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Breathing Oxygen on Mars

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1. Project Synopsis

I have always found space intriguing. Shows like 'Cosmos - A Spacetime Odyssey' have fascinated me as much for the knowledge they provide as much for the further questions they raise. An Elon Musk interview where he spoke passionately about humans going to Mars, left a lasting impression on me. It resulted in a book called 'The Red Rings of Friendship' which is a book I have written about four friends who get split while migrating to Mars / Saturn.

Humans can survive without food and water, for some time at least. And maybe even without family and friends. However, there can be no human life without Oxygen. And, from the perspective of space exploration, Mars is the next big stop for humans. Therefore, I decided to focus on generating Oxygen on Mars to improve the feasibility of human landing and habitation on Mars.

There are multiple existing ways of creating oxygen in space. The simplest way is by electrolysis of water. However, it is highly water inefficient i.e. to get 1 oxygen molecule you require 2 molecules of water. And water is another scarce resource limiting space travel. NASA is working on another experimental method, called MOXIE[1]. It splits carbon dioxide into carbon monoxide and oxygen. While NASA plans to send MOXIE to Mars in 2020, the key challenge with MOXIE are that it releases carbon monoxide, which is very harmful to humans. Further, it operates at a high temperature of 800^{o}C.

While the idea of utilising the carbon dioxide on Mars is a great one (it constitutes 96% of Mars' atmosphere), what would be better was to be able to break-up this carbon dioxide into Carbon and Oxygen. However, further research showed that most methods to do this were still too experimental and highly challenging to scale up even on Earth, let alone Mars.

[1] Mars Oxygen In-situ Resource Utilisation Experiment

The simplicity of electrolysis of water is quite appealing. Early evidence suggests that there are sources of water on Mars. Yet, traditional electrolysis involves significant wastage of water and does not utilise the abundant carbon dioxide on Mars. Was there a way to combine carbon dioxide with electrolysis?

This thinking led to ***'BOOM - Breathing Oxygen on Mars'***. It involves 2 processes - Electrolysis of water followed by, a less-commonly known, Sabatier Reaction. Electrolysis of water is basically passing electricity through water to split it into hydrogen and oxygen. This oxygen can be stored for breathing purpose. The hydrogen is then reacted with carbon dioxide (from the Martian atmosphere) under high pressure at $400^{o}C$ to get water and methane, using the Sabatier Reaction.

In this manner, the water efficiency increases to 75% as against 50% in the case of simple electrolysis by utilising the oxygen from the carbon dioxide molecule to reduce the overall consumption of water. Also, the reaction happens at a much lower temperature of $400^{o}C$ and the by-product, methane, can be used as a fuel source.

The reactions are as written here:

- Electrolysis: $8H_2O + 8e^- = 4H_2 + 2O_2 + 4H_2O + 8e^-$
- Sabatier Reaction: $CO_2 + 4H_2 = CH_4 + 2H_2O$
- Net Result: $2H_2O + CO_2 = 2O_2 + CH_4$

The solution would not have been possible without the help and support of various experts. They included Dr Snehangshu Patra, Dr Biswajit Bhattacharyya and Prof. Cheuk-Yiu Ng. They provided great insights on using other methods like Artificial Photosynthesis, and splitting Carbon Dioxide with Vacuum Ultraviolet Laser, to generate oxygen.

Equally important were the insights of Dr Anuj Thakar, a Ph.D. in organic chemistry and Dr Paul Menacherry, a Ph.D. in Heterogeneous Catalysts from Yale University. Both thought that the solution was very innovative because it was sustainable, and it utilized almost all the by-products. I have also shared the solution with Dr Anil Bhardwaj, Director of Physical Research Lab, ISRO Ahmedabad.

2. Identification of the Problem

I have always been very interested in space travel. I have written a book about inter-planetary travel and have also watched numerous shows and movies like Cosmos - A Spacetime Odyssey, Lost in Space, Martian, and Gravity. In my book, four boys migrate from the Earth to Mars and Saturn with their families. I had a great time researching about the planets and writing the book. That's what gave me the idea of wanting to solve a problem related to long term space exploration.

It is the nature of a human being to be curious. Since time immemorial we have been looking at the stars and wanting to go up and see what is out there. In 1961, Yuri Gagarin orbited the Earth. In 1969 Neil Armstrong set foot on the moon. Yet, each of these were visits and did not result in human settlements. Till the year 2000, when the International Space Station was built and humans had a first, even if semi-permanent, base in space.

