JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A CRITICAL REVIEW ON HYDROGEN STORAGE AND MICROBIAL ACTIVITIES IN SUBSURFACE

[1] **Amal Chandar,** [2] **Hridai Mallick,** [3] **Someshwar Dodda**

[1,2,3,4] Department of Chemical and Petroleum Engineering, School of Chemical Engineering and Physical Sciences, Lovely Professional University, Punjab, INDIA.

Abstract:

The goal of reducing CO_2 emissions to net zero in the coming decades by reducing traditional fossil fuel energy systems has been implemented in the industry for a long time. However, there has been a significant change in the solar and wind energy-driven economy system, which has turned out to be quite beneficial for humankind. Since this energy in the form of electricity cannot be stored on a large scale to balance the energy fluctuations, the need for storing hydrogen gas in Indian subsurface depleted reservoirs because of their immense storage volume will serve as an excellent opportunity. Underground storage has been proven to store a tremendous amount of energy after converting it into hydrogen. It has higher energy content per unit mass than other gases such as methane and natural gas, as the calorific value of hydrogen is roughly twice that of the conventional fossil fuels energy system. The overall efficiency of injecting and reproducing hydrogen for both homogenous and heterogeneous reservoirs will be analysed using numerical reservoir simulation to identify the displacement process. Storing hydrogen comes with more significant challenges, such as bacterial conversion in reservoirs and potential losses. These will be carried throughout the study and serve as a great alternative to a sustainable future. This paper reviews the feasibility and technical aspects of underground hydrogen storage, mainly depleted gas reservoirs, natural or artificial salt caverns, and saline aquifers. The purity of hydrogen produced, leakage from the reservoir, interactions with formations, formation fluids, microbes, the effect of cushion gas, rock properties other challenges in storage will be briefly discussed.

Keyword: Underground storage, biocides, rock properties, hydrogen storage, applications, ATP, MPN, serial solution.

1.INTRODUCTION

The transition from conventional fuels to sustainable renewable energy sources is critical to mitigate climate change and build a sustainable, reliable, and secure energy system. Hydrogen gas (H_2) will most likely have a significant role in this energy transition (van Renssen, S. (2020)). Hence, large-scale energy storage that mitigates production variability is considered a crucial element in a global energy force chain for the future (Mohseni, S., & Brent, A. C. (2020)). For H_2 storage in the subsurface, depleted gas reservoirs, depleted oil reservoirs, artificial salt caverns, deep aquifers, rugged rock caverns, and abandoned mines are available (Basniev et al., 2010; Flesch et al., 2018; Heinemann et al., 2018; Caglayan et al., 2020). These subterranean structures are substantially not lifeless (sterile) but harbor a variety of different and diverse microorganisms (Pedrós-Alió and Manrubia, 2016; Varjani and Gnansounou, 2017). In case of H_2 storage, this “microbial biosphere” will be in direct contact with the stored H_2, and the activity of those microbes will directly influence most operating processes.

Hydrogen is a critical microbial metabolite produced and consumed by various organisms in support of different lifestyles. The challenge is to harness these capacities for the practical production of hydrogen as a renewable fuel (Hallenbeck, 2014). Hydrogen concentrations are frequently maintained in low situations due to microbial consumption processes, which may hide an active but cryptic hydrogen frugality (Gregory et al., 2019a). However, the artificial elevation of the H_2 concentration in the subsurface may stimulate the growth of H_2 oxidizing (hydrogenotrophic) bacteria and archaea, then inclusively appertained to as microorganisms, with possible adverse counteraccusations for gas injectivity and withdrawal via permeability reduction, H_2 volume loss (Berta et al., 2018; Gregory et al., 2019b).

In underground gas storage sites and oil reservoirs, the most abundant H_2-oxidizers are hydrogenotrophic sulfate reducers that couple H_2-oxidation to sulfate reduction to produce hydrogen sulfide (H_2S); hydrogenotrophic methanogens that reduce carbon dioxide (CO_2) to methane (CH_4) by oxidizing H_2; and homo-acetogens that couple H_2 oxidation to carbon dioxide (CO_2) reduction to produce acetate (Gregory et al., 2019b; Pannekens et al., 2019; Dopffel, Jansen and Gerritse, 2021). Microorganisms can be present and active in various locations for underground H_2 storage. The chance of microbial activity is highest in aquifers and former gas reservoirs and lower for salt caverns. However, specific conditions will explosively depend on the specific original conditions and are possible in all cases. Potential effects include the microbial transformation of stored H_2, resulting in undesired side products (such as hydrogen sulfide, methane, and acids), corrosion and clogging, and dissolution of the reservoir material. These transformations are mediated by microorganisms, particularly sulfate reducers, methanogens, and acetogenins. These microbially triggered effects have already been reported in field and laboratory experiments, but more experience from more field sites is needed to make general predictions on microbial risks. Countermeasures such as biocides might be effective but always have to be applied with care, and their effect on H_2 consumption needs to be evaluated. As microbial effects of H_2 storage result from a complex interplay between microbiology, geochemistry, and physics, which is site-specific and largely unknown, more knowledge should be gained through laboratory, field, and modeling research, using a cross-disciplinary approach involving microbiologists, physicists, chemists, and engineers. This review will summarize the main microbial aspects during industrial H_2 storage in the subsurface and potential ensuing problems. Furthermore, this review aims to describe and explain microbial processes for engineers, operators, and alike to help understand microbial risks and successfully implement H_2 UGS in the future.

2. UNDERGROUND HYDROGEN STORAGE AND ITS MECHANISM

An implemented UHS field requires a good understanding of the governing bodies and mechanisms of the storage cycle along the depleted body. The mixture of Hydrogen and several other gases in an allegation can either play the role of cushion gas or serve as a way of good withdrawal injection rate instead of storing pure Hydrogen. There had been a lot of site experiences while storing CO_2 and natural gases, which are considered extensive. Although the process of storing CO_2 is similar to the structure required for storing Hydrogen, a higher amount of CO_2 can be stored as a long-term implementation since the process of storing CO_2 is not cyclic and the process is termed CO_2 sequestration (Ajayi et al, 2019, Belhaj et al, 2017)).

The storage of Hydrogen in a porous medium (either aquifers or depleted reservoirs) is kept in consideration to that of natural gas of a well confined porous and permeable formation bounded by impermeable cap rock or seal geological structure looking into Hydrogen losses. Due to the variation of the physicochemical properties of Hydrogen to that of natural gases because of its less density, viscosity, and molecule size hydrogen, while maintaining several withdrawal frequencies, there could be potential losses (Carden et al, 1979).

In the case of aquifers, the injection pressure of Hydrogen should generally be higher than that of the reservoir natural pressure so that water can easily be displaced from the depleted site. However, due to the less viscosity and density, fingering and gas overriding of injected hydrogen are obvious in the situations of maintaining constant pressure and variable volume over the period of months and constant volume and variable pressure over the period of days in the aquifer (Carden et al (1979)). Although, the injection of Hydrogen is also governed by many geometrical factors such as porosity, permeability, and reservoir geometry as well as the fluids saturation and well locations; which can be best described using Darcy's law and multiphase transport equations. Due to the various phenomenon's occurring the location of the transition zone in contrast to hydrogen and water saturation can be estimated using the capillary pressure and relative permeability curves and this phenomenon greatly depends on the mobility ratio of the fluid phases (Sáinz-García, et al (2017), Hagemann et al (2015)).

