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EARTH ENGINEERING CENTER
COLUMBIA UNIVERSITY AND CITY COLLEGE OF NEW YORK

Welcome from Earth Engineering Center | CCNY

Marco J. Castaldi

Associate Professor, Chemical Engineering Department

City University of New York

Director, Earth Engineering Center|CCNY

The 2014 Bi-annual Meeting of

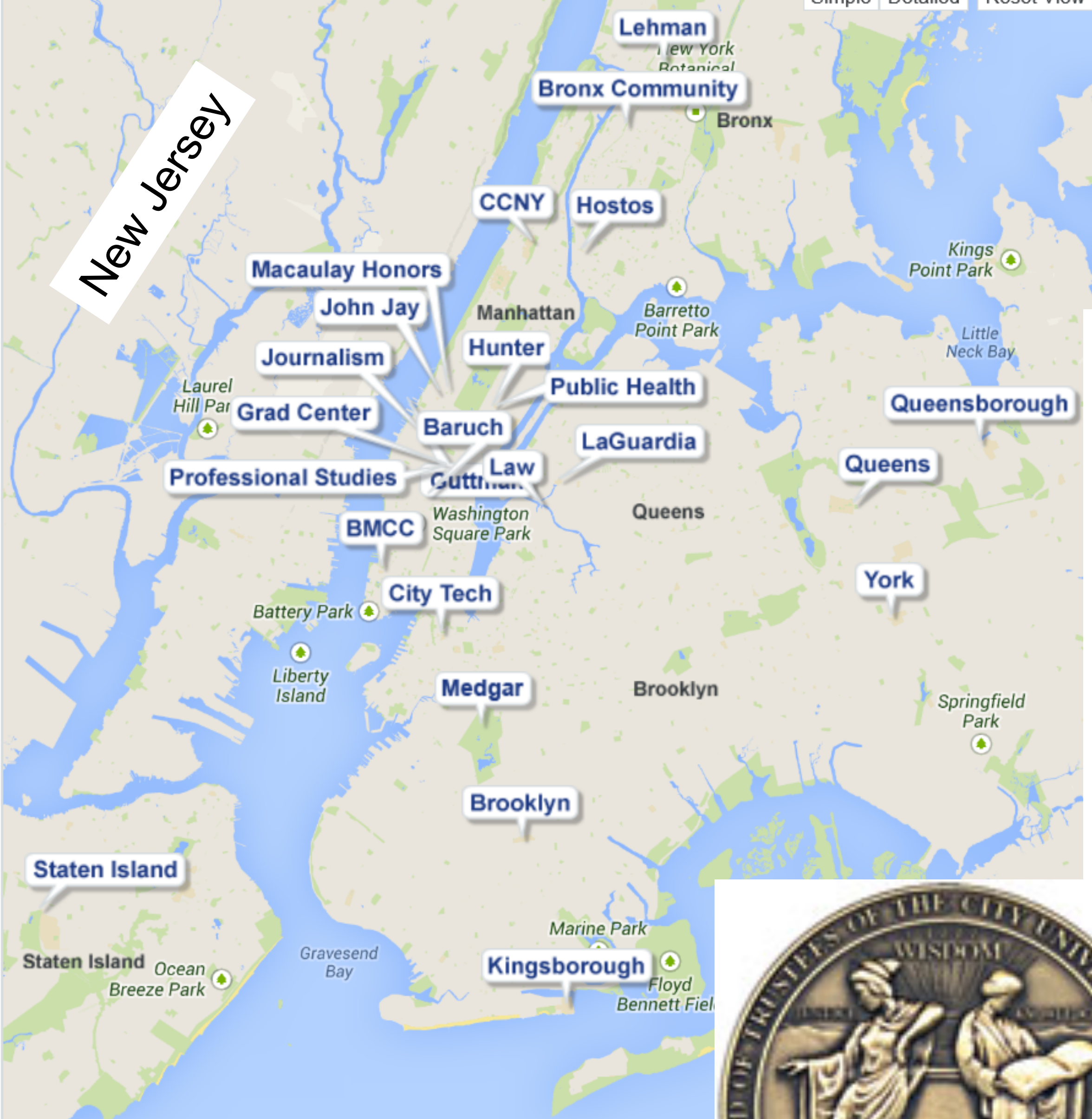
WTERT

Waste-to-Energy Research & Technology Council

Advancing Sustainable Waste Management

Combustion & Catalysis Laboratory

WTERT
Waste-To-Energy Research and Technology Council



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COLUMBIA UNIVERSITY AND CITY COLLEGE OF NEW YORK

CUNY

- Public university of New York City system
- Largest urban university in U.S.
  - 11 senior colleges
  - 7 community colleges
  - 540,000 students total
- 3rd Largest University in U.S.
- $6.3 Billion budget
- 6,700 full-time faculty
- Rank 8th among Regional Public U.S. News & World Report

Combustion & Catalysis Laboratory

WTERT
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CCNY

EARTH ENGINEERING CENTER
COLUMBIA UNIVERSITY AND CITY COLLEGE OF NEW YORK

Founded 1847 by Townsend Harris (1st U.S. Consul General to Japan) as the "Free Academy of the City of New York"

Nine Nobel Laureates gradated from CCNY

-Hofstadter (1961) Penzias (1978) Lederman (1988)

-Most of any public institution

First U.S. Lecture by Albert Einstein, 1921

Prominent Graduates:

Jonas Salk – First Polio Vaccine (Salk Institute)

Andrew Grove – Intel

George Goethals – Panama Canal Engineer

Neuroscientist Dr. John O'Keefe ('63) is CCNY's 10th Nobel Laureate

- 48 PhD students
- 14 faculty
- Support Staff: 3 administrators, 2 technicians, and 2 RAs
- Facilities: Multi-million dollar, cutting-edge, shared characterization facility (SEM, IR, Clean Room, Confocal microscope, AFM, pendent-drop set up, evaporators, etc…)
- 3 National Academy Members (Acrivos, Denn, and Shinnar)
- $2.4M/per year in research funding

Catalysis Laboratory

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EEC | CCNY

The goal of EEC|CCNY is to bring to bear rigorous engineering solutions that enable responsible use of energy and materials for the advancement of society. Through industry collaborations and research sponsorship EEC|CCNY develops novel solutions to some of the world's most pressing problems. EEC|CCNY routinely engages students with industry professionals enabling a holistic approach to creative realistic, forward-looking applications. The reach of EEC|CCNY is international in scope with many projects connecting international students and companies with a global presence.

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Reasearch at EEC|CCNY: Materials and Energy Recovery from Waste and biomass

Marco J. Castaldi
Chemical Engineering Department
City University of New York (CCNY)
The City University of New York (CUNY)

Director of Research: WTERT
Associate Director, Earth Engineering Center

WTERT 2014 Bi-Annual Meeting, Columbia University
NEW YORK CITY, OCTOBER 9&10, 201

WTERT Waste-to-Energy Research and Technology Council

Advancing the Goals of Sustainable Waste Management

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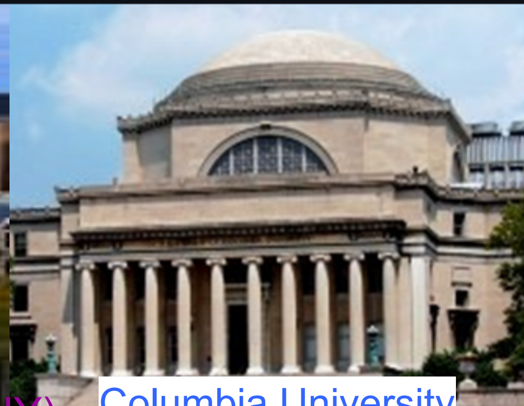
City College of New York (CUNY)



Columbia University

What is WTERT

The Waste-to-Energy Research and Technology Council (WTERT) is a top-tier-technical group that brings together engineers, scientists, and managers from industry, universities, and government with the objective of advancing the goals of sustainable waste management globally.