Since then, humans have set their eye on a red object in the distance, Mars. Various space agencies have done extensive research on getting to Mars. Multiple Martian rovers like Curiosity, Pathfinder, Opportunity and Spirit have already visited the Red Planet. India has also launched Mangalyaan high has successfully reached Mars. These rovers have provided us some amazing photographs and samples of the surface which give us great insights about Mars, its environment, weather patterns, resources, overall habitability and so on. Multiple movies and TV shows have been made on this topic, generating further excitement among the people about this seemingly impossible task.

Getting to Mars itself is not easy, though. With current technology, it will require nearly 7 months of one-way travel through outer space. The total time for a "short" Martian crewed mission is around 650 days or 21 months. Till date, the maximum time a human has spent in space is 14 months, on the Mir Space Station, only 491 km away from the Earth. In contrast, our Mars explorers will have to endure 50-100 *million* km one-way travel plus 7-9 months of stay on an alien planet. The challenges faced by the astronauts while going on these long duration space exploration missions are almost endless. Long-term space exploration brings several problems, each just as challenging as the last.

2.1 Option Generation

The initial research threw up multiple problems that are faced by astronauts during long duration space exploration. A combination of desktop research and interactions with experts[2], helped me come up with a shortlist that I spent further time evaluating:

2.1.1 Space Debris

Space Debris is essentially “junk” that humans have left behind in space. They may be remains of satellites or just small pieces of metal chipped from a satellite. Space debris orbits the Earth at speeds of upto 28,000 kilometres per hour. A piece of space debris the size of a fleck of paint could easily dent any spacecraft, while debris the size of a tennis ball could rupture the International Space Station (ISS). These space debris are one of the first challenges to encounter while leaving Earth’s orbit.

I thought about various solutions including a robot which could attract the space debris and send the same to the Moon to help NASA in its Deep Space Getaway plan wherein they plan to set up a base on the Moon before going to Mars.

2.1.2 Space Radiation

There are three types of Space radiation which could pose problems to astronauts during long-duration space exploration:

1. Galactic Cosmic Rays originating from outside the solar system
2. Solar Particles emitted by the sun
3. Radiation trapped by Earth’s magnetic field

[2] Mikhail Kornienko, a Russian Cosmonaut; Akshay Patel, an aerospace engineer from Cornell University, with experience in spacecraft design and satellites.

Each of these types of radiation are harmful for the human body and can result in diarrhoea, nausea and vomiting, in the short term. Long-term exposure to these radiations could result in increased chances of cataract, cancer and damage to the nervous system. Also, these harmful effects may pass on to the offspring of these astronauts. The long-term impact of Space radiation makes it one of the more critical problems for astronauts undertaking long-distance space exploration.

2.1.3 Micro-Gravity

We have all seen funny clips of things and humans floating around in microgravity within space crafts. Little do we realise, then, that this is another big challenge faced by astronauts spending months in space like aboard the ISS. Some of the issues that Microgravity leads to include increase of height, loss of bone mass and vision problems. Upon returning to Earth, everything feels weird to them and astronauts must go through a whole recovery procedure to overcome the difference of gravity.

One way to solve this could be by creating artificial gravity in space. This could be done by spinning the spacecraft or using magnets to attract the astronauts towards the floor of the vehicle. This seemed to be a fascinating and fun problem to deal with.

2.1.4 Insomnia

Insomnia is basically the shortage of sleep. Signs of insomnia had been seen aboard the ISS where a combination of microgravity and hourly sunrises made it difficult for astronauts to sleep. It results in astronauts being distracted while working and feeling tired throughout the day.

Research shows that red light and soft music are very good aids to enable sleep. Maybe the solution could involve making sleeping pods for the astronauts so that it is not too difficult to sleep aboard a spacecraft. Further, a mechanism on the spacecraft which could turn off all the lights during the earth-night and switch them on during the earth-day, could help in creating a feeling of actual day and night.

2.1.5 Reducing Payload and Resources

Payload is basically what is carried by the spacecraft into space. For long distance space exploration, the basic requirements of the crew would have to be met. Increasing payload means increase in weight and hence cost. Based on current flights by SpaceX, the cost for sending one kg of payload to the ISS is around $10,000. Further, the greater the load, the greater the complications with designing the spacecraft which could accommodate resources for a two-year journey. Most common payloads include oxygen, water, food, machinery, fuel and engines.

Given how expensive and space-constrained this expedition is going to be it is important to recycle and reuse the materials on board the spacecraft. Urine is already getting recycled to get water. NASA has developed a washing machine which works in microgravity to give astronauts clean clothes. Plastic wastes on the spacecraft can be recycled to make radiation shields and as a material for a 3D printer to print tools, etc.

