Objectives

- Better awareness of waste incineration technology
  - Fundamentals of waste properties and physical/chemical processes that are relevant to waste incineration
  - Selected examples of the practice of incineration

- Good starting point to learn more about waste incineration
The Overall Process: Thermal Oxidation

- **Exothermic**
  - High temperature as hot gas and hot ash
  - Self-sustaining once started

- **Different processes with same principle**
  - Forest fires
  - Combustion engines
  - ....

- **Waste management overall strategy has been considered**
**Scope: Waste Incineration**

- **Waste**
  - No value or negative value
  - Auxiliary fuel may be needed

- **Similar processes with different “economics”**
  - Power plants
  - Energy recovery systems
  - ....

Diagram:

- Waste Incineration (WI)
- Waste
- Aux Fuel
- Flue Gas
- Air
- Ash
Rationale for Waste Incineration

- Detoxification or sterilization
  - High Temperature
- Reduction in disposal requirement
  - Ash < Waste
- Energy and/or material recovery
- Reduction in wildlife interactions
  - No edible left
Exclusion #1: No Pre/Post-Incineration Processes

- **Scrubber**
  - Air pollution control device (APCD)
  - Cleans air emissions

- **Ash Treatment**
  - Prevents leaching of contaminants when landfilled
  - Makes it safe for use

- **Waste “Pre-treatment”**
  - Form changes
  - Compaction
  - Segregation
Exclusion #2: “Analyses” and Environmental Regulations

- Sampling and analysis
  - Waste
  - Flue gas
  - Ash

- Environmental regulations will be cited ONLY as examples

- Variations
  - Jurisdictions
  - System Size
  - Applications
Exclusion #3: Not about different designs

- Different types and designs are shown ONLY as examples
1. Waste Characteristics
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
   3. Form, Heating Value and Bulk Density

2. Incinerator design and operation
   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
   3. Operating mode and dependence on waste properties

3. Air emissions and ash quality
   1. Particulate matter
   2. Acid gases
   3. Metals
   4. POHCs and PICs
Physical state and combustion modes

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http://www.chem.purdue.edu/gchelp/atoms/states.html
Gas-phase combustion

Waste gas and oxygen molecules “collide” and react in a gas-phase reaction.
Liquid Incineration

Use a nozzle: liquid is atomized → droplets evaporate → gas-phase combustion
Solid Incineration

- Melting
  - Evaporation
  - Vapour
    - Gas-phase Combustion

Solid Waste → Drying → (De)Volatilization → Char (FC) Burning → Ash

- FC: Fixed Carbon

Heat

- Char
- Volatiles, Soot
- Ash

Solid Waste
Solid Suspension Combustion

Heterogeneous reactions (Solids)

- Applications
  - Pulverized coal fired boilers; cement kilns; Soot formation; etc.
- Particles get heated up to devolatilization temperature
  - Released volatiles burn in gas phase
- Remaining solid undergoes heterogeneous reactions
  - Reactant gas molecules transfer to solid surface by convection or diffusion
  - Adsorbed by solid surface
  - Surface reaction at solid surface
  - Desorption of product of reaction
  - Transport of product by convection or diffusion to surrounding

Coal fired boiler → Flue gas → Ash

BOTTOM
Particulate Matter in Flue Gas (1)

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3. Air emissions and ash quality
   1. Particulate matter
   2. Acid gases
   3. Metals
   4. POHCs and PICs
Recall Solid Waste Combustion
Proximate Composition (2) for Solids

1. Waste Characteristics
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
   3. Form, Heating Value and Bulk Density

2. Incinerator design and operation
   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
   3. Operating mode and dependence on waste properties

3. Air emissions and ash quality
   1. Particulate matter
   2. Acid gases
   3. Metals
   4. POHCs and PICs
Examples

http://users.tkk.fi/~rzevenho/BR_ch2.pdf
PM Emission from Bulk Solid Incineration

1. Waste Characteristics
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
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   1. Conditions for complete combustion
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   1. Particulate matter
   2. Acid gases
   3. Metals
   4. POHCs and PICs
Source: carry-over of PM to the Stack

Complex factors: waste form + air flow rate + “geometry” + “flow pattern”
Strategy #1: Minimize air flow (Dual Chamber, Starved Air)

Air flow in contact with waste is less than total air flow for combustion
Strategy #2: Minimize disturbance
(Batch Operation)

Environment Canada recommends Batch Operation for Small-Scale Solid Waste Incinerator
Strategy #3: Modify waste form

Wood Logs

Wood Pellets
Results from Strategy #3

“Complexity”: Results from Strategies #1 and 2

Regulatory Limits for PM: 17 – 50 mg/Rm³
Stoichiometry

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   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
   3. Operating mode and dependence on waste properties

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   2. Acid gases (SO₂, HCl, NOx ....)
   3. Metals
   4. POHCs and PICs
Example and Definitions

- Diesel combustion stoichiometry
  - 14.7 kg air/kg diesel
  - 11.3 m³ air/L diesel

- Definitions
  - Incineration: Air > Stoichiometric Requirement (SR)
    - In actual operation excess air is used to ensure complete combustion
  - Gasification”: Air < SR
    - Exothermic process generating combustible gases (and soot)
  - Pyrolysis: Air = 0
    - Endothermic (External heat required) producing many products
Examples of “good” waste (C,H,O)

