

## Exploring Oxidative Chemistry and Metabolic Pathways in Enceladus' Ocean

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### 1. Introduction

The detection of molecular hydrogen in the plume of Saturn's icy moon Enceladus implies that there is positive chemical affinity (i.e., free energy available) for methanogenesis, the metabolic reaction of hydrogen with carbon dioxide to form methane and water [1]. Methanogenesis, however, is just one of many possible metabolic pathways that could be utilized by putative microorganisms. While reduced species are abundant in the plume, CO<sub>2</sub> was the only oxidant observed. To constrain the amount of other metabolically important oxidants including sulfate (SO<sub>4</sub><sup>2-</sup>), molecular oxygen (O<sub>2</sub>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) and ferric iron (for which we choose FeOOH (goethite) as representative of ferric oxyhydroxide solids) in Enceladus' ocean, we present a geochemical model of the ocean based on detections made by the Cassini INMS instrument [1] and likely equilibrium mineralogies of Enceladus' core.

### 1. Methods

#### 2.1 Production of O<sub>2</sub> and H<sub>2</sub>O<sub>2</sub>:

We use a model of water ice radiolysis on the surface of Enceladus to estimate the amount of molecular oxygen and hydrogen peroxide contained in the ice, and calculate the delivery rate of oxidants from the surface ice to the ocean using previous estimates of the rate of ice plume particle deposition on the south polar region [2]. We also consider O<sub>2</sub> and H<sub>2</sub>O<sub>2</sub> produced radiolytically in the ocean from electrons and gamma rays released by the decay of <sup>40</sup>K atoms, from the inferred <sup>40</sup>K concentration in Enceladus' ocean (based on [3] and [4]) and rate equations for radiolytic reactions in primitive ocean waters from [5].

#### 2.1 Production of SO<sub>4</sub><sup>2-</sup> and FeOOH:

The oxygen and peroxide that is produced can react with sulfides and ferrous iron dissolved in the ocean to produce SO<sub>4</sub><sup>2-</sup> and FeOOH, respectively. We set upper limits on the concentrations of these species from the equilibrium solubilities of different possible ocean floor minerals, calculated using the Geochemist's Workbench [6]. We then determine the final concentrations of SO<sub>4</sub><sup>2-</sup> and FeOOH in the ocean using oxidation reaction rate laws in natural waters from [7-10].

### 3. Results and Discussion:

We calculate the amount of chemical energy that could be available from a wide range of alternate metabolic pathways over time. We consider reactions involving O<sub>2</sub>, H<sub>2</sub>O<sub>2</sub>, SO<sub>4</sub><sup>2-</sup> and FeOOH reacting with reductants such as molecular hydrogen, sulfides, ferrous iron, ammonia and hydrocarbons, and compare it with the energy available from methanogenesis reported in [1], and the maintenance energy requirements to sustain microbial life on Earth. Finally, we consider how the production of oxidants from radiolysis of pore water in the core, and how the abiotic hydrothermal consumption of oxidants by reduced minerals in the core, could affect the reported results.

### 4. References

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