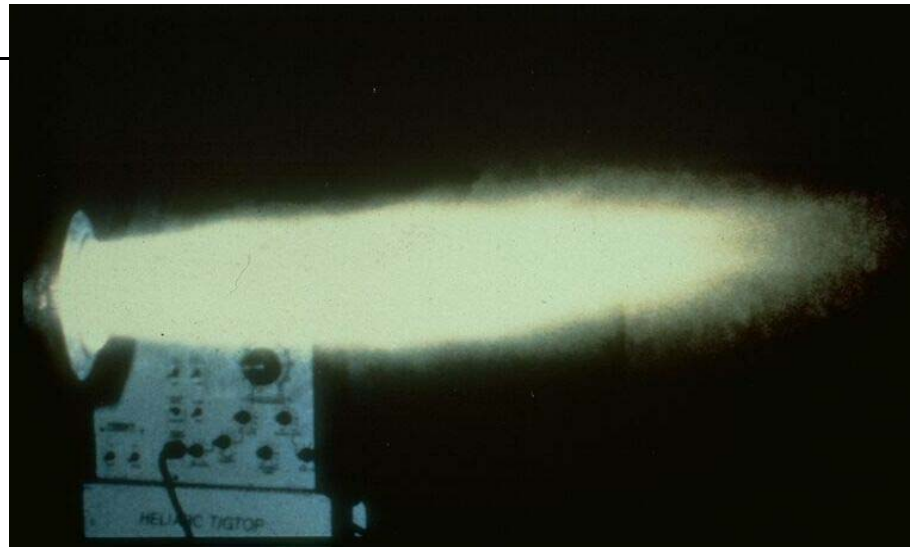
- Plasma torch power levels from 100 kW to 200 MW produce high energy densities (enthalpies)
- Temperatures over 7,000°C
- Torch operates with most gases
  * Air most common
- A gasification process
  * Not an incineration process
  * Except from energy, other products (synthesis gas, MeOH, H_2, etc.)





Plasma arc gasification technology is ideally suited for waste treatment

Hazardous & toxic compounds are broken down to elemental constituents by high temperatures



- Organic materials
  → Gasified
  → Converted to syngas (mainly H_2 & CO)

- Residual materials (inorganics, heavy metals, etc.) immobilized in a rock-like vitrified mass (slag), which is highly resistant to leaching

The Gasification Equilibrium (GasifEq) model

Modeling and optimization of the plasma gasification process for the treatment and energy recovery from MSW

- Thermodynamic analysis
- Energy optimization
- Economic analysis

- A. Mountouris, E. Voutsas, D. Tassios “Solid Waste Plasma Gasification: Equilibrium Model Development and Exergy Analysis“, Energy Conversion & Management, 47 (2006) 1723.
- A. Mountouris, PhD Thesis, NTUA, 2007.
- A. Mountouris, E. Voutsas, D. Tassios, “Plasma Gasification of Sewage Sludge: Process Development and Energy Optimization”, *Energy Conversion & Management*, 49/8 (2008) 2264.
- A. Nikolaou, Dimpola Thesis, NTUA, 2010.

Input Information - Mass and Energy balances

- MSW: C, H, O, N, S, Cl, H2O, Ash
- Synthesis gas: H2, CO, CO2, H2O, N2, CH4, Cl2, S, HCl, H2S
- General reaction in the gasifier:

$$CH_xO_yN_zS_mCl_n + w\cdot H2O + m\cdot O2 + f(m)\cdot N2 \Rightarrow$$
$$n_1\cdot CO + n_2\cdot H2 + n_3\cdot CH4 + n_4\cdot H2O + n_5\cdot CO2 + n_6\cdot N2 + n_7\cdot Cl2 + n_8\cdot S + n_9\cdot HCl + n_{10}\cdot H2S$$

- From the general reaction, the stochiometric mass balances for the elements C, H, O, N, S, Cl and the total energy balance are defined

Independent reactions

- Independent reactions (thermodynamic analysis):
  1. Water gas shift: $CO + H_2O \leftrightarrow CO_2 + H_2$
  2. Methane Decomposition: $CH_4 + H_2O \leftrightarrow CO + 3H_2$
  3. Formation of HCl: $1/2H_2 + 1/2Cl_2 \leftrightarrow HCl$
  4. Formation of H_2S: $H_2 + S(g) \leftrightarrow H_2S$

- For each independent reaction the equilibrium constant (K) is defiend, which depens only on temperature:

  $\ln K = -\Delta G°/RT$

  $d\ln K\,(T) / dT = \Delta H°\,(T)/RT^2$

$\Delta G° = \Sigma \nu_i * \Delta G_{fi}°$: is the standard Gibbs free energy of the reaction

$\Delta H° = \Sigma \nu_i * \Delta H_{fi}°$: is the standard enthalpy of the reaction

GasifEq

- **Design parameters**
  - Gasification temperature
  - moisture content of the input waste
  - amount of input oxygene
- **Output results**
  - composition of the synthesis gas
  - gasification energy required
  - heating value of the SG
  - net electricity

Model validation
(Data from a pilot unit of Thermoselect)

Composition: w/w% (daf waste)	
C	39,8
H	4,4
O	47,5
N	6,9
S	0,33
Cl	1,3
Moisture (% as received)	22,6
Ash (% as received)	16,6
T (K)	1473
Pure O_2 (kmol/kmol daf)	0,37

Results: Output composition w/w%

Compound	**Gasifeq**	**Thermoselect**
CO	30,8	30,8
H_2	1,66	1,98
CH_4	0	0
CO_2	34,3	34,2
H_2O	28,5	28,7
N_2	3,9	3,4
Cl	0	0
HCl	0,571	0,0151
H_2S	0,198	0,146