- Hydrocarbons: \( C_xH_y \)
  - Methane \((\text{CH}_4)\), Diesel* \((C_{12}H_{23})\) ..... 
- Plastics **: \((C_xH_y)_n\) polymer 
  - Polyethylene \((C_2H_4)\), Polypropylene \((C_3H_6)\), Polystyrene \((C_8H_8)\) ..... 
- Fatty acids: \( C_xH_y\text{COOH} \)
- Cellulose: \((C_6H_{10}O_5)_n\)
- Wood ***: \( \text{CH}_{1.44}\text{O}_{0.63} \)
  - ..... others

* Diesel is Not a single compound, but a mixture, ranging from \(C_{10}H_{20}\) to \(C_{15}H_{28}\)
** Not PVC (Polyvinyl chloride)
*** Wood also contains nitrogen (~ 1%) and ash (~ 1%)
Sources of “acid gases”

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   1. Particulate matter
   2. Acid gases (SO$_2$, HCl, NOx ....)
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Sulphur and chlorine-containing materials

Vulcanized Rubber
S ~ 1.6%

PVC (Polyvinyl chloride)
Cl ~ 57%
Nitrogen-containing materials

<table>
<thead>
<tr>
<th>Compound</th>
<th>N-content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein</td>
<td>16%</td>
</tr>
<tr>
<td>Ammonia</td>
<td>87%</td>
</tr>
<tr>
<td>Urea</td>
<td>47%</td>
</tr>
<tr>
<td>Uric acid</td>
<td>33%</td>
</tr>
</tbody>
</table>

1. **Waste Characteristics**
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
   3. Form, Heating Value and Bulk Density

2. **Incinerator design and operation**
   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
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3. **Air emissions and ash quality**
   1. Particulate matter
   2. Acid gases (SO₂, HCl, NOx ...)
   3. Metals
   4. POHCs and PICs
### Examples in Canada

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Limit, mg/Rm³ @ 11% O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrochloric acid (HCl)</td>
<td>17 - 75</td>
</tr>
<tr>
<td>Sulphur dioxide (SO₂)</td>
<td>56 - 260</td>
</tr>
<tr>
<td>Nitrogen Oxides (NOx)</td>
<td>110 - 400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element in Waste **</th>
<th>Max content g/100 kg waste</th>
<th>Examples ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl 17 Cl 20 35 g PVC or 0.035% wt</td>
<td>20</td>
<td>35 g PVC or 0.035% wt</td>
</tr>
<tr>
<td>SO₂ 56 S 61 3.8 kg vulcanized rubber or 3.8% wt</td>
<td>61</td>
<td>3.8 kg vulcanized rubber or 3.8% wt</td>
</tr>
<tr>
<td>NOx 110 N 91 Note: Burner contribution is significant</td>
<td>91</td>
<td>Note: Burner contribution is significant</td>
</tr>
</tbody>
</table>

** Reg Lim* | Element in Waste ** | Examples ***
mg/Rm³ | Max content g/100 kg waste |
--- | --- | --- |
HCl 17 | Cl 20 | 35 g PVC or 0.035% wt |
SO₂ 56 | S 61 | 3.8 kg vulcanized rubber or 3.8% wt |
NOx 110 | N 91 | Note: Burner contribution is significant |

* Dry, 25 C, 101.3 kPa, 11% O₂, NOx as NO₂
** Type 3 (M=70%, A=5%, HHV = 17 MJ/kg DB; Diesel; 1000 C)
*** 57% Cl in PVC; 1.6% S in vulcanized rubber
Note on Interpretation of Results

<table>
<thead>
<tr>
<th>Element in Waste **</th>
<th>Max content g/100 kg waste</th>
<th>Examples ***</th>
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<tbody>
<tr>
<td>HCl</td>
<td>17</td>
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<td>20</td>
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</tr>
<tr>
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<td>56</td>
<td>Note: Burner contribution is significant</td>
</tr>
<tr>
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<td>61</td>
<td></td>
</tr>
<tr>
<td>NOx</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>91</td>
<td></td>
</tr>
</tbody>
</table>

* Dry, 25 C, 101.3 kPa, 11% O₂, NOx as NO₂

** Type 3 (M=70%, A=5%, HHV = 17 MJ/kg DB; Diesel; 1000 C)

*** 57% Cl in PVC; 1.6% S in vulcanized rubber

- Keeping contents below the above values will ensure “no problem”.
- Otherwise, the actual situation is complex and uncertain since there could be alkali in the incinerator that would reduce the concentrations of acid gases.
Metal Vapours in Flue Gas

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Relevance of Vapour Pressure: Mercury and Cadmium

Pamb = 101.35 kPa, T = 25°C

<table>
<thead>
<tr>
<th>Substance</th>
<th>MW (g/mol)</th>
<th>VP 25°C (Pa)</th>
<th>Vol Conc (%)</th>
<th>Mass Conc (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>18</td>
<td>3169</td>
<td>3.1%</td>
<td>22,972</td>
</tr>
<tr>
<td>Hg</td>
<td>200.6</td>
<td>0.25</td>
<td>0.00025%</td>
<td>20</td>
</tr>
</tbody>
</table>

CCME standard = 20 ug/m³ or 0.020 mg/m³

<table>
<thead>
<tr>
<th>Substance</th>
<th>C</th>
<th>VP, Pa</th>
<th>Vol Conc (%)</th>
<th>Mass Conc (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>300</td>
<td>6.5</td>
<td>0.0064%</td>
<td>293</td>
</tr>
</tbody>
</table>

Regulatory limits: 14 – 200 ug/m³

Keeping metal contents below the above value will ensure “no problem”.

