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Title Gold mining in the classroom: a lab activity to teach sustainability

Teacher guide: detailed procedure

Materials

For 1 gram of recovered circuitry, the following are required:

- 1 ml of a 1:1 mixture of 37% hydrochloric acid (HCl) and 30% hydrogen peroxide (H_2O_2)
- a few spatula-tips of potassium permanganate ($KMnO_4$)
- diluted hydrochloric acid solution for rinsing: obtained by diluting 37% hydrochloric acid 1:10 with distilled water
- distilled water

> **Safety note**: always add the acid to the water, never the other way around.

- 2 g of urea
- 2 g of sodium metabisulfite ($Na_2S_2O_5$)
- filter papers: thickness (0.17 mm), particle retention (5–8 µm)
- fume hood
- beaker
- flasks
- spatulas
- muffle furnace or alternatively a Bunsen burner
- magnetic stirrer with stir bar
- funnels
- conical flasks (100 ml and 500 ml, if using 10 g of selected circuits)
- ceramic crucible
- To retrieve the circuits from the smartphone, pliers and screwdrivers are needed
- an ice-water bath, or, if larger quantities are involved, an ice-sodium chloride (NaCl) bath.

Reagents for alternative routes:

- Alternative to hydrochloric acid (HCl): 20% sulfuric acid (H_2SO_4)
- Alternative to potassium permanganate ($KMnO_4$): 10% NaOH and manganese dioxide (MnO_2)

Procedure

1. Preparation: Disassemble the discarded cell phones, separate the circuit boards, and select the components which are known or suspected to contain gold.

> Parts of the phone that contain gold:[1]
>
> - Circuit board/motherboard
> - SIM card
> - internal connectors

2. Acid digestion: Add the selected components containing the gold to a beaker. For each gram of selected circuits, gradually add 1 ml of a 1:1 mixture of 37% hydrochloric acid and 30% hydrogen peroxide (The mixture is prepared before being added; for every gram of circuitry, add enough liquid to submerge all solid parts, if necessary). Hydrochloric acid is used as a source of acidity and can be replaced by another strong acid, such as sulfuric acid, as described below. Hydrochloric acid was selected due to its high volatility, which allows for its easy removal from the solution. Use a vessel sized appropriately for the initial quantity of electronic circuit boards.

> **Safety note**: Exercise extreme caution when mixing hydrogen peroxide and hydrochloric acid; the reaction is highly exothermic and must be performed in a fume hood, while wearing gloves, a lab coat and safety goggles. Always add the acid to the water, never the other way around, and do so very slowly, drop by drop. If the reaction becomes very vigorous, cool the vessel in an ice-water bath.

During this phase, the gold transitions from its metallic state to gold(III) (chloroaurate species) and enters into solution, according to the following reaction. The equation shown is a simplification of what actually happens: **$2\ Au + 3\ H_2O_2 + 6\ H^+ \rightarrow 2\ Au^{3+} + 6\ H_2O$.**

Concentrated hydrogen peroxide, in the presence of a concentrated strong acid, is capable of oxidising metallic gold to gold(III). In this reaction, hydrogen peroxide acts as an oxidising agent, while the acid is required to provide hydronium ions that are involved in the reaction.

> **Safety note**: This mixture is highly corrosive and extremely dangerous. Handle with extreme caution under a fume hood while wearing lab gloves and safety goggles. To avoid formation of chlorine gas, 20% sulfuric acid can be used instead of hydrochloric acid. However, this increases the quantity and acidity of the waste requiring disposal.

3. Oxidation reaction: stir the mixture at room temperature using a magnetic stirrer and stir bar for approximately 12 hours to allow the metals, including gold, to dissolve and separate from the non-metallic materials. During this time, the solution will turn dark green due to the presence of various metal cations: copper imparts a blue hue, while gold contributes a

yellow one. Subsequently, distilled water is carefully added to the reaction mixture (approximately 5 ml per ml of oxidising solution used), and the liquid is separated from the residual solid material via gravity filtration using a pleated filter. This step requires a filter, a funnel and a vessel (such as an Erlenmeyer flask or round-bottom flask) of appropriate capacity; a 500 ml vessel is recommended for 10 g of circuit boards.

4. Excess peroxide elimination: Before reducing the dissolved gold, any residual oxidising agents must be removed. Dilute the solution by adding 20 ml of distilled water per ml of solution and transferring the mixture to a larger flask (recommendation: a 500 ml flask if starting with 10 grams of circuit boards). Then, gradually add a few spatula-tips of potassium permanganate to the solution to eliminate excess hydrogen peroxide.

