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Production of Artificial Liquid Hydrogen on Mars for Nuclear Thermal Propulsion

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***Abstract*— *Besides being a renewable fuel, liquid hydrogen would potentiate nuclear thermal propulsion systems on missions to Mars. However, using liquid hydrogen requires carrying large tanks on space trips, which is challenging since rockets have a limited volume available and space related travel costs are mass related, with increased costs for increasing mass. Therefore, producing liquid hydrogen on Mars becomes fundamental for missions back to Earth. Previous research has primarily relied on producing Martian carbon dioxide fuel, however, a pioneer system of artificial liquid hydrogen production on Mars was studied to feasibly make trips to the red planet and lower the costs of space missions. The system involves extracting water from Martian artificial glaciers to produce artificial hydrogen through water electrolysis. Analyzing the system under Martian conditions proved that the model could theoretically be deployed on Mars. With theoretical and practical research, it will be possible to build a safe, effective, and realistic system of artificial liquid hydrogen production on Mars for nuclear thermal propulsion.*

I. INTRODUCTION

The eagerness to leave Earth and explore vast space has challenged the traditional propulsion systems, which lack infrastructure for long-duration space trips. However, the dream of traveling to Mars is taking shape due to an alternative propulsion system called Nuclear Thermal Propulsion (NTP) [1]. NTP engines produce heat by atomic fission, whereas conventional chemical rocket engines add warmth through combustion [2].

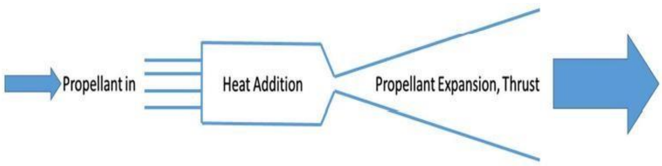

Fig. 1: Basic propulsion system [1]

The studies on NTP began in the United States as an Air Force program to develop nuclear reactors to propel intercontinental ballistic missiles in 1947. Then, from 1958 until 1972, NASA managed a program called Nuclear Engine for Rocket Vehicle Application (NERVA) to explore space. NERVA´s highest thrust and specific impulse (*I*sp) were 890 kN and 835 s, while the J-2 engine used by the Saturn Vat was 1000 kN and 424 s [2]. That way, NTP promotes faster travel times, almost doubling the specific impulse of the hydrogen-oxygen chemical engines [1].

$$I_{SP}[s] \propto \sqrt{\frac{T_{cbr}[k]}{MW[kg/Kmol]}}$$

Eq. 1: Calculation of Isp from propellant "chamber" temperature (Tcbr) and molecular weight (MW) [1]

Equation n°1 states that low-molecular-weight propellants produce high *I*sp, considering hydrogen the propellant with the lowest molecular weight at 2 kg/kmol. In chemical rockets, hydrogen reacts with oxygen to produce water molecules (18 kg/kmol), whereas NTP uses hydrogen molecules alone, providing higher *I*sp [2]. Moreover, the energy density of hydrogen is 140 MJ/kg, whereas typical solid fuels have an energy density of 50 MJ/kg [3]. Despite the positive results of NTP, the NERVA program ended due to the redirection of government funds to the Vietnam War. However, interest in the Mars mission and NTP system returned in 1989 [2], currently being studied by NASA.

Hydrogen is the primary fuel of NTP engines due to its low molecular weight. It must be stored in its liquid state, with a pressure of 2 atm and a temperature of 20 K, for the propellant tanks to be of an appropriate storage volume [1]. Although it is a sustainable and renewable fuel [4], liquid hydrogen is challenging because of its storage density. It is highly compressible but also much less dense than hydrogen. Therefore, carrying large tanks to store the ideal mass of liquid hydrogen is required for space trips. In addition, the rocket volume increases for long-duration travel like a mission to Mars since more propellant mass is necessary [1]. Considering the limited volume of rockets, the high cost of space trips, and the required mass in low Earth orbit, liquid hydrogen production on Mars becomes crucial for return missions to Earth [5].