A truly international organization: Sister organizations in many nations

- WTERT, U.S. (2002) — www.wtert.org
- SYNERGIA, Greece (2007) — www.wtert.gr
- WTERT, China (2008) — www.wtert.cn
- WERT, Germany (2009) — www.wtert.eu
- WTERT, Japan (2010) — www.wtert.jp
- WTERT-Brasil, Brazil (2010) — www.wtert.com.br

- **Under formation: France, U.K., India, Argentina, Mexico, Thailand, Italy, Czech Republic**

Combustion & Catalysis Laboratory

- State University of New York, Marine Sciences Research Center (U.S.)
- Delft University of Technology, Dept. of Applied Earth Sciences (The Netherlands)
- Sheffield University Waste Incineration Centre (United Kingdom)
- National Tech. University of Athens (Greece)
- University of Patras (Greece)
- Institute for Thermal Power Engineering of Zhejiang University (China)
- Collage of Mechanical and Energy Engineering Zhejiang University (China)
- Chongqing Waste to Energy Technology Research Institute (China)

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EEC|CCNY - WTERT

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Transition to CCNY Complete
2000 ft^2 new lab space

Education/teaching activities

Columbia University – Earth & Environmental Engineering
Waste to Energy Course (Fall 2013 – Enrollment 11 students)

ASME WTE Webinar
~ 400 "attendees" part of ASME Energy Forum

Environmental Research & Education Foundation (EREF)
On-line WTE course: State Approved Continuing Education

EREF Environmental Research & Education Foundation
Lighting a path to sustainable waste management practices

Sustainability in Urban Environment & Chemical Engineering

"An Integrated Waste-to-Energy Plan for New York City"

Input/Feedback
- Rick Brandes
- Elizabeth Balkan - NYC Mayoral Senior Policy Advisor on Solid Waste
- Samantha McBride – Assistant Professor, Baruch College

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Waste-To-Energy Research and Technology Council

2012 - 2014 Activities

- NOx modeling – Full 1st pass model → formation of NO from fuel
- Corrosion – Impact of sulfur and type of salt coverage
- Ash – New uses: Catalytic & Fuel Cell Applications
- Specific individual project research requested by WTE companies
- General Activities: WTE Courses; WTE Capstone Project; Nerd Night (OR)
- Testimony (Michigan/New York)
- Publications: 14 papers in 2013, *Annual Review – Invitation only,*
- Environmental Impact of Fabric Filter Bag Incineration, (FFB White Paper)
  - ASME/MER and ASME Research Comm – Energy Environment & Waste
- International: Canada (AWMA & WTERT-CA), France, Japan (Materials Recovery Symposium), Brazil (Combustion Institute)

Major Efforts

NOx Modeling in WTE Boilers

- 800,000 grid nodes – largest produced; detailed chemical reactions included
- Fuel bound nitrogen is main contribution to NOx
- In-boiler (in-situ) NOx reduction maximum is 50%

WTE Corrosion Research

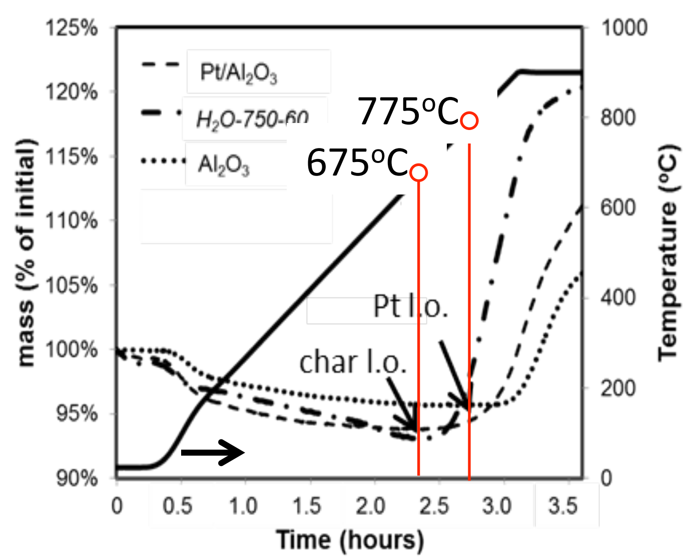
- Major cause: Molten chloride deposition breaks down protective oxide layer
- SO_2/HCl ratio in gas flow reduces molten chloride attack
- Economics of increasing SO_2/HCl ratio vs cost of replacing SH tubes

Ash Environmental Fuel Cell Catalyst

Ash catalyst (Precious metal content)
Reaction ≈ precious metal catalyst (high surface area, metals present)
Active at 100^{o}C lower than a commercial catalyst from BASF

Testing MSW ash for microbial fuel cell anode

Ash electrode must be similar to micro-structured stainless steel (20 Am^{-2})
student developing the electrode, company will to test/demonstrate



Klinghoffer et. al., I&ECR, 51 (2012) 13113–13122

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NRP Heating Value Confirmation

American Chemistry Council[SM]

Grab samples taken directly from unsorted trash bag

- Experimentally determined LHV for as-received, contaminated, non-recycled waste plastics.
- Tests included rigid and film plastics with varied contamination.
- Typical NRP mixture in MSW = HHV of 33.5 MJ/kg.

  Accepted resin HHV = 35 MJ/kg

Waste Plastic	Associate Resin	Measured LHV, MJ/kg	Literature LHV, MJ/kg
Clear cup	PET	21	24
Coffee cup lid	PS	40	41
Flexible mail packaging	mostly PE	40	44
Potato chip bag with metal coating	mostly PE	40	44

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Modeling Effort of RDF/EF in Cement Kilns

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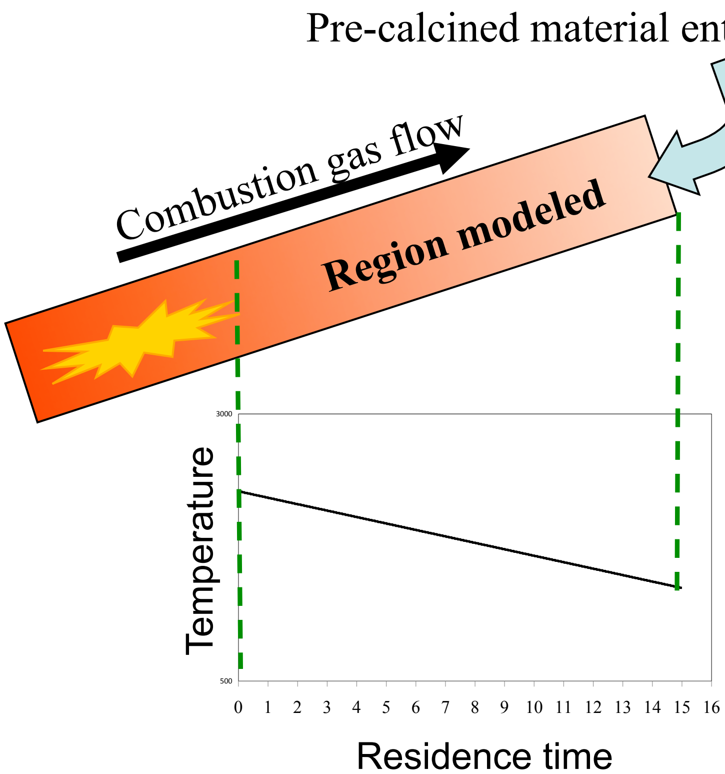
Elementary step mechanism anchored by combustion gas residence time (15 seconds)



