Metals Recovery from e-scrap in a global environment
Technical capabilities, challenges & experience gained

Dr. Christian Hagelüken
Umicore Precious Metals Refining

6th session of OEWG  Basel Convention
Geneva, 7. September, 2007
Umicore today provides ...

the automotive catalysts for almost 1 in 4 cars produced in the world

key materials for the rechargeable batteries for more than 30% of all cell phones and laptops sold this year

the semiconductor substrates for more than 60% of all satellite solar cells in the last 2 years

recycling services for complex materials like electronic scrap, batteries and spent catalysts to gain more than 20 different metals
Umicore structure: activities in four business groups

- 17,000 people
- 50 industrial locations around the world
- 8.8 billion € turnover (2006)

• Research
• Corporate & Investments
• Traxys

Precious Metals Management

Precious Metals Services

Precious Metals Products & Catalysts
- Automotive Catalysts
- Catalyst Technologies
- Technical Materials
- Thin Film Products
- Jewellery & Electro-plating

Electro-Optic Materials
Specialty Oxides & Chemicals
Engineered Metal Powders

Zinc Alloys
Zinc Chemicals
Building Products
Padaeng Industry

Zinc Specialties
Advanced Materials

Umicore

BC OEWG – Metals Recovery from e-scrap, Christian Hagelüken, 07-09-2007
Creating a recycling society – the art of metals recycling
Introduction: Why do we need e-scrap recycling?
- Impact on resources, environment & economics

- Technical capabilities
- Experience gained
- Business execution
- Challenges
- Conclusion
Material composition of e-scrap: a delicate cocktail to cope with

E-scrap, a complex mix of:
- Ag, Au, Pd, ... (precious metals)
- Cu, Al, Ni, Sn, Zn, Fe, ..., In, Sb, Bi, ... (base & special metals)
- Hg, Be, Pb, Cd, As, ..., (metals of concern)
- Halogens (Br, F, Cl, ...)
- Plastics & other organics
- Glass, ceramic

⇒ Modern electronics can contain > 60 elements
⇒ High risk of environmental damage if landfilled or if not treated in an environmentally sound way
⇒ Significant resource base for the future (mine above ground)

Most toxic & most valuable metals are contained in the circuit boards

Why recycling:
- Toxic control
- Value recovery
- Resource conservation
Plastics & steel dominate weight - precious metals mostly dominate economical & ecological value

<table>
<thead>
<tr>
<th>weight-%</th>
<th>plastics</th>
<th>Fe</th>
<th>Al</th>
<th>Cu</th>
<th>Ag [ppm]</th>
<th>Au [ppm]</th>
<th>Pd [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV-board</td>
<td>28%</td>
<td>28%</td>
<td>10%</td>
<td>10%</td>
<td>280</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>PC-board</td>
<td>23%</td>
<td>7%</td>
<td>5%</td>
<td>20%</td>
<td>1000</td>
<td>250</td>
<td>110</td>
</tr>
<tr>
<td>mobile phone</td>
<td>56%</td>
<td>5%</td>
<td>2%</td>
<td>13%</td>
<td>3500</td>
<td>340</td>
<td>130</td>
</tr>
<tr>
<td>portable audio</td>
<td>47%</td>
<td>23%</td>
<td>1%</td>
<td>21%</td>
<td>150</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>DVD-player</td>
<td>24%</td>
<td>62%</td>
<td>2%</td>
<td>5%</td>
<td>115</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>calculator</td>
<td>61%</td>
<td>4%</td>
<td>5%</td>
<td>3%</td>
<td>260</td>
<td>50</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>value-share</th>
<th>Fe</th>
<th>Al</th>
<th>Cu</th>
<th>Ag</th>
<th>Au</th>
<th>Pd</th>
<th>sum PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV-board</td>
<td>4%</td>
<td>10%</td>
<td>50%</td>
<td>7%</td>
<td>22%</td>
<td>7%</td>
<td>36%</td>
</tr>
<tr>
<td>PC-board</td>
<td>0%</td>
<td>1%</td>
<td>18%</td>
<td>5%</td>
<td>61%</td>
<td>15%</td>
<td>81%</td>
</tr>
<tr>
<td>mobile phone</td>
<td>0%</td>
<td>0%</td>
<td>9%</td>
<td>13%</td>
<td>64%</td>
<td>14%</td>
<td>91%</td>
</tr>
<tr>
<td>portable audio</td>
<td>2%</td>
<td>0%</td>
<td>82%</td>
<td>3%</td>
<td>10%</td>
<td>2%</td>
<td>15%</td>
</tr>
<tr>
<td>DVD-player</td>
<td>13%</td>
<td>3%</td>
<td>42%</td>
<td>5%</td>
<td>32%</td>
<td>5%</td>
<td>42%</td>
</tr>
<tr>
<td>calculator</td>
<td>0%</td>
<td>5%</td>
<td>14%</td>
<td>7%</td>
<td>69%</td>
<td>4%</td>
<td>80%</td>
</tr>
</tbody>
</table>

Note: indicative numbers only; value can differ significantly also within one category!

Prices of Oct. 2006
Example lead (Pb):

- Environmentally sound recycling of WEEE can generate Pb as important resource, e.g. for car batteries (price Pb ~ 2300 €/t in August 2007)
- If landfilled or recycled in an inappropriate way, high Pb emissions into groundwater, soil, air.