II. MATERIALS AND METHODS

2.1 Process of Building Artificial Glaciers

As there is very little gaseous hydrogen on Mars, an alternative way to acquire it would be in liquid form through water (2%) [6]. Considering the low temperatures on the red planet, a solution for its extraction would be to build artificial glaciers. Unlike natural glaciers, artificial glacier pools change states seasonally. They collect and store seasonal water from existing natural glaciers for use later in the year [7] since the meltwater of winters would remain unutilized [8]. Thus, they capture glacial meltwater in October and November, directing it to a specific site through pipes and channels, where it freezes for use in March and April [9]. They do not freeze water from the top down; instead, they are produced by freezing thin layers of water, creating overlapping sheets of ice. Artificial glaciers´ ice storage capacity varies between 17,000 to 23,500 m³ [10]. Engineer Chewang Norphel and his research team developed this technology to solve the unavailability of irrigation water for agriculture in the cold arid deserts of Ladakh, India [8]. However, artificial glaciers do not increase the available water but rather promote the efficient use of water sources [9].

Fig. 2: Structure of an artificial glacier [11]

On Earth, these artificial glaciers are placed at an altitude of nearly 4,000 m in a north-facing valley or at least shaded less than one mile from a village for operational access and maintenance. Their structure includes diversion channels (generally made of concrete or stone masonry), regulator gates, silting tanks/distribution chambers, and retaining pools enclosed by stonewalls.

Diversion channels carry a part of the natural glacier´s meltwater toward a silting tank/distribution chamber or directly into the retaining pools to store ice until spring. Regulator gates control the amount of water that enters the diversion channels at different times of the year. It remains closed in the summer due to the high volume and velocity of the water. Water passes through the distribution chamber after the silting tank and enters the retaining pools through tiny openings in the metal pipes on the side of the distribution chamber closest to the retaining collections. Distribution chambers ensure that water flows into different locations in the retaining pools to freeze uniformly [7].

Mars under the remote supervision of an astronaut crew. The system includes an auger apparatus, a down-hole heating system, a peristaltic pump with a fine mesh filter, and sensors providing data.

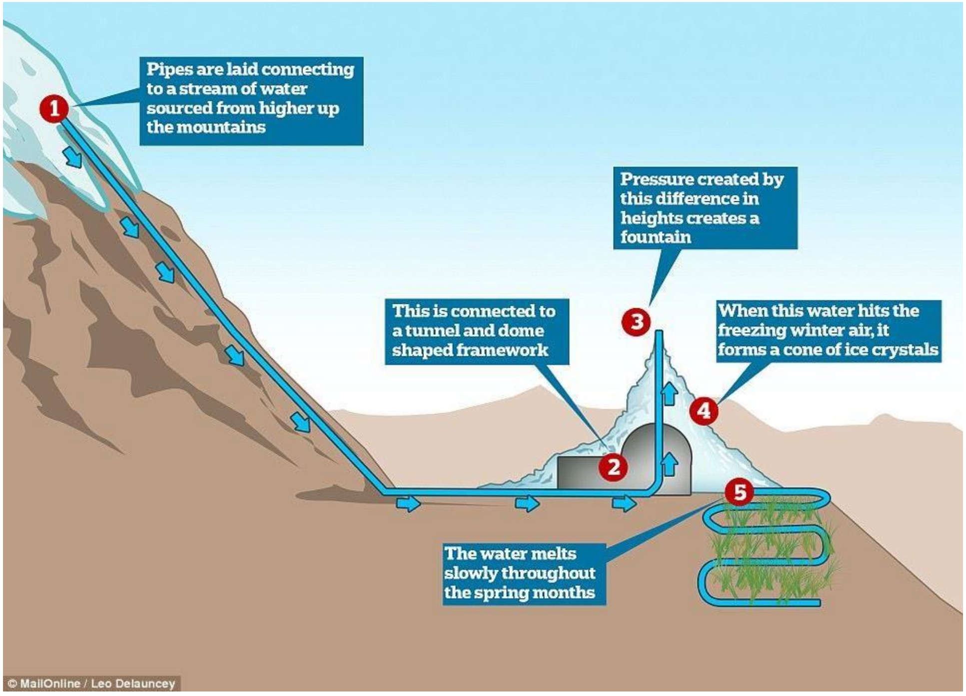

Fig. 3: Process of building artificial glaciers [12]

2.2 Process of Extracting Water

Building artificial glaciers on Mars would rely on extracting water from ice at the poles, vapor in the atmosphere, or liquid in subglacial layers [13]. Unfortunately, Mars has no rainfall due to its thin atmosphere, low temperature, and lack of a magnetosphere [14]. The Earth and Mars conditions are compared in figure 4.

