Natural Hydrogen Generation via Serpentinization : A Reaction Engineering Perspective

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Abstract

As the world races toward net-zero targets, the high cost of manufactured hydrogen remains one of the biggest obstacles to its adoption as a mainstream energy carrier. Natural hydrogen, formed deep within the Earth's crust through serpentinization, offers a chemically distinct and far cheaper pathway: a geological process that essentially runs itself, given the right rock chemistry and thermal conditions.

At its core, serpentinization is a coupled dissolution–redox reaction: iron-rich olivine and pyroxene react with water, iron oxidizes from Fe^{2+} to Fe^{3+}, and the electrons released reduce water to liberate H_2, while the rock recrystallizes into serpentine and magnetite. Thermodynamically, this reaction is comfortably spontaneous ($\Delta G°$ well below the –40 kJ/mol threshold) and exothermic, meaning the system can sustain hydrogen generation without external energy input. The more interesting engineering question is kinetics. At realistic subsurface temperatures, reaction rates follow Arrhenius-type behavior: too cold, and activation energy is insufficient; too hot, and the reaction's ΔG flips from spontaneous to non-spontaneous, shutting generation down entirely. This narrow operating window—around 150–200°C—combined with mineral surface area, water supply, and rock fracturing, governs how much hydrogen a given system can realistically produce, and why low rate constants remain the central technical bottleneck for commercial-scale extraction.

We apply this reaction engineering lens to field data from the East Sulawesi Ophiolite, one of the world's largest ophiolite formations, focusing on the seepage at Tanjung Api, Ampana. Gas flows of 1,000–1,400 m^3/day and on-site hydrogen readings up to 1,000 ppm confirm an active system, with laboratory analysis showing a gas composition exceeding 35% H_2. Beyond generation, we examine two practical chemical engineering concerns: hydrogen degradation through oxidative loss in shallow, oxygen-rich zones, and abiogenic methanation, where magnetite formed during serpentinization acts as a natural catalyst—via Sabatier and reverse water-gas shift pathways—silently converting valuable H_2 into methane before it ever reaches the surface. We also outline how standard gas processing unit operations (separation, sweetening, dehydration, compression) can be adapted to bring raw geologic gas to market-ready purity, drawing on operating precedents such as Mali's field. A preliminary techno-economic estimate puts Tanjung Api's levelized cost of hydrogen at approximately 0.74 USD/kg, underscoring the resource's commercial promise once these reaction engineering challenges—catalysis, kinetics, and process design—are systematically addressed.

Keywords: clean energy, low emissions, natural hydrogen, serpentinization kinetics, reaction thermodynamics.