INTEGRATED WASTE MANAGEMENT FOR A SMART CITY

FOCUSSED ON MSW, C&D AND E-WASTE MANAGEMENT

Welcome to Week-8

BRAJESH KUMAR DUBEY

DEPARTMENT OF CIVIL ENGINEERING

During this week (Week-8)

- Thermal Treatment Details
- Landfill Basics, Liner Requirement

Stoichiometric Combustion

- the principle elements of solid waste are C, H, O, N and S
- under ideal combustion conditions, the following gases are formed:
  - carbon dioxide (CO_2),
  - water (H_2O and the water content of flue gas),
  - nitrogen (N_2), and
  - small amounts of sulphur dioxide (SO_2)
- oxygen is required for combustion of the:
  - carbon
  - hydrogen (minus the fraction that enters as H_2O with the SW)
  - sulphur

Stoichiometric Combustion

- the basic reactions for the stoichiometric combustion of the C, H and S in the organic fraction of waste are as follows:
  - for carbon: $\underset{12}{C} + \underset{32}{O_2} + heat \rightarrow CO_2$
  - for hydrogen: $\underset{4}{2H_2} + \underset{32}{O_2} + heat \rightarrow 2H_2O$
  - for sulphur: $\underset{32.1}{S} + \underset{32}{O_2} + heat \rightarrow SO_2$

Stoichiometric Combustion

- if we assume that dry air contains 23.15% oxygen by weight, then the amount of air required for the oxidation of 1 kg of carbon would be 11.52 kg:

$$M_{air,\,C} = (1\ \text{kg C})\left(\frac{32\ \text{g/mol}}{12\ \text{g/mol}}\right)\times\left(\frac{1}{0.2315}\right) = 11.52\ \text{kg air}$$

- and, the amount of air for hydrogen:

$$M_{air,\,H} = (1\ \text{kg H})\left(\frac{32\ \text{g/mol}}{4\ \text{g/mol}}\right)\times\left(\frac{1}{0.2315}\right) = 34.56\ \text{kg air}$$

- and, the amount of air for sulphur:

$$M_{air,\,S} = (1\ \text{kg S})\left(\frac{32\ \text{g/mol}}{32.1\ \text{g/mol}}\right)\times\left(\frac{1}{0.2315}\right) = 4.31\ \text{kg air}$$

Stoichiometric Combustion

- it should be noted that the amount of hydrogen must first be adjusted by subtracting 1/8th of the percentage of oxygen from the total percentage of hydrogen initially present in the waste
- this subtraction accounts for the oxygen in the waste combining with hydrogen to form water
  - remember, H_2O = (2 g/mol H) + (16 g/mol O)
- then the total O_2 can then be converted to total air
- these calculations define the exact (*stoichiometric*) amount of oxygen (or air) needed for complete combustion
- combustion with oxygen in excess of the stoichiometric amount is called *excess-air combustion*, and this is done to ensure that complete combustion occurs
- excess air is usually 120 – 200% of the design requirement

Excess Air

- the objective of combustion is the complete destruction of the organic waste to form harmless gases
  - the combustion process needs excess air as a result of the non-homogeneous mixture of waste
  - but, too much oxygen reduces the combustion temperature
- the 3 Ts of combustion are:
  - **temperature** – high enough to ignite the constituents
    - less than 790°C and odorous compounds are released
    - greater than 980°C , and we get a reduction in dioxins, furans, and VOCs
  - **time** – enough for complete combustion of the waste
    - in the combustion chamber
    - in the flue gas (secondary chamber)
  - **turbulence** – mixing of the waste material with oxygen
    - provides for good mixing to promote more complete combustion
    - both in the primary chamber (MSW) and the secondary chamber (gases)

Excess Air

- theoretical oxygen requirements can be determined by balancing chemical reactions, or
- using an easy-to-use formula for O_2 needed to combust a fuel or waste

$$O_2\ (m^3/kg \cdot fuel) = 24.6 \cdot \{(C/12) + (H/4) + (S/32) - (O/32)\}$$

- C, H, S and O are the decimal fractions of each of the element in a kg of fuel on a dry weight basis
- for example, for C_aH_b:

$$\%\ C = \left(\frac{a(12)}{a(12) + b(1)}\right)$$

- this formula takes into account the water formed

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Mechanisms of Combustion

- the combustion process is accomplished in 4 phases
- Phase 1 – the drying phase
  - moisture is driven off at up to 150°C
- Phase 2 – volatilization of vapours and gases
  - combustible volatile organics diffuse out when their flash points occurs (150°C – 700°C)
- Phase 3 – burn-down of solids
  - when heated further, the remaining fixed carbon volatile material (partially oxidize cellulose, lignin, …) are oxidized (700°C – 1100°C)
- Phase 4 – final burn-down of char
  - remaining char is burned down to bottom ash
  - this material is the end product of the reaction
  - after a short period of cooling on the grate this ash is dumped into a dry hopper (the ash-receiving system)

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Types of Incinerators

- there are generally 2 types of MSW incinerators:
- fixed-hearth incinerators – have a stationary kiln
  - first type of waste combustion system designed/used
  - normally used for smaller quantities of waste (medical, pharmaceutical, research and development, …)
  - waste is charged into the incinerator and combusted as it passes through the combustion chamber
  - ash residue comes out the last hearth

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Types of Incinerators

- rotary kiln incinerators
  - consists of 2 chambers
  - waste is charged into the primary combustion chamber, which is a refractory-lined rotary kiln that is sloped slightly downhill
  - the kiln is slowly turned (at approximately 1 RPM)
  - material is burned while it tumbles down the kiln
  - the secondary chamber is used for gas phase combustion

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

The Combustion Process

- combustion starts with the unloading of the MSW collection trucks into a storage pit
  - storage capacity is usually equal to the volume of waste for 2 days
- an overhead crane is used to batch load waste into the feed (charging) chute
- the chute directs wastes to the furnace
- the crane can be used to select wastes of different types to blend the C/N ratio
- solid waste lands on the grates where they enter the mass-fired furnace
- air may be introduced from the bottom (below the grates) or from above the grates by a forced draft fan
  - this controls the burning rate and temperature

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

The Combustion Process

- gases and particulate matter are driven off the combusted organic material, and rise into the combustion chamber where they are burned in excess of 800°C
- heat recovery occurs using water filled tubes in the walls of the combustion chamber
- air pollution control equipment may include:
  - injected ammonia for NO_x control
  - dry scrubber for SO_2 and acid gas control
  - bag house (fabric filter) for particulate matter
- ashes and unburned material from the grates fall into a residue hamper
  - residue ash + fly ash (bag house) are mixed together for ash treatment

Typical Combustor Design

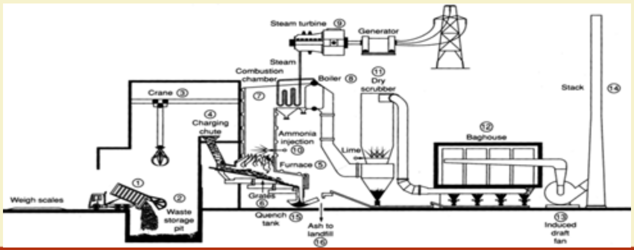
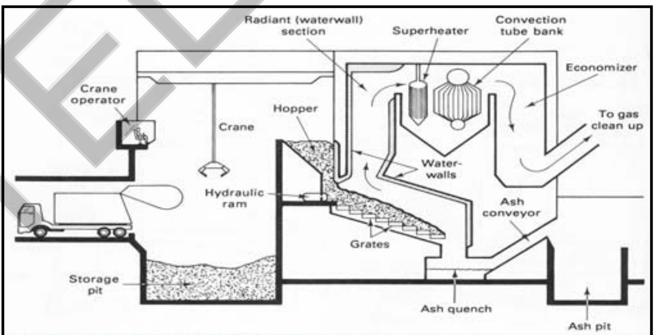
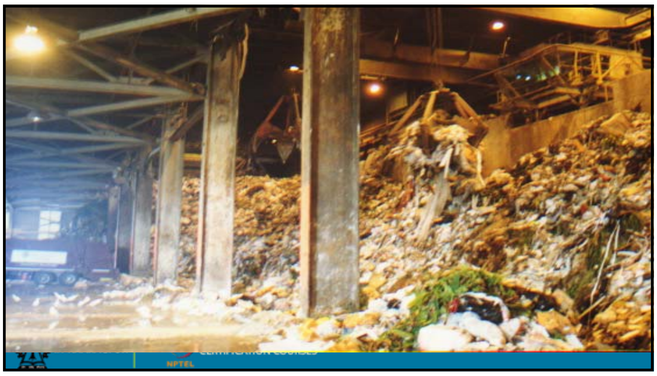