Elementary Reaction step	A	n	E_{act}
2O+M<=>O2+M	1.200E+17	-1.000	.00
H2/ 2.40/ H2O/15.40/ CH4/ 2.00/ CO/ 1.75/ CO2/ 3.60/ C2H6/ 3.00/ AR/ .83/			
O+H+M<=>OH+M	5.000E+17	-1.000	.00
H2/2.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/2.00/ C2H6/3.00/ AR/ .70/			
O+H2<=>H+OH	3.870E+04	2.700	6260.00
O+HO2<=>OH+O2	2.000E+13	.000	.00
O+H2O2<=>OH+HO2	9.630E+06	2.000	4000.00
O+CH<=>H+CO	5.700E+13	.000	.00
O+CH2<=>H+HCO	8.000E+13	.000	.00
O+CH2(S)<=>H2+CO	1.500E+13	.000	.00
O+CH2(S)<=>H+HCO	1.500E+13	.000	.00
O+CH3<=>H+CH2O	5.060E+13	.000	.00
O+CH4<=>OH+CH3	1.020E+09	1.500	8600.00
O+CO(+M)<=>CO2(+M)	1.800E+10	.000	2385.00
LOW/ 6.020E+14 .000 3000.00/			
H2/2.00/ O2/6.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/3.50/ C2H6/3.00/ AR/ .50/			
O+HCO<=>OH+CO	3.000E+13	.000	.00
O+HCO<=>H+CO2	3.000E+13	.000	.00
O+CH2O<=>OH+HCO	3.900E+13	.000	3540.00
O+CH2OH<=>OH+CH2O	1.000E+13	.000	.00
O+CH3O<=>OH+CH2O	1.000E+13	.000	.00
O+CH3OH<=>OH+CH2OH	3.880E+05	2.500	3100.00
O+CH3OH<=>OH+CH3O	1.300E+05	2.500	5000.00
O+C2H<=>CH+CO	5.000E+13	.000	.00
O+C2H2<=>H+HCCO	1.350E+07	2.000	1900.00

CEMEX → Kiln outlet temperature
Calc → adiabatic flame temperature

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SOx and NOx & Cl Production

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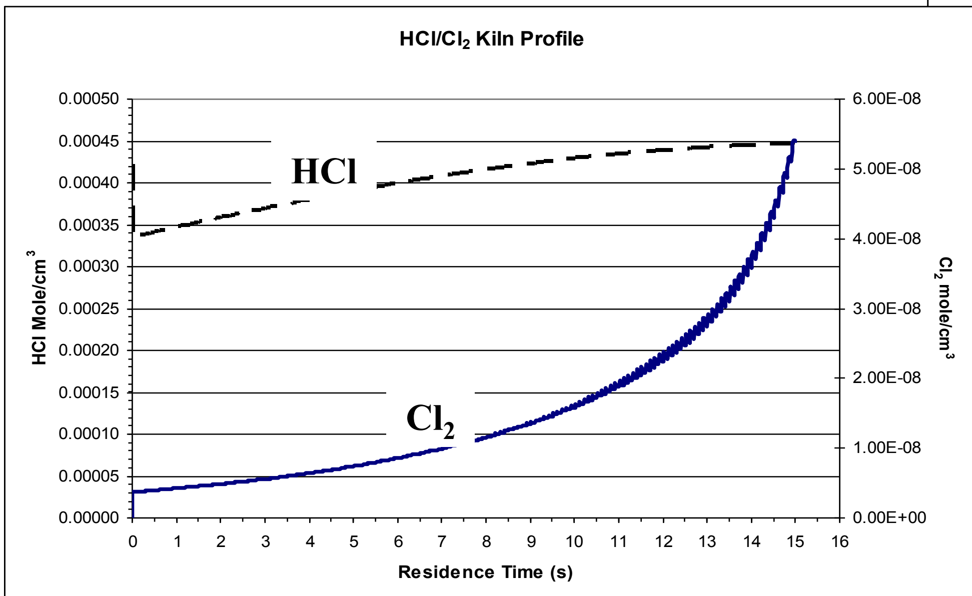

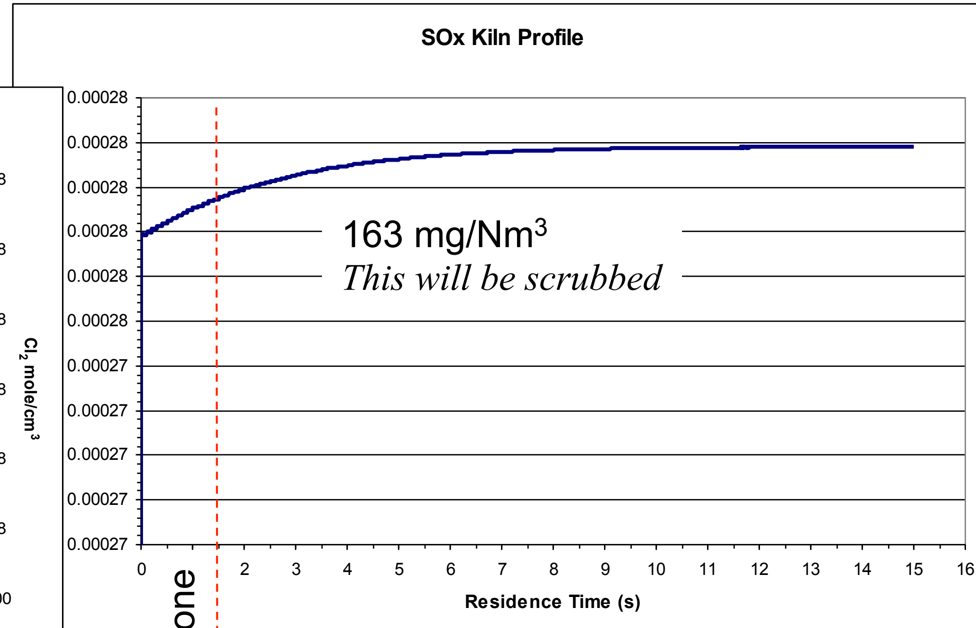

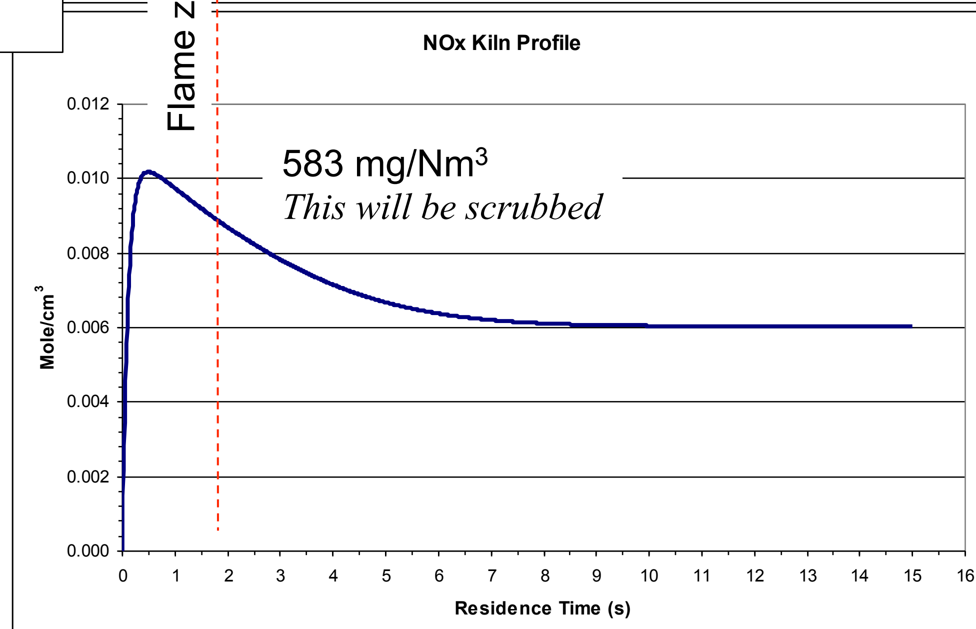

NOx : SOx trade-off in gas phase

Consistent with concept of Cement Kiln Dust (CKD) as a scrubber. Factor of 2 better than $CaCO_3$

