Lecture #9

Environmentally Responsible Design and Manufacturing

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all values in Mmt per year (1Mt = 1Gg)

Figure 1

Inputs
- 1,960 Energy
- 1,921 Construction Minerals
- 249 Industrial Minerals
- 112 Metals
- 260 Forestry Products
- 629 Agriculture
- 634 Imports

Outputs
- 244 Recycled
- 1,735 Air Emissions
- 1,880 Domestic Stock
- 555 Other Wastes
- 145 Dissipation
- 413 Exports

Extractive Wastes
- >10,000 (mostly waste rock)

130,000 Water (consumptive use)
Figure 2

**Inputs**

- 21.5 Energy
- 21.1 Construction Minerals
- 2.7 Industrial Minerals
- 1.2 Metals
- 2.9 Forestry Products
- 6.9 Agriculture

**Values in kg/day**

**Outputs**

- 19.0 Air Emissions
- 20.6 Domestic Stock
- 6.1 Wastes
- 1.6 Dissipation

- 4.5 Exports
- 1,425 Water (consumptive use)
- >100 Extractive Wastes (mostly waste rock)
# Material Reserves

<table>
<thead>
<tr>
<th>Material</th>
<th>Range of Reserves at Current Price Levels</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>3,247.7 - 4,726.4</td>
<td>Tg</td>
</tr>
<tr>
<td>Copper</td>
<td>335.7 - 459.9</td>
<td>Tg</td>
</tr>
<tr>
<td>Gold</td>
<td>31.1 - 57.5</td>
<td>Gg</td>
</tr>
<tr>
<td>Iron</td>
<td>87,724.8 - 186,880.1</td>
<td>Tg</td>
</tr>
<tr>
<td>Lead</td>
<td>87.1 - 130.6</td>
<td>Tg</td>
</tr>
<tr>
<td>Nickel</td>
<td>41.9 - 90.3</td>
<td>Tg</td>
</tr>
<tr>
<td>Tin</td>
<td>4.2 - 9.4</td>
<td>Tg</td>
</tr>
<tr>
<td>Titanium</td>
<td>143.3 - 296.6</td>
<td>Tg</td>
</tr>
<tr>
<td>Zinc</td>
<td>118.8 - 235.9</td>
<td>Tg</td>
</tr>
</tbody>
</table>
More on Flow Charts

Production

End Life

Usage

Raw Mat’l
Energy

Waste
By-products

Energy
Mat’l Supplies

Wastes
Recoverables

Energy

Wastes
Recoverables

Energy
Flow Charts (continued)

On the flowsheet indicate the inputs and the outputs on the arrows. Plastic Drink Bottle.

- **Ethylene**
- **Acquire HDPE Resin**
- **HDPE Pellets**
- **Blow Mold Bottle**
- **Bottle**
- **Fill & Package**
- **Filled Bottle**
- **Consumer Use**
- **Empty Bottle**
- **Disposal**

Inputs:
- Drink
- Paper

Outputs:
- Bottle
More on Flow Charts

Once flowsheet is prepared, determine the data needed and where to get it (quality of the data?)

- number of bottles
- makeup of caps
- makeup of labels
- packing boxes
- foils
- post use of plastic
- energy usage
More on Materials (courtesy of Prof. Rundman) ** also see the “materials.pdf” document **
**Figure 5-2**

**Material Flow Diagram: Recycle, Reuse, or Remanufacturing**

- Location and Evaluation of Raw Materials
- Extraction of Raw Materials from Earth
- Physical Separation and Refining
- Processing to Form a Product
- Purchase and Use of Product
- Disposal of Product at End of Life

- Recycle
- Reuse
- Remanufacture
### Table 7-2: World and U.S. Production Statistics of Primary Metals and Castings (in millions of metric tons)

<table>
<thead>
<tr>
<th>Primary Metals*</th>
<th></th>
<th></th>
<th>Castings**</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>World</td>
<td>U.S.</td>
<td>Metal</td>
<td>World</td>
<td>U.S.</td>
</tr>
<tr>
<td>Steel (97)</td>
<td>792.8</td>
<td>128.5</td>
<td>Cast Iron and Steel</td>
<td>59.6</td>
<td>11.7</td>
</tr>
<tr>
<td>Aluminum (96)</td>
<td>20.7</td>
<td>3.6</td>
<td>Aluminum base</td>
<td>6.37</td>
<td>1.64</td>
</tr>
<tr>
<td>Copper (97)</td>
<td>10.8</td>
<td>1.7</td>
<td>Copper base</td>
<td>1.03</td>
<td>0.31</td>
</tr>
<tr>
<td>Zinc (97)</td>
<td>7.7</td>
<td>0.45</td>
<td>Zinc base</td>
<td>0.81</td>
<td>0.37</td>
</tr>
<tr>
<td>Magnesium (96)</td>
<td>0.34</td>
<td>0.13</td>
<td>Magnesium base</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Percent Ferrous</td>
<td>95.2</td>
<td>95.6</td>
<td></td>
<td>88</td>
<td>83</td>
</tr>
</tbody>
</table>

