Physics and Chemistry of the Earth 36 (2011) 1616–1623

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Molecular hydrogen: An abundant energy source for bacterial activity in nuclear waste repositories

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ARTICLE INFO

Article history:
Available online 9 November 2011

Keywords:
Hydrogen metabolism
Hydrogen bacteria
Autotrophy
Nuclear waste disposal
Deep geological environments
Biocorrosion

ABSTRACT

A thorough understanding of the energy sources used by microbial systems in the deep terrestrial subsurface is essential since the extreme conditions for life in deep biospheres may serve as a model for possible life in a nuclear waste repository. In this respect, H_2 is known as one of the most energetic substrates for deep terrestrial subsurface environments. This hydrogen is produced from abiotic and biotic processes but its concentration in natural systems is usually maintained at very low levels due to hydrogen-consuming bacteria.

A significant amount of H_2 gas will be produced within deep nuclear waste repositories, essentially from the corrosion of metallic components. This will consequently improve the conditions for microbial activity in this specific environment. This paper discusses different study cases with experimental results to illustrate the fact that microorganisms are able to use hydrogen for redox processes (reduction of O_2, NO_3^-, Fe III) in several waste disposal conditions. Consequences of microbial activity include: alteration of groundwater chemistry and shift in geochemical equilibria, gas production or consumption, biocorrosion, and potential modifications of confinement properties.

In order to quantify the impact of hydrogen bacteria, the next step will be to determine the kinetic rate of the reactions in realistic conditions.

1. Introduction

The main purpose of this paper is to provide a state-of-the-art review on the role of hydrogen as a bacterial substrate and adds our own experience with laboratory cases illustrating the potential impact on nuclear waste disposal.

Numerous studies concluded on the existence of a subsurface biosphere e.g. in granitic rocks (Pedersen, 1997), clay formations (Stroes-Gascoyne et al., 2007; Vinsot et al., 2008), underground basalts (Stevens and Mckinley, 1995), geothermal water (Daumas et al., 1986; Roh et al., 2006), and oil facilities (Duncan et al., 2009).

A thorough understanding of the energy sources used by microbial systems in the deep terrestrial subsurface is required due to the fact that the extreme conditions for life in deep biospheres may serve as a model for possible life in a nuclear waste repository.

Most of these environments are poor or devoid of organic matter. They consequently support the development of chemolithotrophic bacteria (able to develop without organic matter, using mineral carbon) such as iron reducing bacteria (Lovley et al., 1990; Roh et al., 2002), sulphate reducing bacteria (Lovley and Chapelle, 1995), methanogens (Chapelle et al., 2002) and homoacetogens bacteria (Stevens and Mckinley, 1995).

This raises the question as to what the possible energetic substrates may be for these bacteria. They gain energy and fix carbon by reacting CO_2 and H_2 provided by geochemical processes, instead of undergoing organic matter oxidation.

Hydrogen is known as one of the most energetic substrates for deep subsurface ecosystems; it forms a connexion between the geological world and the biological world, see Fig. 1 (Nealson et al., 2005). But where does hydrogen come from?

Hydrogen is produced by abiotic and biotic processes. When dealing with abiotic processes, hydrogen is a product of various chemical reactions.

(i) Interactions of hot anaerobic water (90–100 °C) with highly reduced iron-containing rocks ($FeO + H_2O \rightarrow H_2 + FeO_2$), a process called serpentinization of ultrafamic rock systems. Though this process may not support microbial metabolism in subsurface as discussed by Anderson et al., 1998, other major abiotic systems have been studied.
(ii) Active volcanic activities or seismic activity in deep faults tapping the lower crust generate volatile compounds such as H_2, CO_2, and H_2S.
(iii) And finally some (Lin et al., 2005a, 2005b) have proposed a significant H_2 production consistent with that predicted by the radiolytic dissociation of water during the radioactive decay of natural radionuclides U, Th, and K in the host rock.

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doi:10.1016/j.pce.2011.10.010

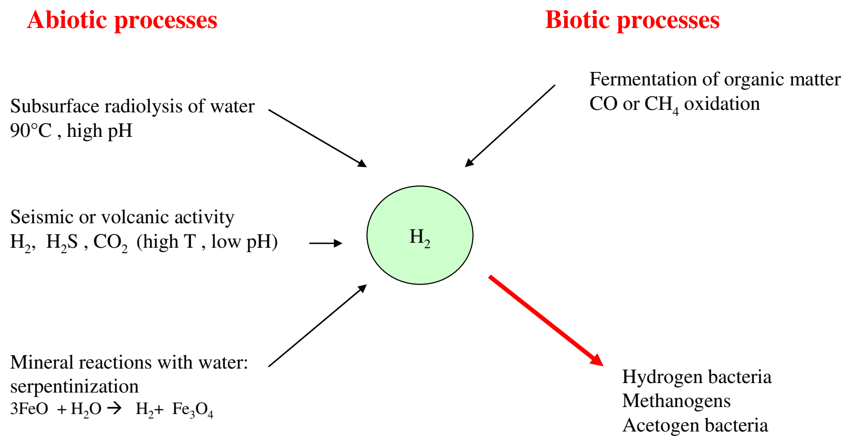

Fig. 1. Role of hydrogen in the connexion between the geological world and the biological world (Nealson et al., 2005).