Treatment of MSW with energy production: A Case Study

Case study

Feed MSW (Greek) : 750 tn /day ≈ 250 ktn/year

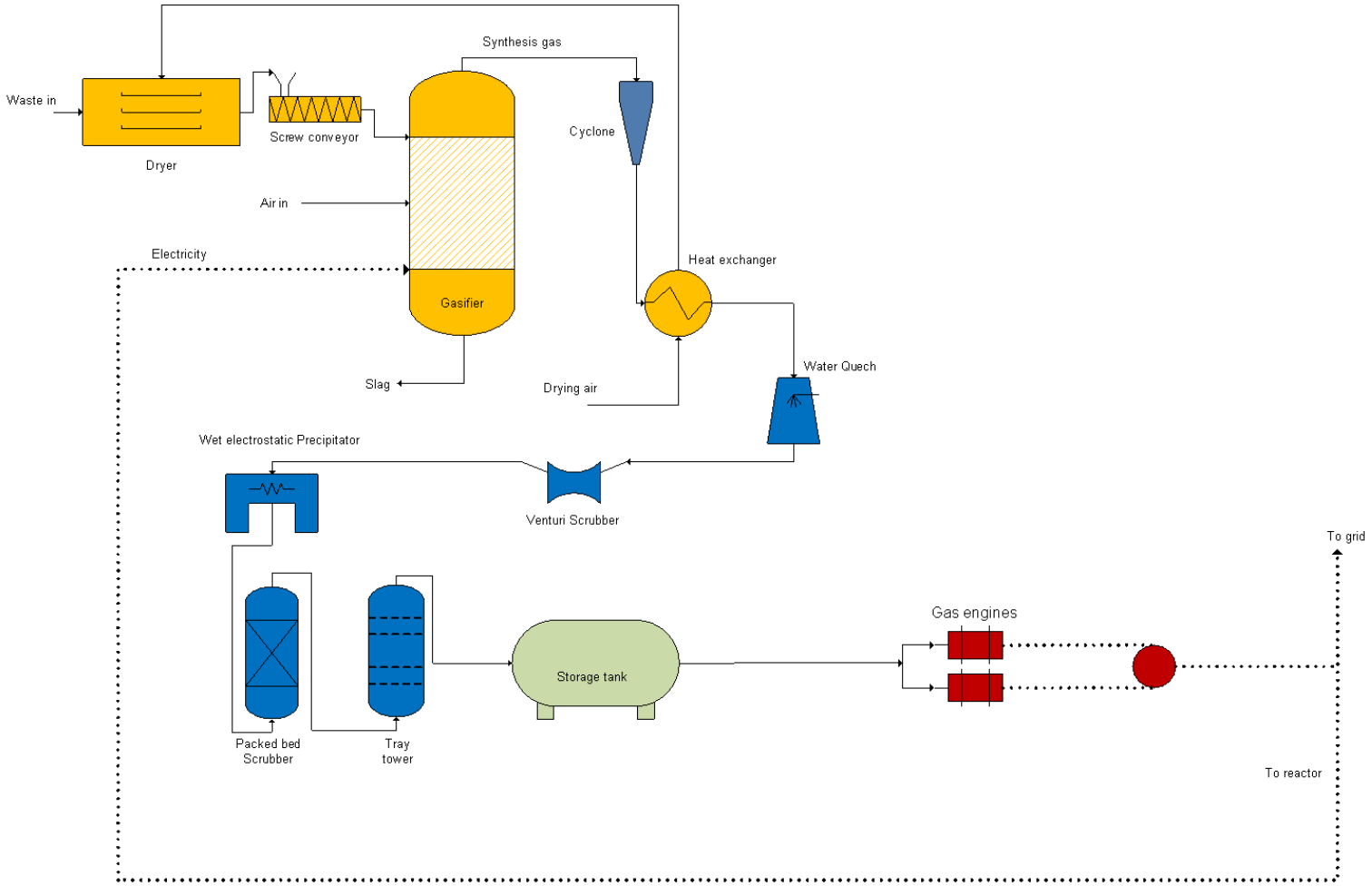
LHV: 2.76 MWh/ton ≈ 10 MJ/kg

Operational parameters optimized:
moisture content, oxygen amount and gasification temperature

Choice of temperature:

- From the energy point of view low T's are needed
- Restrictions: chemical equilibrium – reaction kinetics, destroy of toxic compounds
- Gasification temperature chosen: 1000 ^{0}C