> **Safety note**: Always perform the entire procedure under a fume hood, due to the formation of chlorine and oxygen. Exercise particular caution with potassium permanganate, as it is highly reactive and reacts vigorously with the reaction mixture. Make sure to add the potassium permanganate slowly in small amounts.

The permanganate serves to oxidise the hydrogen peroxide to oxygen, thereby removing the excess oxidant. The reaction is considered complete when effervescence ceases. A faint pink colouration appears in the solution, caused by a slight excess of potassium permanganate.

> A more eco-friendly but more elaborate alternative involves neutralising the solution with a 20% sodium hydroxide (NaOH) solution, after filtration, until a neutral or slightly basic pH is reached.
>
> **Safety note**: the neutralization reaction is highly exothermic, and the sodium hydroxide (NaOH) solution is extremely caustic. If the reaction becomes very vigorous, cool the vessel in an ice-water bath.
>
> Once neutrality is achieved, excess hydrogen peroxide is removed using a spatula of manganese dioxide, which catalyses its decomposition.
>
> **Safety note**: This reaction is also highly exothermic and releases oxygen in gaseous form; therefore, the entire operation should be carried out in a fume hood.[2]

5. Precipitation: Add urea (2 g per gram of circuits used), heat gently (at 50°C for 1 hour to eliminate any remaining oxidant), add sodium metabisulfite ($Na_2S_2O_5$) (2 g per gram of circuits used), and allow the reaction to proceed until a dark brown or black precipitate forms. This may take several hours, depending on the chosen circuits. During this step, the gold is reduced from gold(III) to metallic gold. According to the following reaction:

$$4\ HAuCl_4 + 3\ Na_2S_2O_5 + 9\ H_2O \rightarrow 4\ Au\downarrow + 6\ NaHSO_4 + 16\ HCl$$

Urea is used to reduce any remaining oxidants left after the permanganate treatment. Sodium metabisulfite, on the other hand, is capable of reducing (and thus precipitating) gold(III) as metallic gold.

6. Filtration and Collection: Pour the suspension over fluted filter paper. If the reduction worked correctly, sufficiently large particles will remain on the paper. The resulting precipitate is then washed with approximately 5 ml of hydrochloric acid solution, which dissolves any metals other than gold, allowing them to pass through the filter paper too.

7. Calcination and Melting: Place the dried filter paper with the remaining precipitate in a suitable crucible and calcine (burn off) the filter paper to resolve it. Melt the remaining gold-containing powder in the crucible using either a Bunsen burner or a muffle furnace to fuse the separated powder particles into one compact piece. Pure gold melts at approximately 1064°C; therefore, if using a Bunsen burner, you must use an oxidising flame (by properly adjusting the air intake), whereas if a muffle furnace is available, the temperature should be set to 1100°C.

> **Safety note**: Given the intense heat, use metal tongs of an appropriate length and heat-resistant gloves. The crucible containing the molten gold must cool slowly so that it does not crack from thermal shock.

Results

The final product obtained after melting consists of small gold nuggets, whereas, without the melting stage, a black or brown powder is produced. Gold in the form of extremely fine powder appears black (or dark brown) due to an optical phenomenon linked to the microscopic size of its particles and the way they interact with light.[5]

The process yield depends on the amount of gold present in the selected printed circuit boards and is therefore highly variable, making it impossible to determine an exact value beforehand. Consequently, the careful selection of printed circuit boards is crucial for effective gold recovery.[1] Meanwhile, the other metals largely remain in the aqueous phase as salts, which can be reused for further metal recovery.

Chemical explanations:

If we look at the potential standards:[3]

Au^{+} (aq) + e^{-} → Au (s) E° = + 1.69 V

Au^{3+} (aq) + 3 e^{-} → Au(s) E° = + 1.50 V

with the standard reduction potential of readily available oxidising agents:

H_2O_2 (aq) + 2 H^+ (aq) + 2e^- → 2 H_2O (l) E° = + 1.78 V

For the oxidation, we therefore opted for hydrogen peroxide; given that the reaction requires an acidic environment, we selected hydrochloric acid (due to its high volatility).

For the reduction, we decided to use urea and sodium metabisulfite, which is known in the literature for reducing gold.[4]

References

[1] How much gold is in a cell phone: https://learn.apmex.com/learning-guide/science/how-much-gold-is-in-a-cell-phone/

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[3] The standard potential (in Italian): www.gmpe.it/chimica/potenziali-standard-riduzione

[4] How to refine precious metals using nitric acid and urea: https://alliancechemical.com/blogs/articles/critical-metal-recovery-101-how-to-refine-precious-metals-using-nitric-acid-urea-more?srsltid=AU7gw4VSGa5BOOnTmJFor_vzt07czKBsO1LXdKXngcVmtj84Gqd0Oh0K

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