Cl_2 – HCl trade-off

Rev. Fac. Ing. Univ. Antioquia N.° 56 pp. 49-57. Diciembre, 2010

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Emissions to Environment

Exit Emissions change using 15% EF

	Actual	Calculated
SO2	66%	85 – 88%
NOx	35%	58%
CO	121%	35%

Cement Kiln Production & Emissions

- *Kilns produce cement/no residual*
- *Utilization of heat*
- *Dioxin ~0.01 ng TEQ/Nm^3*
  - *order of magnitude below limits*

Discrepancy with CO – likely due to two possible reasons

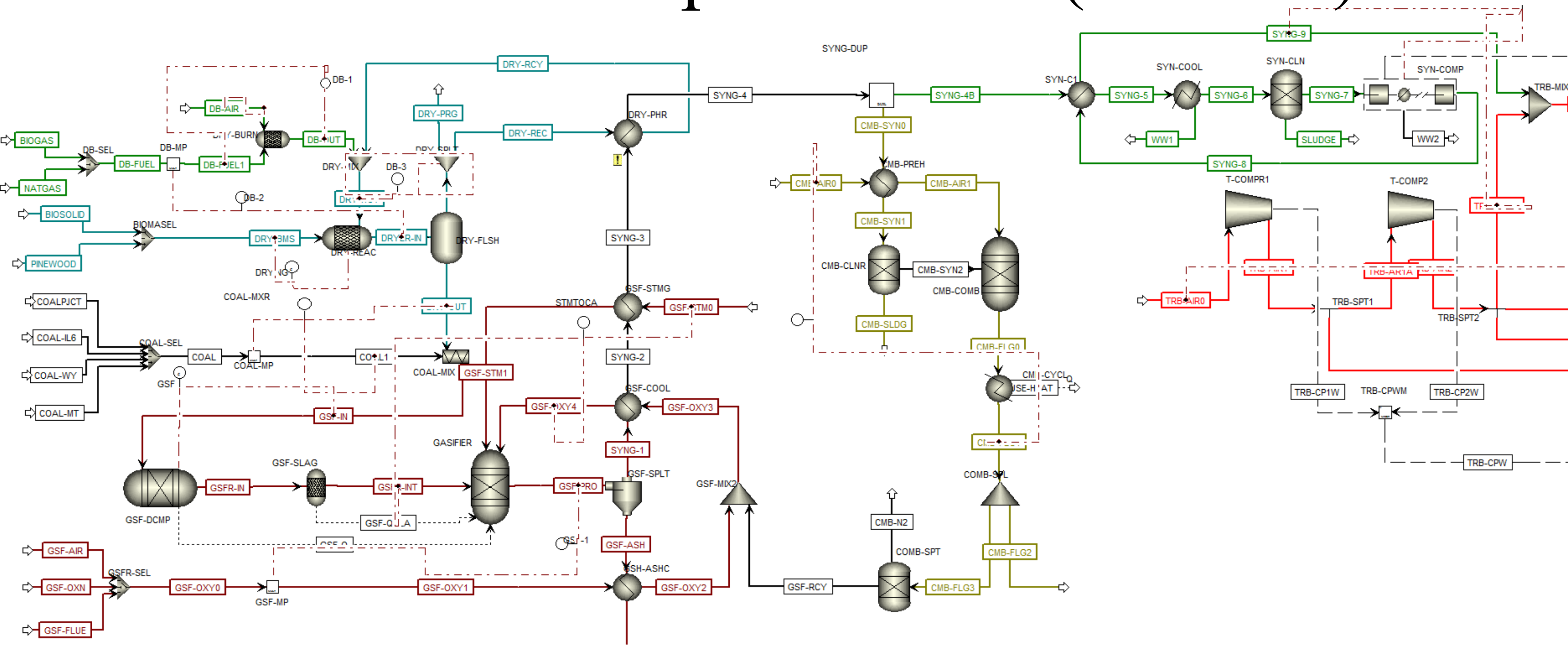
1. more volatile matter in RDF compared to Pet. Coke.
2. RDF should be fluff → density issue

Engineered Fuel (EF) Fluff

Engineered Fuel (EF) densified pellet

CEMEX
Building the future

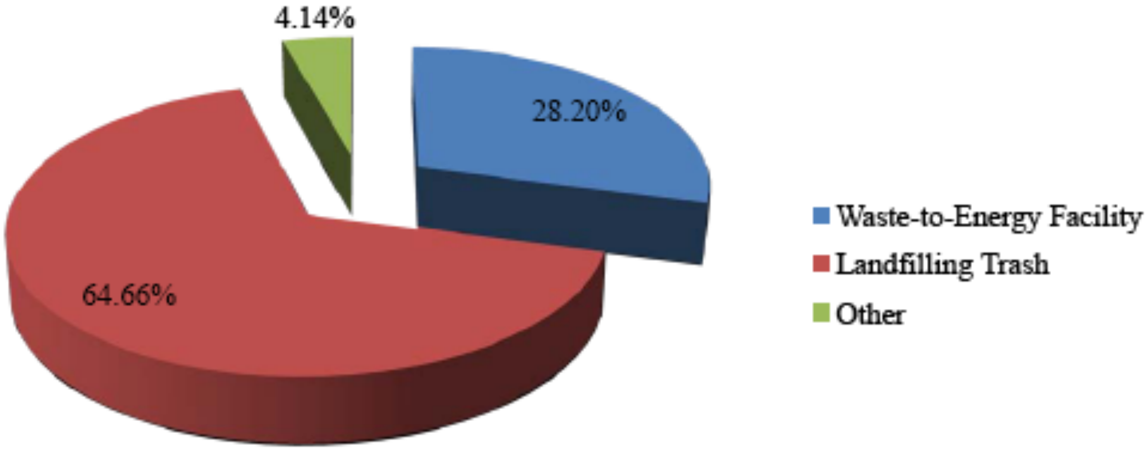
WTE Co-feed Optimization (ASPEN)



- Energy Efficiency Optimization – MSW Combustion/Gasification
  - co-feed natural gas
  - co-feed biosolids (sludge)
  - co-feed biogas (LFG)
  - co-feed biomass