Otherwise, the actual situation is complex since metallic compounds can be formed in the incinerator. They have different vapour pressures. For example CdO has a much lower vapour pressure compared to Cd.

In general it is better to lower the temperature that the waste is exposed to in the incinerator.

<table>
<thead>
<tr>
<th>Element in Waste **</th>
<th>Max content mg/100 kg waste</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg</td>
<td>17</td>
<td>4-ft fluorescent bulb: 10 - 50 mg Hg (&quot;NR&quot;) (2)</td>
</tr>
<tr>
<td>Cd</td>
<td>12</td>
<td>NiCd AA battery: 21 g with 18% Cd content (1)</td>
</tr>
</tbody>
</table>

* Dry, 25°C, 101.3 kPa, 11% O2
** Type 3 (M=70%, A=5%, HHV = 17 MJ/kg DB; Diesel; 1000°C)
(2) http://www.ec.gc.ca/mercure-mercury/default.asp?lang=En&n=2486B388-1 ("R": 3 - 12 mg)
# Mercury-Containing Products

<table>
<thead>
<tr>
<th>Product</th>
<th>Amount of Mercury*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent light bulbs</td>
<td>0 - 50mg</td>
</tr>
<tr>
<td>Pocket Calculator</td>
<td>0 - 50mg</td>
</tr>
<tr>
<td>LCDs</td>
<td>0 - 50mg</td>
</tr>
<tr>
<td>Button-cell batteries (watches)</td>
<td>0 - 100mg</td>
</tr>
<tr>
<td>Thermostats</td>
<td>10mg - 1000mg</td>
</tr>
<tr>
<td>Switches</td>
<td>10mg - 1000mg</td>
</tr>
<tr>
<td>Dental amalgam</td>
<td>100mg to 1000mg</td>
</tr>
<tr>
<td>Thermometers</td>
<td>0mg to 3g</td>
</tr>
<tr>
<td>Older pressure gauges</td>
<td>3g - 10g</td>
</tr>
<tr>
<td>Manometers and barometers</td>
<td>50g to several pounds</td>
</tr>
<tr>
<td>Plumbing traps</td>
<td>100g to several pounds</td>
</tr>
</tbody>
</table>

* Purdue University and NEWMOA (Northeast Waste Management Officials’ Association) Mercury in Products database.

Environment Canada also has data on quantities of mercury in various products

[http://www.co.thurston.wa.us/health/ehhm/mercury.html](http://www.co.thurston.wa.us/health/ehhm/mercury.html)

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Concerns with groundwater contamination
Regulatory Test Protocol (TCLP*)

“Simulation” of Leaching in a Landfill

“Solution”

“Everything” is specified and standardized
• Solution composition
• Sample size distribution
• Amount and ratio of solution to sample
• Container geometry
• Mixing intensity and time
• ……”

Sample

Mixing to Simulate Leaching

Filtration

- Leachate is analysed for the regulated compounds
- Concentrations compared to regulatory limits

Other Complications:
- Wet sample allowed
- Organic compounds included, including “volatiles”, pesticides
- 8 metals and 32 organics