Flow diagram of the process for MSW treatment and energy recovery



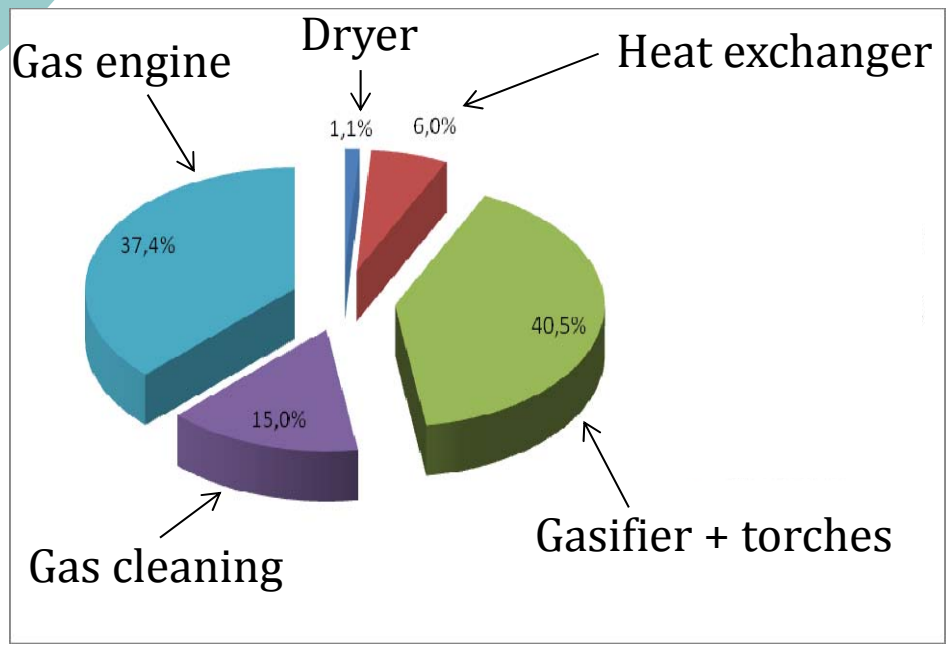
Energy optimization results

- Synthesis gas heating value: ≥1,25 kWh/Nm^3
- The sensible heat that is recovered from the cooling of the SG is enough for drying the MSW at the desired moisture before entering the gasifier

Input data	
Feed (ton /day)	**750 (≈250000 ton/year)**
Temperature (K)	**1273**
Moisture (%)	**11**
oxygene (kmol/kmol daf)	**0,44**
Results	
SG heating value (KWh/Nm^3)	**1,25**
Net electricity (MW)	**20.12 (643 kWh/tn waste)**
Electricity consumption (MW)	**10.52 (336 kWh/tn waste) (34% of the total)**
Electrical Yield (based on LHV of the MSW)	**23,3 %**

Techno-Economic Analysis

- Equipment sizing
- Calculation of equipment capital cost
- Calculation of operational cost



Equipment capital cost breakdown

Installed Capital Cost
157 MEuro (573 €/annual t cap.)
Mass burning: 530 €/ a.t.c

Operational cost (excl. labor) = 45 €/ton
Mass burning: 25-35 €/ton

Summary (1/2)

- Plasma arc gasification is a technology that can handle with success a great variety of wastes (MSW, industrial, medical, sewage sludge, ash etc).
- It has a very good environmental performance, leading to minimization of the final solid residue for landfilling.
- The GasifEq model enables a detailed energy and cost analysis of the plasma gasification process.
- Plasma arc gasification has a very good energy efficiency (ca. 23 % based on the LHV of the MSW – incineration 18%)

Summary (2/2)

- It is a relatively expensive technology for the moment as compared to well established thermal methods, e.g. mass burning.
- PAGT has not find, at least for the moment, wide commercial application in the treatment of MSW like mass burning.
- Some of the plasma-assisted gasification pilot units and plants in construction face operational and/or financial problems.

Thank you for your attention !!!

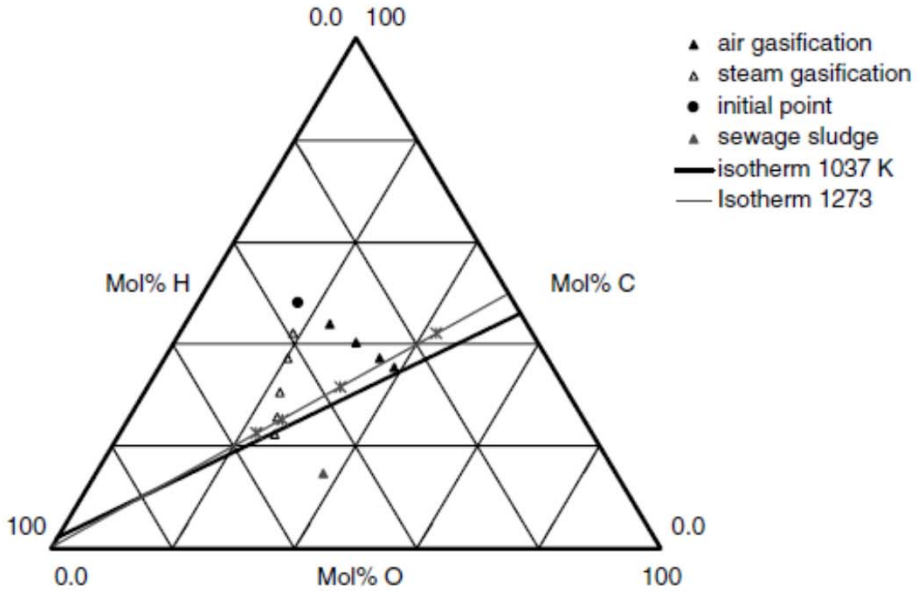
QUESTIONS ?

BACKUP SLIDES

Soot formation

Heterogeneous equilibrium of solid carbon (soot) with synthesis gas

$$C(s) + H_2O \leftrightarrow CO + H_2$$
$$C(s) + O_2 \rightarrow CO_2$$
$$C(s) + CO_2 \leftrightarrow 2CO$$



Molar ternary diagram showing carbon formation boundaries for C–H–O system at pressure of 1 atm.

Degrees of freedom

Gibbs phase-rule:

$F = k - r + 2 + \varphi - SC$

where:

k = number of components present at equilibrium (10).

r = number of independent reactions (4).

φ = number of phases (1).

SC = number of imposed special constraints (6).