Example printed wiring boards (PWB):

- High net metal value if recycled appropriately (~ 4000 €/t), source for Ag, Au, Pd, Cu, Pb, Sn, Bi, Sb, …
- In case of landfill or inappropriate treatment, significant emissions of dioxins, heavy metals and other toxic substances
**Impact on metals demand & resources**

### Global sales, 2006 estimates:

#### Cell phones:
1000 Million units
- $250 \text{ mg Ag} \approx 250 \text{ t Ag}$
- $24 \text{ mg Au} \approx 24 \text{ t Au}$
- $9 \text{ mg Pd} \approx 9 \text{ t Pd}$
- $9 \text{ g Cu} \approx 9000 \text{ t Cu}$

#### PC & laptops:
230 M units
- $1000 \text{ mg Ag} \approx 285 \text{ t Ag}$
- $200 \text{ mg Au} \approx 46 \text{ t Au}$
- $80 \text{ mg Pd} \approx 18 \text{ t Pd}$
- $500 \text{ g Cu} \approx 115,000 \text{ t Cu}$

- 60 M laptop batteries
  - $75 \text{ g Co} \approx 4500 \text{ t Co}$

**World Mine Production:**
- Ag: 20,000 t/a $\approx 3\%$
- Au: 2,500 t/a $\approx 3\%$
- Pd: 215 t/a $\approx 12\%$
- Cu: 15 Mt/a $\approx 1\%$
- Co: 58,000 t/a $\approx 15\%$

* Li-ion type

**Other metals of relevance:** In (LCD-screens), Bi+Sn (Pb-free solders), Ru (resistors, hard disks)

- Although “negligible” metal quantities per piece, the leverage of huge unit sales leads to significant total numbers!
- How much of this will finally be recycled?
- How efficient are we really in achieving a “recycling society”?
Electronics have a significant impact on metals demand

- Significant use of precious & special metals in electronics
- Importance for increasing functionality (& miniaturisation, lead-free solders)
- Highly dissipated in final product → challenge for recycling

By-product = coupled at ppm level from major metals Cu, Zn, Pb, etc, no own mines are existing.
⇒ increase of supply only in parallel with major metals
⇒ No price elasticity of minor metal

<table>
<thead>
<tr>
<th>metal</th>
<th>by-product from</th>
<th>demand for electronic s (EEE)*</th>
<th>demand related to mine production</th>
<th>metal price**</th>
</tr>
</thead>
<tbody>
<tr>
<td>silver Ag</td>
<td>20.000 (Pb, Zn)</td>
<td>6.000 t/a</td>
<td>30%</td>
<td>350 €/kg</td>
</tr>
<tr>
<td>gold Au</td>
<td>2.500 (Cu)</td>
<td>250 t/a</td>
<td>10%</td>
<td>16.000 €/kg</td>
</tr>
<tr>
<td>palladium Pd</td>
<td>215 PGM</td>
<td>32 t/a</td>
<td>15%</td>
<td>8.500 €/kg</td>
</tr>
<tr>
<td>platinum Pt</td>
<td>220 PGM</td>
<td>13 t/a</td>
<td>6%</td>
<td>29.000 €/kg</td>
</tr>
<tr>
<td>ruthenium Ru</td>
<td>30 PGM</td>
<td>6 t/a</td>
<td>20%</td>
<td>18.000 €/kg</td>
</tr>
<tr>
<td>copper Cu</td>
<td>16.000.000</td>
<td>4.500.000 t/a</td>
<td>28%</td>
<td>5 cables, contacts, conductors, transformer, e-motors</td>
</tr>
<tr>
<td>tin Sn</td>
<td>275.000</td>
<td>90.000 t/a</td>
<td>33%</td>
<td>10 (leadfree) solders (incl. other solder uses )</td>
</tr>
<tr>
<td>antimony Sb</td>
<td>130.000</td>
<td>65.000 t/a</td>
<td>50%</td>
<td>4 flame retardants, CRT glass</td>
</tr>
<tr>
<td>cobalt Co</td>
<td>58.000 Ni, Cu</td>
<td>11.000 t/a</td>
<td>19%</td>
<td>40 rechargable batteries</td>
</tr>
<tr>
<td>bismuth Bi</td>
<td>5.600 Pb,W,Zn</td>
<td>900 t/a</td>
<td>16%</td>
<td>16 leadfree solders, capacitors, heat sinks, electrostatic screening, …</td>
</tr>
<tr>
<td>selenium Se</td>
<td>1.400 Cu</td>
<td>240 t/a</td>
<td>17%</td>
<td>37 electrooptic, copiers, solar cells, …</td>
</tr>
<tr>
<td>indium In</td>
<td>480 Zn, (Pb)</td>
<td>380 t/a</td>
<td>79%</td>
<td>520 LCD glass, leadfree solders, semiconductors/LED, …</td>
</tr>
</tbody>
</table>

* rounded, source: USGS Mineral commodity summaries 2007
** rounded, as of 03/2007
Renewed attention on scarcity of some metal resources …

“Providing today’s developed-country level of services for Cu worldwide (as well as for Zn and, perhaps, Pt) would appear to require conversion of essentially all of the ore in the lithosphere to stock-in-use plus near-complete recycling of the metals from that point forward.”