* Toxicity Characteristic Leaching Procedure
<table>
<thead>
<tr>
<th>Contaminant</th>
<th>EPA Hazardous Waste No.</th>
<th>CAS Number</th>
<th>Regulatory Limit (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>D004</td>
<td>7440-38-2</td>
<td>5.0</td>
</tr>
<tr>
<td>Barium</td>
<td>D005</td>
<td>7440-39-3</td>
<td>100.0</td>
</tr>
<tr>
<td>Benzene</td>
<td>D018</td>
<td>71-43-2</td>
<td>0.5</td>
</tr>
<tr>
<td>Cadmium</td>
<td>D006</td>
<td>7440-43-9</td>
<td>1.0</td>
</tr>
<tr>
<td>Carbon Tetrachloride</td>
<td>D019</td>
<td>56-23-5</td>
<td>0.5</td>
</tr>
<tr>
<td>Chlordane</td>
<td>D020</td>
<td>57-74-9</td>
<td>0.02</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>D021</td>
<td>108-90-7</td>
<td>100.0</td>
</tr>
<tr>
<td>Chloroform</td>
<td>D022</td>
<td>67-66-3</td>
<td>6.0</td>
</tr>
<tr>
<td>Chromium</td>
<td>D007</td>
<td>7440-47-3</td>
<td>5.0</td>
</tr>
<tr>
<td>o-Cresol</td>
<td>D023</td>
<td>95-48-7</td>
<td>200.0</td>
</tr>
<tr>
<td>m-Cresol</td>
<td>D024</td>
<td>108-39-4</td>
<td>200.0</td>
</tr>
<tr>
<td>p-Cresol</td>
<td>D025</td>
<td>106-44-5</td>
<td>200.0</td>
</tr>
<tr>
<td>Cresol</td>
<td>D026</td>
<td>**********</td>
<td>200.0</td>
</tr>
<tr>
<td>2,4-D Acid</td>
<td>D016</td>
<td>94-75-7</td>
<td>10.0</td>
</tr>
<tr>
<td>1,4-Dichlorobenzene</td>
<td>D027</td>
<td>106-48-7</td>
<td>7.5</td>
</tr>
<tr>
<td>1,2-Dichloroethane</td>
<td>D028</td>
<td>107-06-2</td>
<td>0.5</td>
</tr>
<tr>
<td>1,1-Dichloroethylene</td>
<td>D029</td>
<td>75-35-4</td>
<td>0.7</td>
</tr>
<tr>
<td>2,4-Dinitrotoluene</td>
<td>D030</td>
<td>121-14-2</td>
<td>0.13</td>
</tr>
<tr>
<td>Endrin</td>
<td>D012</td>
<td>72-20-8</td>
<td>0.02</td>
</tr>
<tr>
<td>Heptachlor (and its epoxides)</td>
<td>D031</td>
<td>76-44-8</td>
<td>0.008</td>
</tr>
<tr>
<td>Hexachlorobenzene</td>
<td>D032</td>
<td>118-74-1</td>
<td>0.13</td>
</tr>
<tr>
<td>Hexachlorobutadiene</td>
<td>D033</td>
<td>87-68-3</td>
<td>0.5</td>
</tr>
<tr>
<td>Hexachloroethane</td>
<td>D034</td>
<td>67-72-1</td>
<td>3.0</td>
</tr>
<tr>
<td>Lead</td>
<td>D008</td>
<td>7439-92-1</td>
<td>5.0</td>
</tr>
<tr>
<td>Lindane</td>
<td>D013</td>
<td>58-89-9</td>
<td>0.4</td>
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<tr>
<td>Mercury</td>
<td>D009</td>
<td>7439-97-6</td>
<td>0.2</td>
</tr>
<tr>
<td>Methoxychlor</td>
<td>D014</td>
<td>72-43-5</td>
<td>10.0</td>
</tr>
<tr>
<td>Methyl Ethyl Ketone</td>
<td>D035</td>
<td>78-93-3</td>
<td>200.0</td>
</tr>
<tr>
<td>Nitrobenzene</td>
<td>D036</td>
<td>98-95-3</td>
<td>2.0</td>
</tr>
<tr>
<td>Pentachlorophenol</td>
<td>D037</td>
<td>87-86-5</td>
<td>100.0</td>
</tr>
<tr>
<td>Pyridine</td>
<td>D038</td>
<td>110-86-1</td>
<td>5.0</td>
</tr>
<tr>
<td>Selenium</td>
<td>D010</td>
<td>7782-49-2</td>
<td>1.0</td>
</tr>
<tr>
<td>Silver</td>
<td>D011</td>
<td>7440-22-4</td>
<td>5.0</td>
</tr>
<tr>
<td>Tetrafluoroethylene</td>
<td>D039</td>
<td>127-18-4</td>
<td>0.7</td>
</tr>
<tr>
<td>Toxaphene</td>
<td>D015</td>
<td>8061-35-2</td>
<td>0.5</td>
</tr>
<tr>
<td>Trichloroethylene</td>
<td>D040</td>
<td>79-01-6</td>
<td>0.5</td>
</tr>
<tr>
<td>2,4,5-Trichlorophenol</td>
<td>D041</td>
<td>95-95-4</td>
<td>400.0</td>
</tr>
<tr>
<td>2,4,6-Trichlorophenol</td>
<td>D042</td>
<td>88-06-2</td>
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<tr>
<td>2,4,5-Triphenyl Chlorobenzene</td>
<td>D017</td>
<td>93-72-1</td>
<td>1.0</td>
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<tr>
<td>Vinyl Chloride</td>
<td>D043</td>
<td>75-01-4</td>
<td>0.2</td>
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</table>

http://contribute.alfred.edu/portals/ehs/docs/TCLPList.pdf
## Regulatory Limits

<table>
<thead>
<tr>
<th>Element</th>
<th>EPA Threshold Limit (ppm)</th>
<th>“Leachable” Concentration in Ash (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>5.00</td>
<td>100</td>
</tr>
<tr>
<td>Barium</td>
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<td>2,000</td>
</tr>
<tr>
<td>Cadmium</td>
<td>1.00</td>
<td>20</td>
</tr>
<tr>
<td>Chromium</td>
<td>5.00</td>
<td>100</td>
</tr>
<tr>
<td>Lead</td>
<td>5.00</td>
<td>100</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.20</td>
<td>4</td>
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<tr>
<td>Selenium</td>
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<td>20</td>
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<tr>
<td>Silver</td>
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<td>100</td>
</tr>
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</table>
### Limitation of Metal Content Based on TCLP

**Example for Cadmium**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis, kg waste</td>
<td>100</td>
</tr>
<tr>
<td>Ash Content, %</td>
<td>10%</td>
</tr>
<tr>
<td>AA NiCd Battery, g</td>
<td>21</td>
</tr>
<tr>
<td>Cd Content, %</td>
<td>18%</td>
</tr>
<tr>
<td>Max Cd Conc in Ash, mg/kg</td>
<td>378</td>
</tr>
</tbody>
</table>

Note: \( \frac{D29 \times 1000 \times D30}{(D27 \times D28)} \)

Recall: US EPA TCLP Limit is 20 mg/kg ash

**Need for ash treatment cannot be ruled out**

Any "convenient" quantity

Data needed

Selected items of interest and relevant data on metal content

(Cell D31)
Some common products with other “heavy metals”