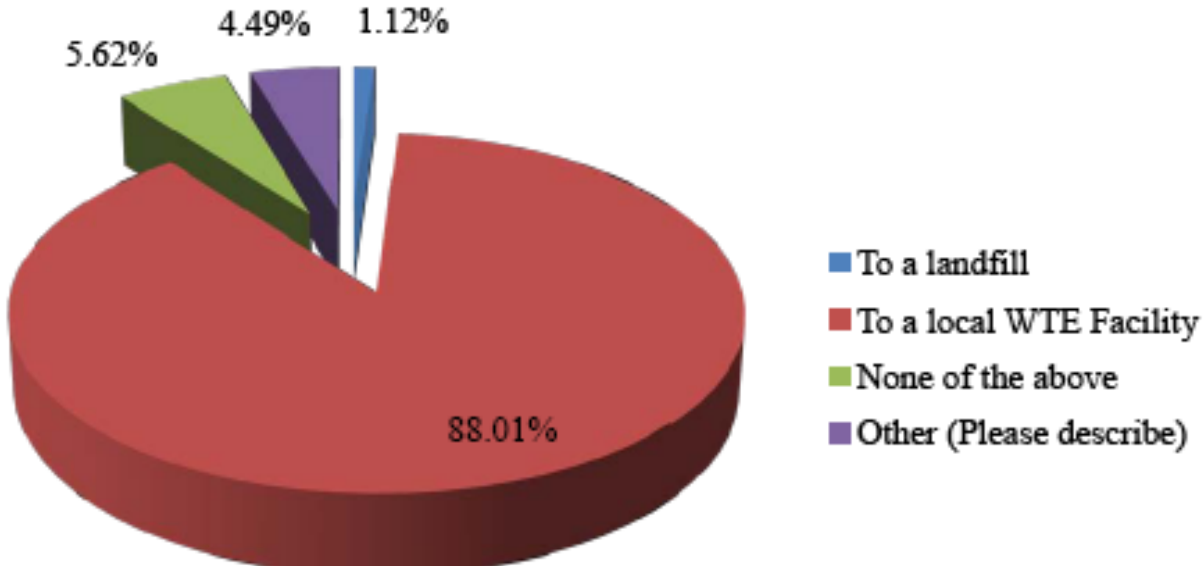
2013 CCNY Survey of NYC residents on WTE

Which option do you think produces more greenhouse gases?



Yet Environmental Groups resist

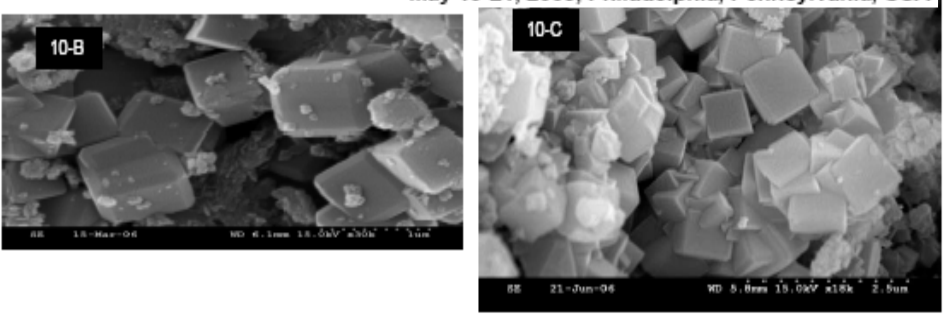
Given what you know about waste-to-energy and landfilling where would you prefer your trash to go?



Novel uses with existing waste residue: Catalysts

Zeolite Catalyst

Proceedings of NAWTEC16
16th Annual North American Waste-to-Energy Conference
May 19-21, 2008, Philadelphia, Pennsylvania, USA



Recycling of Municipal Solid Waste Ash through an Innovative Technology to Produce Commercial Zeolite material of High Cation Exchange Capacity

Maysson Sallam,PhD[1]*, Robert P. Carnahan[2], Abla Zayed[3], and Sermin Sunol[4]

Fuel Cell Catalyst

Testing MSW ash for microbial fuel cell anode

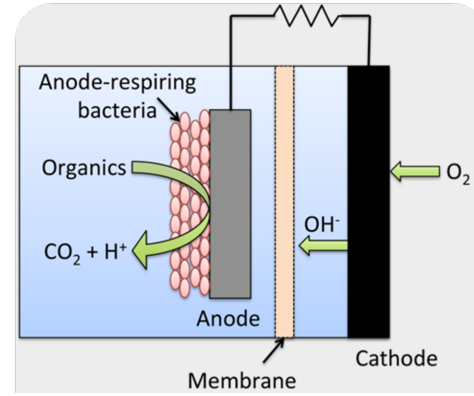


Table 1 Current densities obtained with electrodes of different materials

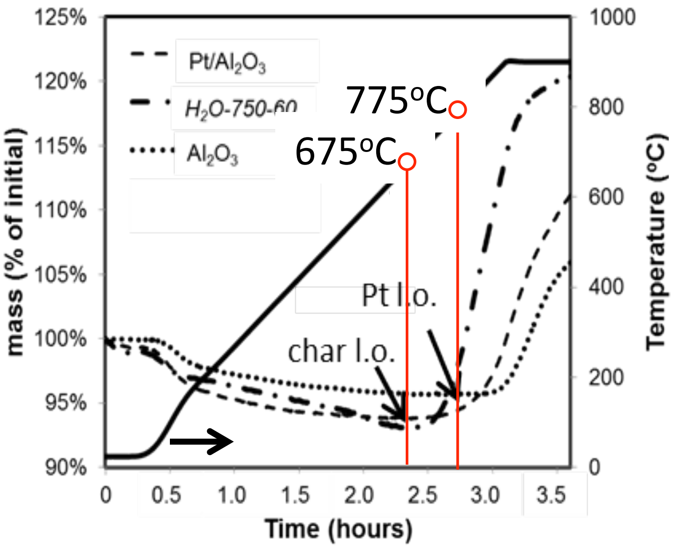
Electrode material	Number of measurements/number of different inoculum samples	Current density A m^{-2} Average value
Smooth stainless steel	4/2	19.7
Macro-structured stainless steel	4/2	20.5
Micro-structured stainless steel	4/2	21.5
Graphite	4/2	9.5
Carbon cloth	6/3	33.7

Ash electrode must be similar to micro-structured stainless steel (20 Am^{-2})

Tar Catalyst

Ash catalyst (Precious metal content)

Reaction ≈ precious metal catalyst (high surface area, metals present)



Klinghoffer et. al., I&ECR, 51 (2012) 13113–13122

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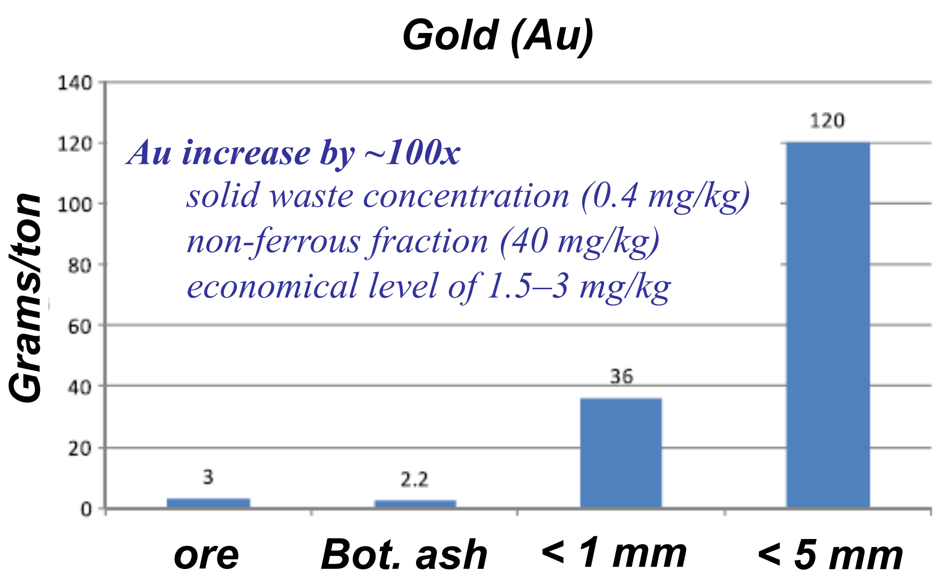
Precious metal extraction from Ash

Values of one facility in Switzerland

83% of the total economical potential/value comprised of seven metals: Au (26%), Sc (17%), Al (17%), Cu (11%), Ag (6%), Pt (4%), Nd (3%).