PNAS, Jan 2006: Metal stocks & sustainability, R. Gordon, M. Bertram, T. Graedel, Yale

… triggered by raising metal prices
New “battle for resources?”
Impact on environment - damage caused by disposal and backyard recycling

**Cell Phones 1999**

Avg: 125 g/unit

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>13%</td>
</tr>
<tr>
<td>Al</td>
<td>1%</td>
</tr>
<tr>
<td>Fe</td>
<td>5%</td>
</tr>
<tr>
<td>Glass</td>
<td>2%</td>
</tr>
<tr>
<td>Others</td>
<td>22%</td>
</tr>
<tr>
<td>Plastics</td>
<td>57%</td>
</tr>
</tbody>
</table>

**Release of (= pollution of groundwater, soil, crops)**

- Pb (up to 3 kg/ t of handset) → 120 000 t Pb for 400 M phones
- Ni, Be, and other substances of concern
- Electrolyte from batteries
- Cyanides or other strong acid from leaching
- Mercury from backyard Au-recovery
- Generation of significant amounts of dioxins and furans if incinerated or smelted without proper offgas cleaning

Source fotos: BAN
Net value calculation for a 10 t lot of handsets:

at 3500 ppm Ag, 340 ppm Au, 130 ppm Pd, 13% Cu
prices (as of May 2007, rounded)
Ag: 13 $/troy, Au: 670 $/troy, Pd: 370 $/troy, Cu: 7700 $/t

Net value: approx. 60,000 € for 10 t lot

Net value is calculated for a toll refining agreement, based on accurate metal assays after sampling.

Net value contains all sampling & treatment costs, but excludes transport to smelter.

For a specific lot, net value depends on individual analysis and actual metal prices.

Make sure that no precious metals are lost in inefficient preprocessing steps.
Introduction: Why do we need e-scrap recycling?
- Impact on resources, environment & economics

- Technical capabilities
- Experience gained
- Business execution
- Challenges
- Conclusion
**Eco-efficient recycling - what does it mean in principle?**

- **Material composition**
  - maximise material recycling (gain 1)
  - minimise environmental damage (burden)
  - consider environmental fingerprint of material (gain 2)
    - Fe < Al < Au

- **Information/communication**
  - maximise revenues from material recycling
  - minimise total recycling costs (incl. side streams)

- **Business ethics**
- **Process technologies**
- **Awareness**

- **Sustainability = environment + economy + social factors**

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- **Reuse, Recycled materials, energy recovery**

- **WEEE**

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The total recycling efficiency is determined by the weakest step in the chain.

*effective recovery rate for e.g. Au, Cu etc. from EOL-streams

Example: 50 x 90% x 80% x 95% = 34%

- Consider the entire chain & its interdependencies.
- Importance of dismantling & preprocessing, but endprocessing (physical materials recovery) is crucial for value generation & toxic control.
- **Success factors**: interface optimisation, specialisation, economies of scale.
- Recycling **trace elements** from complex products needs “high-tech”, large scale processes. Cannot be replicated in any country → international division of labour.
- Recycling technology usually is not the limit factor for high recycling rates.
Example for “high-tech” metals recovery - Umicore’s Hoboken plant near Antwerp

- Unique flowsheet, focus on secondary materials
- Recovering 17 metals: Au, Ag, Pd, Pt, Rh, Ir, Ru, Cu, Pb, Ni, Sn, Bi, Se, Te, Sb, As, In
- Wide range of complex precious metals bearing feed materials
- Market leader (EU) for car catalysts & circuit boards
- Global customer base
- Minimizing waste
- World class environmental standards (BAT)
- > 1 billion € investment
The integrated metals smelting and refining process - how it works in principle

Umicore Process

Recovery of Metals & Energy

1000 tons per day

Clean off gas
Clean waste water
Controlled depot

Sulfuric Acid

1000 tons per day

Base & Special Metals
Pb, Cu, Ni, Sb, Sn, Bi, Se, In, Te, As

Precious Metals
Ag, Au, Pt, Pd, Rh, Ir, Ru

Dykefill Betogrind

… using a unique metallurgy to turn a difficult feed systematically into recycled, useful products
Umicore Hoboken: processing 300,000 tpy, > 200 different raw materials

Recyclable products
- Spent Industrial Catalysts
- Electronic Scrap
- Spent Automotive Catalysts

By-products
- By-products from non-ferrous industry

Others
- Precious metal bearing raw materials
- e.g. drosses from lead smelters, slimes from copper industry, ...
- e.g. fuel cells, photographic residues
All parts, components, fractions that contain precious metals (PM):

- Printed circuit boards (from end-of-life scrap or production residues)
  - computer boards, cell phone boards, boards from hard disk drives, etc.
  - TV- / monitor boards, audio boards after removal of large iron and aluminum parts
  - unpopulated boards with PM

- PM bearing components: IC, multi layer capacitors (MLCC), contacts, etc.

