Energy requirements for recovery of (metallic) nanoparticulate material from waste

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Introduction

- Increased use of nanoparticulate (NP) material will (or already does) give increased amounts of these in end-of-life products
- Energy requirements for producing NP material are significant or high and the same will hold for NP recovery from wastes
- Exergy analysis, normalizing all energy to “the capacity to work” without quality descriptions (like temperature of heat) is a useful and proper tool for energy use (efficiency) assessment
- Here, three products containing metallic NPs are addressed:
  - Silver (Ag) in textile (cotton) giving anti-bacterial properties
  - Zinc (Zn) in plastics (PP) as flame retardant
  - Copper (Cu) in water to give a nano-fluid coolant
- Goal: recovery as metal (preferably NP), avoiding oxidation!
Exergy of (diluted) Ag, Cu, Zn NPs

- Energy needed to separate a material at (molar) fraction $x$ from a mixture can be calculated as exergy of “unmixing” using

$$\text{Exergy of unmixing (J/kg)} = T^0 \cdot R \cdot \frac{x \cdot \ln(x) + (1-x) \cdot \ln(1-x)}{x} \cdot M$$

with gas constant $R$, surroundings temperature $T^\circ (K)$ and molar mass $M$ for the material to be separated.

Here, activity coefficients are $= 1$ for material in different (solid) phases.

- This can be used to calculate the thermodynamic minimum energy requirements for producing (or recovering) a pure (here: metallic) species from ore, a waste stream, or sea water.

- This work addresses three metals and nanoparticles of these.
### Three metals and products with NP

<table>
<thead>
<tr>
<th></th>
<th>Concentration in ocean water kg/kg</th>
<th>Concentration in earth upper crust kg/kg</th>
<th>Concentration in typical ore kg/kg</th>
<th>Concentration as NP in product kg/kg</th>
<th>Description of product containing NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver, Ag</td>
<td>$3 \times 10^{-12}$</td>
<td>$1.2 \times 10^{-9}$</td>
<td>$0.0043 \times 10^{-3}$</td>
<td>$0.013 \times 10^{-3}$</td>
<td>Antibacterial textile</td>
</tr>
<tr>
<td>Copper, Cu</td>
<td>$120 \times 10^{-12}$</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$5.8 \times 10^{-3}$</td>
<td>$0.27$</td>
<td>Nanofluid coolant</td>
</tr>
<tr>
<td>Zinc, Zn</td>
<td>$390 \times 10^{-12}$</td>
<td>$0.47 \times 10^{-9}$</td>
<td>$41 \times 10^{-3}$</td>
<td>$5 \times 10^{-3}$</td>
<td>Flame retardant for polymer</td>
</tr>
</tbody>
</table>

**Sources:**
- Zevenhoven and Beyene (2014) doi:10.5541/ijot.5000070194 (open source)
Exergy of “unmixing”: Ag NP, cotton

Exergy of unmixing: 13 ppmw silver NP in cotton

Molar mass Ag, cotton, sea water, earth crust, ”ore” = 107.9, 162.1, 18, 155.2, 131.5 kg/kmol
Exergy of “unmixing”: Zn NP, PP

Molar mass Zn, PP, sea water, earth crust, ”ore” = 65.4, 42.1, 18, 155.2, 110.3 kg/kmol
Exergy of “unmixing”: Cu NP, water

Exergy for recovery (unmixing) (kJ/kg)

Exergy of unmixing: 27 %-wt Cu NP in water

Molar mass Cu, water, sea water, earth crust, ”ore” = 63.7, 18, 18, 155.2, 109.4 kg/kmol
Conclusions

- **Exergy analysis** allows for quantifying minimum “unmixing” energy requirement for species such as (metal) nanoparticles (NP) in wastes / end-of-life products containing these.

- **Dilution** to levels similar to concentrations in ore can make metal production from ore + NP production more attractive.

- For **silver NP in cotton**, concentrations are similar to ores: NP recovery is motivated by energy needed for NP production from pure silver. Cotton + NP waste dilution should be avoided!

- For **zinc NP in PP plastic**, production of metal NP from ore can be motivated by relatively low zinc (and NP) production energy.

- For **copper NP in cooling water**, recovery as NP is motivated until high levels of dilution.

- This **theoretical assessment** gives guidelines for future technology.