*Data from Metal Statistics 1998, for the years 1996 & 1997, American Metal Market

**Data from Modern Casting, Dec. 1997, American Foundrymen’s Society.
Steel Production

- Mining
- Beneficiation -- Concentrating
- Pelletizing
- Reduction (in a Blast Furnace) -- remove oxygen
- Decarburizing (in Basic Oxygen Furnace) -- remove carbon
**Figure 5-6 Simplified Mining and Beneficiation Mass Balances**

<table>
<thead>
<tr>
<th>Raw Material (10.4)</th>
<th>Mining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore (2.6)</td>
<td>Overburden (7.66)</td>
</tr>
</tbody>
</table>

**Concentrating**
- Crushing
- Grinding
- Separation of Fe₃O₄ and Gangue (Waste)
- Concentrate (1)
- Tailings (1.6)

**Material In [Composition, Wt%]**
- Ore into concentrator [38.7 Fe₃O₄, 7.15 Fe₂O₃, 54.15 SiO₂]

**Material Out [Composition, Wt%]**
- Concentrated Ore [91.16 Fe₃O₄, 8.84 SiO₂]
- Tailings [6.0 Fe₃O₄, 11.6 Fe₂O₃, 82.4 SiO₂]
**Figure 5-7 Simplified Pelletizing Materials Balance**

**Requirements for Fluxed Pellets**
(Numbers in metric tons)

- **Concentrate (0.92)**
- **CaCO₃ (0.089)**
- **MgCO₃ (0.033)**
- **Bentonite (0.006)**
- **Air (0.096)**

**Pelletizing**

- 2 Fe₃O₄ + 1/2 O₂ → 3 Fe₂O₃
- CaCO₃ → CaO + CO₂
- MgCO₃ → MgO + CO₂

**Pellets (1)**

**Gas (0.144)**

---

**Materials In [Composition, Wt %]**
- Iron Ore Concentrate [91.2 Fe₂O₃, 8.8 SiO₂]
- Flux [72 CaCO₃, 28 MgCO₃]
- Air [23.3 O₂, 76.7 N₂]
- Bentonite [(OH)₄Al₄Si₈O₂ₐ]

**Materials Out [Composition, Wt %]**
- Pellets [87.3 Fe₂O₃, 5.8 SiO₂, 5 CaO, 1.6 MgO, 0.3 Al₂O₃]
- Gas [CO₂, N₂]
Figure 5-8 Simplified Blast Furnace Materials Balance

Production of One Metric Ton of Pig Iron

Pellets (1.628) → Reduction
2 Fe₂O₃ + (3+n)C → 4 Fe(C) + 3CO₂
Coke (0.48) → Pig Iron (1)
Gases In → Slag (0.255)

Materials In [Composition, Wt %]
- Pellets [87.3 Fe₂O₃, 5.8 SiO₂, 5 CaO, 1.6 MgO, 0.3 Al₂O₃]
- Coke [90 C, 6 SiO₂, 3.5 Al₂O₃, 0.5 CaO]
- Gases In [O₂, H₂, CH₄, C₂H₆, CO, CO₂]

Materials Out [Composition, Wt %]
- Pig Iron [95 Fe, 4.2 C, 0.8 Si]
- Slag [48.3 SiO₂, 33 CaO, 8.4 Al₂O₃, 10.3 MgO]
- Dust [Fe₂O₃]
- Gases Out [H₂O, CO, CO₂]
Figure 5-9 Simplified (B O F) Materials Balance

Production of One Metric Ton of Steel

- Pig Iron (1.073)
- Lime (0.084)
- Oxygen

Decarburization

2C + O₂ → 2 CO
C + O₂ → CO₂

Steel (1)
Dust (0.01)
Slag (0.112)
Gases (0.099)

Material In [Composition, Wt %]
Pig Iron [95 Fe, 4.2 C, 0.8 Si]
Lime [100CaO]
Oxygen [100O₂]

Material Out [Composition, Wt %]
Steel [99.3 Fe, 0.4 C, 0.3 Si]
Slag [25 Fe₂O₃, 75 CaO]
Dust [100Fe₂O₃]
Gases [90 CO, 10 CO₂]
Breakdown of the Waste Materials by Location in Steel Production