- mobile phone handsets and other small devices with a relatively high PM content
  (after removal of battery)

- Fractions with a high circuit board content (e.g. after shredding and sorting)

- Other output-fractions from mechanical preprocessing with PMs

- Li-Ion & NiMH batteries (in dedicated business line)

**What do we not treat – examples:**

- mere plastic scrap (casings, …)
- CRT-glass
- CRT yokes

E-scrap treated at Umicore
Impressions from the Hoboken refinery

The IsaSmelt furnace serves as main gate for most materials

Oxygen enriched air and oil/nat. gas are injected down the lance

Offgas and fume: special design for efficient offgas collection with minimised solids carryover

Patented lance design
Promotes formation of a frozen slag layer on the lance tip

Frozen slag coating
Protects lance from wear

Vigorously stirred bath
by submerged lance ensuring rapid chemical reactions and good mixing

Agglomerated feed
can be directly charged without further treatment

Refractory lined furnace
designed to facilitate refractory installation

Watercooled taphole
for molten product removal

Plastics in the smelter feed substitute coke & fuel, an extensive offgas treatment safely prevents hazardous emissions

Leaching & Electrowinning:
a fast access to precious metals

Some out of 17 refined metals:
Pb, Bi, Se, Sn, Au, Pd
Offgas emission control installations at Umicore’s IsaSmelt process

- Bag house filter
- Hygienic gases
- Process gases

IsaSmelt furnace

- Radiation chamber
- Adiabatic cooler
- Electrostatic precipitator
- Quenching
- Sulphuric Acid Plant
- Water to Water Treatment Plant

Stack

- Filter dust
- Dust
- Heat recovery: High pressure steam for internal use
- Quenching
- Periodic measurement of SO$_2$, NO$_x$, CO, C$_{tot}$, HF, HCl

Stack

- Continuous measurement of SO$_2$, NO$_x$
- Continuous sampling for dioxin detection

Monthly measurement of dust, metals, SO$_2$, NO$_x$, CO, C$_{tot}$

Continuous measurement of SO$_2$, NO$_x$
Umicore’s battery recycling process
- EEP award in 2004

VAL’EAS™ Process

YIELDS:
- Li-ion batteries: 93%
  --> Metals 69%
  --> Carbon 10%
  --> Plastics 15%
- Li-polymer: 91%
  --> Metals 67%
  --> Carbon 15%
  --> Plastics 15%
- NiMH: 82%
  --> Metals 62%
  --> Plastics 20%
BAT recycling processes for mobile phones recover a whole set of elements

**Umicore output**
- Recovered as metal
- Chemical use as process additive
- Transfer into an inert slag (product)
- Neutralised in effluents
- Isolation and safe deposit

**Material Content of Mobile Phone**
Introduction: Why do we need e-scrap recycling?
- Impact on resources, environment & economics

Technical capabilities

Experience gained

Business execution

Challenges

Conclusion
Recycling of plastics *from mobile phones*? - the view of a plastics recycler*

Best solution for plastics from mobile phones is ...

*presentation by Roger Morton, Axion at Eco-X Conf., Vienna, May 2007*
The scientific view (TU-Delft): Eco-efficiency of mobile phone recycling

Eco-efficiency Directions
(average 2001 cellular phone, 100g, incl. 30g Li-ion battery)

Revenues
- € 0.29
- € 0.24
- € 0.33

Sorting + direct to Cu-smelter

Costs
+ € 0.02
+ € 0.25

MSW

Shredded (with other ‘low value scrap’)

Environmental weight: how much environmental impact/burden by producing 1 kg of a metal?

The „direct smelter route“ was proven to be the most eco-efficient solution
(source: J. Huisman, TU Delft)
Real life example: Processing of a 12 t lot of mobile phones (non reusable)

<table>
<thead>
<tr>
<th>lot</th>
<th>input net weight in kg</th>
<th>Organic - %</th>
<th>AG - g/mt</th>
<th>AU - g/mt</th>
<th>PT - g/mt</th>
<th>PD - g/mt</th>
<th>PB - %</th>
<th>CU - %</th>
<th>Ni - %</th>
<th>SB - %</th>
<th>SN - %</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell phone handsets</td>
<td>11.558,2</td>
<td>44,29</td>
<td>2,922</td>
<td>323</td>
<td>7</td>
<td>162</td>
<td>0,474</td>
<td>12,540</td>
<td>1,400</td>
<td>0,106</td>
<td>0,778</td>
</tr>
<tr>
<td></td>
<td>5.119</td>
<td>33,8</td>
<td>3,7</td>
<td>0,1</td>
<td>1,9</td>
<td>55</td>
<td>1,449</td>
<td>162</td>
<td>12</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

Silver (Ag), gold (Au), palladium (Pd), platinum (Pt), copper (Cu) and lead (Pb) are produced as pure metals and delivered to the industry who needs them to produce finished or semi-finished products.

Ni-bearing fraction is sent to Umicore Advanced Materials who produces NiSO4 out of it, which is sold to the market.

Antimony (Sb) is produced as sodiumantimonate and sold to e.g. the glass industry.

Tin (Sn) is produced as calciumstanate and sold to the tin industry.

Other trace elements that are recovered in the Umicore process: bismuth (Bi), indium (In), ruthenium (Ru), arsenic (As), selenium (Se), tellurium (Te).

* Organics are used as reducing agent and hence as a substitute for coke. Hence our EPA considers treatment of organics fraction from circuit boards or other complex PM bearing materials at our plant to be recycling.

** Fe, Al2O3, CaO, MgO and SiO2 can also be found in natural rock. As application of natural rock is similar to applications for our slags, our EPA regards treatment of these elements from circuit boards.