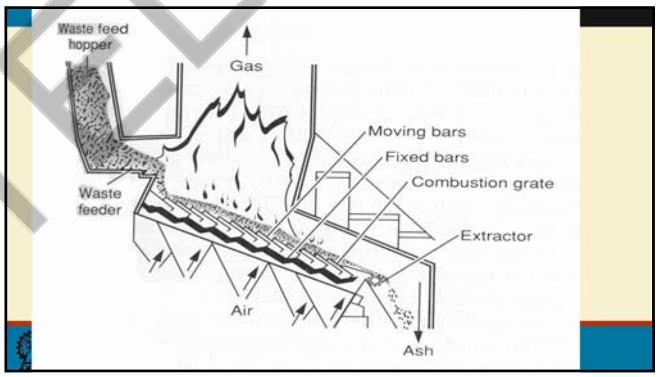
Figure 9.31



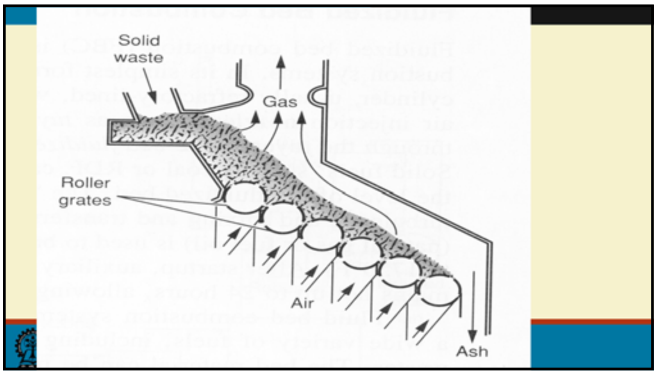



IIT KHARAGPUR
NPTEL ONLINE
CERTIFICATION COURSES


IIT KHARAGPUR
NPTEL ONLINE
CERTIFICATION COURSES


Waste feed
hopper
Gas
Moving bars
Fixed bars
Combustion grate
Waste
feeder
Extractor
Air
Ash


Grates
IIT KHARAGPUR
CERTIFICATION COURSES


Solid
waste
Gas
Roller
grates
Air
Ash

Ash Landfill

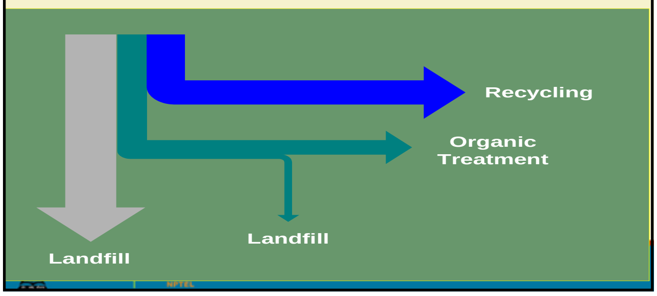
Terminology

- **Thermal treatment (or incineration):** a range of processes where temperature is used to reduce the volume of waste and to render it harmless.
- **Waste to Energy (WTE):** as above, with the recovery of heat energy to produce steam and/or generate electricity.
- **Conventional WTE**: mass burn, fluidized bed, modular, rotary kiln, (refuse derived fuel)
- **Advanced WTE**: gasification, pyrolysis, plasma

The role of thermal treatment

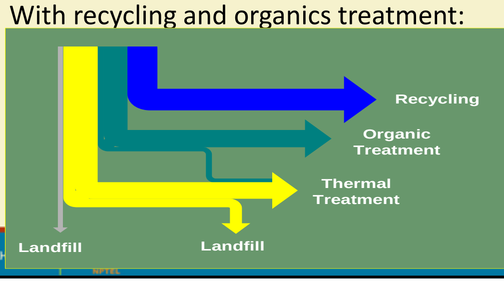
- Waste volume reduction, preservation of landfill space
  - Does NOT replace the need for a landfill
- Energy recovery from the solid waste stream
- Destruction of contaminants
- Reducing waste transportation requirements
- Dealing with waste here and now

The role of thermal treatment (2)



The role of thermal treatment (3)

- With recycling and organics treatment:



The role of thermal treatment (4)

- Last treatment of waste before land disposal
- Applied after recycling, organics management
- If recycling goal is 60%, then WTE can treat balance of waste
- Recovers remaining energy
- Converts energy into heat
- Electricity can be sold to the grid
- Offsets fossil fuel use for power generation

The role of thermal treatment (5)

- One tonne of waste can deliver 400 to 700 kWh of electricity to the grid
- One tonne of waste has the same energy as one barrel of oil, or a quarter tonne of coal
- 24 tonnes of waste can provide all the electricity for a Canadian home for a year
- One home of 4 persons: (1.5 kg/person-day) * 4 * 365 = 2.2 tonnes

IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

How thermal treatment works

- Technologies offer different ways of releasing the energy in the waste
  - Conventional combustion/WTE
  - Advanced thermal treatment (Gasification/pyrolysis, plasma systems)
- WTE systems are essentially power plants using waste as fuel instead of coal, natural gas or uranium

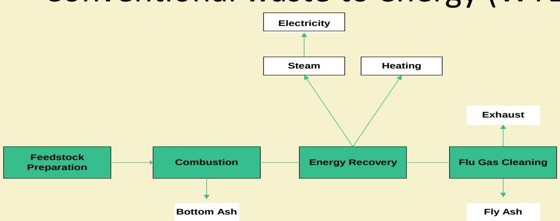
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Conventional combustion technologies

- Mass burn – most common (Burnaby, and upcoming York-Durham and Peel Region plan)
- Fluidized bed – mid sized and specialty applications (wood, coal)
- Modular – smaller systems
- Rotary kiln – hazardous and medical waste - rarely used for MSW
- Refuse Derived Fuel (RDF)– Dongara plant in GTA area

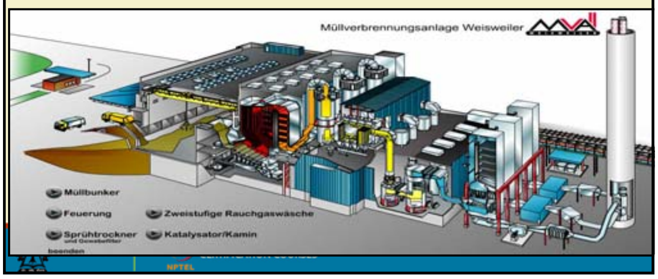
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Conventional waste to energy (WTE)