The unbalanced reaction between the active forces in the reservoir along with the high injection rate can significantly lead to higher hydrogen losses and since the saturation during each storage and withdrawal cycle changes so a flow behavior is recommended to avoid the losses generated (Feldmann et al (2016), Sáinz et al (2016), Pfeiffer et al (2016)). Reservoirs with low heterogeneity and through proper selection of injection rates can help to control losses due to residual gas saturation and solution into connate water, diffusion and dissolution losses, pumping losses (Coats et al (1967)).

The withdrawal of stored Hydrogen needs to be very frequent to meet the market demand at a very high rate which is difficult to be achieved because of the loss of the inflow and the reservoir pressure also the time-dependent expansion of gases inside the reservoir during the withdrawal stage. As a result of this, some amount of unrecovered gas remains inside the huge reservoir (approximately one-third of the total capacity). Therefore, gases such as CO_2, CH_4, and N_2 are used as a cushion gas to pressurize or maintain the reservoir pressure. Although, cushion gases can also lead to Hydrogen losses, therefore the amount of hydrogen mixed into cushion gas is normally 1-3% (Srinivasan & B. S. (2006)). A similar issue may arise in the case of a depleted oil reservoir where a portion of Hydrogen gets dissolved in the oil phase because of the microscopic or macroscopic trapping, dissolution in connate water or groundwater depending upon the recovery rate, caprock strength, and reservoir heterogeneity, capillary forces, initial and connate water saturation, and diffusion coefficients wherein the solubility is reduced to 1.5 mol. % at 100^0 C at 150 bars in heavy oil (Torres et al (2013)). Now, depending upon the extent of fingering, gas dissolution and diffusion, mixing, surface tension, solubility, water saturation, capillary effect, and withdrawal rate, some unwanted phases such as free water, water vapor, and other contaminated gases might be produced along the main Hydrogen stream which results in additional losses of energy-requiring effort, equipment, processes, and energy to remove these from the hydrogen (Hassannayebi, N., Azizmohammadi, S., De Lucia, M., & Ott, H. (2019), Walters, A. B. (1976), Hagemann, B., Rasoulzadeh, M., Panfilov, M., Ganzer, L., &Reitenbach, V. (2016), GUT, D. (2017)).

Likewise, the forenamed hydrodynamic, geochemical must be covered because each exertion can lead to the loss of hydrogen or affect the chastity of hydrogen. Utmost of the monitoring ways have been espoused and applied grounded on the experience of other geological sites similar as carbon dioxide insulation and natural gas storehouse. The monitoring of carbon isotopy could be more instructional as it provides the extent and kinetics of methane products due to the bacterial responses of hydrogen (Lord, A.S.

(2009)). Chemical and electrochemical tools and ways could be useful to estimate the microbial effect on hydrogen using an abiotic batch reactor in a triphasic water/ gemstone/ gas terrain under high hydrogen pressure (Truche, L., Berger, G., Destrigneville, C., Guillaume, D., &Giffaut, E. (2010), Panfilov, M. (2016)).

3. APPLICATIONS OF STORED HYDROGEN ENERGY

Power-to-fuel online is a utility that generally makes use of electric-powered electricity to produce a flammable fuel line. As hydrogen is assumed to be a flammable Fueloline with as an alternative excessive strength density, electricity-to-hydrogen applications Are gaining momentum. The hydrogen produced via way of means of an electrolyzer can then be methanated into methane and injected into the herbal fuel online grid, or stored, presenting a balancing provider to the strong market. New hydrogen markets need to be advanced withinside the coming decades. Hydrogen as a promising strength transition answer must be taken into consideration in all factors which have suffered from resource exhaustion and pollution: industry, trucking, aviation, shipping, chemical sectors, etc. Besides, growing onboard hydrogen programs also can reduce the want to boom the ability of grid infrastructure for vehicle charging. As the hydrogen refueling infrastructure may be considered Withinside the mild of the present fuel and diesel stations, the recharging Stations for opportunity electric powered automobiles ready with batteries may be much less in demand (Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., &Hissel, D. 2021).

Hydrogen fuelling from metallic hydrides has been appreciably used for numerous stationery and cellular applications. One such Software becomes used to run an inner combustion engine Wherein the warmth of decomposition for the release of hydrogen from Metal Hydride is provided through the Engine. When the hydride mattress is exhausted it can be recharged through Hydrogen (Jain, I. P. 2009).

Generally, hydrogen can be used for petroleum refining (Barreto, L., Makihira, A., &Riahi, K 2003). ammonia production and, to a lesser extent, steel refining which includes nickel, tungsten, molybdenum, copper, zinc, and uranium, and leads It amounts to extra than 50 million metric tonnes international in 2006 (Richards, M., & Shenoy, A. 2007). In the future, hydrogen is probable for use as gasoline in nearly all Packages wherein fossil fuels are used today. For transportation, in particular, hydrogen might provide instantaneous advantages in phrases of decreased pollutants and a purifier environment (Barbir, F.2009).

Water electrolysis may also play a critical function in this machine because it produces hydrogen the usage of renewable electricity as a gasoline fuel line for heating packages and as an electricity storage mechanism. When considerable renewable electricity is available, immoderate electricity can be saved withinside the shape of hydrogen via way of means of water electrolysis. The saved hydrogen can then be utilized in gasoline cells to generate energy or used as a gasoline fuel line (Isherwood, W., Smith, J. R., Aceves, S. M., Berry, G., Clark, W., Johnson, R., ... & Seifert, R. 2000).

The power generated with the aid of using the renewable Strength is both merged into the grid or used to supply hydrogen OR zinc. With this sort of hybrid strength system, 50% of diesel gasoline and30% annual price financial savings with the aid of using wind generators have been estimated. Energy Garage gadgets along with phosphoric acid gasoline molecular and zinc-air gasoline Mobileular have been discovered to be beneficial to lessen the gasoline intake further (Young, D. C., Mill, G. A., & Wall, R. 2007).

Fuel cells integrate hydrogen and oxygen to make water and convey power in the manner. Only 40% of the power launched in the recombining manner is used to make energy. The different 60% is misplaced as waste heat. With co-generation, as plenty as 90% of the power launched may be recovered. Fuel Cells want to heat up so that they will produce their rated capacity. This heat-up time can Lead them to a beside-the-point software for call for power. Fuel cells require plenty of Extra area than thermal engines for the identical given capacity. Despite the limitations of gasoline cells, maximum proponents of hydrogen (Berndt, D. 2004).

Based on the growing strain of electricity saving and emission discount and wanting to are seeking for the leap forward technology to beautify the competitiveness for the iron and metallic enterprises, growing the hydrogen share of discount gases to reap hydrogen metallurgy manufacturing is being studied widely, which can't simply lessen CO_2 emissions, but additionally aid the sustainable improvement of metallic plants (Shao-bo, Z. H. E. N. G. 2012).

Present, the packages of hydrogen in steel enterprises may be more or less divided into aspects:

(1) as lowering agent to lessen iron oxide, in particular worried in BF Manufacturing system and gas-primarily based totally direct discount iron (DRI)System;

(2) as gas for heating, inclusive of assistant sintering Manufacturing, palletizing system, heating ladle furnace (Liu, W., Zuo, H., Wang, J., Xue, Q., Ren, B., & Yang, F. 2021).