Estimated annual flow of selected precious metals, REE and other metals in the waste input of the SWI in Hinwil, Switzerland (kilograms/year) including uncertainty (standard deviation).

		Annual flow (kg/a) ± uncertainty (sd)
Iron	3,400 tons	6,300,000 ± 309,000
Aluminum	⟷	3,400,000 ± 191,000
Copper	⟷	440,000 ± 44,000
Zinc	440 tons	320,000 ± 60,000
Barium		150,000 ± 12,000
Lead		110,000 ± 9800
Chromium		36,000 ± 2800
Strontium		26,000 ± 1800
Nickel		24,000 ± 2300
Zirconium		23,000 ± 8400
Tin		15,000 ± 1400
Wolfram		11,000 ± 9600
Vanadium		2200 ± 150
Cobalt		2100 ± 160
Lithium		1800 ± 120
Cadmium		1800 ± 110
Molybdenum		1700 ± 180
Rubidium		1700 ± 90
Yttrium	1.5 tons	1600 ± 710
Neodymium	⟷	1500 ± 590
Silver	⟷	1100 ± 140
Bismuth	1.1 tons	570 ± 31
Hafnium		530 ± 187
Niobium		500 ± 19
Gallium		440 ± 27
Praseodymium		380 ± 170
Tantalum		250 ± 110
Scandium	⟷	190 ± 16
Gadolinium		150 ± 35
Selenium		89 ± 4.1
Gold	⟷	81 ± 40
Indium		58 ± 4.4
Beryllium		56 ± 6.2
Germanium		41 ± 2.8
Tellurium		17 ± 2.2
Thallium		16 ± 4.1
Platinum	⟷	12 ± 4.4
Ruthenium		0.10 ± 0.033

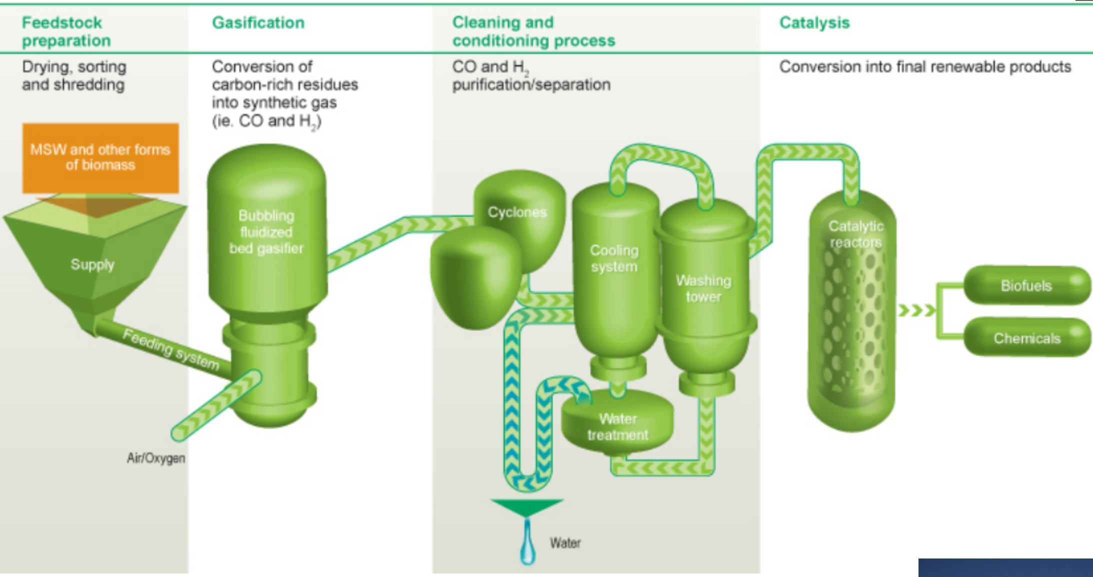
Source: Morf, L.S., et al. Waste Management (2012), http dx.doi.org/10.1016/j.wasman.2012.09.010

Looking over the horizon

- Next generation combustors – higher energy density
  - Low NOx operation
  - Approach 3+ MW m^{-2}
- Limits to Recycling (Deepak Sharma – MS|CCNY & Mr. Rick Brandes)
  - Theoretical study on limits of recycling and what would happen if WTE and landfill were not available
- In-situ reduction of corrosive gases (Tim Sharobem (CU))
  - Injection of halogen scavengers
- Novel uses of ash – catalytic and property adjustment/Microbial Fuel Cells
  - Livolt/CUNY- Center for Advanced Technology project
- LFGTE Applications and LFG to fuels (Liubov Melnikova (CU) & Leah Curry (CCNY)
- **Perception!!** – Public seems OK but environmentalists resist – Paper to be published based on CCNY Survey

Enerkem

Non recyclable municipal solid waste



Feedstock (s)	Municipal solid waste and wood residues
Size	300 short tons (300 metric tons) per day
Primary Products	Ethanol and methanol
Capacity	10 million gallons per year
Locations	Edmonton & Mississippi
GHG Reduction	83.4%

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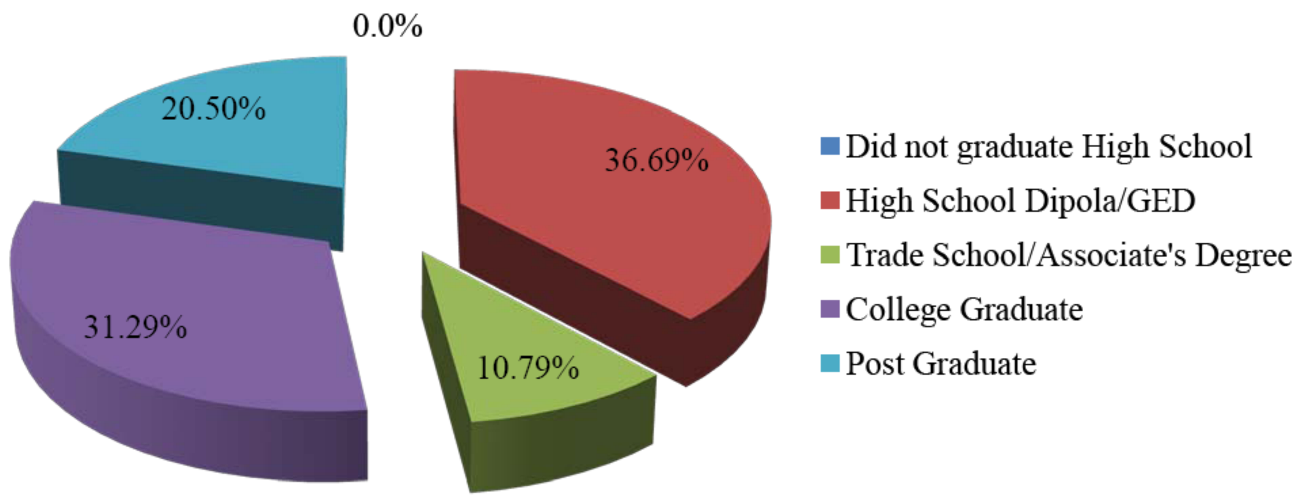
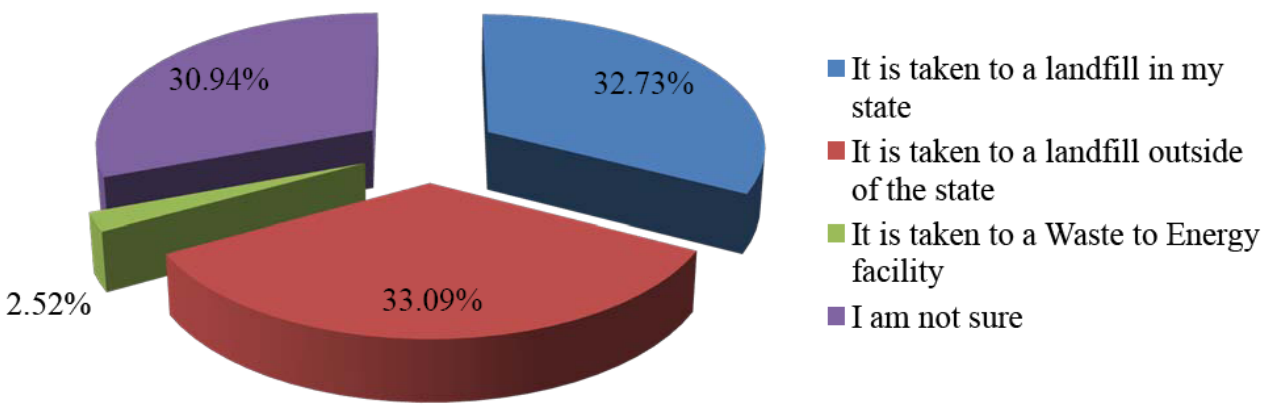
2013 CCNY Survey of NYC residents on WTE