Non-ferrous metals recycled as metals or compounds

Other elements - transfer into inert slag, use as product (construction material, additive for concrete)**

<table>
<thead>
<tr>
<th></th>
<th>ZN - %</th>
<th>MGO - %</th>
<th>AL2O3 - %</th>
<th>CAO - %</th>
<th>SIO2 - %</th>
<th>FE - %</th>
<th>MN - %</th>
<th>TIO2 - %</th>
<th>BAO - %</th>
<th>ZRO2 - %</th>
<th>CEO2 - %</th>
<th>BE - g/mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg output</td>
<td>1,377</td>
<td>3,570</td>
<td>4,771</td>
<td>2,154</td>
<td>11,220</td>
<td>5,322</td>
<td>1,361</td>
<td>0,731</td>
<td>0,107</td>
<td>0,103</td>
<td>0,103</td>
<td>93</td>
</tr>
</tbody>
</table>

Energy content cell phones 10652 kJ/kg

Energy demand for smelting and metal refining 7431 kJ/kg

Net energy balance 3221 kJ/kg*

For entire lot: 37229 MJ*

% energy required from energy content 70%

* energy surplus is used to smelt other materials in input-mix, e.g. car catalysts
## Composition of cell phone lots recycled at Umicore (examples)

| NDW kg | Organics % | AG - /mt | AU - g/mt | PT - g/mt | PD - g/mt | PB - % | CU - % | Ni - % | SB - % | SN - % | ZN - % | MGO - % | AL2O3 - % | CAO - % | SIO2 - % | FE - % | MN - % | TIO2 - % | BAO - % | BE - g/mt | ZRO2 - % | CEO2 - % |
|--------|-----------|---------|---------|---------|---------|-------|------|------|-------|-------|-------|-------|-------|---------|--------|--------|-------|-------|---------|--------|--------|---------|--------|
| **Cell phone handsets** |
| 846    | 43        | 3409    | 276     | 4       | 161    | 0.7   | 11.7 | 1.9  | 0.1   | 0.9   | 0.9   | 4.5   | 4.6   | 2.1   | 12.9  | 5.4   | 0.2   | 1.5   | 0.8   | 5.8   | 0.1   | 0.1   |
| 3.025  | 46        | 5441    | 446     | 5       | 349    | 0.6   | 13.0 | 1.3  | 0.1   | 1.1   | 0.7   | 0.6   | 3.0   | 1.7   | 12.9  | 6.8   | 0.1   | 1.9   | 1.1   | 154.0 | 0.1   | 0.3   |
| 7.973  | 37        | 2792    | 353     | 5       | 98     | 0.5   | 15.0 | 2.0  | 0.1   | 0.9   | 1.3   | 5.3   | 4.4   | 2.5   | 12.1  | 7.0   | 0.2   | 1.3   | 0.9   | 64.0  | 0.1   |
| 5.292  | 42        | 3309    | 352     | 4       | 141    | 0.6   | 12.9 | 1.5  | 1.0   | 1.0   | 1.0   | 4.0   | 7.1   | 1.7   | 11.1  | 6.8   | 0.3   | 1.8   | 0.9   | 70.0  | 0.2   | 0.1   |
| 11.485 | 41        | 3661    | 311     | 5       | 132    | 0.7   | 12.7 | 1.4  | 0.1   | 1.0   | 1.0   | 5.4   | 4.2   | 1.3   | 11.5  | 6.9   | 0.2   | 1.9   | 0.9   | 81.0  | 0.1   | 0.1   |
| 6.451  | 45        | 3880    | 334     | 4       | 152    | 0.7   | 12.2 | 1.3  | 0.1   | 1.0   | 1.2   | 3.6   | 2.7   | 1.7   | 10.3  | 6.2   | 0.2   | 2.5   | 1.2   | 132.0 | 0.2   |
| 12.509 | 40        | 3941    | 363     | 3       | 122    | 0.7   | 13.5 | 1.4  | 1.1   | 1.1   | 1.3   | 3.6   | 6.0   | 1.9   | 11.2  | 7.3   | 0.3   | 2.0   | 1.0   | 121.0 | 0.2   |
| 11.883 | 40        | 3221    | 349     | 5       | 119    | 0.6   | 12.5 | 1.4  | 0.1   | 1.0   | 1.4   | 3.1   | 5.4   | 1.8   | 11.2  | 8.0   | 0.3   | 1.7   | 0.9   | 81.0  | 0.1   |
| 17.627 | 45        | 3350    | 357     | 5       | 105    | 0.5   | 12.3 | 1.3  | 0.1   | 1.1   | 0.8   | 1.7   | 3.6   | 2.0   | 11.2  | 7.3   | 0.2   | 2.0   | 1.0   | 80.0  | 0.3   |
| 11.558 | 44        | 2922    | 323     | 7       | 162    | 0.5   | 12.5 | 1.4  | 0.1   | 0.8   | 1.4   | 3.6   | 4.8   | 2.2   | 11.2  | 5.3   | 1.4   | 0.7   | 93.0  | 0.1   |
| 15.883 | 43        | 4005    | 351     | 6       | 122    | 0.7   | 12.5 | 1.1  | 0.1   | 1.0   | 1.6   | 2.3   | 6.0   | 2.0   | 11.5  | 4.7   | 2.1   | 1.0   | 88.0  | 0.4   |
| 104.531| 42        | 3630    | 347     | 5       | 151    | 0.6   | 12.8 | 1.5  | 0.1   | 1.0   | 1.1   | 3.4   | 4.7   | 1.9   | 11.6  | 6.5   | 0.2   | 1.8   | 0.9   | 88.2  | 0.2   |
| **Shredded mobile phones** |
| 1.105  | 35        | 3459    | 425     | 6       | 173    | 0.8   | 15.2 | 1.5  | 0.1   | 1.0   | 1.0   | 9.3   | 4.2   | 1.6   | 12.7  | 3.9   | 0.1   | 1.4   | 0.9   | 61.0  | 0.1   |
| 4.976  | 49        | 846     | 267     | 143     | 38     | 0.2   | 10.7 | 2.0  | 0.1   | 0.5   | 1.6   | 0.6   | 8.7   | 1.9   | 7.3   | 7.6   | 0.2   | 1.7   | 0.4   | 44.0  | 1.9   |
| 7.881  | 47        | 2515    | 370     | 5       | 128    | 0.4   | 14.4 | 1.8  | 0.1   | 0.8   | 1.4   | 2.1   | 3.1   | 1.8   | 11.5  | 4.1   | 0.2   | 1.0   | 0.7   | 95.0  | 0.1   |
| 13.961 | 44        | 2273    | 354     | 51      | 113    | 0.5   | 13.4 | 1.8  | 0.1   | 0.8   | 1.3   | 4.0   | 5.3   | 1.8   | 10.5  | 5.2   | 0.2   | 1.4   | 0.7   | 66.7  | 0.7   |
| **Cell phone circuit boards** |
| 9.613  | 26        | 5541    | 982     | 7       | 287    | 1.1   | 25.1 | 1.6  | 0.1   | 2.3   | 0.6   | 0.9   | 3.2   | 2.2   | 12.2  | 7.7   | 0.4   | 2.6   | 1.8   | 103.0 | 0.1   |