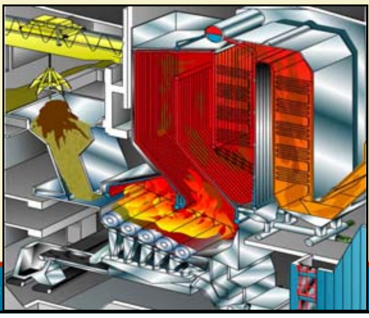


IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

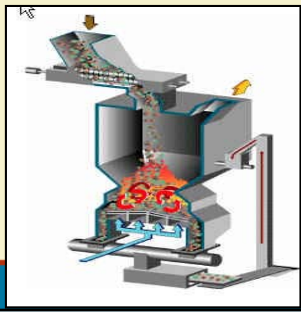
Mass burn: Facility overview



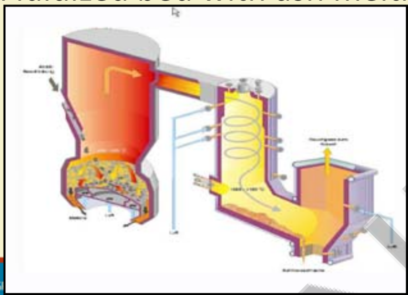
Mass burn: Furnace section



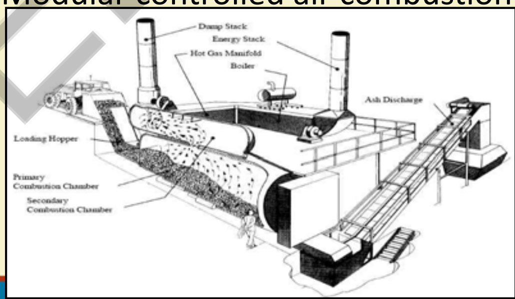
Fluidized bed furnace



Fluidized bed with ash melting



Modular controlled air combustion



Refuse derived fuel (RDF)

- Solid waste made into homogenous fuel
  - Can be sold and used off site, replacing other fuels such as coal or gas
  - Used by:
    - Cement kilns
    - Industry power boilers
    - Dedicated WTE plants

Ideal Incinerator

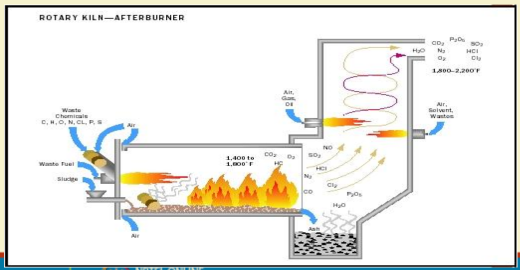
- rocking kiln incinerator
  - new variation of the rotary kiln
  - rotates only ¾ of a revolution, then reverses
  - thus, waste is subjected to less turbulence, but as a result releases less particulate matter into the secondary combustion chamber
  - no need to shred waste – less tumbling of larger items through the unit
- can handle a variety of waste (including hazardous waste)
  - solids, liquids, containers, …
- slowly rotating refractory-lined cylinder that is slightly inclined and rocking:
  - insulation provided by fireclay, dense aluminum, silica, silicon carbide
- length to diameter ratio of 2:1 to 10:1
- rotation at 0.3 to 3 m/min
  - continually mixes waste, and entrains combustion air

Ideal Incinerator

- combustion temperatures ranging from 800°C to 1100°C
- requires large amounts of excess air due to leakage
  - remember: excess air = 120 to 200%
- retention time varies in combustion chambers
  - 0.1 to 2 s for gases and liquids
  - minutes to hours for solids
- minimizing products of incomplete combustion (PICs) requires further oxidation of gases
  - afterburner (secondary combustion chamber)
  - residence time of up to 3 seconds
  - temperatures of 1100°C to 1300°C
- continuous ash generation
  - non-putrescible – does not decay
  - sterile – free of living organisms
  - inert – does not react in any way

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Ideal Incinerator



IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES | www.pollutionissues.com/Ho-Li/Incineration.html

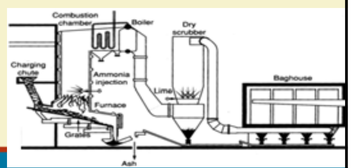
Disadvantages

- high capital cost
- skilled operators required
- some materials are non-combustible
- some materials require supplemental fuel
- air contaminant potential
  - dioxin, mercury (90% reduction since 1995), particulate matter, …
- volume of gas from incineration is 10 times as great as other thermochemical conversion processes
  - greater cost for gas clean-up/pollution control
- public disapproval
  - risk imposed rather than voluntary
  - incineration will decrease property value (perceived)
  - distrust of government/industry – ability to regulate

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Ash

- ash is the residue left over from the combustion of MSW
- bottom ash
  - recovered from combustion chamber
- heat recovery ash
  - collected in the heat recovery system (boiler, economizer, superheater)
- fly ash
  - particulate matter removed prior to sorbents
- air pollution control residue
  - combined with fly ash
- combined ash
  - most US facilities combine all ashes together



IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Ash Treatment / Re-use

- there are a variety of methods of treating incinerator ash
- generally it is processed to standardize the material and remove contaminants
  - ferrous metal removal (magnetic separation)
  - non-ferrous metal (aluminum, copper) removal
  - screening and crushing
- so that it can be used as an aggregate
  - construction fill
  - road construction (asphalt, pavement concrete)
  - landfill daily cover
  - cement block production
  - treatment of acid mine drainage

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Flue Gas

- flue gas is the gas that exits the incinerator stack (i.e. the flue) to the atmosphere, and may include:
  - particulate matter
  - acid gases – principally H_2S and CO_2 (which produces H_2CO_3)
  - NO_x – NO + NO_2 – react to form smog, acid rain
  - CO – a weak greenhouse gas
  - organic hazardous air pollutants – e.g. PCDD, PCDF, …
  - metal hazardous air pollutants – e.g. mercury, …
- each of these components must be considered in the design of air pollution control facilities

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Particulates

- solid particles – usually defined as PM2.5 < 2.5µm
- condensable PM – vapours that condense to form particulates
- causes
  - too low of a combustion temperature (incomplete combustion)
  - insufficient oxygen or overabundant EA (too high temperature)
  - insufficient mixing or residence time
  - too much turbulence, entrainment of particulates in the air stream
- control
  - cyclones – can remove large particles, but not effective for removal of small particulates
  - electrostatic precipitator – efficient removal using an electrostatic charge
  - fabric filters (bag houses)

Acid Gases

- come from Cl, S, N, Fl in the refuse
  - plastics
  - textiles
  - rubber
  - yard waste
  - paper
- uncontrolled incineration generates 18 – 20% HCl with pH = 2.0
- acid gas scrubbers (SO_2, HCl, HFl) usually ahead of electrostatic precipitator or bag house
  - wet scrubber – like a venturi scrubber
  - spray dryer
  - dry scrubber injectors – injects a dry sorbent like lime

Air Pollution Control Process

- electrostatic precipitator
  - removes particles from a flowing gas using an induced electrostatic charge
- bag houses
  - uses engineered fabric filter long bags/tubes to remove particulate matter
- acid gas scrubbers
  - wet scrubber
  - dry scrubber
  - chemicals added in slurry to neutralize acids
- activated carbon
- selective non-catalytic reduction
- catalytic converters
  - recently started using them in Germany for converting NO_x and PCDD/F
  - using titanium dioxide (TiO_2) as a base

Comparison of Air Pollution Control Systems

Parameter / Component	Spray Dry Absorber	Venturi	Packed Bed	Dry Electrostatic Precipitator
Particulate Removal	Poor to Fair	Good	Poor	Excellent
Heavy Metal Removal	Excellent *	Good	Poor	Good
Acid Gas Removal	Good to Exc.	Good	Excellent	Poor
Residue	Fly Ash	Scrub Liquor	Scrub Liquor	Fly Ash
Auxiliary Equipment Needed	Bag House Handling	Demister Liquid S&T **	Demister Liquid S&T	Ash Handling
Turndown	3:1	2:1	5:1	5:1
Plume Suppression	Easy	Difficult	Difficult	Easy
Pressure Drop	Low	High	Moderate	Low
Capital Cost	Moderate	Low	Low	High