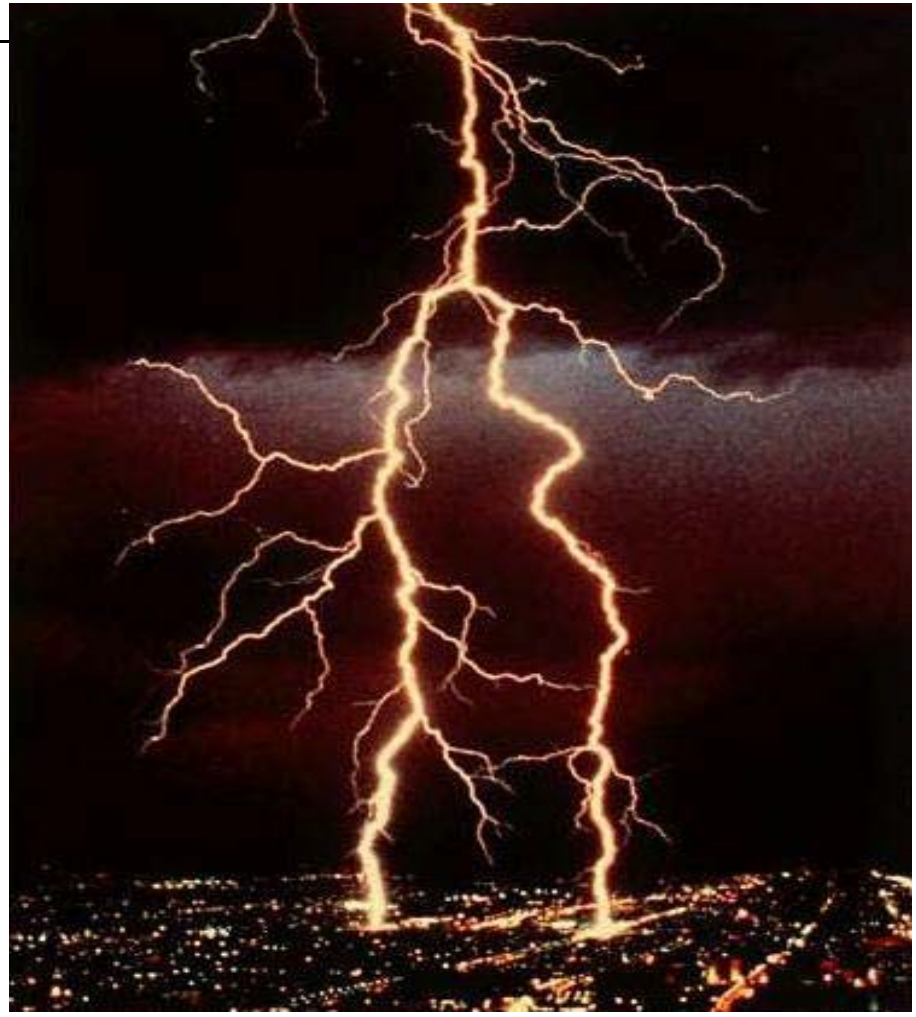
F = number of degrees of freedom (3).

- With the phase rule the number of degrees of freedom, i.e. the number of design parameters are defined.

Plasma Arc Gasification Technology

What is plasma?

- Plasma, often referred to as the “fourth state of matter”, is the term given to a gas that has become ionized.
- It is produced when a high voltage between two electrodes is applied in a common gas, like air.
- The sun and lightning are examples of plasma in nature.

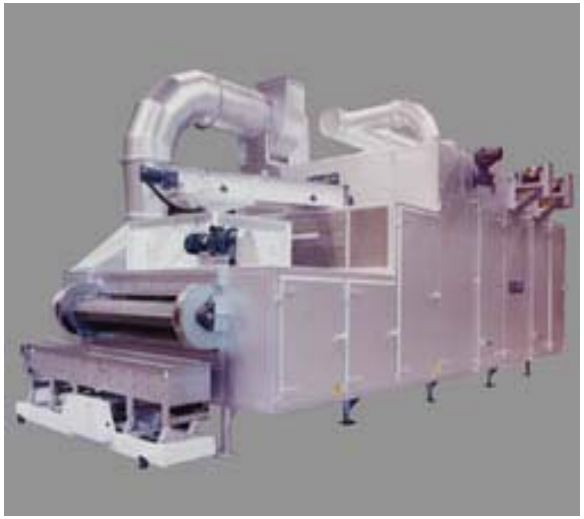


Description of the Plasma Gasification System for the treatment of MSW (1/7)

- **Waste Preparation and Feeding System**

The purpose of the waste preparation and feeding system is to reduce the size of waste and to reduce its moisture content.