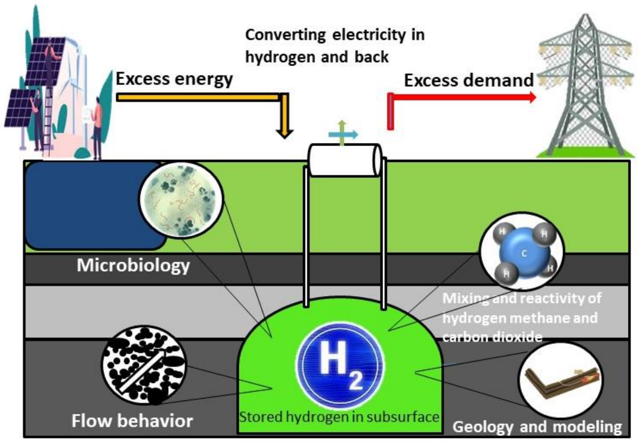

Figure1. Usage of Hydrogen and reconversion

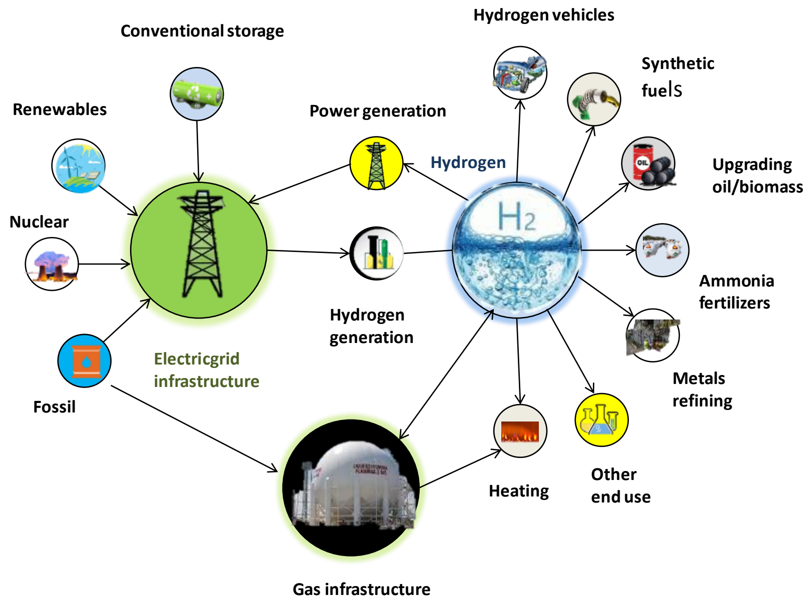

Figure 2. Different applications of storing Hydrogen as an energy carrier

Figure 3. Various sources of applied use of Hydrogen energy

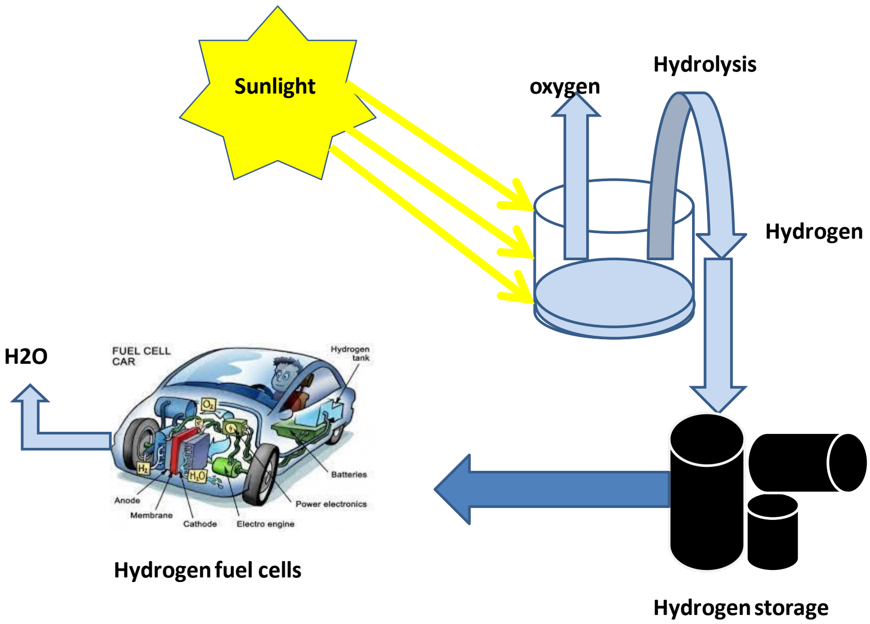

Figure 4. Hydrogen conversion diagram into energy sources

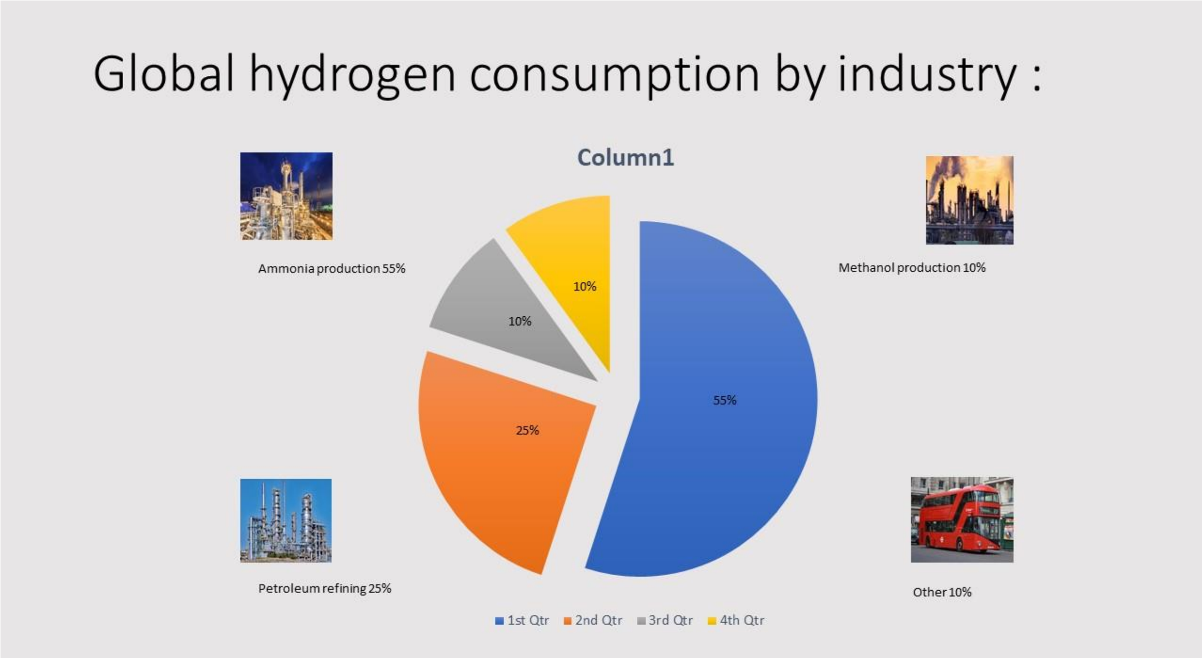

Figure 5. Industrial usage percent ratio of hydrogen consumption

4. DETECTION METHODS OF MICRO-ORGANISMS IN HYDROGEN STORAGE

The detection of bacteria in the subsurface is essential for the understanding of rate of corrosion, Microbiologically Induced Souring (MIS) and other treatments in oil and gas recovery and underground hydrogen storage (Cowan, 2005; Morris et. al, 1994). Some of the majorly used detection methods for microbes is:

4.1 API SERIAL DILUTION METHOD

The method is used to detect and estimate the number of micro-organisms present in a given sample. The method is carried out by the dilution of the sample with a suitable diluent, which can be distilled water or 0.9% concentrated saline water accordingly. The dilution is done to different concentrations as a step-by-step procedure. Finally, the diluted samples are kept in an agar plate for the culture and determination of the size and number of the microbial colonies present in the sample. This method takes 28 days to get the final result (David and Davidson, 2018).