Oxygen, the most critical thing for survival in space, however still needs to be carried from Earth in the form of water. A self-sustainable method to generate oxygen could solve multiple problems and genuinely enable long-distance space exploration.

2.2 Elimination

I knew that I couldn't solve multiple problems. Therefore, I created a set of criteria which I could refer to and eliminate problems.

Space debris is an important but not the most critical problem in space. We have already sent multiple rovers to Mars and space crafts like Mangalyaan, Mars Odyssey and ExoMars Trace Gas Orbiter have already cleared the belt of space debris. The ISS is located amidst a huge mass of space debris and has successfully avoided almost all of it. Also, several companies like Astroscale are already working solutions for space debris clean-up.

Solving the issue of micro-gravity certainly will help astronauts who spend long periods of time in space. There are hardly any existing solutions for Micro-gravity. Many space organisations have tried but have still not come up with a solution.

Space Radiation is an important problem which affects astronauts upon their return to Earth. However, a lot of research has already been done on this topic. NASA has developed a material which is radiation-proof and can be used in spacesuits. Many companies have developed radiation shields for the spacecraft using water, recycled plastic and electromagnetic fields. Further, the topic seemed too complex and I was unsure if I was going to be able to do justice to it.

Insomnia was a problem which I initially liked. It causes grave dangers to astronauts aboard the spacecraft who many not be able to work properly due to lack of sleep. It was also mission critical and could result in fatal mistakes. However, research showed that multiple solutions had already been developed to tackle insomnia. The astronauts had personalised sleeping plans given by doctors. They had proper sleeping pods with almost all the features which I had already been thinking of including red lighting, soothing music, and so on.

This left the problem of Oxygen. Oxygen is extremely critical for human life in space. Without Oxygen no human can survive. While many solutions have been developed which could generate

Oxygen in space, these solutions have their own shortcomings. Maybe I could help generate Oxygen in space in a unique, problem-free manner.

My eventual decision was to develop ways to generate oxygen on Mars.

	Critical to Long Duration Space Exploration	Quality of Existing Solutions
Space Debris	✓✓✓	✓✓✓
Microgravity	✓✓	✓✓✓
Space Radiation	X	✓✓✓
Insomnia	✓✓✓	✓✓✓
Oxygen	✓✓	X

Summary of the evaluation process is captured in the table above.

2.3 Problem Identification

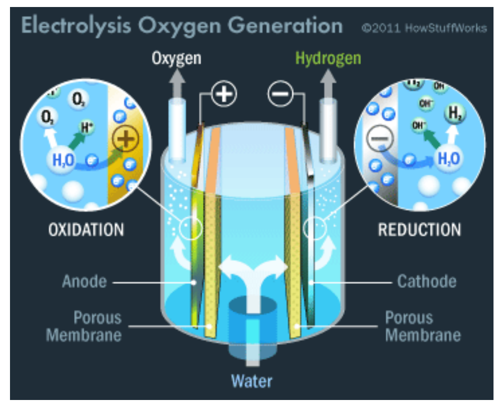
A human can live for 2 weeks without food, 2 days without water but not even for 2 minutes without Oxygen. Oxygen and its constant supply is a basic physical need for sustenance of human life. Creating a self-sustainable source of oxygen is one of the first steps to tackle for long duration space exploration. Hence, I decided to focus on developing solutions for generating oxygen on Mars.

3. Current Solutions for Generating Oxygen on Mars

Oxygen has been a topic of great thought and research. Space Agencies have already come up with solutions to create Oxygen in space. While these are functional, they suffer from severe drawbacks.

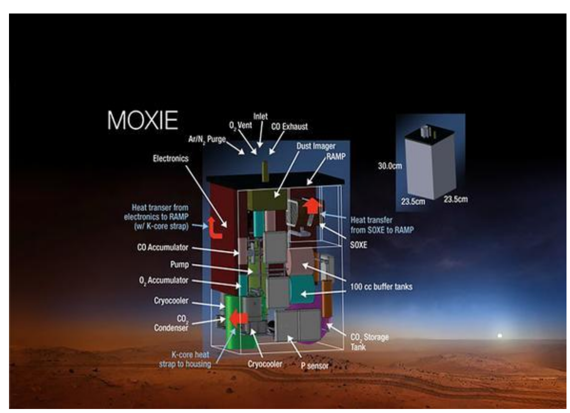
3.1 Electrolysis of Water

Electrolysis of water is the most common method for generating oxygen. This method is being used aboard the ISS. It requires passing an electric current through water to separate hydrogen and oxygen. This method is the simplest and most viable but is highly inefficient in its use of water, a precious resource which may not be found in abundance in outer space.