- 53% Blast Furnace Slag
- 22% Other Slags
- 17% BOF Slag
- 8% BOF Slag

- 4% Mill Scale
- 5% Mill Rubble
- 9% Dusts, Sludges
- 2% Coal Byproducts
- 1% Ferric Sulphate

1% Miscellaneous
Copper Production

1. Mining - Removal of Ore in Seams (1.2 wt Pct Cu) Leaving Waste Rock Underground
2. Beneficiation - Production of Concentrate containing 30.5 wt. pct Copper. Discard Waste Rock in Tailings Pond
3. Smelting - Production of Matte (62.5 wt pct Copper) in a coal-fired reverberatory furnace. Discard Slag to Dump and SO2 Gas into the Atmosphere
4. Converting - Production of Blister Copper (99 wt. pct Copper) with release of SO2 gas to Atmosphere and Slag Recycled to the Reverberatory Smelting Furnace
5. Fire Refining - Deoxidizing the Blister Copper to Produce Anode Copper (99.7 wt. Pct Copper)
6. Anode Casting and Electro-refining - Produce Anode Shape, Electro-refine to Produce 99.997 Wt. Pct Copper. Send Slimes to Recover Precious Metals (Ag, Au, Pt, etc.)
Ore From Mining Operation
114 Tons (1.2 Wt. Pct. Cu)

Beneficiation

Tailings to Waste Pond
110.1 Tons (0.15 Wt. Pct. Cu)

Concentrate
(30.5 Wt. Pct. Cu)

Smelting

Matte
1.79
(62 Wt. Pct. Cu)

Blister Cu
1.21
(99 Wt. Pct. Cu)

Anode Cu
1.20
(99.7 Wt. Pct. Cu)

Converting

Slag (0.8 Wt. Pct. Cu)

0.79 Tons

Refining & AC

Electrorefine

SO₂
Ore (Lumps) 4 Ton

Typical Composition: (55Al₂O₃, 20Fe₂O₃, 15SiO₂, 10TiO₂)

Ore (Fines) 4 Ton

Crushing and Grinding

NaOH liquor 3.13 Ton
Dissolved NaAlO₂

145°C Digestion & Filtering

NaOH Recycling

2.05 Ton
Red Mud

controlled cool from 145 to 25°C
Seeding & Filtering

1.10°C Calcining

2.98 Ton
Al(OH)₃

1.95 Ton
Al₂O₃

950°C Hall Cell Electrorefining
Carbon-containing
Consumable Soderberg Electrode

1.02 Ton
H₂O

950°C Hall Cell Electrorefining
Carbon-containing
Consumable Soderberg Electrode

Power Consumption in the Hall Cell amounts to

2.3 Ton CO₂
Production of Plastics

Feedstock Flowsheet

- **PETROLEUM**
  - 1. Olefins
    - a. ethylene
    - b. propylene
    - c. butadiene
  - 2. Aromatics
    - a. benzene
    - b. toluene
    - c. p-xylene
    - d. o-xylene
- **NATURAL GAS**
  - 3. Ammonia
  - 4. Methanol
Feedstock for all purposes
1.87 Million tons
U.S. 1990

Thermal Cracking (Produce Olefins)

{OXIDATION}

Ethylene

\[
\begin{align*}
\text{H} & \quad \text{C} = \text{C} \\
\text{H} & \quad \text{H}
\end{align*}
\]

Oxygen

\[+ O = \]

Epoxide

\[
\begin{align*}
\text{H} & \quad \text{C} - \text{C} - \text{O} \\
\text{H} & \quad \text{H}
\end{align*}
\]

Water

\[\text{H-O-H}\]

Alternate Route, Direct Esterification with Ethylene Glycol @ High Temp. & Pressure Eliminates Methanol Byproduct

Ethylene Glycol

\[
\begin{align*}
\text{H} & \quad \text{H} \\
\text{H-O-C-C-O-H} & \quad \text{H}
\end{align*}
\]

Dimethyl Terephthalate

\[
\begin{align*}
\text{H} & \quad \text{O} \\
\text{H-C-O-C-C-O-C-H} & \quad \text{H}
\end{align*}
\]

{TRANSESTERIFICATION}

In presence of trace amounts of metal ion catalysts

Polyethylene Terephthalate (PET)

\[
\begin{align*}
\text{H} & \quad \text{O} \\
\text{H-C-O-C-C-O-C-H} & \quad \text{H}
\end{align*}
\]

Methanol

\[
\begin{align*}
\text{H} & \quad \text{H-C-O-H} \\
\text{H} & \quad \text{H}
\end{align*}
\]