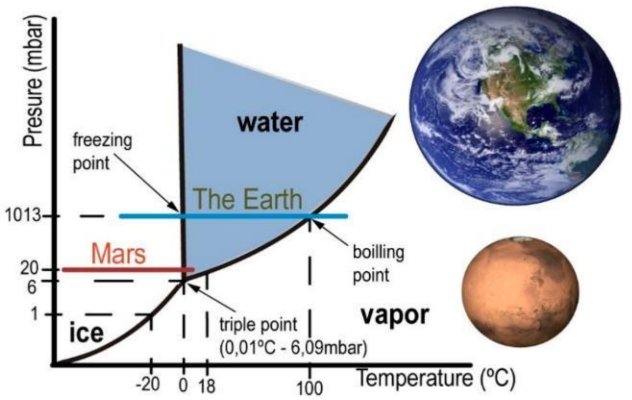

Fig. 4: Relation between pressure and temperature of the water on Earth and Mars [13]

A method for water extraction on Mars is suggested by the MIT HYDRATION III project [15], extracting water from the polar ice. HYDRATION III is an Earth-based analog system that will enable water extraction on

A drill is activated and lowered over the selected place. Controlling the drill bit to produce only the required amount of water is necessary to prevent it from freezing in the hole. The excavation finishes when the drill penetrates nearly 400 mm into the ice. Then, the auger is withdrawn and translated by a distance of 132 mm to position the stack of water

production over the borehole. Inside, the heater melts the ice sheet before the peristaltic pump pumps the meltwater out of the hole. During these two stages, 2 liters of water can be extracted in 25 minutes. Once water production slows down to almost no display, the stack collects the water and is removed [16].

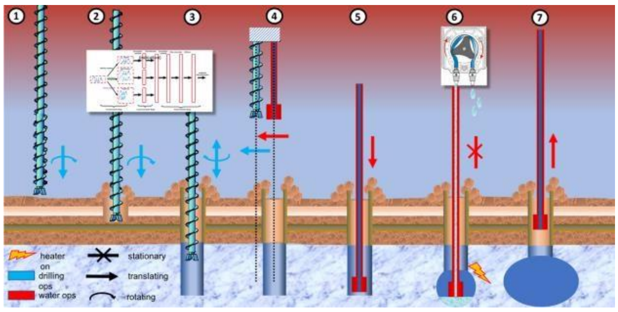

Fig. 5: Water production and extraction through HYDRATION III: (1) position drill bit (2) drill through overburden while collecting sensor data (3) drill through the ice layer and extract the drill bit (4) translate heater stack over the borehole (5) lower heater stack into ice borehole (6) activate the heater and the peristaltic pump to produce and collect water (7) remove the heater stack from the empty borehole [16]

The building of artificial glaciers on the red planet would rely on the water collected through the HYDRATION III system. Due to the shallow temperatures, artificial glacier pools would not change states seasonally, and the process of building them would occur at any time of the year. Thus, diversion channels would carry the water collected toward a silting tank/distribution chamber or directly into the retaining pools. Regulator gates would control the amount of water that enters the diversion channels at all times of the year. Then, the water would pass through the distribution chamber after the silting tank, enter the retaining pools, and freeze [7].

2.3 Process of Artificial Liquid Hydrogen Production

Liquid hydrogen can be produced by condensing gaseous hydrogen from water electrolysis. That way, a required amount of ice should be extracted from artificial glaciers and melted at temperatures above 32º F (0º C) to produce water for electrolysis. The Proton Exchange Membrane Water Electrolysis (PEMWE) is an alternative to producing hydrogen since it emits zero carbon dioxide (CO2), provides fast responses, has a compact design, and has a purity of 99.9% of the hydrogen produced. Water is the reactant dissociated into hydrogen and oxygen [3]. The system consists of a proton-conducting membrane with electrodes containing catalysts on both sides. Thus, the porous transport layers (PTL) and the bipolar plates (flow field for water and gas) clamp the membrane electrode assembly (MEA).