- Batteries
  - Lead acid (Pb)
  - Ni-Cad (Ni and Cd)
  - Ni MH (Ni)

- Consumer electronics
  - Pb and Cd
## Proximate and Ultimate Comps

### Table 10.3.4*

<table>
<thead>
<tr>
<th>Category</th>
<th>Dry Basis, %</th>
<th>WB %</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Ash</td>
<td>VM</td>
</tr>
<tr>
<td><strong>Organics/Combustibles</strong></td>
<td></td>
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<tr>
<td>Ash VM FC C H N Cl S O Moist Comb</td>
<td>7.7</td>
<td>82.6</td>
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<tr>
<td><strong>Paper</strong></td>
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<td></td>
</tr>
<tr>
<td>Newspaper</td>
<td>6.3</td>
<td>83.5</td>
</tr>
<tr>
<td>Corrugated &amp; kraft paper</td>
<td>5.2</td>
<td>83.8</td>
</tr>
<tr>
<td>High-grade paper</td>
<td>2.2</td>
<td>85.8</td>
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<tr>
<td>Magazine</td>
<td>9.1</td>
<td>83.4</td>
</tr>
<tr>
<td>Other paper</td>
<td>6.9</td>
<td>83.8</td>
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<tr>
<td><strong>Yard waste</strong></td>
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<tr>
<td>Yard waste</td>
<td>9.6</td>
<td>73</td>
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<td>Grass clippings</td>
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<tr>
<td>Leaves</td>
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<td>Other yard waste</td>
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<td><strong>Food waste</strong></td>
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<td>Food waste</td>
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<td><strong>Plastic</strong></td>
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<td>PET bottles</td>
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<td>Polyethylene bags &amp; film</td>
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<td>Other plastic</td>
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<td><strong>Other Organics</strong></td>
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<td>Textiles/rubber/leather</td>
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<td>Disposable diapers</td>
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<td>Other organs</td>
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<td><strong>Inorganics/Noncombustibles</strong></td>
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<tr>
<td>MSW</td>
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September 2, 2015
Let’s Take a Break
Complete Combustion

1. Waste Characteristics
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
   3. Form, Heating Value and Bulk Density

2. Incinerator design and operation
   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
   3. Operating mode and dependence on waste properties

3. Air emissions and ash quality
   1. Particulate matter
   2. Acid gases (SO$_2$, HCl, NOx ….)
   3. Metals
   4. POHCs and PICs
Conditions for Complete Combustion

- **Enough oxygen**
  - Excess air is needed in practice

- **Sufficiently long time**
  - Nothing happens “instantaneously”

- **Sufficiently high temperature***
  - Higher temperature → Faster reaction rate

- **Sufficient “turbulence” (mixing of waste and oxygen molecules)**
  - Cannot react without “meeting”
  - Higher turbulence → More collision → Faster reaction rate

* Above “ignition” temperature

3T’s of Combustion “AND”-type of conditions
Careful with readings and calculation results!

\[
\text{Aux Burner} \quad \text{Combustion Chamber Vol: } V \\
\text{Air} \quad \text{Total Gas Flow (F)} \\
\text{O}_2 \\
\text{Stack} \\
\text{Residence Time } RT = \frac{V}{F} \\
\text{Waste Gas}
\]

\[\text{O}_2 = 10\%; \ T = 1000\ C \text{ and } RT = 2 \text{ seconds} , \ \text{BUT} \ \ldots.
\]

Some waste molecules “experience” \( T < 1000\ C \) and \( \text{O}_2 < 10\% \) for \( < 2 \text{ sec} \).
Same Readings, Different Outcome

$O_2 = 10\%$; $T = 1000 \text{ C}$ and $RT = 2 \text{ seconds}$ produce different results
Incomplete Combustion

Soot → Incomplete Combustion
No Soot Does NOT NECESSARILY Mean Complete Combustion
Consequences of Incomplete Combustion

- Residual waste in flue gas and/or in ash
  - Detoxification failure
  - DE or DRE of POHCs*
    \[ D(R)E = \frac{IN - OUT}{IN} \times 100\% \]

- Formation PICs (Products of Incomplete Combustion)
  - “Intermediate” products of combustion (CO, CH₄ ... )
    \[ C + \frac{1}{2} O_2 \rightarrow CO + \frac{1}{2} O_2 \rightarrow CO_2 \]
  - Newly-formed compounds
    - Poly Aromatic Hydrocarbons (PAHs), Chlorobenzenes, Chlorophenols
    - “Dioxins”

- Non-compliance with air emission and/or ash quality standards

* Destruction and Removal Efficiency; Principal Organic Hazardous Constituents*  
Note: DRE > 99.9999% → 6 (six) 9’s DRE
Ash Quality Criteria Related to Incinerator Design and Operation

- TCLP on “organic compounds”
  - (a long list of 32 compounds)
- Maximum “Loss on Ignition” (LOI)

\[ \text{LOI} = \frac{(W1 - W2)}{W1} \times 100\% \]
Consequences of Incomplete Combustion

- Residual waste in flue gas and/or in ash
  - Detoxification failure
  - DE or DRE of POHCs*
    \[ D(R)E = \frac{IN - OUT}{IN} \times 100\% \]