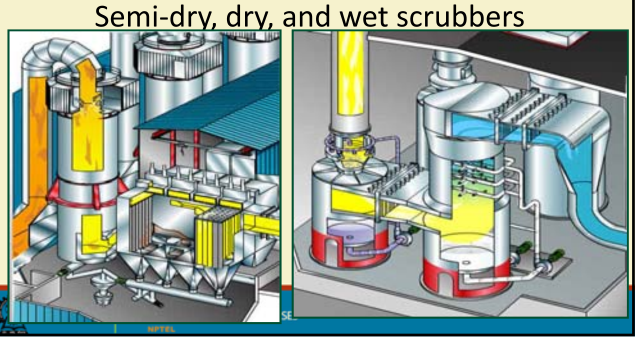
* when used with a baghouse or Esp
** Storage and Treatment

52

Major Components at WTE Plants (2)

- Air pollution control
  - Mature technology.
    - Systems available to meet most stringent air emission standards
    - Custom matched to combustion technology
  - WTE most highly regulated form of waste management
  - Emission standards more stringent than for most coal fired power plants or industrial boilers

Semi-dry, dry, and wet scrubbers



Major Components at WTE Plants (3)

- Solid Residues:
  - Conventional combustion
    - Metals recovered and recycled
    - Bottom ash and fly ash,
      - 25% by weight and 10% by volume of treated waste
      - Bottom ash suitable for road base, landfill cover or disposal
      - Fly ash usually needs to be stabilized before disposal
  - Advanced Combustion
    - Slag with varying amounts of fixed carbon, up to 30% by weight
    - Slag may be reduced by reprocessing
    - Plasma systems have almost no residue

Air Emissions

- WTE most highly regulated form of waste management
- Most countries have very strict standards
- EU and Ontario A7 guidelines considered to be the most stringent in the world
- Technologies have been developed and are applied to meet these standards
- In Europe, emissions from WTE are so low, that they are often considered irrelevant compared to industrial and transportation sources

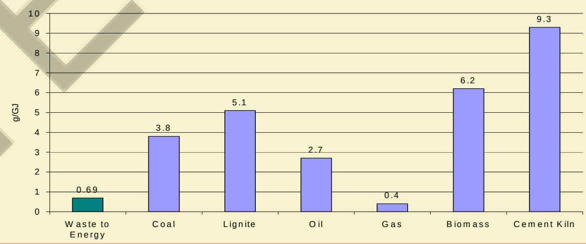
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Comparison of Relevant Air Emissions from Selected Combustion Technologies

- Paper presented by Helmut Rechberger and Gerald Schoeller, Technical University of Vienna, 2006 CEWEP Congress
- Extensive emissions comparisons based on energy production (mg/GJ)
- WTE figures from 50 existing WTE facilities in Europe
- Cement kiln data from Association of German Cement Kilns
- Other data from literature

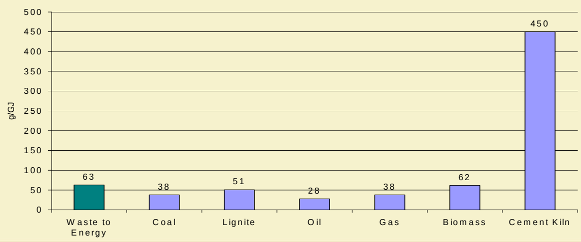
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Comparison of Dust/Particulate Emissions



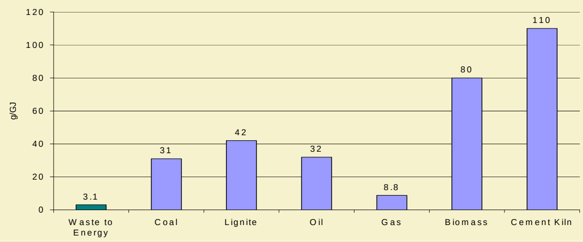
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Comparison of NO_x Emissions



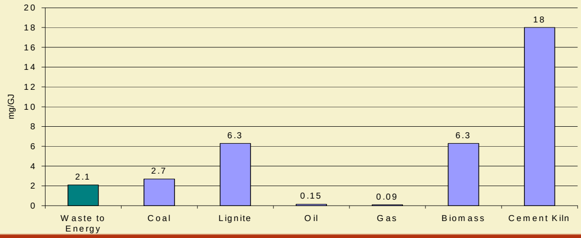
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Comparison of SO_2 Emissions



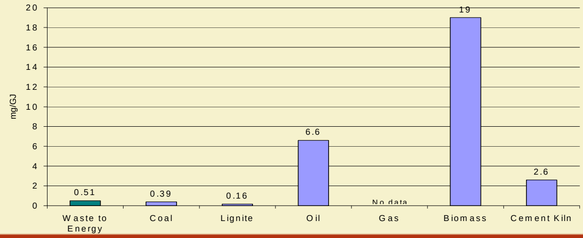
IIT KHARAGPUR NPTEL ONLINE CERTIFICATION COURSES

Comparison of Mercury Emissions



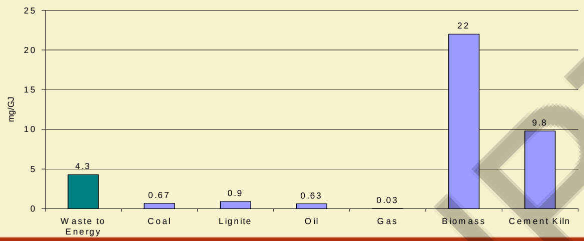
IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Comparison of Cadmium Emissions



IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Comparison of PCDD/F Emissions



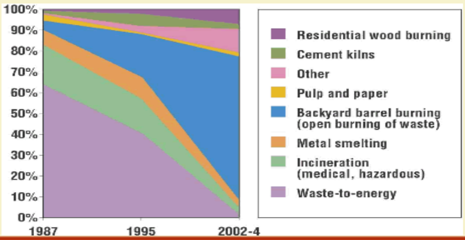
IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Notes to emissions slides

- Values shown in previous slides are for existing facilities, some of which are older
- Newer facilities are made to meet more stringent emission targets
- Metro Vancouver's Burnaby WTE facility often has no detectable dioxins
- New technologies exist to remove mercury from flue gas

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

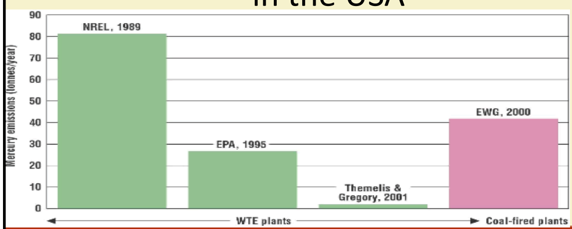
Dioxin Emissions in the USA



Source: *(P. Deriziotis, MS Thesis, Columbia University, 2003; data by U.S. EPA)*

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Reduction of Mercury from WTE in the USA



Source: Waste-to-Energy Research and Technology Council (WTERT)

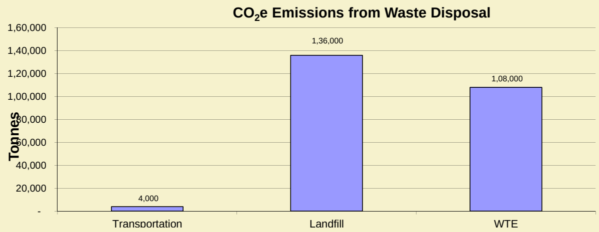
IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Carbon Dioxide (CO_2)