~400 respondents → 95% confidence level ±5.1error margin

Highest level of education completed



Where do think your trash goes after you throw it away?



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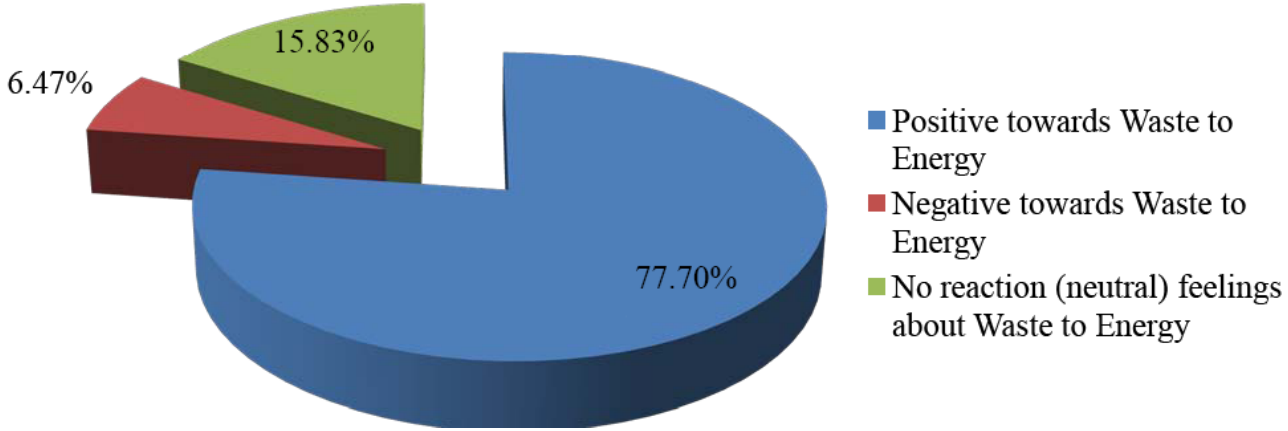
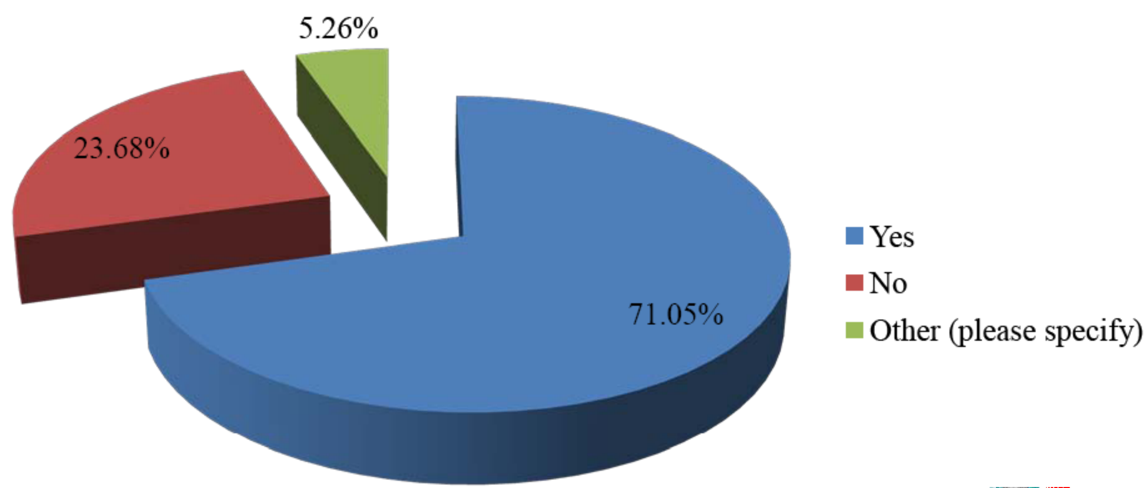
When you hear "Waste-to-Energy do you feel a positive or negative reaction?



True or False: Waste-to-Energy technology is considered a renewable energy in New York State?



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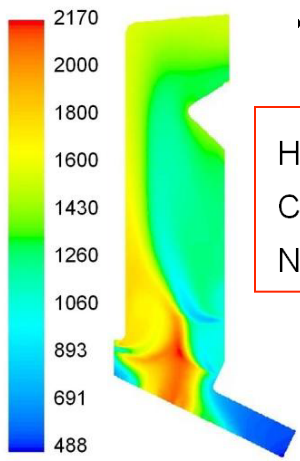
Future Research Directions

- Direct Combustion/ Co-Combustion/ Engineered Fuel Production
  - Utilization Expansion – Cement, Lime, Steel Industries
  - Emissions (fine PM and NOx)
- Syngas cleanup from Gasification of wastes
  - Impact of by-products
  - Hot gas cleanup (zeolite systems)
- Chlorine removal
  - Sulfur Addition
- Ash valorization