3.2 MOXIE

MOXIE stands for Mars Oxygen In-Situ Resource Utilization Experiment. It is a device created by NASA which electrochemically splits Carbon Dioxide into Oxygen by releasing a by-product of Carbon Monoxide. It operates at 800^{o}C. It is still in an experimental stage and will be sent by NASA in a rover supposed to land on Mars in 2020.

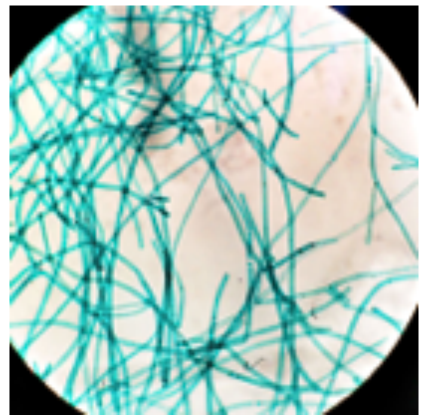


One of the main disadvantages of MOXIE is that it releases carbon monoxide. Carbon monoxide is very harmful for humans. If by any chance the gas leaks into the habitation chamber some of the astronauts may die. Also, it requires a temperature of 800^{0}C which is very difficult to achieve.

4. Probable Methods to Generate Oxygen on Mars

4.1 Cyanobacteria

Cyanobacteria, also called blue-green algae, are photosynthetic bacteria. They normally grow in water and can survive in dimly lit areas. However, they require a constant temperature of 20-30^{o}C.



Cyanobacteria can be used to create oxygen through the process of photosynthesis. Cyanobacteria are said to have been the main creators of oxygen in Earth's atmosphere. They have also been found in the deep trenches of the ocean, Antarctica as well as on the edge of the ISS. A Mars mission could carry a small amount of cyanobacteria with itself. The bacteria require Carbon Dioxide, sunlight, and water and can double in 30 minutes. This would help create a large amount of cyanobacteria on Mars, which would provide a constant flow of oxygen by utilising the abundant carbon dioxide in the Martian air.

4.2 Artificial Photosynthesis

Another method to convert Carbon Dioxide to Oxygen is by Artificial Photosynthesis. Since I had studied photosynthesis in school I thought that it should not be too difficult to carry out. Photosynthesis requires carbon dioxide, sunlight, water and chlorophyll. Sunlight and carbon dioxide are already available on Mars and chlorophyll is easy

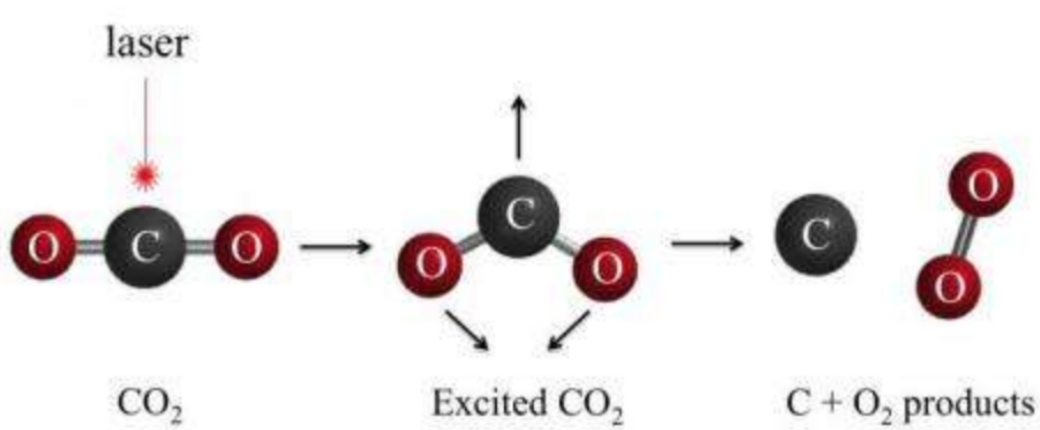
to extract from leaves.

I came across artificial silk leaves which have been made by various experts in India, like Dr Biswajit Bhattacharyya, and abroad too. These artificial leaves carry out the process of photosynthesis clinically. They use semiconductor materials and capture sunlight to do photosynthesis.

4.3 Ultraviolet Laser

Ultraviolet Light has a wavelength less than that of violet colour. Its wavelength is shorter than 400 nanometres. The shortest wavelength of Ultraviolet Light is called Vacuum Ultraviolet Light. Using Vacuum Ultraviolet Light, it is possible to split carbon dioxide to get oxygen and carbon. However, breaking a Carbon Dioxide molecule requires a lot of energy and generating Vacuum Ultraviolet Light is extremely difficult.