- PICs (Products of Incomplete Combustion)
  - “Intermediate” products of combustion (CO, CH₄ ...)
    \[ C + \frac{1}{2} O₂ \rightarrow CO + \frac{1}{2} O₂ \rightarrow CO₂ \]
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    - Poly Aromatic Hydrocarbons (PAHs), Chlorobenzenes, Chlorophenols
    - “Dioxins”

- Non-compliance with air emission and/or ash quality standards

* Destruction and Removal Efficiency; Principal Organic Hazardous Constituents
Note: DRE > 99.9999% → 6 (six) 9’s DRE
“Dioxins”

- Chemical names
  - polychlorinated dibenzo-para-dioxins (PCDDs)
  - polychlorinated dibenzo-furans (PCDFs)

2,3,7,8-tetrachlorodibenzodioxin (TCDD)


**“Dioxins”**

- **Chemical names**
  - polychlorinated dibenzo-para-*dioxins* (PCDDs)
  - polychlorinated dibenzo-*furans* (PCDFs)

- **Family of compounds (number and positions of chlorine atoms)**
  - 75 *congeners* of PCDDs
  - 135 *congeners* of PCDFs

- **Homologue**: congeners with the same number of chlorine

- **Toxicity is congener-dependent**
  - Toxicity Equivalent Factor (TEF)
  - Toxic Equivalence (TEQ)

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<td>T</td>
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<td>P</td>
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<td>8</td>
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</table>
“Dioxins”

- **Chemical names**
  - polychlorinated dibenzo-para-dioxins (PCDDs)
  - polychlorinated dibenzofurans (PCDFs)

- **Family of compounds (number and positions of chlorine atms)**
  - 75 *congeners* of PCDDs
  - 135 *congeners* of PCDFs

- **Homologue**: congeners with the same number of chlorine

- **Toxicity is congener-dependent**
  - Toxicity Equivalent Factor (TEF)
  - Toxic Equivalence (TEQ)

---

<table>
<thead>
<tr>
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<th>TEF</th>
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<td>2378 TCDD</td>
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<tr>
<td>12378 PCDD</td>
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<tr>
<td>123478 HxCDD</td>
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<td>123678 HxCDD</td>
<td>0.1</td>
</tr>
<tr>
<td>123789 HxCDD</td>
<td>0.1</td>
</tr>
<tr>
<td>1234678 HpCDD</td>
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</tr>
<tr>
<td>OCDD</td>
<td>0.001</td>
</tr>
<tr>
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</tr>
<tr>
<td>12378 PCDF</td>
<td>0.05</td>
</tr>
<tr>
<td>23478 PCDF</td>
<td>0.5</td>
</tr>
<tr>
<td>123478 HxCDF</td>
<td>0.1</td>
</tr>
<tr>
<td>123678 HxCDF</td>
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</tr>
<tr>
<td>234678 HxCDF</td>
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<tr>
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Example of TEQ calculations

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<th>TEF</th>
<th>Actual, ng</th>
<th>TEQ, ng</th>
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<tr>
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<td>0.086</td>
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<td>OCDF</td>
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<tr>
<td>TOTAL</td>
<td>18.33</td>
<td>1.94</td>
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</tr>
</tbody>
</table>

\[
TEQ = \sum TEF_i \times Ci
\]
Perspective on Dioxins Limit

- Environment Canada: **80 pg (TEQ) /Rm³**
  - 1 R m³ ~ 1.2 kg
  - 1 pg = $10^{-15}$ kg
  - 67 parts in $10^{+15}$ whole
  - < 1 part in $10^{+13}$ whole

- 1 second in 320,000 years

- 1 human hair (100 um) in 25 x Earth Equators (25 x 40,000 km)

- 1.5 cm in earth-sun distance (150 million km)

Elimination of Chlorine to prevent PCDD/Fs formation is “FUTILE”

Recall: HCL limit in mg/m³ and Dioxins in pg/m³

1 mg = 1,000,000,000 pg
Recent Test Results (2003 - 2014)

PCDD/F Emission: DC, SA Incineration, Batch Operation

CCME: 80 pg/Rm3
Post-Incineration Formation

http://www.ejnet.org/dioxin/dioxinpr2.pdf
Summary: Relative Roles of (1) and (2) on (3)

1. Waste Characteristics
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
   3. Form, Heating Value and Bulk Density

2. Incinerator design and operation
   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
   3. Operating mode and dependence on waste properties

3. Air emissions and ash quality
   1. Particulate matter
   2. Acid gases (SO₂, HCl, NOx ....)
   3. Metals
   4. POHCs and PICs
## Air Emission Regulations in Canada

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Limits or Guidelines</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>CWS</td>
<td>CCME1</td>
</tr>
<tr>
<td>Chlorinated Dioxins and Furans</td>
<td>Dioxins</td>
<td>80</td>
<td>500</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>PM</td>
<td>20</td>
<td>20, 50 *</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>57</td>
<td>57</td>
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<tr>
<td>Hydrochloric Acid</td>
<td>HCl</td>
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<tr>
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<tr>
<td>Nitrogen Oxides</td>
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<td>Total Hydrocarbons</td>
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<tr>
<td>Mercury</td>
<td>Hg</td>
<td>20</td>
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<tr>
<td>Cadmium</td>
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<tr>
<td>Chromium</td>
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<tr>
<td>Lead</td>
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</tr>
<tr>
<td>Chlorobenzenes</td>
<td>CB</td>
<td></td>
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</tr>
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</table>