without batteries
Average composition from > 100 t of mobile phone handsets

- **org.** 41%
- Others 34%
- Fe 7%
- Cu 13%
- Ni 1.5%
- Zn 1.1%
- Sn 1%
- Pb 0.6%
- PM 0.4%

avg. content of precious metals (PM)

<table>
<thead>
<tr>
<th>Metal</th>
<th>g/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>3630</td>
</tr>
<tr>
<td>Au</td>
<td>347</td>
</tr>
<tr>
<td>Pd</td>
<td>151</td>
</tr>
<tr>
<td>Pt</td>
<td>5</td>
</tr>
<tr>
<td>total</td>
<td>4133</td>
</tr>
</tbody>
</table>

Ag, Au, Pd, Pt, Cu, Pb, Bi: recovered with > 95% yield in Umicore process

additionally recovered: Sn, Ni, In, Sb, As
Example “low tech” – a „precious metals refinery“ (leaching) at Bangalore/India (EMPA study)

Total Au-recovery efficiency only \( \approx 25\% \),
Example: Results of an EMPA-study in Bangalore / India on low-tech refining

Total Au-recovery efficiency only ≈ 25% while environmental & health damage is dramatic

- informal / SME sector recyclers use 3 wet chemical processes:
  - Cyanide leaching
  - Amalgamation (Hg)
  - Au stripping (electrolytic)
- efficiencies are very low:
  - >60% losses during mechanical pre-processing
  - >50% losses during chemical processes
- Emissions are dramatic; up to 370x CH thresholds
- exporting to state of the art refiner might be profitable for all

Source: EMPA/Rolf Widmer: StEP side event at Care Innovation Conference, Vienna 15.11.06

⇒ “backyard recycling”: low economic results only → key to changes?
not recommended because:

• creation of (precious) metal containing dust which is difficult to handle

• significant losses of valuable metals in side streams (plastics, Al, Fe, dust) from where they cannot be recovered

• separated plastics usually are too impure for material recovery

• Fe, Al, Mg in mobile phones & motherboards are of minor economical & environmental relevance (don’t „sacrifice“ precious metals to win Al)

→ most preprocessors for WEEE do not shred mobile phones. & motherboards but send them directly to integrated smelters

Computer boards should be removed manually (or mechanically). Manual dismantling of circuit boards from cell phones is an option to upgrade quality if labour costs are affordable. Still outlet needed for dismantled plastic casings.
Why to avoid shredding of mobile phones & computer boards?

Circuit boards, cell phones & other small, “high grade” devices are highly complex, especially with respect to precious metals distribution.

Occurrence of PMs with:

- **metallics**: contacts, connector, solders, hard disk drives, ...
- **ceramics**: Multi layer capacitors (MLCC), ICs, hybrid ceramics, ...
- **plastics**: ICs, PCB-tracks, inter-board layers, ...

→ PM containing parts are closely interlinked, PMs are highly disseminated.
→ Shredding cannot really liberate the different materials/metals. Shredded parts still are a partial mix of plastics, Fe, Al, Cu and PMs.
→ Sorting of these shredded parts by traditional separation techniques (magnetic, eddy current, etc.) can lead to substantial losses of PMs in the Fe-, Al- or plastic fractions.
→ Especially Pd and Ag from ceramic components on the surface are lost into dust.