Example of a Shredder

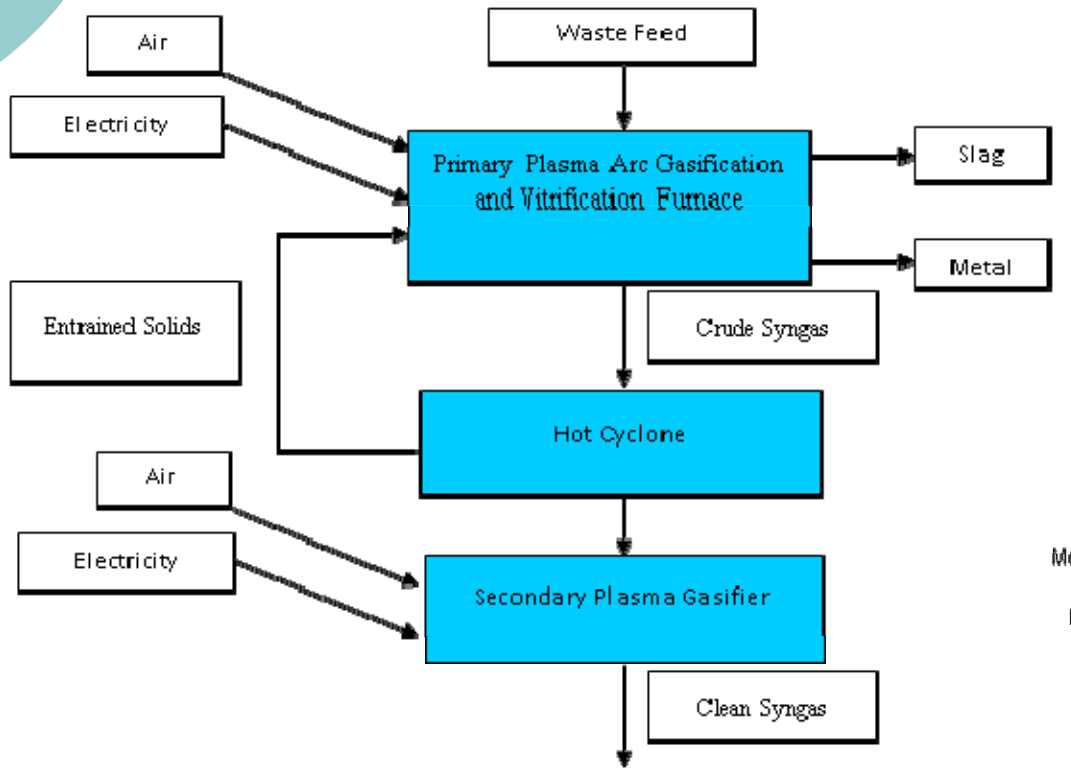


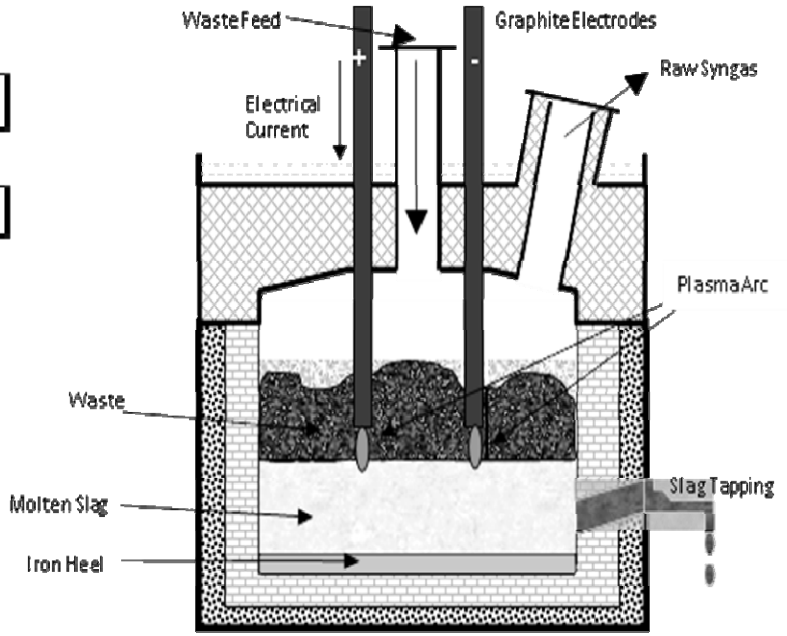
Example of a Dryer

Description of the Plasma Gasification System for the treatment of MSW (2/7)

- **Plasma Thermal Treatment System**

Its purpose is to convert the organic part of waste into syngas, consisting mainly of H2 and CO and suitable for use as fuel and the inorganic part of waste into molten metals and inert, usable slag.





Primary Gasification Furnace Schematic

Description of the Plasma Gasification System for the treatment of MSW (4/7)

Quench Vessel

The water quench is the first step in the synthesis gas cleaning system. The quench is used to freeze the high temperature (i.e. 1400 K) thermodynamic equilibrium of the gases, eliminating the possibility of reformation of dioxins and furans (formation from 300 to 500 °C).

Typical off-gas outlet temperatures range from 70 to 90 °C.

Description of the Plasma Gasification System for the treatment of MSW (5/7)

Cooling Absorber

A packed-bed scrubber is used to remove acid gases (mainly HCl) from the process off-gas streams.

In order to efficiently absorb contaminants such as HCl, a large surface area of contact is required to achieve interaction between the liquid and gaseous phases.

The scrubbers are filled with randomly oriented packing material such as saddles and rings.

Description of the Plasma Gasification System for the treatment of MSW (6/7)

- **Venturi and Entrainment Separator**

Fine entrained fly ash is removed in a Venturi scrubber. Gas passing through the Venturi throat is accelerated to a velocity that fragments the water into a mass of fine droplets. Downstream of the throat, the cleaned gas decelerates and the water droplets agglomerate to a size easily separated from the gas stream. The droplets are separated from the gas in the entrainment separator.

- **H_2S Absorber**

The sulfur in waste will be converted to hydrogen sulfide (H_2S) in the synthesis gas by the gasification process. A wide number of processes have been evaluated to remove and recover hydrogen sulfide. Redox is one economical and simple technology