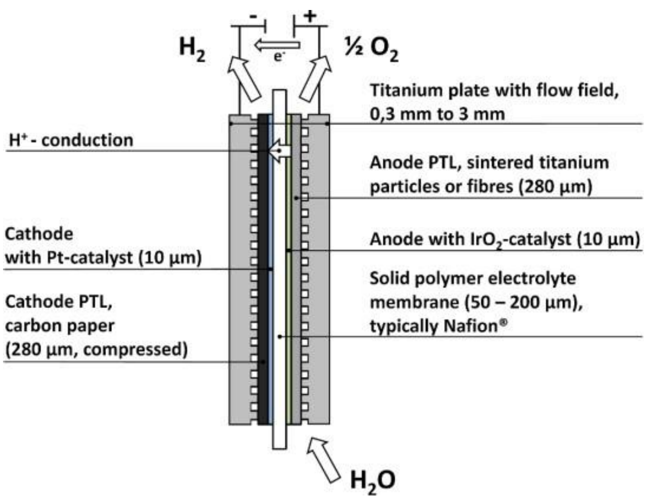

Fig. 6: Parts of a PEMWE cell [17]

The anode side receives deionized water. The cathode produces hydrogen, and the anode produces oxygen. For supplying the overall reaction enthalpy of +286 kJ/mol, the minimum voltage must be 1.48 V.

$$\text{Anode: } H_2\,O \rightarrow \frac{1}{2}O_2 + 2e^- + 2H^+$$

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2$$

$$\text{Sum: } H_2\,O \rightarrow \frac{1}{2}O_2 + H_2 \quad (\Delta H^0_{298} = +286\ \text{kJ/mol})$$

Eq. 2: Water electrolysis equation [17]

The protons are conducted from the anode to the cathode through the membrane. At the same time, the electrons are driven through the external electric circuit.

The PEMWE stack is a connection of cells in a series. The system adds upper and lowers current collectors and end plates. The former is made of copper or aluminum for the electrical connection, and the latter is made of aluminum or steel with bolts and sets of stacked flat springs for a uniform compression of the cells [17].

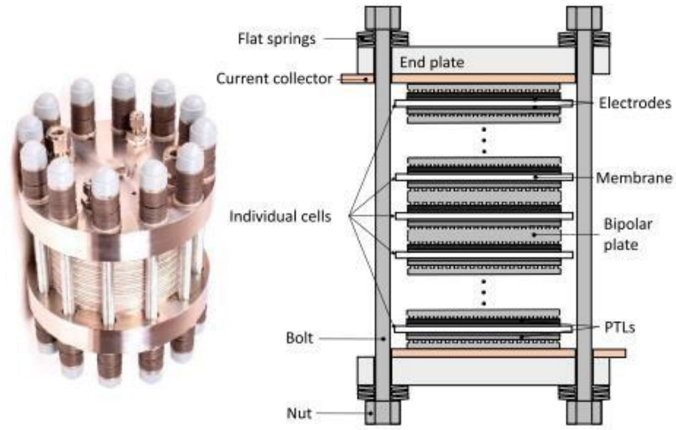

Fig. 7: Parts of a PEMWE stack of the lower power class up to 100 kW [17]

The hydrogen gas produced would be converted to a liquid at -252,87 °C. At -252,87 °C and 1.013 bar, liquid hydrogen has nearly 71 kg/m³ density. At this pressure, 5 kg of hydrogen can be stored in a 75-liter tank to be used later as fuel for nuclear thermal propulsion engines [18].

III. RESULTS

3.1 Process of Building Artificial Glaciers

Artificial glaciers in Ladakh showed they need reinforced masonry walls, stakeholder participation, and dispersing multiple retention walls to increase their effectiveness and durability. They also need glaciercameras to monitor the systems from afar and enclosed pipes, concrete dams, and on/off valves to reduce water losses. However, funding limits improvements.

Future goals include better field data, enhanced collection of and access to hydrological information, a more streamlined design approach, and metal mesh and earth-buttressed walls to strengthen the pool structure. Nonetheless, researchers must still quantify this technology's benefits and relative cost analysis [7].

3.2 Process of Extracting Water

MIT´s HYDRATION III project showed it could handle a range of regolith substrates and clays. However, some sublimation will occur before sealing the hole on Mars, requiring analysis in adding an inflatable packer to the water stack to seal the borehole before the melting stage. Instead of causing significant water loss, the sublimation will help to clean the spot, purify the water, and reduce operational risk. A scroll compressor and a cold trap will replace the peristaltic pump and filter to pressurize the water vapor and cool the steam into a liquid. The water will be gravity-fed to a collection tank, and the pressure from the scroll compressor will inflate a choke around the rod housing the downhole equipment. However, extensive testing will be required.

The system will likely have a longer life since it has fewer moving parts, and water production is expected to be higher. Other factors to consider when developing the final product are the presence of dust, perchlorates, and regoliths on the red planet, the radiation and launch environment, the reduction of gravity, and the need for simplicity and water filtering [16].