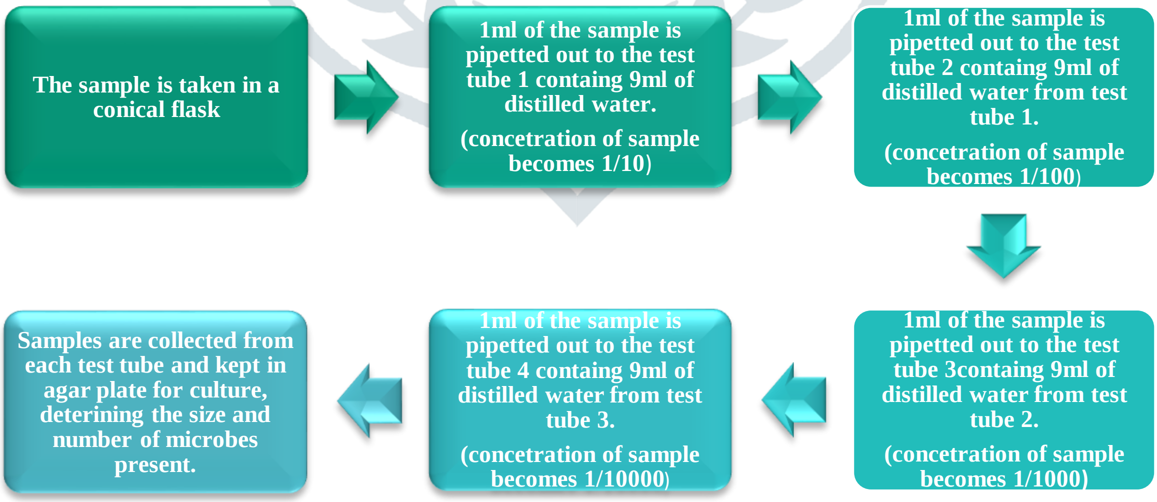

Figure 6. Experimental descriptive diagram of API dilution method

4.2 ATP METHOD OR ENZYMATIC ASSAY

Adenosine triphosphate ($C_{10}H_{16}N_5O_{13}P_3$) is the energy carrying molecule, which is the keystone of metabolic activity in a living organism. The energy is also stored and transported in the form of ATP. The ATP will convert to Adenosine monophosphate, Adenosine diphosphate depending upon the cellular requirements of the organism (Knowles, 1980). The method can be conducted and results can be obtained in minutes rather than days and do not require any cultural mediums (Whalen et al, 2018). The ATP molecule will only be present in a living organism where the metabolic activity is taking place. The higher ATP levels in an organism indicates greater mass and cell volume (Johnston et al. 2012). This detection method is carried out by introducing luciferin to the sample (containing ATP) in the presence of luciferase enzyme (catalyst). Luciferin is a light emitting compound seen in the living organisms which initiates bioluminescence. The catalyzed reaction of luciferin with oxygen results in emission of light as an exited state intermediate is produced and decayed to the ground state (Hastings, 1996). The ATP can be measured by measuring the intensity of light which is created due to the bioluminescence reaction when the sample cells are exposed to luciferin and luciferase as the chemical energy produced from ATP breakdown is transformed into light energy (Whalen et al, 2018). The amount of light generated is measured using luminometer and is expressed in Relative Light Unit-RLU (Berthold et al. 2000).

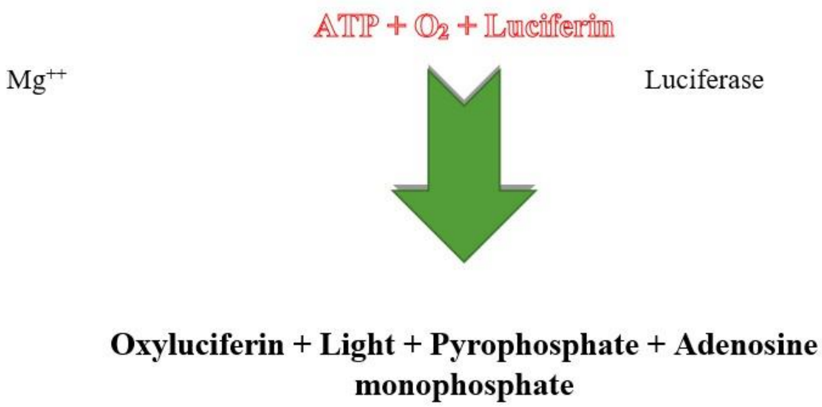

Figure 7. Diagram of ATP enzymatic method

4.3 COLORIMETRIC METHOD

This method includes passing light through the microbial containing sample using a colorimeter. The absorbance of the sample (coloured) is measured when the light is passing through the cuvette which is placed in the colorimeter and further analysis is done with the help of Beer-Lambert's law (Greenan et al, 1995).

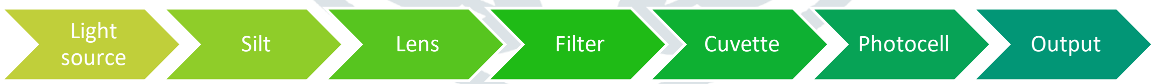

Figure 8. Indicative colour diagram of light source passing via colorimeter

4.4 MOST PROBABLE NUMBER TECHNIQUE

Most probable number technique is the tradition way of detecting and computing the number of bacteria (Barton and Hamilton, 2007; Oblinger and Koburger, 1975). The method uses changes in the color of the solution to identify the number of bacterial colonies present in the sample. The sample added in different amounts to the sets of test tubes which is initially contains a suitable broth for the growth of the bacteria. After the addition of samples to the test tube, it is incubated for 24 hours at a temperature of 37ºC. After the incubation period the color changes in the solution in test tubes are noted and counted. The color change is due to the activity of bacteria as the broth is been provided. The ratios are taken with respect to the color change and compared with respect to a standard reference table and the MPN number and confidence index is calculated (Bennet, 2016; Oblinger and Koburger, 1975).