Remove such components/devices prior to mechanical processing. For low grade materials, a coarse shredding process followed by manual or optical sorting could be a valid alternative. Make use of manual dismantling where labour costs allow.
Mechanical & metallurgical processes to be used in the right combination

Mechanical processes
require good liberation of substances to be separated
→ dismantling, shredding/crushing

Sorting by physical properties:
magnetic, eddy current, density separation,
supported by screening/sizing, further crushing

Limitations:
• Selectivity (overlap between physical properties)
• Handling of dust and fines
• Conflict concentration↔yield ("concentration dilemma")
• Unintended co-separation of minor metals (PM)

→ The more complex/interlinked the material, the less selective are mechanical processes and the higher are losses by co-separation
Excursion: Pyrometallurgical and hydrometallurgical processes

**Pyrometallurgy: “Smelting”**
Using thermal energy and chemical/metallurgical properties of substances to melt down ores or secondary materials, in order to concentrate target metals for further processing and separate non-target substances into a slag and/or volatile phase.
(example: IsaSmelt furnace, blast furnace, converter, calcination).

**Hydrometallurgy: “Leaching”**
Using acidic or alkaline solutions (and pressure and/or temperature) and chemical properties of substances to separate target from non-target substances via a leachate (solution) and a leaching residue (or via a vapour phase).
(example: cyanide leaching of Au, electro winning of Cu, precipitation, cementation, distillation, solvent extraction, electrolysis etc.)

Usually, pyrometallurgical & hydrometallurgical steps are combined for treatment of complex materials. Umicore uses hydrometallurgy for further upgrading and purification of output streams from initial pyrometallurgy. The final precious metals refining processes are largely hydrometallurgical.
Limits of hydrometallurgy ("leaching")
for e-scrap

Given the complex composition of e-scrap, hydrometallurgical plants are typical "cherry picking" operations.
• leaching Au, (Pd, Ag) from IC’s and rich cut-off parts (contacts etc.)
• sometimes recovering Cu from leaching solutions by cementation

Pros:
+ quick access to PMs
+ low investment costs
+ often local available

Cons:
- lower recovery yields than pyrometallurgy (also for PMs)
- No recovery of Pb, Sn, Ni, Sb, In, ….
- Leaching agents (cyanide, aqua regia) need special awareness, significant risks for worker’s health & environment. Often, Hg is involved for final upgrading.
- Often inadequate treatment of toxic leaching solutions and residues.
- Leaching agents “activate” heavy metals & make them easier accessible to groundwater etc.
- No solution for low grade parts of circuit boards (which is by far the biggest part) → These parts have to go to pyrometallurgy anyway (unless they are just dumped)
Introduction: Why do we need e-scrap recycling?
- Impact on resources, environment & economics

- Technical capabilities
- Experience gained
- Business execution
- Challenges
- Conclusion
Toll refining - how does it work in principle?

- Refiner assays the exact metals content in the individual customer lot.
- Payable metals are credited to customer.
- Customers pays an agreed price for the assaying & refining service.
- Recoverable metals remain in property of customer during the entire process.
Toll refining - a well established procedure in metals refining

• Refiner offers a refining service for which a fee is charged
• Supplier remains owner of metals contained in the material
• Supplier can decide to do with “his property” whatever he finds appropriate as metals returnable will be put on a metal account
  – e.g. pick-up refined metals
  – sell metals to refiner
  – have one metal “swapped” into another metal (e.g. Pd in Au)
• Final quantities of metals are determined through a sampling and assaying procedure, safeguarding the interests of the supplier
• Toll refining at Umicore also means doing business with a company
  – financially sound, committed and active on a world-wide basis
  – having certified experience in smelting/refining of complex precious metals bearing materials in an environmentally sound way
  – guaranteeing absolute transparency
  – looking forward to establish long-term partnerships with his suppliers by offering customised commercial solutions
Toll refining does not mean:

- Paying cash prices upon pick-up of material (⇒ telquel or “as-is” buying).
- Not really knowing where material will end up and what will happen to it.
- Appearing today & disappearing tomorrow.

Telquel buying / “as-is”-buying:

attractive if: small quantities and /or immediate payment is needed for reason of cash constraints

but:

- Supplier loses control over what happens with material afterwards? (environmental & social concern, unauthorised reuse?)
- No traceability, impossible to report to first supplier the real final whereabouts of his material.
- Telquel buyer has to make his living ⇒ indirect payment of extra margin for his involvement and risk coverage (lower net payment than from toll refining).
- No possibility to take advantage of “active metal account management” (AMAM).
The components of a toll refining contract are technically based

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>treatment price [€]</strong></td>
<td>-- process costs</td>
</tr>
<tr>
<td>- sampling &amp; assay charge</td>
<td>[€/lot]</td>
</tr>
<tr>
<td>- treatment charge</td>
<td>[€/net dry weight]</td>
</tr>
<tr>
<td>- refining charge</td>
<td>[€/kg metal credited]</td>
</tr>
<tr>
<td><strong>metal credit [% of assay]</strong></td>
<td>-- technical yield</td>
</tr>
<tr>
<td><strong>metal availability [days]</strong></td>
<td>-- process time</td>
</tr>
</tbody>
</table>

The economic viability of a toll refining offer only can be evaluated by considering all contract components!