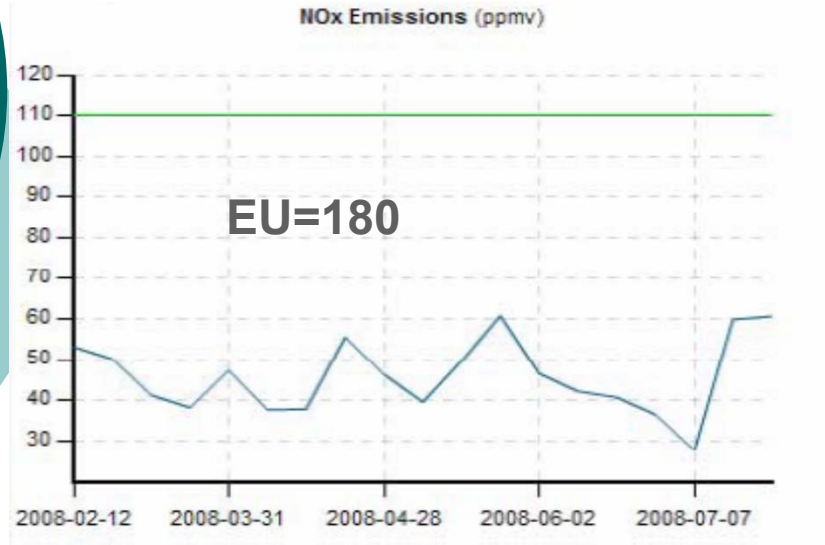
In the liquid Redox process a chelated iron solution is used to convert H_2S to elemental reusable sulfur. The process units can be designed for better than 99.9% H_2S removal efficiency.

Description of the Plasma Gasification System for the treatment of MSW (7/7)

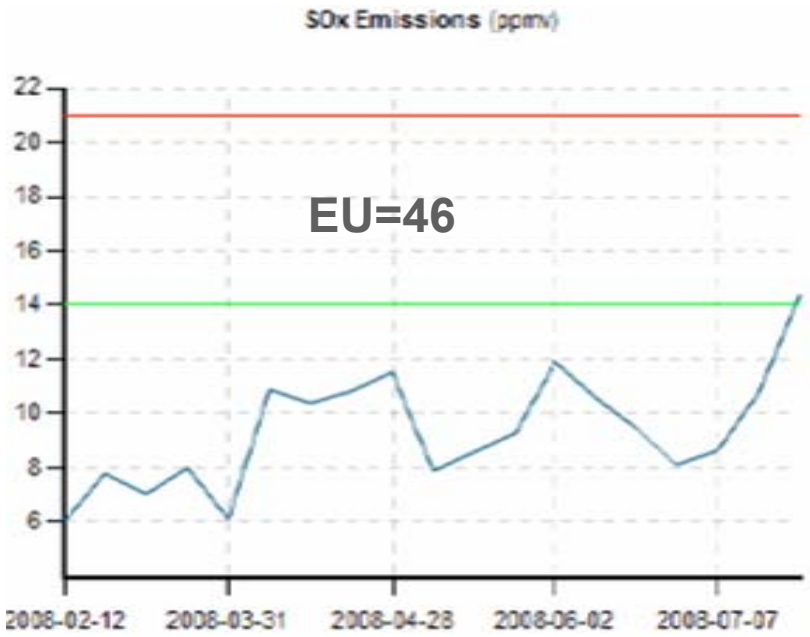
- **High-Efficiency Particulate Arresting (HEPA) and Activated Carbon Filter**

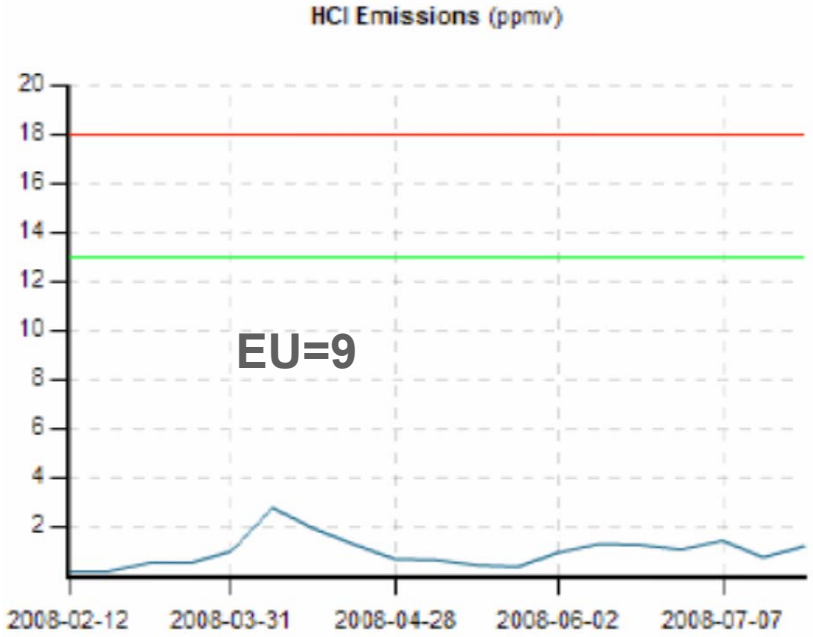
After removal of fine particles, acid gases and hydrogen sulfide, the synthesis gas may still contain traces of metals and other contaminants. In order the remove what is left of fine particles, lead, cadmium, mercury and total reduced sulfur, a deep bed gas scrubber is installed right after the hydrogen sulfide removal system. Filters are accessible on both sides. A bag-in, bag-out type construction gives the operator the possibility of changing the filters without any risks of getting in contact with the contaminants.