- WTE emits CO_2 like any other combustion process
- 40 to 60% is biogenic and is therefore part of the active carbon cycle
  - Unlike CO_2 from fossil fuels, this does not count as contributing towards climate change
- Electricity from WTE reduces the need to generate power from other sources (fossil fuels, nuclear)
- Generally, WTE results in less CO_2 equivalents than landfilling
- One European study calculated that in the EU:
  - WTE emits 0.348kg CO_2 eq. / kg of waste
  - Landfills emit 0.69 kg CO_2 eq. / kg of waste

Ffact Management Consultants. Waste to Energy and the revision of the Waste Framework Directive. Opportunities to reduce climate change by using energy from waste. FF/KW/2006.023-final. Delft, January 2007

CO_2 of Transportation and WTE



IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Costs of WTE

- High initial capital costs
- Operating costs generally offset by energy sales (for larger facilities)
- Tipping fees must generally cover capital repayment
- Once paid for, WTE can be revenue generator
- Facility life 20 to 50 years

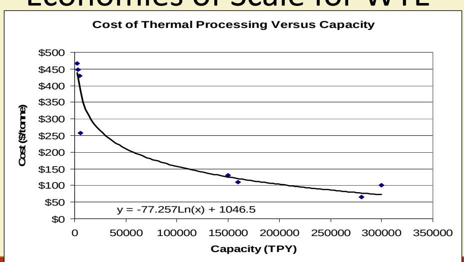
IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Revenues from WTE

- Tipping fees
- Electricity sales
- Steam sales (cogeneration, if available)
- District heat (if feasible)
- Recycled metals from ash or upfront processing
- CO_2 credits (future)

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Economies of Scale for WTE



IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Political/social acceptance of WTE as diversion

- Europe
  - In practice used as diversion
  - Looking for official recognition to capitalize on tax credits
- USA
  - In some states considered renewable fuel
  - In other states not recognized as diversion
- Japan
  - Over 90% of solid waste combusted, mostly for energy
- Canada
  - Alberta recognizes WTE as diversion, Ontario does not, BC is undecided

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Issues: Opposition and hurdles

- Negative public perception
- Lack of public awareness of technological progress and high regulated standards
- Large initial investment needed
- Higher operating costs than most local landfills
- Need for long term waste supply contracts

Issues: Opposition and hurdles (2)

- Full cost accounting and long term benefits rarely considered
- Waste has not yet been defined as renewable energy in Canada
- GHG credits are difficult to define and do not flow into the economics calculations

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

WTE in the USA

- 65 mass burn plants
  - 20 million tonnes per year capacity total
- 9 modular and 10 RDF plants
  - About 5 million tonnes per year capacity
- 15 RDF plants
  - 6 million tonnes per year
- 13% of USA waste managed by WTE

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Comparison of WTE with selected Renewable Energy Sources in USA

Energy Source	% of Renewable energy
Geothermal	28%
WTE	28%
Landfill gas	14%
Wood/biomass	17%
Solar thermal	2%
Wind	11%

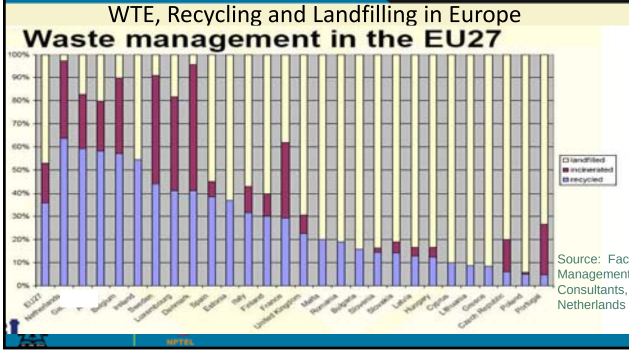
IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

WTE in Europe

- More than 370 WTE plants with total annual capacity over 53 million tonnes
- Average EU recycling rate 36% - long term goal 60%
- EU WTE rate 17%
- Landfilling in EU 48%
- Landfill Directive progressively prohibits landfilling of organic materials
- High cost of energy = good revenue from heat and electricity
- Carbon credits enhance economics of WTE and help meet national reduction goals

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

WTE, Recycling and Landfilling in Europe



Source: Fact Management Consultants, Netherlands

Isle of Man, UK

- 200 tonnes per day

Lille, France

Karlsruhe, Germany

- Gasification Plant (shut down, but similar

Paris, France

- 350 tonnes per day

Vienna Austria

- Designed by famous artist Hundertwasser

http://truththeory.com/2014/09/17/sweden-is-now-recycling-99-percent-of-its-trash-heres-how-they-do-it/

The Japan Experience

- Very strict land disposal guidelines
  - No raw waste
  - No ash without stabilization
- Over 90 % of solid waste combusted, mostly with energy recovery
- 2300 combustion facilities in Japan
- 23 WTE facilities in Tokyo
- High standards for social integration and environmental performance
- Double typical north American/European costs

Japanese WTE and Sludge burning

Miscellaneous Issues

- diversity of waste
  - requires that better incineration controls are used to ensure that complete combustion occurs
- delivering constant waste to the combustion chamber
- maintaining sufficient temperature
  - can not start and stop operation
- replacement of refractory material is expensive
- competing against 3Rs for input material
  - common sense would suggest it's a problem
    - the same material that is useful from recycling is also combustible
  - practical experience suggests it's not
    - we do not capture all the recyclable material
    - combination of recycling and incineration is a more complete and integrated waste management approach

Effectiveness of Incinerators

- destruction efficiency (DE)
  - takes place in the combustion chamber
- removal efficiency (RE)
  - takes place in the APCE
- DRE is a combination of both
- required efficiencies:
  - most organic compounds at 99.99%
  - PCBs at 99.9999%
    - required to minimize formation of dioxins
  - in addition, HCl
  - particulate matter
- example of PCB DRE
  - inlet = 637 kg/h
  - outlet = 0.012 kg/h

$$DRE = \left(\frac{637 - 0.012}{637}\right) \times 100 = 99.9981 \rightarrow \text{FAILS}$$

Energy from Waste

- energy from waste (EFW) facilities use high temperature to extract energy from the trash
  - generate electricity or heat/steam from the waste combustion
  - and employ sophisticated emissions control systems
- incinerators only reduce the volume of the trash
- typical mass-burn 1,500 tonne per day (TPD) EFW facility produces enough clean, renewable electricity for 45,000 homes
  - which saves more than 450,000 barrels of oil each year
- offers net benefits in terms of greenhouse gases
  - emits 2/3 less carbon dioxide (CO_2) than coal fired power plants
  - emits 2/3 less carbon dioxide (CO_2) than oil and natural gas power plants
- life-cycle analysis of a 1,500 TPD EFW facility
  - annually reduces about 270,000 tons of CO_2 equivalent emissions
- Europe ~400 plants and 60,000,00 tonnes per year (500 TPD)

Co-generation

- takes advantage of lost heat for another process
  - thermal power plants reject 50 – 65% heat to the environment
- local generation station near a facility that needs heat
  - transport the heat via low temperature hot water
  - use steam if distance less than 4 – 5 kilometers
- various fuels can be used to generate electricity
  - natural gas, coal, wood residue, MSW, biofuels
- captured heat used for secondary processes
  - greenhouse operation, paper producing facilities, petrochemical industry, bio energy, fuel cells, WWTP, Universities
- an example – Stuttgart WWTP
  - dries it's sludge and incinerates it with MSW – produces heat
  - also heat from anaerobic digestion
  - used to produce electricity
  - methane gas from anaerobic digestion piped into the natural gas system