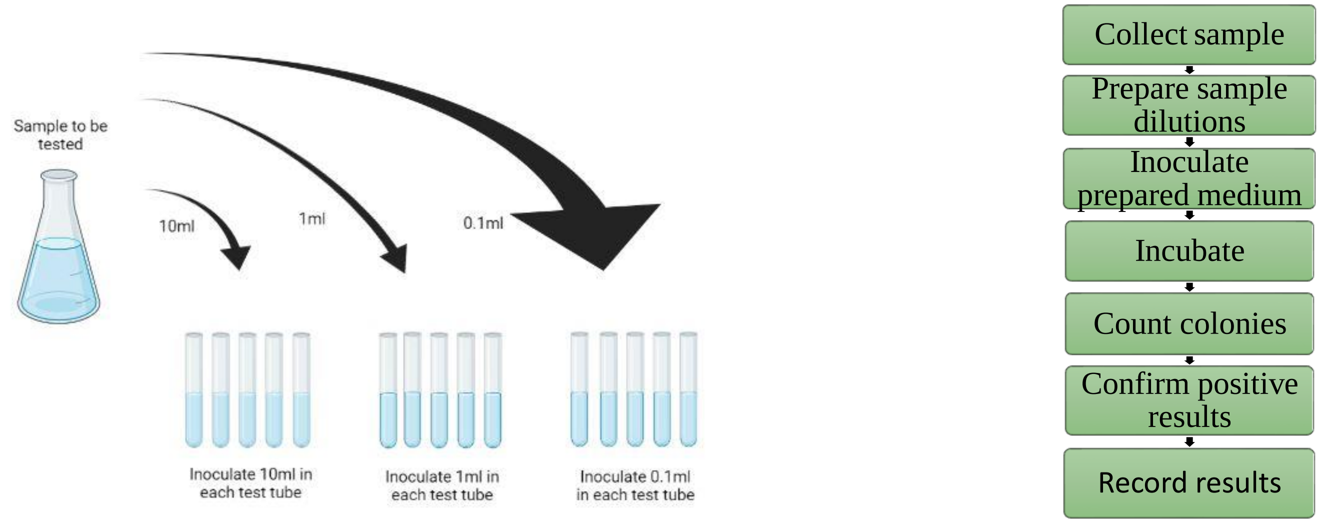

Figure 9. Diagram of steps followed in MPN Technique

5. ASSESSMENT OF THE ACTIVITY OF BIOCIDES

The most common thing in the oil and gas industry is the contamination of these microbial activities which can cause serious problems and reduce the quality of the hydrocarbon which is produced. Maintaining biological control in the oilfield is critical. The main and key problems caused due to these microbiological activities are sulfate-reducing bacteria and acid-producing bacteria (Williams, T. M., & Schultz, C. M. (2015, April)).

Biocides have also played a role for many decades in the oil and gas industry mainly in secondary oil recovery techniques like water flooding same these biocides can also be used in this hydraulic fracturing this microbial control is the key thing in the process of hydraulic fracturing because it may lead to clogging (Kahrilas, G. A.et al., Blotevogel, J., Stewart, P. S., Borch, T 2015). These microbial activities can be reduced and controlled by a relatively less amount of Biocides including glutaraldehyde, quaternary ammonium compounds (quats), cocodi-amine, acrolein, tetrakishydroxymethylphosphonium sulfate (THPS), and dibromonitrilopropionamide(DMNPA). (McGin-Ley et al., 2011; Williams and Cooper, 2014).

At present days some nonoxidizing biocides which are new to this oil and gas domain showing some effectiveness in sulfate-reducing bacteria and acid-producing bacteria which include 2-hydroxymethyl-2-nitropropane-1,3-diol (THNM), 1-(3-chloroallyl)-3,5,7-triaza-1-azoniaadamantane chloride (CTAC), And 4,4-dimethyl oxazolidine (DMO) (Enzien et al., 2010)

Oxidizing biocides normally can be used for the water treatment process and has a good grip on controlling these microbial activities in this oil and gas industry these include chlorine dioxide, sodium hypochlorite, peracetic acid, and ozone (Rimassa et al., 2011). Based on the compatibility and stability these non-oxidizing and oxidizing biocides can be used to control the microbial activities in hydraulic fracturing. The process of these biocides can be expressed in three phases:

Phase 1: This phase mainly controls and pretreatment the top side water before injection for fracturing which reduces the load of microbes in the fracture water. This phase is also called the topside biocide treatment.

Phase 2: This phase is designed to kill the bacteria before and after hydraulic fracturing. This biocide should have good stability and compatibility to perform in moderate conditions.

Phase 3: This microbial phase is developed to protect the reservoir from microbial souring, plugging, and corrosion. In this phase, biocides should remain for more time to kill the growth of the microbes. Because of this the production and quality of the petroleum reserves are enhanced. To control the microbial control in the hydraulic fracturing a variety of Biocides being added.

Table 1. Different biocides added to control microbial growth

Trade name	Chemical formula	MOA	Frequency of use
Gultaraldehyde	$C_5H_8O_2$	E	27%
Dibromo-nitrilopropionamide	$C_3H_2Br_2N_2O$	E	24%
Tetrakishydroxymethylphosphonium sulfate	$C_8H_{24}O_{12}P_2S$	E	9%
Didecyl dimethyl ammonium chloride	$C_{22}H_{48}ClN$	L	8%
Chlorine dioxide	ClO_2	O	8%
Tributyl tetradecyl phosphonium chloride	$C_{26}H_{56}ClP$	L	4%
Alkyl dimethyl benzyl ammonium chloride	$C_{19}H_{34}clN$	L	3%
Methylisothiazalinone	C_4H_5NOS	E	3%
Sodium hypochlorite	NaClO	O	3%
Dazomet	$C_5H_{10}N_2S_2$	E	2%
Dimethyloxazolidine	$C_5H_{11}NO$	E	2%
Trimethyloxazolidine	$C_6H_{14}NO$	E	2%
N-bromosuccinimide	$C_4H_4BrNO_2$	E	1%
Bronopol	$C_3H_6BrNO_4$	E	<1%
Peracetic acid	$C_2H_4O_3$	O	<1%

These biocides can also be often as the fluids in oil field industry can be used for well constriction and we'll stimulation. Then these biocides do kill the microbes in the wellbore and will increase the stability of the well bore. A new liquid oxidizing biocide introduced recently and relates to stabilized bromine chloride. The effectiveness of this biocide is more compared to others and this product was penetrating and removing the biofilms but it was a bit stabilized bromine is also called as self-regulating biocide which produces HOBr as needed. These biocides produce HOBr under controlled conditions only. (Carpenter, J. F., &Nalepa, C. J. 2005).

6. ADVERSE EFFECTS OF MICROORGANISMS ON HYDROGEN STORAGE

6.1 HYDROGEN LEAKAGE

Underground gas storage sites have a prominent issue of gas leakages (Evans, D. J., & Chadwick, R. A. (Eds.). (2009)). Loss through geological cracks, loss of well integrity, functional failures, garrulity through the caprock are the affecting criteria. CH_4 diffusion rate is less than that of H_2 (Reitenbach, V., Ganzer, L., Albrecht, D., & Hagemann, B. (2015)) and because of which the saturated/mixed liquid of concentrated H_2 gas mixtures can enter the geological horizons during the long- term storage. Due to the arrival of the gas above the surface, the water and soil- chemistry could be triggered affecting the microbiology of the surface.

6.2 CHANGES IN CONCENTRATION OF GAS- MIXTURE

A substantial lead of gases such as CH_4 and H_2S can increase with the simultaneous decline/ rise of CO_2 due to microbial activity inside depleted field consuming H_2 which would decrease its concentration. Various site structures, material integrity, health and safety could be affected due to the increase in H_2S concentration and therefore, would require gas treatment. The overall H_2 concentration within the total/injected gas can also decline by the operations conducted via introduction of available electron and cell number acceptors during field site conditions. Due to the diffusion of H_2 gas during injection/ production cycles into porous spaces, there could be absurd loss during initial stages and decrease during the time. *Methanogenesis/ Acetogenesis* would occur due to the associated decline of CO_2 as well promoting microbial activity. Now because of the methane production in the existing system and criteria mentioned above, *Methanomicrobiales, Methanobacteriales, Methanopyrals, Methanococcals and Methanosarcinales* will be created leading to microbial activity under several conditions (Basso, O., Lascourreges, J. F., Le Borgne, F., Le Goff, C., & Magot, M. (2009), Enzmann, F., Mayer, F., Rother, M., & Holtmann, D. (2018)).

In addition, higher presence of bacteria such as *Clostridium, Acetogenium, Acetobacterium, Acetoanaerobium* can take place due to the increase of acetate and loss of H_2 during *Acetogenesis* (Zabranska, J., & Pokorna, D. (2018)), with a drop in pH.