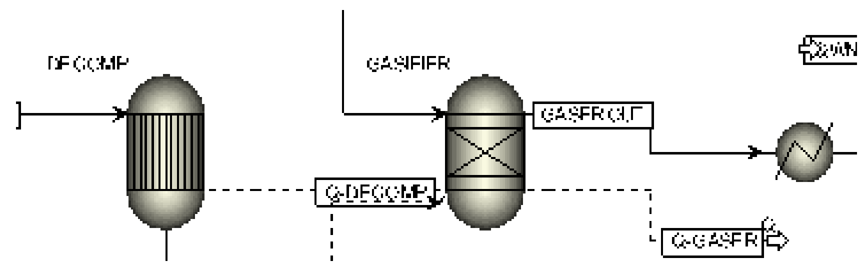


$HCNN + O \Leftrightarrow NO + HCN$

$CN + NO_2 \Leftrightarrow NCO + NO$

$N + CO_2 \Leftrightarrow NO + CO$

CFD Modeling
Combined with detailed reactions

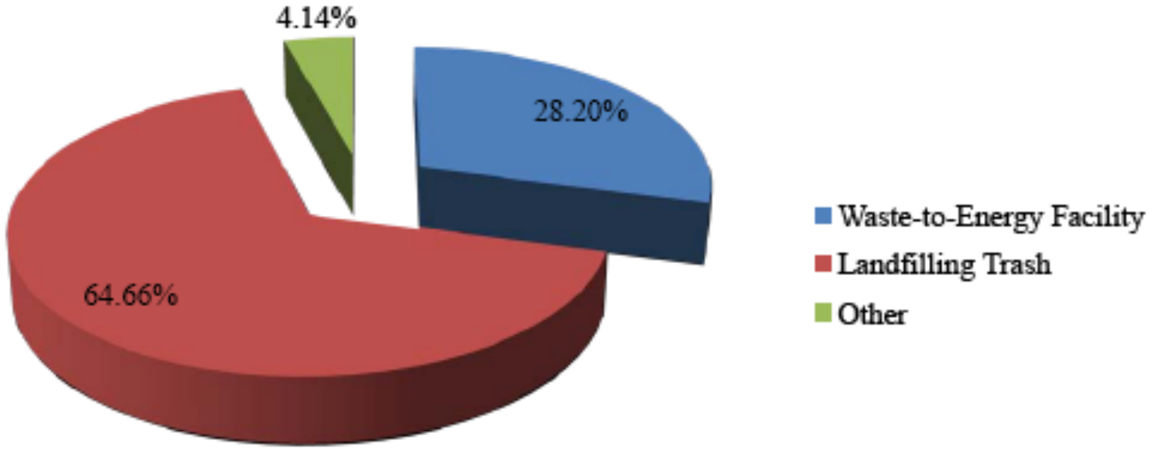


ASPEN^{TM} Modeling
Rigorous Process Modeling

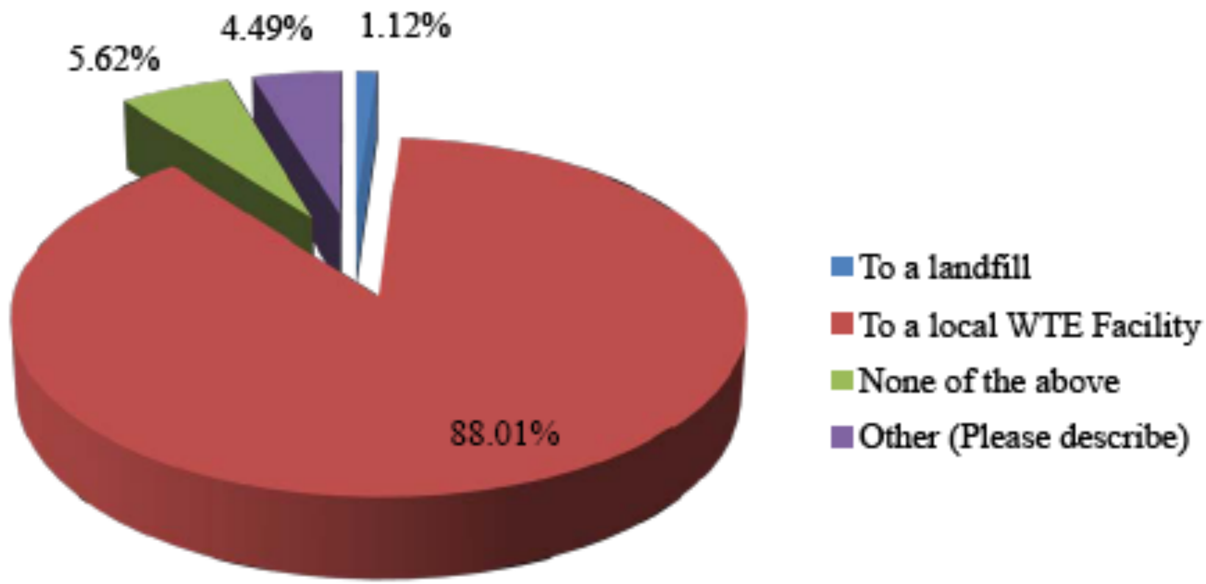
Better understanding of detailed processes leads to next generation designs lower cost, more efficient, higher material recovery

2013 CCNY Survey of NYC residents on WTE

Which option do you think produces more greenhouse gases?



Given what you know about waste-to-energy and landfilling where would you prefer your trash to go?



2013 CCNY Survey of NYC residents on WTE

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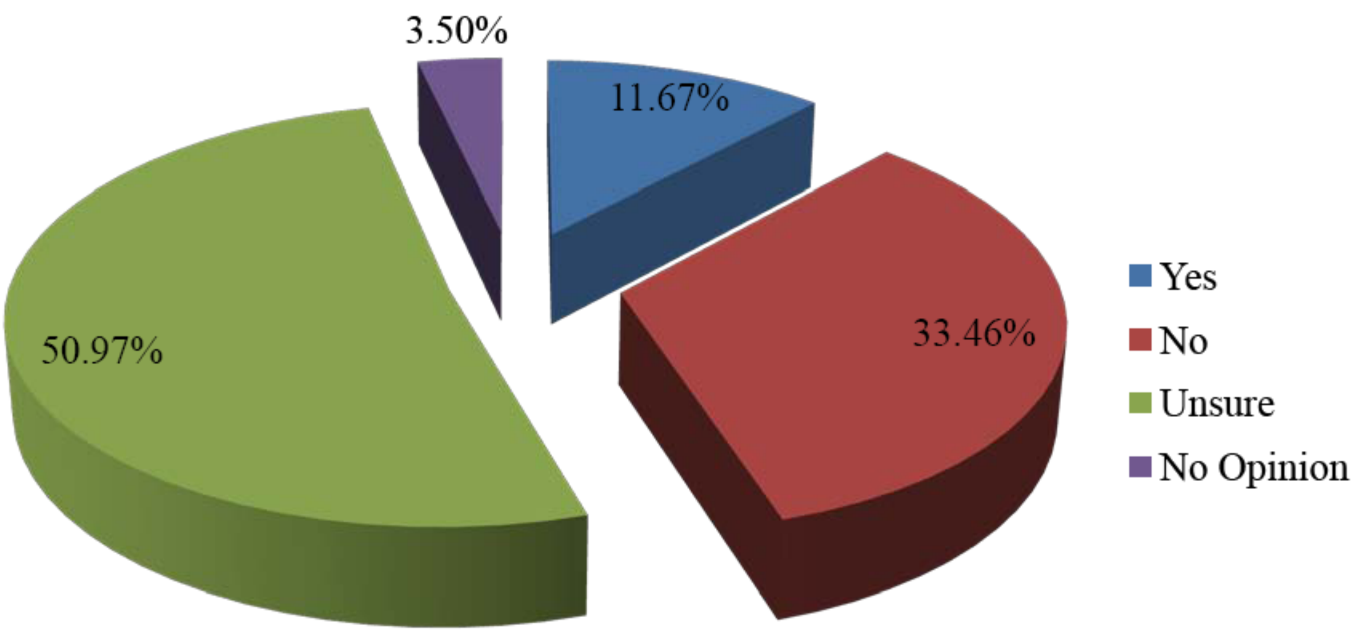
Do you think NYC handles its solid waste in a responsible and sustainable way?

Result



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