Co-incineration

- waste can also be burned at facilities that are not dedicated to waste incineration
- the main candidates are:
  - steam and electricity producers
  - blast furnaces
  - lime and cement kilns
- few technical barriers exist as long as the waste is pre-treated to suit the primary (existing) process
- the main limitation is the composition of the waste and its possible contamination that might impact the industrial process

Pyrolysis

- involves thermochemical decomposition of organic material in the absence of oxygen
- lower temperature than thermal – 400°C – 800°C
- products are pyrolytic oils and gases, and solid char
  - distribution of these products depends on temperature
- pyrolysis oil used after appropriate post-treatment for:
  - chemicals – which can be extracted from the oil
  - adhesives and other products
  - liquid fuels – the remaining oil can be combusted to generate electricity
- gas stream contains a variety of gases:
  - hydrogen, methane, carbon dioxide and carbon monoxide
- hydrogen and methane can be an important source of energy
  - hydrogen, after cleaning, can be used for fuel cells
  - further thermal treatment converts hydrogen to methane

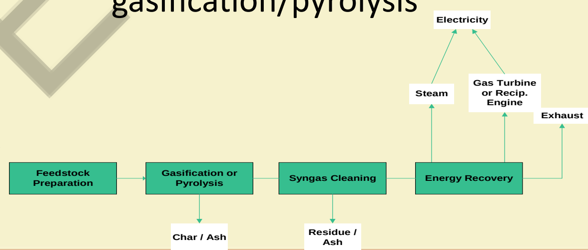
Pyrolysis, Combustion, Gasification

- Pyrolysis, gasification and combustion have been considered as separate thermochemical conversion processes for general classification. **However, in a gasification process, both pyrolysis and combustion processes take place.**
- **Pyrolysis** is the destructive distillation of carbon-based materials with heat in the absence of oxygen into **gaseous products, char, condensable liquids, tar and oils.**

Advanced thermal technologies

- Gasification and pyrolysis
  - Converts solids into synthetic gas
  - Gas is cleaned before combustion or other uses
  - Complex technology
- Plasma
  - Ultra high temperature process, total organics destruction
  - Makes synthetic gas
  - Creates vitrified slag
  - Lowest residuals

Advanced thermal technologies: gasification/pyrolysis

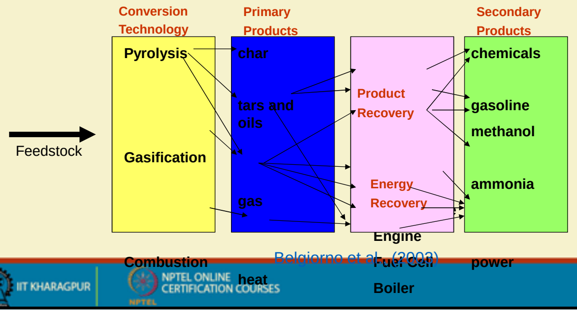


Pros and cons of advanced thermal technologies

Pros
- Few air emissions during syngas generation
- Lower CO_2 generated when syngas formed
- Ash can be vitrified with some processes
- Recovery of energy from waste
- Better environmental perception

Cons
- Syngas must be cleaned, leaving residues
- CO_2 formed when syngas burned
- Vitrification has high energy requirement/cost
- Often lower energy recovery efficiency than conventional combustion systems
- No real environmental advantages over combustion if syngas is used for heat/power

Thermochemical Conversion Processes



Belgiorno et al. (2003)

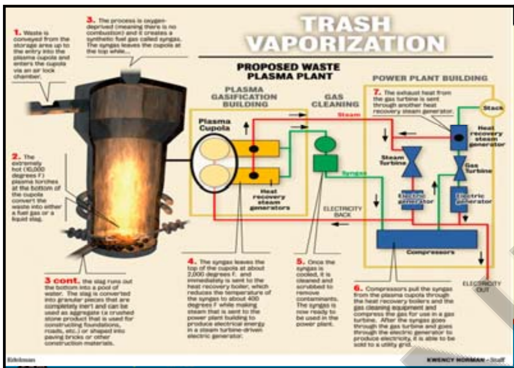
Plasma Arc

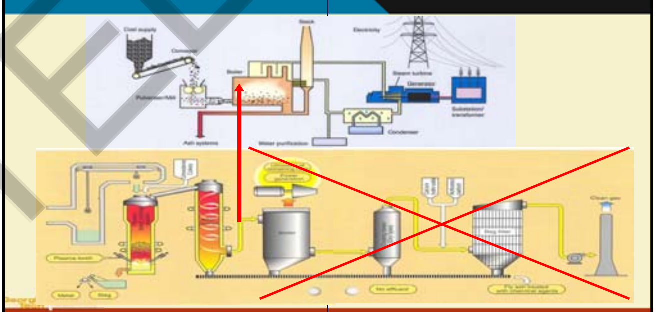
- plasma is a state of matter created by heating a gas in which a certain portion of the particles are ionized
- plasma can be created using almost any kind of gas
  - nitrogen, oxygen, air
- heated to extreme temperature
  - 2000 – 6000°C
- ionized gas conducts electricity
- this energy is transferred to the waste material
  - excites molecular bonds such that the materials break into elemental atoms
  - all waste constituents are completely melted into a solid mass called dross
- minerals can be recovered from the dross
- all known contaminants effectively treated
  - municipal, hazardous, hospital

Plasma Arc

- the process generates PCG – plasma converted gas
  - hydrogen fuel as energy
- lower volume of gas requiring treatment
- power consumptic
- double the cost of
- but, a smaller environmental footprint

www.plasmawastedisposal.com





Example Problem #1

- determine the stoichiometric amount of air required for the combustion of an organic solid waste
  - the waste is defined as C_5H_{12}
  - excess air requirements set at 150% per tonne
- first, write the stoichiometric equation:

$$\underset{72}{C_5H_{12}} + \underset{256}{8O_2} \rightarrow 5CO_2 + 6H_2O$$

  - so → 256 grams of O_2 oxidizes 72 grams of C_5H_{12}
- therefore,

$$\text{oxygen} = \left(\frac{256}{72}\right)\cdot\left(1000\ \frac{\text{kg waste}}{\text{tonne}}\right) = 3555.6\ \text{kg } O_2/\text{tonne}$$

- assume that oxygen is 23.15% of air by weight

Example Problem #1

- therefore,

$$\text{air} = \left(\frac{3555.6\ \text{kg } O_2/\text{tonne}}{0.2315\ \text{kg } O_2/\text{kg air}}\right) = 15{,}359\ \text{kg air/tonne}$$

- the density of air is 1.2928 kg Air/m³:

$$\text{air} = \left(\frac{15{,}358.8\ \text{kg Air/tonne}}{1.2928\ \text{kg Air/m}^3}\right) = 11{,}880\ \text{m}^3\ \text{air/tonne}$$

- therefore, 1 tonne of waste requires 11,880 m³ of air for complete combustion
- or we can use the simplified equation:

$$O_2\ (\text{m}^3/\text{kg}\cdot\text{fuel}) = 24.6\ [(C/12) + (H/4) + (S/32) - (O/32)]$$

Example Problem #1

- element percentages:

$$\%\ C = \left(\frac{5(12)}{5(12) + 12(1)}\right) = \frac{60}{72} = 0.833$$

$$\%\ H = \left(\frac{12}{5(12) + 12(1)}\right) = \frac{12}{72} = 0.167$$

- oxygen requirements: $O_2\ (m^3/kg \cdot fuel) = 24.6\ [(0.833/12) + (0.167/4)]$

$$= 2.733\ m^3/kg\ fuel$$

- air requirements: $air = \left(\frac{2.733}{0.2315}\right) = 11.808\ m^3/kg = 11{,}808\ m^3/tonne$
- excess air @ 150%: $air = (11{,}808 \times 1.50) = 17{,}710\ m^3/tonne$