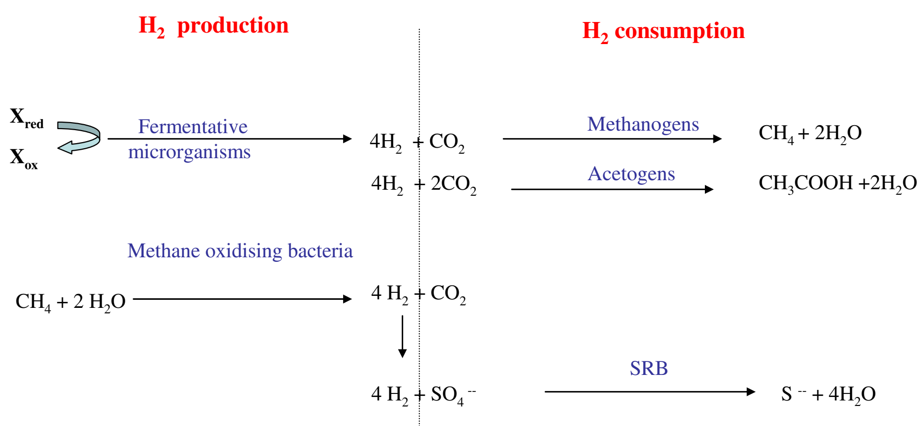

Fig. 2. Hydrogen ecosystems: interspecies hydrogen transfer.

In addition, biotic processes produce H_2 by fermentation of organic matter according to heterotrophic bacteria, or by anaerobic oxidation of CO and CH_4.

2. Hydrogen metabolism

2.1. Hydrogen ecosystems

H_2-producing microorganisms are thermodynamically controlled by the abundance of H_2, but only survive thanks to H_2 consumers which keep the hydrogen concentration in the right range. An example of this reaction is the fermentation of organic acids to shorter acid molecules plus CO_2 and H_2 i.e. $CH_3CH_2CH_2COOH + 2H_2O \rightarrow CH3COOH + 2CO_2 + 6H_2$. The thermodynamic barrier to this reaction ($\Delta G^0 = 39.2$ kJ/mole of electrons) can be overcome by coupling this reaction with H_2 consumers such as methanogenic bacteria catalysing a thermodynamically favourable methanogenesis (Fig. 2). A similar process occurs by sulphate-reducing bacteria which removes H_2 and facilitates the anaerobic oxidation of CH_4 to CO_2, a phenomenon called interspecies hydrogen transfer. The H_2 concentration is kept very low: a steady state is reached in which the production rate is equal to the consumption rate (Heimann et al., 2010).

2.2. Metabolic processes of H_2 utilisation

Many bacteria are able to oxidise hydrogen either under aerobic or under anaerobic conditions, see Table 1. H_2 is linked to the

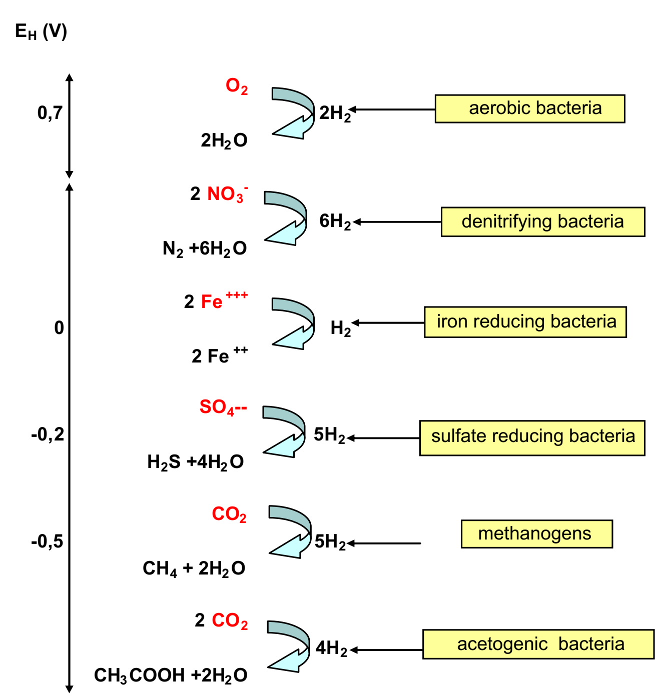

Fig. 3. Reactions catalysed by hydrogen-oxidising bacteria: vertical distribution of thermodynamical hydrogen metabolism (Heimann et al., 2010).