Hydrometallurgy involves the use of aqueous chemistry for the recovery of metals from ores, concentrates, and recycled or residual materials. This process is used in extraction of less electro positive or less reactive metals like gold and silver. Hydrometallurgy is typically divided into three general areas: (1) Leaching, (2) Solution concentration and purification, and (3) Metal recovery.

**Leaching**

Leaching involves the use of aqueous solutions, which is brought into contact with a material containing a valuable metal; the solution may be acidic or basic. In the leaching process, oxidation potential, temperature, and pH of the solution are important parameters, and are often manipulated to optimize dissolution of the desired metal component into the aqueous phase.

**Heap Leaching of Uranium**

Heap leaching is an extraction process by which chemicals (usually sulfuric acid) are used to extract the economic element from ore which has been mined and placed in piles on the surface. Heap leaching is generally economically feasible only for oxide ore deposits. Oxidation of sulfide deposits occurs during the geological process called weathering. Therefore, oxide ore deposits are typically found close to the surface.

Most uranium is found in the upper crust, occurring naturally as $U^{4+}$ and $U^{6+}$ with an average abundance of 2 ppm. Its most naturally occurring mineral is Uraninite ($UO_2$), which typically reacts with oxygen to form $U_3O_8$, the mineral pitchblende. If there are no other economic elements within the ore a mine might choose to extract the uranium using a leaching agent, usually a low molar sulfuric acid. Similar to copper oxide heap leaching, also using dilute sulfuric acid. The final product is yellowcake ($U_3O_8$) and requires significant further processing to produce fuel-grade feed.

Acid leaching is sometimes also referred to as heap leaching (Figure 
\ref{PageIndex{1}})) because the leaching process can be performed on large "heaps" of uranium ore that have been collected from mines. The chemistry of the leaching process revolves around oxidation of the uranium compounds, which is typically achieved using manganese dioxide ($MnO_2$), sodium chlorate ($NaClO_3$), and Fe(II) salts. Equation \ref{23.3.1a} - \ref{23.3.1c} shows a typical reaction pathway for the acid leaching process using sulfuric acid.

\begin{align}
[UO_2(s) + 2Fe^{3+} & \rightarrow UO_2(aq)^{2+} + 2Fe^{2+}] \label{23.3.1a} \\
[UO_3 + H^+ & \rightarrow UO_2(aq)^{2+} + H_2O] \label{23.3.1b} \\
[UO_2(aq)^{2+} + 3SO_4^{2-} & \rightarrow [UO_2(SO_4)_3]^{4-}] \label{23.3.1c}
\end{align}

Sulfuric acid is typically used due to the solubility of uranyl sulfate complexes. The reaction is typically performed at slightly elevated temperatures (~60 °C) and can often release $H_2$, $H_2S$, and $CO_2$ gases during the process. The uranium, which typically begins in the tetravalent state, goes through a series of reactions, eventually leading to the formation of the desired complex, $[UO_2(SO_4)_3]^{4-}$. While the solubility of this complex makes sulfuric acid a desirable leaching agent, nitric and hydrochloric acid can also be used, but are typically not due to their higher cost and corrosiveness.
To convert yellowcake into weapons grade quality, it is converted into uranium hexafluoride ($\text{UF}_6$) ore to be isotopically enriched. $\text{UF}_6$ can be easily turned into a gas for enrichment based off of the differing effusion rates of the different isotopes.

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**Solution Concentration and Purification**

After leaching, the leach liquor must normally undergo concentration of the metal ions that are to be recovered. Additionally, undesirable metal ions sometimes require removal. Precipitation is the selective removal of a compound of the targeted metal or removal of a major impurity by precipitation of one of its compounds. Froth flotation is a process for selectively separating hydrophobic materials from hydrophilic materials.
Metal Recovery

Metal recovery is the final step in a hydrometallurgical process. Metals suitable for sale as raw materials are often directly produced in the metal recovery step. Sometimes, however, further refining is required if ultra-high purity metals are to be produced. The primary types of metal recovery processes are electrolysis, gaseous reduction, and precipitation. For example, a major target of hydrometallurgy is copper, which is conveniently obtained by electrolysis.

Example \( \PageIndex{1} \): Gold

The most selective methods for separating metals from their ores are based on the formation of metal complexes. For example, gold is often found as tiny flakes of the metal, usually in association with quartz or pyrite deposits. In those circumstances, gold is typically extracted by using cyanide leaching, which forms a stable gold–cyanide complex—\( [Au(CN)_2]^- \):

\[
4Au_{(s)} + 8NaCN_{(aq)} + O_{2(g)} + 2H_2O_{(l)} \rightarrow 4Na[Au(CN)_2]_{(aq)} + 4NaOH_{(aq)} \label{23.3.1}
\]

Virtually pure gold can be obtained by adding powdered zinc to the solution:

\[
Zn_{(s)} + 2[Au(CN)_2]^-_{(aq)} \rightarrow [Zn(CN)_4]^{2-}_{(aq)} + 2Au_{(s)} \label{23.3.2}
\]

A related method, which is used to separate \( Co^{3+}, Ni^{2+} \), and \( Cu^+ \) from Fe, Mn, and Ti, is based on the formation of stable, soluble ammonia complexes of ions of the late transition metals.

Contributors and Attributions

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