6.3 MICROBES CAUSING STEEL CORROSION

The aforementioned problem of deterioration of steel infrastructure, subsurface installation, various surrounding is cited by *Microbially influenced corrosion (MIC)*. The corrosion of steel infrastructures and posterior equipment failure is identified by the complex interplay between abiotic and biotic erosion leading to the formation of microbial biofilms on the surface and have a very common appearance in the environment (Donlan, R. M. (2002)). The biofilm acts as a defending guard consisting of exopolymer substances such as sugars, proteins, nucleic acids, etc., which reduces the physical and chemical stresses occurring. Biofilms and corrosion problems are generally caused through sulphate- reducing microorganisms, acid- producing microbes, methanogens, and the latter is identified below a biofilm because of the proximity of redox and chemical factors inside the biofilm (Vigneron, A., Held, I. M., & Tsesmetzis, N. (2018)). The ongoing corrosion however can be caused because of the large cell figures in the liquid/ solid phase specifically the sulphate reducers (Eckert, R. B., & Skovhus, T. L. (2018), El-Shamy, A. M., Soror, T. Y., El-Dahan, H. A., Ghazy, E. A., & Eweas, A. F. (2009)). H_2 can play a role in this process as an electron donor, leading to the growth of microbial biofilms, and can also be a product of corrosion reactions (Atta, N. F., Fekry, A. M., & Hassaneen, H. M. (2011)). Furthermore, microbially formed H_2S can enhance corrosion rates and lead to H_2S induced stress-cracking (Bai, P., Zhao, H., Zheng, S., & Chen, C. (2015)).

6.4 MINERAL DISSOLUTION AFFECTING ROCK PROPERTIES

The drop in pH of the reservoir fluid is caused by heterotrophic microbes, acid- producing microbes, acetogenins and the produced acids lead may lead to the dissolution of carbonate minerals releasing CO_2/HCO^{3-}. The dissolution of carbonate minerals will lead to change in permeability and porosity, fluid flow and behaviour of the reservoir and the dissolved carbonates will promote enhanced microbial growth and activity as a carbon source with higher concentration of CO_2 in the reproduced fluids. Due to the microbial activity, the enzymatic reactions would release surplus of heat leading to exothermic condition (Bayne-Jones, S., & Rhees, H. S. (1929)).

6.5 SOURING OF H_2S FORMATION IN THE SUBSURFACE

The formation of corrosive and toxic H_2S gas is identified by active microbial sulphate reduction (Kleinitz, W., & Boehling, E. (2005, June)). Sulphide minerals such as gypsum or anhydrite contains dissolved sulphate which are present in the underground hydrogen sites experiences microbial activity in the presence of bacteria on gas quality (Kleinitz, W., & Boehling, E. (2005, June)). Sulphate reduction is enhanced by easily available carbon sources like organic acids/ ethanol in the presence of H_2 and because of which low amounts of sulphate can be generated leading to increase in H_2S (Oren, A. (2008), Pallud, C., & Van Cappellen, P. (2006)). Dissolved ferrous ion/ mineral will lead to decrease in dissolved iron and sulphide concentrations in the reproduced fluids as a result of H_2S precipitating with the Fe^{2+} ions.

6.6 MICROBIAL ACTIVITY CAUSING INDUCED PLUGGING

A porous system like rock or sediment, is affected by microbial triggered mineral precipitations, microbial biomass (*proliferation of cells and associated biofilm structures*) and exopolymers which leads to decrease in the porous spaces of the rocks. The plugging/clogging caused also affects the pore space in the pipelines and associated surfaces (Kryachko, Y. (2018)). As discussed, FeS minerals will be precipitated because of dissolved ferrous ion ultimately leading to sulphate reduction producing H_2S. *Ferrihydrite, geothite, magnetite* are some ferric iron minerals which are produced because of Fe oxidizing microbes in lower nitrate or oxygen concentrations. Plugging is frequently caused through large amounts of biofilms and minerals which are especially microaerophilic iron- oxidizers through an oxygen doorway. Biomass/ mineral plugging identified as *Microbial-induced carbonate precipitation (MICP)* is another plugging cause which is long-term and severe since the biofilms are limitedly close inside the matrix phenomenon of the rock promoting mineral disintegration termed as mineral rush which is however more stable than the MICP (Martin, D., Dodds, K., Butler, I. B., & Ngwenya, B. T. (2013)).

7. CONCLUSION

Hydrogen is produced through water electrolysis by introducing it to the electrode cells. Renewable energy development was introduced to decarbonize the traditional systems, which has imposed seasonal variations. The excess produced electricity through solar and wind energy can be converted into oxygen and hydrogen into depleted reservoirs and would provide an option to restore and re-convert the hydrogen to electricity in periods with changing energy crises. Wind energy has an average energy output of 18%, whereas Hydrogen has a versatility of applications either produced through natural gas or electrolysis and has a compelling energy output of 55%. The use of hydrogen storage and electricity regeneration will create a significant change in the renewable sector of the Indian sub-continent and will promote more remarkable green energy changes.

The proposed project/ research work will significantly focus on the energy crisis faced in the country and will provide a greener energy source rather than carbon-based fossil fuel energy by reducing the carbon footprints. As the current world is doing to minimize the number of fossil fuels by depending more on renewable energy sources, introducing the concept of a novel hydrogen economy will serve a great purpose here. The project will highly deviate towards hydrogen storage in Indian depleted gas reservoirs and the rock properties and the chemical reactions taking place. The study will improve the hydrogen losses faced while storing and injecting hydrogen into the reservoir. The vital energy fluctuating nature from other energy renewable sources requires a buffer to store that vast energy and fulfil the demand constantly.

8. ACKNOWLEDGEMENT

It is a privilege to lay earnest thanks to our guide **Mr. Vishesh Bhadariya**, Assistant Professor, Department of Petroleum Engineering, Lovely Professional University, Jalandhar, for their excellent guidance, caring, patience, and providing us with a motivating atmosphere for doing the capstone project. Their expertise motivated us from the inception of this dissertation till the writing of this project report. We could not have imagined having a better advisor and mentor for our project.

We are thankful to **Dr. Kailash Chandra Juglan,** Head of School, Dr. **Prashant Kumar**, Head of Department and distinguished faculty members of the Department of Petroleum Engineering, Lovely Professional University, Jalandhar, for valuable support to help complete our research work in the department has admirable facilities from every aspect as required by any researcher.

Our profound thanks to **Dr. Rohan Kumar** for taking the time to review our capstone project and their valuable feedback.

Finally, we wish to acknowledge our family, whose infinite patience and understanding are never taken for granted and provided us with the energy to complete this work.

REFERENCES

[1] van Renssen, S. (2020). The hydrogen solution? *Nature Climate Change*, *10*(9), 799-801.

[2] Mohseni, S., & Brent, A. C. (2020). Economic viability assessment of sustainable hydrogen production, storage, and utilisation technologies integrated into on-and off-grid micro-grids: A performance comparison of different meta-heuristics. *international journal of hydrogen energy*, *45*(59), 34412-34436.

[3] Basniev, K. S., Omelchenko, R. J., & Adzynova, F. A. (2010). Underground hydrogen storage problems in Russia. *Essen, proceeding WHEC (May 2010)*.

[4] Flesch, S., Pudlo, D., Albrecht, D., Jacob, A., & Enzmann, F. (2018). Hydrogen underground storage—Petrographic and petrophysical variations in reservoir sandstones from laboratory experiments under simulated reservoir conditions. *International Journal of Hydrogen Energy*, *43*(45), 20822-20835.