Example Problem #2

- determine the amount of air required for the combustion of an organic solid waste
  - an organic waste is defined as $C_{760}H_{1980}O_{875}N_{13}S$
  - excess flowrate/hour if 500 tonnes/day waste (dry basis)
  - excess air requirements set at 175% per tonne
  - for efficiency, incinerator operation is 24/7
- waste processing:

$$production\ rate = \left(500\ \frac{tonne}{day} \times \frac{1\ day}{24\ hour} \times \frac{1000\ kg}{tonne}\right) = 20{,}833\ kg/hr$$

- mass of waste:

$$molar\ mass = (760\ x12.0) + (1980\ x1.0) + (875\ x16.0) + (13x14.0) + (32x1)$$
$$= 25314.1\ g/mol$$

Example Problem #2

- element percentages:

$$\%\ C = \left(\frac{760(12)}{25314}\right) = \frac{9120}{25314} = 0.360$$

$$\%\ H = \left(\frac{1980(1)}{25314}\right) = \frac{1980}{25314} = 0.078$$

$$\%\ O = \left(\frac{875(16)}{25314}\right) = \frac{14000}{25314} = 0.553$$

$$\%\ N = \left(\frac{13(14)}{25314}\right) = \frac{182}{25314} = 0.007$$

$$\%\ S = \left(\frac{1(32.1)}{25314}\right) = \frac{32.1}{25314} = 0.001$$

* very small contribution

Example Problem #2

- using the simplified equation:

$$O_2\ (m^3/kg \cdot fuel) = 24.6\ [(C/12) + (H/4) + (S/32) - (O/32)]$$

$$O_2\ (m^3/kg \cdot fuel) = 24.6\ [(0.360/12) + (0.078/4) + (0.001/32) - (0.553/32)]$$
$$= 24.6\ [(0.0300) + (0.0196) + (0.00004) - (0.0173)]$$
$$= 24.6\ (0.0323)$$
$$= 0.7953\ m^3/kg\ fuel$$

- amount of O_2 per hour:

$$oxygen = (20{,}833\ kg\ fuel/hr \times 0.7953\ m^3/kg\ fuel) = 16{,}566\ m^3/hr$$

Example Problem #2

- amount of air per hour:

$$air = \left(\frac{16{,}568\ m^3/kg}{0.2315}\right) = 71{,}570\ m^3\ air/hr$$

- based on excess air = 175%

$$air = 1.75 \cdot (71{,}570\ m^3\ air/hr) = 125{,}248\ m^3\ air/hr$$

- power requirements:

$$P = Q \cdot \gamma \cdot H$$

Q = flowrate

γ = specific weight

H = head drop

$$Q = \frac{125{,}248\ m^3\ air/hr}{3600\ sec/hr} = 34.8\ m^3/s$$

$$\gamma\ (air\ @\ 20\ ^\circ C) = 11.8\ N/m^3$$

$$H = 10\ m$$

$$P = (34.8 \times 11.8 \times 10)$$
$$= 4{,}130\ N \cdot m/s$$
$$= 4.13\ kW$$

Example Problem #2

- using a centrifugal fan, with an efficiency of 70%:

$$P = \frac{4.13\ kW}{0.70} = 5.7\ kW$$

$$P = \frac{5.7\ kW}{745.69} = 7.6\ Hp$$

- we need to blow 125,000 m^3/hour of air into the combustion chamber, using a 7.6 Hp blower

Example Problem #3

Let's Look at Wood from C&D Debris

- Wood:

%C = 41.20, %H = 5.03, %O = 34.55, %N = 0.24, %Cl = 0.09
%S = 0.07, %Moisture = 16, %Ash = 2.82

$$VS = \frac{M_{VS}}{M_{Dry}} \qquad VS = \frac{100 - 16 - 2.82}{100 - 16}$$

VS = 96.6%

Let's Find the Heat Value

- Use the Dulong Equation

$$BTU/lb = 145C + 610(H - \frac{O}{8}) + 40S + 10N$$

$$BTU/lb = 145(41.2) + 610(5.03 - \frac{34.55}{8}) + 40(0.24) + 10(0.07)$$

BTU per pound = 6,418

Heat Value in KJ/kg = 14,890

Let's Compare to Value in Table

ULTIMATE ANALYSIS OF MUNICIPAL SOLID WASTE COMPONENTS (percent by weight)

MATERIAL	C	H	O	N	Cl	S	Moisture	Ash	HHV (Btu/lb)
Mixed Waste	27.5	3.7	20.6	0.45	0.5	0.83	23.2	23.4	4,830
Corrugated	36.79	5.08	35.41	0.11	0.12	0.23	20	2.26	6,322
Newsprint	36.62	4.66	31.76	0.11	0.11	0.19	25	1.55	6,233
Magazines	32.93	4.64	32.85	0.11	0.13	0.21	16	13.13	5,466
Other Paper	32.41	4.51	29.91	0.31	0.61	0.19	23	9.06	5,481
Plastics	56.43	7.79	8.05	0.85	3.00	0.29	15	8.59	11,586
Rubber/Leather	43.09	5.37	11.57	1.34	4.97	1.17	10	22.49	8,433
Wood	41.20	5.03	34.55	0.24	0.09	0.07	16	2.82	6,933
Textiles	37.23	5.02	27.11	3.11	0.27	0.28	25	1.98	6,595
Yard Waste	23.29	2.93	17.54	0.89	0.13	0.15	45	10.07	4,005
Food Waste	17.93	2.55	12.85	1.13	0.38	0.06	60	5.10	3,265

Source: D.A. Tillman, "The Combustion of Solid Fuels & Wastes," Academic Press, San Diego, 1991

BTU per pound = 6,418 6,933

BTU Value

- Values are close (note that Dulong Equation is only an estimate and other methods of estimation are out there).
- But what about water? Water as not factored in.
- Remember, energy is consumed in the evaporation of water. 1,040 BTU/lb

Heat Consumed by Evaporation

$$Heat\ Consumed\ by\ Evaporation = \left(\frac{0.16\ lb\ water}{1\ lb\ waste}\right)\left(\frac{-1{,}040\ BTU}{lb\ water}\right)$$

$$Heat\ Consumed\ by\ Evaporation = -166\ \frac{BTU}{lb\ waste}$$

- Actual Heat Value = 6,252 BTU/lb = 14,505 KJ/kg

C&D Debris Wood is not Pure Wood

- Other components: Metal, Dirt
- If we assume X% contamination, we could reduce our heat value by that amount.
- But for this example, let's work with pure wood

Process to Calculate Air Requirement

- Use basic equations:

$$C + O_2 \rightarrow CO_2$$

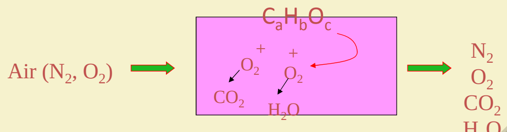
$$2H_2 + O_2 \rightarrow 2H_2O$$

$$S + O_2 \rightarrow SO_2$$

Assumptions for Solution

- Only consider oxidation of carbon and hydrogen for air demand.
- Let's go ahead and work everything from a total weight standpoint.
- We will operate at 50% excess air.
- Remember, oxygen in the waste contributes some oxygen toward combustion.