- Ab* (dry basis, 25°C, 101.3 kPa, 11% vol O₂)
- 1 mg = 0.001 g = 1,000 ug = 1,000,000 pg
# Roles of Waste Properties vs. Incinerator Design/Operation

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
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<th>Units</th>
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<tr>
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<tr>
<td>Sulphur Dioxide</td>
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<td>Nitrogen Oxides</td>
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<td>Hg</td>
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</tbody>
</table>

*a Rm³: dry basis, 25 C, 101.3 kPa, 11% vol O₂; 1 mg = 0.001 g = 1,000 ug = 1,000,000,000 pg*
Other Waste Properties and Incinerator operation

1. Waste Characteristics
   1. Physical state (gas, liquid or solid) and combustion modes
   2. “Ultimate” and “Proximate” compositions
   3. Form, Heating Value and Bulk Density

2. Incinerator design and operation
   1. Conditions for complete combustion
   2. Consequences of incomplete combustion
   3. Operating mode and dependence on waste properties

3. Air emissions and ash quality
   1. Particulate matter
   2. Acid gases (SO₂, HCl, NOx ....)
   3. Metals
   4. POHCs and PICs
Heating Value [MJ/kg]

- Calorific value, Heat of combustion
- High (Gross) vs. Low (Net)
  - Latent Heat of water
  - H-content and water content

Adiabatic Combustion

Material → Products

Material → HX1 → Liquid Water

Material → HX2 → Water Vapour

HIGH (Gross) Heating Value → LOW (Net) Heating Value
Heating Value and Need for Aux. Fuel

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   1. Particulate matter
   2. Acid gases (SO$_2$, HCl, NOx ....)
   3. Metals
   4. POHCs and PICs
## “Book values”

<table>
<thead>
<tr>
<th>Waste</th>
<th>Moist.</th>
<th>Ash</th>
<th>Comb</th>
<th>HHV As- Fired</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type 0</strong>: paper, cardboard, plastics ...</td>
<td>10%</td>
<td>5%</td>
<td>85%</td>
<td>19.8</td>
</tr>
<tr>
<td><strong>Type 1</strong>: Type 0 + garbage (&lt; 20%)</td>
<td>25%</td>
<td>10%</td>
<td>65%</td>
<td>15.0</td>
</tr>
<tr>
<td><strong>Type 2</strong>: Type 0 + garbage (20 - 65%)</td>
<td>50%</td>
<td>7%</td>
<td>43%</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>Type 3</strong>: “Garbage” (residential, restaurants .)</td>
<td>70%</td>
<td>5%</td>
<td>25%</td>
<td>5.8</td>
</tr>
<tr>
<td><strong>Type 4</strong>: Pathological/Anatomical waste</td>
<td>80%</td>
<td>10%</td>
<td>10%</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Paper</strong></td>
<td>10%</td>
<td>6%</td>
<td>84%</td>
<td>17.6</td>
</tr>
<tr>
<td><strong>Wood</strong></td>
<td>19%</td>
<td>1%</td>
<td>80%</td>
<td>20.0</td>
</tr>
<tr>
<td><strong>Rags</strong></td>
<td>9%</td>
<td>2%</td>
<td>88%</td>
<td>17.8</td>
</tr>
<tr>
<td><strong>Coated Fabric (Rubber, Latex)</strong></td>
<td>1%</td>
<td>20%</td>
<td>78%</td>
<td>25.6</td>
</tr>
<tr>
<td><strong>Polyethylene (Plastics, Oil, Fats)</strong></td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>42.0</td>
</tr>
<tr>
<td><strong>Grass</strong></td>
<td>43%</td>
<td>7%</td>
<td>50%</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Heating Value and Stoichiometric Air

\[ y = 0.0731x \]
\[ R^2 = 0.991 \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beech</td>
<td>Kerosene</td>
</tr>
<tr>
<td>Black Locust</td>
<td>Methanol, CH3OH</td>
</tr>
<tr>
<td>Douglas Fir</td>
<td>Ethanol, C2H5OH</td>
</tr>
<tr>
<td>Hickory</td>
<td>Coke-oven tar</td>
</tr>
<tr>
<td>Rice Hulls</td>
<td>Charcoal</td>
</tr>
<tr>
<td>Cotton gin trash</td>
<td>Carbon Monoxide, CO</td>
</tr>
<tr>
<td>n-octane</td>
<td>Water Hyacinth (Florida)</td>
</tr>
<tr>
<td>Benzene, C6H6</td>
<td>Brown Kelp, Giant, Soquel Point</td>
</tr>
</tbody>
</table>
Incinerator Capacity or Throughput

- Often rated as x kg/hr
  - Can an incinerator designed to burn 100kg/h of household refuse (A) be used to burn 100 kg/h plastics (B) ?