Environmental behavior – Air Emissions



Plasco Plasma Facility in Ottawa, Canada (100 ton/day MSW)





Environmental behavior – Solid residue

Air-cooled slag forms rocks

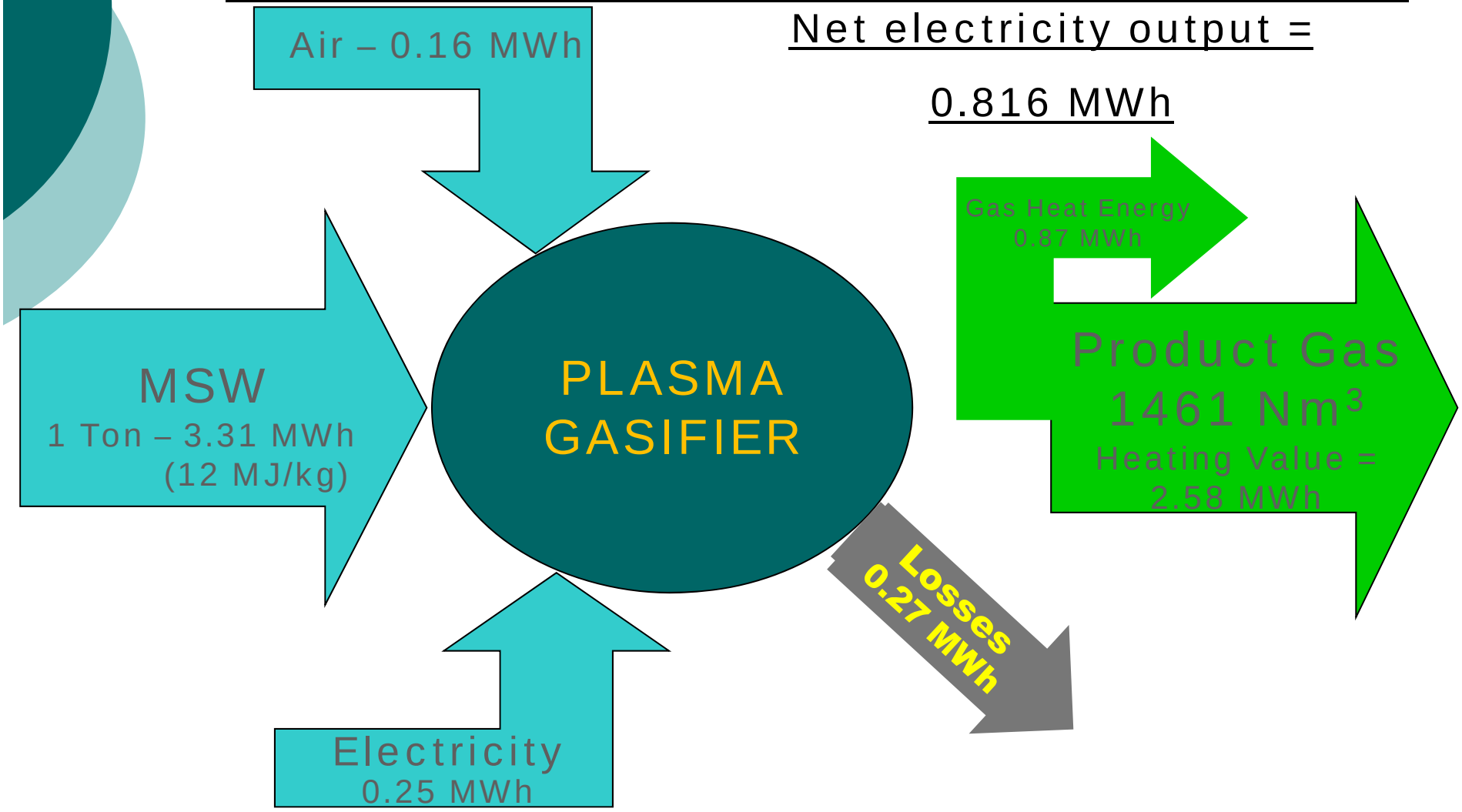
Water-cooled slag forms sand

	EU legislation limits for inert materials (2003/33/EC)	Experimental results
As	0.5	0.03
Cd	0.04	0.01
Cr	0.5	0.01
Pb	0.5	0.01
Hg	0.01	0.0004

mg/kg dry (L/S=10 l/kg)

- No ash is produced.
- The leaching tests in the produced slag give values much lower than the EU legislation limits.
- In Japan, around 75 % of vitrified product is utilized as a road construction material.

Energy performance: Plasma Gasification of MSW



Municipal Solid Waste (MSW) – to – Electricity Thermal Process Comparisons

Process (1)	Net Electricity to Grid (kWh/ton MSW) (2)	Plasma Advantage
• Plasma Arc Gasification	816	-
• Conventional Gasification	685	20%
- Fixed/Fluidized Bed Technologies		
• Pyrolysis & Gasification	685	20%
- Thermoselect Technology		
• Incineration	650	25%
- Mass Burn Technology		

(1) 300 – 3,600 TPD of MSW

(2) Steam Turbine Power Generation

Reference: EFW Technology Overview, The Regional Municipality of Halton, Submitted by Genivar, URS, Ramboll, Jacques Whitford & Deloitte, Ontario, Canada, May 30, 2007

Commercial Plasma Waste Processing Facilities (Asia)

Location	Waste	Capacity (TPD)	Start Date
Mihama-Mikata, JP	MSW/WWTP Sludge	28	2002
Utashinai, JP	MSW/ASR	300	2002
Kinuura, JP	MSW Ash	50	1995
Kakogawa, JP	MSW Ash	30	2003
Shimonoseki, JP	MSW Ash	41	2002
Imizu, JP	MSW Ash	12	2002
Maizuru, JP	MSW Ash	6	2003
Iizuka, JP	Industrial	10	2004
Osaka, JP	PCBs	4	2006
Taipei, TW	Medical & Batteries	4	2005

Commercial Plasma Waste Processing Facilities (Europe & North America)