To determine the total costs metal-credit and metal-availability have to be transferred into monetary numbers and to be added to the treatment price (bottom-line-calculation).

commercial contact: thierry.vankerckhoven@umicore.com,
Introduction: Why do we need e-scrap recycling?
- Impact on resources, environment & economics

Technical capabilities

Experience gained

Business execution

Challenges

Conclusion
What must be avoided in end-of-life treatment

- Landfill or any other kinds of disposal
- Incineration
- Backyard recycling („open sky“ incineration, cyanide leaching, …)
- Treatment in smelters without the appropriate offgas purification installations \(\rightarrow\) most copper smelters cannot recycle mobile phones in an environmentally sound way.
- „Fake“ recycling (\(\rightarrow\) it needs more than a nice building, ISO & OHSAS certificates, and some dismantling \(\rightarrow\) check material streams to the final destination)

- Today: Large exports of old IT-devices from industrial countries all around the globe.
- Often falsely labelled as “reuse” (to circumvent restrictions on waste exports). Insufficient controls of real physical streams.
- Reuse is only a temporary solution \(\rightarrow\) will lead to scrap that needs to be recycled.
- No recycling without awareness, adequate infrastructure and some minimum technology & experience.
  \(\rightarrow\) otherwise, exports even for ”real reuse” are environmentally counterproductive.

Remember the Citiraya case?
Cell phone recycling largely fails today → close the loops for IT equipment

Recycling potential 2005*: 400 million units per anno x 100 g = 40,000 t/a

<table>
<thead>
<tr>
<th>collected</th>
<th>Not collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>%?</td>
<td>%?</td>
</tr>
</tbody>
</table>

Reuse
- Stored “in drawer” (potential for recycling at later stage)
- Disposed with household waste (unrecoverable loss)

Recycling¹
- 25-35% of professionally collected phones are not fit for reuse and sent directly to recycling.
- Global quantities treated for material recovery efficiently and environmentally sound.
- Uncontrolled release of fumes, effluents and waste

¹ 25-35% of professionally collected phones are not fit for reuse and sent directly to recycling.
² Global quantities treated for material recovery efficiently and environmentally sound.
³ Uncontrolled release of fumes, effluents and waste

Global Sales of new phones:
- 2001: 400 M
- 2003: 500 M
- 2004: 650 M
- 2005: 800 M
- 2006: 1000 M estimate

* Not to scale
BC OEWG – Metals Recovery from e-scrap, Christian Hagelüken, 07-09-2007
In Asia/China recently some industrial leaching plants for electronics were built

- nice buildings & infrastructure
- professional cyanide leaching with security measures
- recovery of Au, Ag, Pd, Cu
- leaching residue (sludge) is “sealed” in plastic pallets

but:

- Pb, Sn, Ni etc. are not recovered
- Yields for precious metals lower than in BAT pyrometallurgical processes
- How secure is in daily praxis the final handling of spent cyanide in the current Chinese context?
- “Sealing” chemically agitated toxic metals like Pb & Cd in plastic pallets? What if the pallet surface gets damaged during use? What is happening at the EOL of the pallets? → Landfill? Incineration?

► Sooner or later the toxic elements will be emitted into the environment!
Introduction: Why do we need e-scrap recycling?
- Impact on resources, environment & economics

- Technical capabilities
- Experience gained
- Business execution
- Challenges

Conclusion
Recycling of complex WEEE needs “high tech”, specialisation & experience
Economies of scale & adequate infrastructure are key to success
It does not make sense to replicate large and expensive plants in every country → Umicore e.g. receives complex fractions from global sources
Critical fractions make only small % of total WEEE → no big transboundary shipments
Recovered metals can be credited back to countries of origin (“toll refining”) → no loss of resources from a country’s perspective
Conclusion – how to sustainably improve material recovery from e-scrap

- Improve collection … everywhere (incl. reused electronics in developing countries)
- Consider WEEE as a “mine above ground” (resource, not waste)
- Monitor all material streams up to the final destination
- Stop (illegal) shipments to non-compliant destinations
- Stop backyard recycling, but integrate the informal sector whenever possible
- Minimise losses of precious/special metals and spillage of toxics
- Avoid deep mechanical pre-processing of “high grade” materials, make use of benefits from smart manual dismantling if labour costs allow this
- Treat circuit boards etc. directly in an appropriate smelter process
- Use holistic approaches for evaluation of recycling processes
- Adopt recycling processes to the specific regional environment
- Benefit from an (international) division of labour and economies of scale
- Promote re-export of critical fractions (cell phones, circuit boards) from other countries to certified environmentally sound recovery plants … … and adapt Basel convention mechanisms to facilitate such shipments
  (target to reduce transboundary movements of waste here indirectly leads to less efficient & more polluting local “recycling”).
Conflicting interests have to be solved

Best resource conservation ("recycling society")
→ no global reuse streams as long as efficient recycling cannot be secured at final EOL
→ questioning the "waste hierarchy", reuse is only "better" than recycling within the same system boundary

Lifetime extension & social support
→ reuse in non-industrial parts of the world: "Bridging the digital divide", donations, improved communication, ...
→ Social improvement, work, ...
→ but inevitable resource losses and toxic spillage at final EOL under present conditions

- We cannot have both today
- Not a simple "good" or "bad" solution, holistic view is needed (see also www.step-initiative.org of the United Nations University UNU)
- Priorities to be set on a case by case basis → search for individual solutions
- Without a global "recycling society" this conflict cannot be solved
- Closed loops in consumer goods are a long term future perspective only (dream?)
- Much still needs to be done!
Thanks for your attention

For some reason, there is e-scrap that never reaches us

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