- The answer is NO because:
  - A requires ~ 300 m$^3$/h air stoichiometric
  - B requires ~ 2300 m$^3$/h air stoichiometric

- Incinerator capacity should be expressed as MJ/h (Btu/h)
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   3. Metals
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Bulk Density [kg/m³]

- The volume basis of m³ INCLUDES air space
- Compacted vs. non-compacted
- “Densification” increases BD
- (Incinerator capacity)
- High variability
## Bulk Density Data Variability

### Mixed glass

<table>
<thead>
<tr>
<th>Vehicle/container</th>
<th>Mixed glass</th>
<th>Mixed glass</th>
<th>Mixed glass</th>
<th>Mixed glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rear End Loader (compacted)*</td>
<td>Kerbsider (no compaction)</td>
<td>1,100 litre wheeled bin (no compaction)**</td>
<td>45/55 litre kerbside box (no compaction)</td>
</tr>
<tr>
<td><strong>Data type</strong></td>
<td>Field work: Operational bulk density</td>
<td>Field work data: Material bulk density</td>
<td>Field work data: Material bulk density</td>
<td>Self reported data: Material bulk density</td>
</tr>
<tr>
<td><strong>Mean, kg/m³</strong></td>
<td>265</td>
<td>456</td>
<td>694</td>
<td>276</td>
</tr>
<tr>
<td><strong>No. samples</strong></td>
<td>14</td>
<td>28</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>86.4</td>
<td>110.1</td>
<td>25.8</td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Coefficient of Variance</strong></td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>95% Confidence Interval +/- kg/m³</strong></td>
<td>45.3</td>
<td>40.8</td>
<td>28.6</td>
<td>7.7</td>
</tr>
<tr>
<td><strong>Lowest value</strong></td>
<td>149</td>
<td>199</td>
<td>664</td>
<td>259</td>
</tr>
<tr>
<td><strong>Highest value</strong></td>
<td>438</td>
<td>734</td>
<td>764</td>
<td>287</td>
</tr>
</tbody>
</table>

*due to H&S considerations data calculated based on the whole volume of the vehicle  **Filled using a 360° slew from a pile of kerbsider collected material
Incinerator Operation Mode

“Mode” refers to methods of feeding waste and ash removal

1. Continuous
2. Intermittent
3. Batch (one operation per cycle)
Continuous and/or Intermittent Feed and Ash Removal

- Operation in one cycle can run indefinitely: independent of waste properties, limited by break-down, maintenance …
- Typical operation for gas and liquid (A) and large-scale solid waste incinerators (A and B)
Example 1

Circulating Fluidized-Bed (CFB) Boiler

How a CFB unit works

1. Solid Fuel
2. Limestone
3. Feed Water
4. Ammonia Injection
5. Circulating Fluidized-Bed Boiler
6. Air Preheater
7. State-of-the-Art Air Quality Control System
8. Stack

Feed

Secondary Air

Bed Ash

Air

Steam

Economizer

Condenser

To Byproduct Storage

Air

High-Pressure Steam

Low-Pressure Steam

Water

Particulate

Lime Slurry

Ash

To Byproduct Storage

Steam

Generator
Example 2

Intermittent Feeding

Continuous Ash Removal
Intermittent Feed, Batch Ash Removal

- Burn stage is limited by combustion chamber filled up by ash (ash content and bulk density of ash)
- Often used in small-scale solid waste incinerators
Small-scale Intermittent Feeding

- Emission of PICs soon after feeding due disturbance of already burning waste batches in chamber
Batch Feeding and Batch Ash Removal

- **Preparation (Ash Removal)**
- **Preheat**
- **Burn Stage**
- **Burn-Down**
- **Cool-Down, Maintenance ... etc**
- **Waste Feeding**
- **“Do Nothing”**
- **Ash Removal**
Notes on Batch Feeding and Ash Removal

- Batch size (kg) is limited by combustion chamber volume and bulk density of waste

- Recommended by Environment Canada for small-scale bulk solid incineration
  - Minimum air emissions both for PM and PICs
  - Ease of operation
  - Low man-power requirements

- Re-burning may be necessary, which reduces capacity

- Other factors are also important
  - Experience, judgement .....

  ❖ Scaling-up is not straightforward
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### Information and Tools

#### Waste Characteristics
- Proximate & Ultimate Compositions
- Form, Heating Value & Bulk Density

#### Incineration Design and Operation
- Combustion and Opn modes (esp. solid)
- 3T's and xs O₂ *

#### Environmental Regulations
- Case-specific + implementation

#### Tools
- Understanding
- MHB, VP, IDL .... *

* Mass and heat balance, Vapour Pressure, Ideal gas law

### Summary

<table>
<thead>
<tr>
<th>Medium</th>
<th>Regulated Parameters</th>
<th>&quot;Remedy&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas</td>
<td>POHCs &amp; PICs</td>
<td>Incinerator</td>
</tr>
<tr>
<td></td>
<td>Acid gases &amp; metals</td>
<td>Waste (mainly)</td>
</tr>
<tr>
<td></td>
<td>Particulate</td>
<td>Both</td>
</tr>
<tr>
<td>Ash</td>
<td>Metals</td>
<td>Waste</td>
</tr>
<tr>
<td></td>
<td>POHCs &amp; PICs</td>
<td>Incinerator</td>
</tr>
</tbody>
</table>
Concluding Remarks

- Better awareness of waste incineration technology
  - Fundamentals of waste properties and physical/chemical processes that are relevant to waste incineration
    - Not that difficult to understand
  - Selected examples of the practice of incineration
    - Complexity and thus the need for experience and judgement ("Art" also involved)

- Good starting point to learn more about waste incineration
  - "Within" waste incineration itself AND "other" relevant topics.
Thank you

Email: albert.liem@ketek.ca
Phone: +1 780 447 5050
www.ketek.ca