[5] Heinemann, N., Booth, M. G., Haszeldine, R. S., Wilkinson, M., Scafidi, J., & Edlmann, K. (2018). Hydrogen storage in porous geological formations–onshore play opportunities in the midland valley (Scotland, UK). *International Journal of Hydrogen Energy*, *43*(45), 20861-20874.

[6] Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., & Stolten, D. (2020). Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*, *45*(11), 6793-6805.

[7] Pedrós-Alió, C., & Manrubia, S. (2016). The vast unknown microbial biosphere. *Proceedings of the National Academy of Sciences*, *113*(24), 6585-6587.

[8] Varjani, S. J., & Gnansounou, E. (2017). Microbial dynamics in petroleum oilfields and their relationship with physiological properties of petroleum oil reservoirs. *Bioresource technology*, *245*, 1258-1265.

[9] Hallenbeck, P.C. (2014) "Microbial paths to renewable hydrogen production," http://dx.doi.org/10.4155/bfs.11.6, 2(3), pp. 285–302. doi:10.4155/BFS.11.6.

[10] Gregory, S.P. et al. (2019a, b) "Subsurface Microbial Hydrogen Cycling: Natural Occurrence and Implications for Industry," Microorganisms, 7(2). doi:10.3390/MICROORGANISMS7020053.

[11] Berta, M., Dethlefsen, F., Ebert, M., Schäfer, D., & Dahmke, A. (2018). Geochemical effects of millimolar hydrogen concentrations in groundwater: an experimental study in the context of subsurface hydrogen storage. *Environmental science & technology*, *52*(8), 4937-4949.

[12] Pannekens, M. et al. (2019) "Oil reservoirs, an exceptional habitat for microorganisms," New biotechnology, 49, pp. 1–9. doi: 10.1016/J.NBT.2018.11.006.

[13] Dopffel, N., Jansen, S. and Gerritse, J. (2021) "Microbial side effects of underground hydrogen storage – Knowledge gaps, risks and opportunities for successful implementation," International Journal of Hydrogen Energy, 46(12), pp. 8594–8606.

[14] Ajayi, T., Gomes, J. S., & Bera, A. (2019). A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. *Petroleum Science*, *16*(5), 1028-1063.

[15] Belhaj, H., & Bera, A. (2017). A brief review of mechanisms for carbon dioxide sequestration into aquifer reservoirs. *International Journal of Petroleum Engineering*, *3*(1), 49-66.

[16] Carden, P. O., & Paterson, L. (1979). Physical, chemical and energy aspects of underground hydrogen storage. International Journal of Hydrogen Energy, 4(6), 559-569.

[17] Sáinz-García, A., Abarca, E., Rubí, V., & Grandia, F. (2017). Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. International Journal of Hydrogen Energy, 42(26), 16657-16666.

[18] Hagemann, B., Rasoulzadeh, M., Panfilov, M., Ganzer, L., & Reitenbach, V. (2015). Mathematical modeling of unstable transport in underground hydrogen storage. Environmental Earth Sciences, 73(11), 6891-6898.

[19] Feldmann, F., Hagemann, B., Ganzer, L., & Panfilov, M. (2016). Numerical simulation of hydrodynamic and gas mixing processes in underground hydrogen storages. Environmental Earth Sciences, 75(16), 1-15.

[20] Sáinz-García, A., Abarca, E., & Grandia, F. (2016, April). Efficiency and impacts of hythane (CH4+ H2) underground storage. In EGU General Assembly Conference Abstracts (pp. EPSC2016-16603).

[21] Pfeiffer, W. T., Al Hagrey, S. A., Köhn, D., Rabbel, W., & Bauer, S. (2016). Porous media hydrogen storage at a synthetic, heterogeneous field site: numerical simulation of storage operation and geophysical monitoring. Environmental Earth Sciences, 75(16), 1-18.

[22] Coats, K. H., & Richardson, J. G. (1967). Calculation of water displacement by gas in development of aquifer storage. Society of Petroleum Engineers Journal, 7(02), 105-112.

[23] Srinivasan, B. S. (2006). The impact of reservoir properties on mixing of inert cushion and natural gas in storage reservoirs. West Virginia University.

[24] Torres, R., De Hemptinne, J. C., & Machin, I. (2013). Improving the modeling of hydrogen solubility in heavy oil cuts using an augmented Grayson Streed (AGS) approach. Oil & Gas Science and Technology–Revue d'IFP Energies nouvelles, 68(2), 217-233.

[25] Hassannayebi, N., Azizmohammadi, S., De Lucia, M., & Ott, H. (2019). Underground hydrogen storage: application of geochemical modelling in a case study in the Molasse Basin, Upper Austria. Environmental Earth Sciences, 78(5), 1-14.

[26] Walters, A. B. (1976). Technical and environmental aspects of underground hydrogen storage. In 1st World Hydrogen Energy Conference, Volume 2 (Vol. 2, pp. 2B_65-2B_79).

[27] Hagemann, B., Rasoulzadeh, M., Panfilov, M., Ganzer, L., & Reitenbach, V. (2016). Hydrogenization of underground storage of natural gas. Computational Geosciences, 20(3), 595-606.

[28] GUT, D. (2017). The Effects of hydrogen injection in natural gas networks for the Dutch underground storages.

[29] Lord, A. S. (2009). Overview of geologic storage of natural gas with an emphasis on assessing the feasibility of storing hydrogen (No. SAND2009-5878). Sandia National Laboratories.

[30] Truche, L., Berger, G., Destrigneville, C., Guillaume, D., & Giffaut, E. (2010). Kinetics of pyrite to pyrrhotite reduction by hydrogen in calcite buffered solutions between 90 and 180 C: Implications for nuclear waste disposal. Geochimica et Cosmochimica Acta, 74(10), 2894-2914.

[31] Panfilov, M. (2016). Underground and pipeline hydrogen storage. In *Compendium of hydrogen energy* (pp. 91-115). Woodhead Publishing.

[32] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews*, *146*, 111180.

[33] Jain, I. P. (2009). Hydrogen the fuel for 21st century. *International journal of hydrogen energy*, *34*(17), 7368-7378.

[34] Barreto, L., Makihira, A., & Riahi, K. (2003). The hydrogen economy in the 21st century: a sustainable development scenario. *International Journal of Hydrogen Energy*, *28*(3), 267-284.

[35] Richards, M., & Shenoy, A. (2007). H2-MHR pre-conceptual design summary for hydrogen production. *Nuclear Engineering and Technology*, *39*(1), 1-8.

[36] Isherwood, W., Smith, J. R., Aceves, S. M., Berry, G., Clark, W., Johnson, R., ... & Seifert, R. (2000). Remote power systems with advanced storage technologies for Alaskan villages. *Energy*, *25*(10), 1005-1020.

[37] Young, D. C., Mill, G. A., & Wall, R. (2007). Feasibility of renewable energy storage using hydrogen in remote communities in Bhutan. *International journal of hydrogen energy*, *32*(8), 997-1009.

[38] Berndt, D. (2004). Hydrogen energy systems: concepts and practical applications. *Refocus*, *5*(6), 48-51.

[39] Shao-bo, Z. H. E. N. G. (2012). Basic Research on Hydrogen Metallurgy and New Ironmaking Idea-Process. *China Metallurgy*.

[40] Liu, W., Zuo, H., Wang, J., Xue, Q., Ren, B., & Yang, F. (2021). The production and application of hydrogen in steel industry. *International Journal of Hydrogen Energy*, *46*(17), 10548-10569.

[41] Cowan, J. K. (2005, April). Rapid enon of sulfate reducing bacteria. In CORROSION 2005. OnePetro.