Contribution of O_2



- Wood:

%C = 41.20, %H = 5.03, %O = 34.55, %N = 0.24, %Cl = 0.09
%S = 0.07, %Moisture = 16, %Ash = 2.82, VS = 96.6%

Start With Carbon

$$41.2\left(\frac{kg\,C}{100kg\ waste}\right)\left(\frac{1\,kg-mole\ C}{12\ kg\,C}\right)\left(\frac{1\,kg-mole\ O_2}{1\,kg-mole\ C}\right)\left(\frac{22.4\ cum\ \ O_2}{1\,kg-mole\ O_2}\right)\left(\frac{100\ cum\ \ air}{21\ cum\ \ O_2}\right)$$

$$\Rightarrow \left(\frac{366\ cum\ \ air}{100kg\ waste}\right)$$

- Note: this is the air demand from Carbon only!!!

Next, Hydrogen

$$5.03\left(\frac{kg\,H}{100kg\ waste}\right)\left(\frac{1\,kg-mole\ H}{1\,kg\,H}\right)\left(\frac{1\,kg-mole\ H_2}{2\ kg-mole\ H}\right)\left(\frac{1\,kg-mole\ O_2}{2\ kg-mole\ H_2}\right)\left(\frac{22.4cumO_2}{1\,kg-mole\ O_2}\right)\left(\frac{100\ cum\ air}{21cum\,O_2}\right)$$

$$\Rightarrow \left(\frac{134\ cum\ air}{100kgwaste}\right)$$

- Note: this is the air demand from Hydrogen only!!!

Now, O_2 Contribution

$$34.55\left(\frac{kg\ O}{100kg\ waste}\right)\left(\frac{1\,kg-mole\ O_2}{32\ kg\,O}\right)\left(\frac{22.4\ cum\,O_2}{1\,kg-mole\ O_2}\right)\left(\frac{100\ cum\,air}{21\ cum\,O_2}\right)$$

$$\Rightarrow \left(\frac{115\ cum\ air}{100kg\ waste}\right)$$

- Note: This is the air contribution from oxygen only!!!

Net Air Demand

$$\left(\frac{366\ cum\ air}{100kg\ waste}\right) + \left(\frac{134\ cum\ air}{100kg waste}\right) - \left(\frac{115\ cum\ air}{100kg waste}\right)$$

$$= \left(\frac{385\ cum\ air}{100kg\ \ waste}\right)$$

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Factor in Excess Air

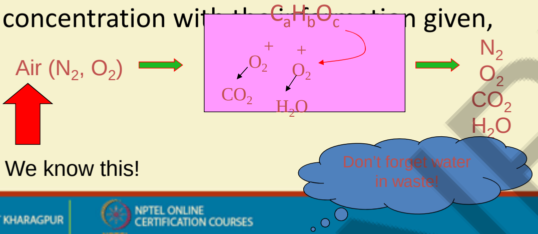
- We want to use 50% excess air

$$\left(\frac{385\,cum air}{100kg\ \ waste}\right) * 1.5 = \ \ 578\,\frac{cum air}{100kg\ \ waste}$$

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Exit Gas Concentration

- You should be able to easily solve the exit gas concentration with the $C_aH_bO_c$ equation given,



IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Future of thermal treatment

- Rising energy costs will make WTE attractive for power generation/heat utilization
- Increasing costs and long-term environmental concerns with landfills will support WTE
- Energy recovery increasingly recognized as logical and integral part of WM process
- Waste increasingly recognized as renewable energy with GHG benefits
- European legislation supports WTE as opposed to landfilling

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Future challenges of thermal treatment

- Education required to achieve a balanced public perception and acceptance
- Increasing thermal efficiencies
- Finding markets for heat
- Reducing operating costs and increasing revenues from sale of energy
- Regionalization required to achieve economies of scale
- Regulatory and policy support needed
- Acceptance of WTE as renewable energy

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

What is a Landfill?

- Concept fostered in early 20th century
- An area of land that has solid waste deposited on it in such a quantity to noticeably change the surface elevation.

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Why to use a landfill?

Potential Landfill Problems

- Landfill can present problems with respect to:
  - Spread of disease
  - Odors
  - Fires

  Controlled by sanitary landfill techniques

  - Contamination of groundwater
  - Gas emissions

  Controlled by modern landfill design

Sanitary Landfill

- Landfills may be:
  - Excavated and filled
  - Fill existing depressions
  - Built up from the ground
  - A combination of above
- Operate landfills in a controlled safe fashion
  - Use cover soil
  - Excavate cells
  - Compact the waste
  - Control access

Modern Landfills are Engineered Structures

- Designed to Contain Leachate and Minimize Release of Pollutants from the Landfill

Leachate

- Leachate is the liquid (or wastewater) that forms when water (rainfall, groundwater) travels through solid waste
- Leachate can migrate into underlying groundwater, resulting in contamination
- Leachate can contain many different chemicals, depending on what is in the solid waste

Landfill Gas

- Landfill gas consists primarily of methane and carbon dioxide
- Results from the anaerobic decomposition of biodegradable solid wastes

Typical Regulatory Requirements

- Location restrictions
  - Airports
  - Wetlands
  - Fault lines
  - Unstable areas
  - Endangered species

Typical Regulatory Requirements

- Liners -- Low permeability barrier layers
  - Compacted soil (clay)
  - Geomembranes (plastic)
  - Composites of both
- Liner keep leachate from migrating out of the landfill
- Leachate must be collected and removed

Single Liner System

- One liner consisting of compacted soil ***or*** geomembrane

Composite Liner

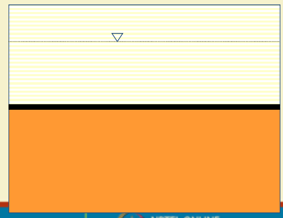
- A single liner consisting of compacted soil and geomembrane in intimate contact

Double Liner

- A liner system with low permeability barrier layers with a leak detection system layer in between. The upper and lower components are either compacted soil, geomembrane, or composite.

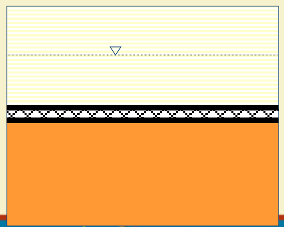
Typical Subtitle D Liner

Single Composite Liner



Typical Subtitle C Liner

Double Liner



Types of Geomembrane Materials

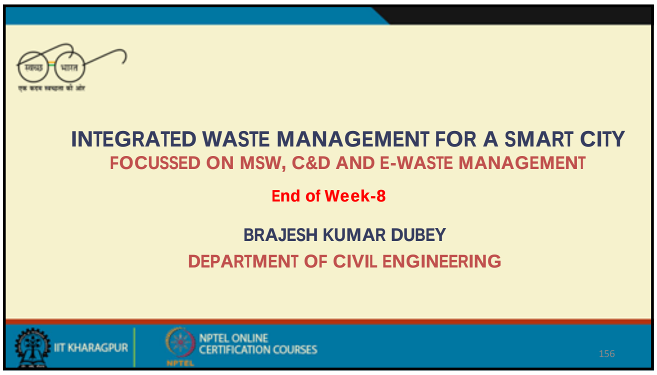
- HDPE
- PVC
- VLDPE
- PP

What Controls Head on the Liner?

- Liner Slope
- Pipe Spacing
- LCS Hydraulic Conductivity
- Impingement Rate

What is a Geosynthetic Clay Liner?

- A manufactured product that contains a soil component (dry bentonite) contained in a fabric or affixed to a geomembrane.


INTEGRATED WASTE MANAGEMENT FOR A SMART CITY
FOCUSSED ON MSW, C&D AND E-WASTE MANAGEMENT
End of Week-8
BRAJESH KUMAR DUBEY
DEPARTMENT OF CIVIL ENGINEERING
IIT KHARAGPUR
NPTEL ONLINE CERTIFICATION COURSES
156