Location	Waste	Capacity (TPD)	Start Date
Bordeaux, FR	MSW ash	10	1998
Morcenx, FR	Asbestos	22	2001
Bergen, NO	Tannery	15	2001
Landskrona, SW	Fly ash	200	1983
Jonquiere, Canada	Aluminum dross	50	1991
Ottawa, Canada	MSW	100	2007
Anniston, Alabama	Catalytic converters	24	1985
Honolulu, Hawaii	Medical	1	2001
Hawthorne, Nevada	Munitions	10	2006
Alpoca, West Nevada	Ammunition	10	2003
U.S. Navy	Shipboard	7	2004
U.S. Army	Chemical Agents	10	2004

Commercial Project
Plasma Gasification of MSW in Japan

Commissioned in 2002 at Mihama-Mikata, Japan by Hitachi Metals, LTD

- Gasifies 24 TPD of MSW & 4 TPD of Wastewater Treatment Plant Sludge
- Produces steam and hot water for local industries

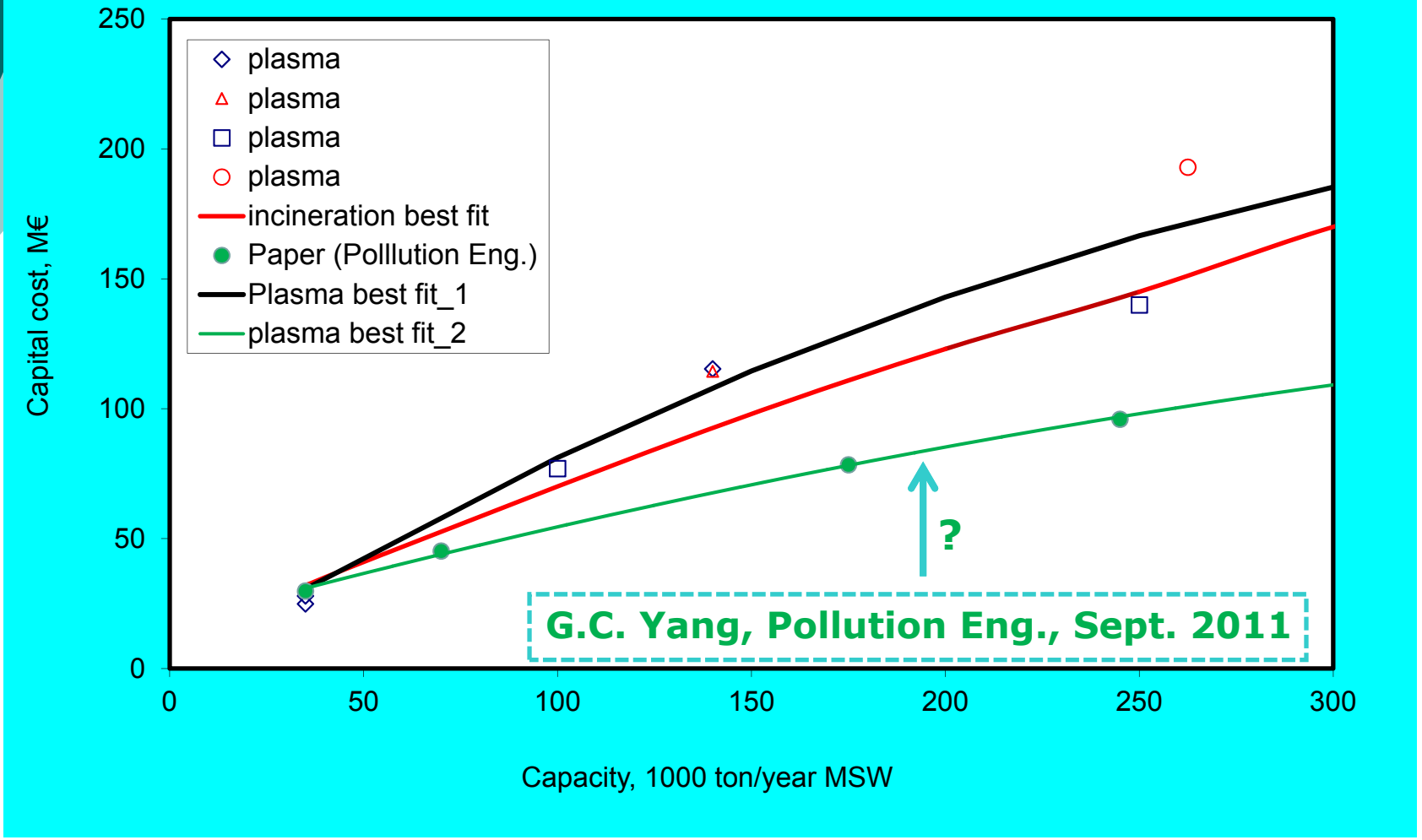
The Plasma Direct Melting Reactor (PDMR) at Mihama-Mikata, Japan converts unprocessed MSW and WWTP Sludge to fuel gas, sand-size aggregate, and mixed metal nodules

Commercial Project
Plasma Gasification of MSW in Japan

- Commissioned in 2002 at Utashinai, Japan by Hitachi Metals, LTD
- Original Design – gasification of 170 TPD of MSW and Automobile Shredder Residue (ASR)
- Current Design – Gasification of approximately 300 TPD of MSW
- Generates up to 7.9 MW of electricity with ~4.3 MW to grid

The Plasma Direct Melting Reactor (PDMR) at Utashinai, Japan converts unprocessed MSW and ASR to electricity, sand-size aggregate, and mixed metal nodules

Capital Costs: Incineration vs. Plasma Gasification Facilities



MSW composition daf (% w/w)	
C	55.6
H	7.6
O	33.3
N	1.4
S	0.412
Cl	1.6
Moisture % as received	35.2
Ash– % as received	16,2