[42] Morris III, E. A., Dziewulski, D. M., Pope, D. H., & Paakkonen, S. T. (1994). Field and laboratory studies into the detection and treatment of microbiologically influenced souring (MIS) in natural gas storage facilities (No. CONF-940222-). NACE International, Houston, TX (United States).

[43] Ben-David, A., & Davidson, C. E. (2014). Estimation method for serial dilution experiments. Journal of microbiological methods, 107, 214-221.

[44] Knowles, J. R. (1980). Enzyme-catalyzed phosphoryl transfer reactions. Annual review of biochemistry, 49(1), 877-919.

[45] Whalen, P. A., Tracey, D. R., & Duguay, J. (2018). Adenosine Triphosphate (ATP) measurement technology. Microbiological Sensors for the Drinking Water Industry. IWA.

[46] Johnston, I. G., Gaal, B., Neves, R. P. D., Enver, T., Iborra, F. J., & Jones, N. S. (2012). Mitochondrial variability as a source of extrinsic cellular noise. PLoS computational biology, 8(3), e1002416.

[47] Hastings, J. W. (1996). Chemistries and colors of bioluminescent reactions: a review. Gene, 173(1), 5-11.

[48] Berthold, F., Herick, K., & Siewe, R. M. (2000). Luminometer design and low light detection.

[49] Greenan, N. S., Mulvaney, R. L., & Sims, G. K. (1995). A microscale method for colorimetric determination of urea in soil extracts. Communications in soil science and plant analysis, 26(15-16), 2519-2529.

[50] Barton, L. L., & Hamilton, W. A. (Eds.). (2007). Sulphate-reducing bacteria: environmental and engineered systems. Cambridge University Press.

[51] Oblinger, J. L., & Koburger, J. A. (1975). Understanding and teaching the most probable number technique. Journal of Milk and Food technology, 38(9), 540-545.

[52] Bennet, D. G. (2016, March). Oilfield Microbiology: Detection Techniques Used in Monitoring Problematic Microorganisms Such as Sulphate-Reducing Bacteria SRB. In Offshore Technology Conference Asia. OnePetro.

[53] Williams, T. M., & Schultz, C. M. (2015, April). Effect of Environmental Parameters on the Stability and Performance of Oil and Gas Biocides. In *SPE International Symposium on Oilfield Chemistry*. OnePetro.

[54] Kahrilas, G. A., Blotevogel, J., Stewart, P. S., & Borch, T. (2015). Biocides in hydraulic fracturing fluids: a critical review of their usage, mobility, degradation, and toxicity. *Environmental science & technology*, *49*(1), 16-32.

[55] McGinley, H. R., Enzien, M. V., Jenneman, G., & Harris, J. (2011, April). Studies on the chemical stability of glutaraldehyde in produced water. In *SPE International Symposium on Oilfield Chemistry*. OnePetro.

[56] Williams, T. M., & Cooper, L. E. (2014). The Environmental Fate of Oil and Gas Biocides: A Review. *CORROSION 2014*.

[57] Bottero, S., Picioreanu, C., Enzien, M., Van Loosdrecht, M. C., Bruining, H., & Heimovaara, T. (2010, February). Formation damage and impact on gas flow caused by biofilms growing within proppant packing used in hydraulic fracturing. In *SPE international symposium and exhibition on formation damage control*. OnePetro.

[58] Rimassa, S. M., Howard, P., MacKay, B., Blow, K., & Coffman, N. (2011, April). Case study: evaluation of an oxidative biocide during and after a hydraulic fracturing job in the Marcellus shale. In *SPE International Symposium on Oilfield Chemistry*. OnePetro.

[59] Carpenter, J. F., & Nalepa, C. J. (2005, February). Bromine-based biocides for effective microbiological control in the oil field. In *SPE International Symposium on Oilfield Chemistry*. OnePetro.

[60] Evans, D. J., & Chadwick, R. A. (2009). Underground gas storage: an introduction and UK perspective. *Geological Society, London, Special Publications*, *313*(1), 1-11.

[61] Reitenbach, V., Ganzer, L., Albrecht, D., & Hagemann, B. (2015). Influence of added hydrogen on underground gas storage: a review of key issues. *Environmental Earth Sciences*, *73*(11), 6927-6937.

[62] Basso, O., Lascourreges, J. F., Le Borgne, F., Le Goff, C., & Magot, M. (2009). Characterization by culture and molecular analysis of the microbial diversity of a deep subsurface gas storage aquifer. *Research in microbiology*, *160*(2), 107-116.

[63] Enzmann, F., Mayer, F., Rother, M., & Holtmann, D. (2018). Methanogens: biochemical background and biotechnological applications. *Amb Express*, *8*(1), 1-22.

[64] Zabranska, J., & Pokorna, D. (2018). Bioconversion of carbon dioxide to methane using hydrogen and hydrogenotrophic methanogens. *Biotechnology advances*, *36*(3), 707-720.

[65] Donlan, R. M. (2002). Biofilms: microbial life on surfaces. *Emerging infectious diseases*, *8*(9), 881.

[66] Tsesmetzis, N., Alsop, E. B., Vigneron, A., Marcelis, F., Head, I. M., & Lomans, B. P. (2018). Microbial community analysis of three hydrocarbon reservoir cores provides valuable insights for the assessment of reservoir souring potential. *International Biodeterioration & Biodegradation*, *126*, 177-188.

[67] Eckert, R. B., & Skovhus, T. L. (2018). Advances in the application of molecular microbiological methods in the oil and gas industry and links to microbiologically influenced corrosion. *International biodeterioration & biodegradation*, *126*, 169-176.

[68] El-Shamy, A. M., Soror, T. Y., El-Dahan, H. A., Ghazy, E. A., & Eweas, A. F. (2009). Microbial corrosion inhibition of mild steel in salty water environment. *Materials chemistry and physics*, *114*(1), 156-159.

[69] Atta, N. F., Fekry, A. M., & Hassaneen, H. M. (2011). Corrosion inhibition, hydrogen evolution and antibacterial properties of newly synthesized organic inhibitors on 316L stainless steel alloy in acid medium. *International journal of hydrogen energy*, *36*(11), 6462-6471.

[70] Bai, P., Zhao, H., Zheng, S., & Chen, C. (2015). Initiation and developmental stages of steel corrosion in wet H2S environments. *Corrosion Science*, *93*, 109-119.

[71] Bayne-Jones, S., & Rhees, H. S. (1929). Bacterial calorimetry II. Relationship of heat production to phases of growth of bacteria. *Journal of Bacteriology*, *17*(2), 123-140.

[72] Kleinitz, W., & Boehling, E. (2005, June). Underground gas storage in porous media–operating experience with bacteria on gas quality (spe94248). In *67th EAGE Conference & Exhibition* (pp. cp-1). European Association of Geoscientists & Engineers.

[73] Oren, A. (2008). Microbial life at high salt concentrations: phylogenetic and metabolic diversity. *Saline systems*, *4*(1), 1-13.

[74] Pallud, C., & Van Cappellen, P. (2006). Kinetics of microbial sulfate reduction in estuarine sediments. *Geochimica et Cosmochimica Acta*, *70*(5), 1148-1162.

[75] Kryachko, Y. (2018). Novel approaches to microbial enhancement of oil recovery. *Journal of biotechnology*, *266*, 118-123.

[76] Martin, D., Dodds, K., Butler, I. B., & Ngwenya, B. T. (2013). Carbonate precipitation under pressure for bioengineering in the anaerobic subsurface via denitrification. *Environmental science & technology*, *47*(15), 8692-8699.