3.3 Process of Artificial Liquid Hydrogen Production

A PEMWE commercial product developed in 1978 presented a higher operating density than other alkaline water electrolysis technologies. Besides, balancing PEMWE plants is much simpler and provides faster responses. Even though the precious metals that are used make it more expensive than alkaline electrolysis, the cost of a PEMWE may reduce to 1/4 of the current price when hydrogen production reaches 1000 kg/d.

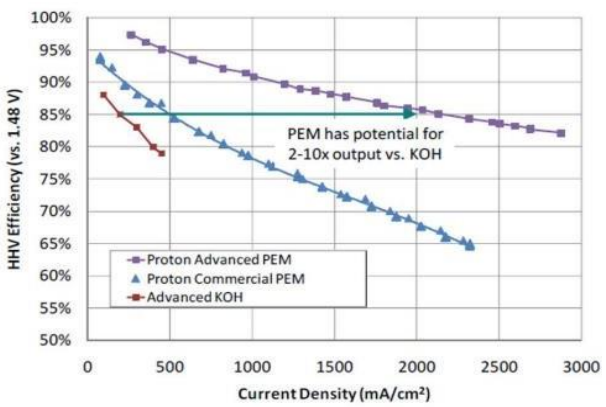

Fig. 8: Comparison of efficiency and operating current density of alkaline electrolysis and PEMWE [3]

Using top catalysts for PEMWE, such as RuO2 and IrO2, can enhance water-splitting performance. Thus, investing in research on electrocatalysts for oxygen evolution reaction (OER) with high activation, durability, and low cost can increase energy efficiency and electrolyzer stability.

Introducing a second cheaper metal, such as Ru, Sn, and Co, can reduce the electrode cost and improve the effectiveness. Along with electrode preparation methods that enhance morphology at the nanoscale, cheaper metals could lead to improvements in electrocatalyst performance toward OER [3].

IV. DISCUSSION

4.1 Process of Building Artificial Glaciers

Results indicate that deploying artificial glaciers on the red planet would achieve the goal of joining the raw material for producing artificial liquid hydrogen [7]. Furthermore, the estimated erosion rates on Mars of 10^{-2}-10^{-1} nm/yr during the Hesperian and Amazonian periods [19] would corroborate their effectiveness. However, it is crucial to be aware that there is no evidence of artificial glacier tests under Martian conditions, which challenges the expectation of their operation. Moreover, they would not reach their high potential for effectiveness since the funding is still a problem to evaluate their benefits and costs and implement enhancements. Thus, tests under Martian conditions and financial support are needed to build safe, durable, accurate, and practical artificial glaciers on Mars [7].

4.2 Process of Extracting Water

Results indicate that the HYDRATION III project would achieve the goal of extracting water from the ice at the poles to build artificial glaciers on Mars, which then in return create more water and ice readily available for hydrogen extraction than drilling alone. Through its simulation, it was defined what structures should be withdrawn, replaced, or added for the project could perform efficiently under Martian conditions. However, it is crucial to be aware that tests were not made to ensure the new structure. Moreover, other factors should be considered while developing the final product. Thus, simulations that test new changes and deployments are needed to create a compelling and accurate final product that will work on Mars [16].

4.3 Process of Artificial Liquid Hydrogen Production

Results indicate that PEMWE would achieve the goal of producing gaseous hydrogen to be converted to a liquid for nuclear thermal propulsion. Besides its plants being easy to balance and providing fast responses, PEMWE costs may be reduced. However, it is crucial to be aware that PEMWE is currently more expensive than other alkaline water electrolysis technologies and that there is no evidence of PEMWE tests under Martian conditions. Furthermore, using top catalysts, introducing a second cheaper metal, investing in research on electrocatalysts for OER, and using electrode preparation methods that enhance morphology at the nanoscale are necessary to improve PEMWE performance and reduce its costs. Thus, simulations under Martian conditions and scientific research are needed to test improvements and develop an effective, cheap, and feasible PEMWE that will work on Mars [3].

V. CONCLUSION

The research involved preexisting and successful equipment in a single system of liquid hydrogen production on Mars for NTP engines. In addition, it studied the system's applicability, considering adaptive changes in the model for Martian conditions. From a theoretical standpoint, the scientific analysis proved that the system could be deployed on Mars.

With financial support, future studies should closely simulate the system under Martian conditions, considering suggested improvements. Then, with theoretical and practical research, it will be possible to build a realistic system of artificial liquid hydrogen production on Mars for NTP.

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