If the ultraviolet laser can strike the carbon dioxide exactly on the carbon atom, the atom will be pushed outwards and the Oxygen will bond while the carbon atom will bond with another carbon atom from another Carbon molecule. However, if the laser strikes in a different place it will result in the carbon dioxide molecule breaking up into carbon monoxide and oxygen. This process can be seen in the picture below.



4.4 Modified electrolysis

This solution attempts to use the most common method of generating oxygen, electrolysis of water, and using the Sabatier Reaction to replenish some of the water used in electrolysis. In this way it reduces overall water consumption.

The first part is Electrolysis of water. The Oxygen from the electrolysis process is sent to an oxygen storage tank while the Hydrogen is further used in the second part.

The second part involves the Sabatier Reaction. The reaction happens at a temperature of $400^{o}C$ and at a high pressure.

The Hydrogen from the electrolysis will react with carbon dioxide separated from Mars' atmosphere. The output, water, can be recycled back into the electrolysis chamber while the Methane (CH_4) can be utilised as a fuel.

4.5 What I chose?

Cyanobacteria was appealing to me. But one of the major problems with cyanobacteria was that they needed water to live. On Earth, they grow in deep trenches and seas and not much in the open. Also, there was little scope to bring innovation into this topic as cyanobacteria was bacteria which was already doing the photosynthesis process.

Artificial Photosynthesis also utilised water. In fact, the process actually breaks up water to get oxygen and doesn't break up carbon dioxide. According to experts, if one were to build an artificial leaf for artificial photosynthesis on Mars, it would be as tall as a 15-storey building. It would be impossible to carry that big a leaf all the way to Mars.

Using Ultraviolet Laser to split the carbon dioxide seemed best solution because it split carbon dioxide to get oxygen and did not use water at all. However, it was very difficult to understand the concepts involved in generating the VUV rays. Also, the movement of the molecules was difficult for me to understand. As per experts, one of the biggest problems was related to the yield. This method only split 5% of the carbon dioxide into oxygen and carbon while the remaining 95% split as oxygen and carbon monoxide. This made little point because I was not doing anything innovative and it was more or less similar to MOXIE.

Electrolysis of Water followed by the Sabatier Reaction was, in my view, the best method to use. It involved combining two processes no one had thought of before, it would result in a solution which was sustainable and reused almost all the byproducts.

	Technical Viability	By-Products	Availability of Resources on Mars	Water Efficiency	Other Operating Requirements
Cyanobacteria	✓✓✓	✓✓✓	✓	✓	✓✓✓
Artificial Photosynthesis	✓✓	✓✓✓	✓	✓	✓
Ultraviolet Light	X	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Electrolysis of Water	✓✓✓	✓✓✓	✓	✓	✓
MOXIE	✓✓	X	✓✓✓	✓✓✓	✓✓✓
Electrolysis of Water and Sabatier Reaction	✓✓✓	✓✓✓	✓✓	✓✓	✓

5. The Innovative Solution

5.1 The Solution

Carbon Dioxide is available as 96% in Mars' atmosphere whereas oxygen is a mere 0.13%. This makes Mars' atmosphere hostile to humans and it is important to have an oxygen source on Mars. My solution for this problem is called BOOM- Breathing Oxygen on Mars.

The most efficient way to produce oxygen is by doing electrolysis of water. Electrolysis of water is basically passing electricity through water to get oxygen and hydrogen. Once the water is ionised it will split into H+ ions (hydrogen cations) and OH- ions (hydroxide anions). After ionising the H+ ions will attract to the negative cathode while the OH- ions will attract to the positive anode. In this manner, electrolysis will help generate two different gases, hydrogen and oxygen. The reaction for this is as follows:

$$8H_2O + 8e^- = 4H_2 + 2O_2 + 4H_2O + 8e^-$$

The material used to make the electrodes in electrolysis will be graphite. These electrodes will be covered by aluminium oxide, which will act as a catalyst to make the reaction more efficient. Also, the electrodes will have small bumps on the outer surface to increase surface area. Since distilled water is not a conductor of electricity, sulphuric acid is added to help improve conductivity.

The Oxygen from the electrolysis will be sent into a storage tank whereas the Hydrogen will be sent to the Sabatier reaction chamber. Here, it will react with Carbon dioxide, extracted from the Martian atmosphere, under high pressure and at a temperature of at least 400^{o}C.

The Sabatier reaction goes like this:

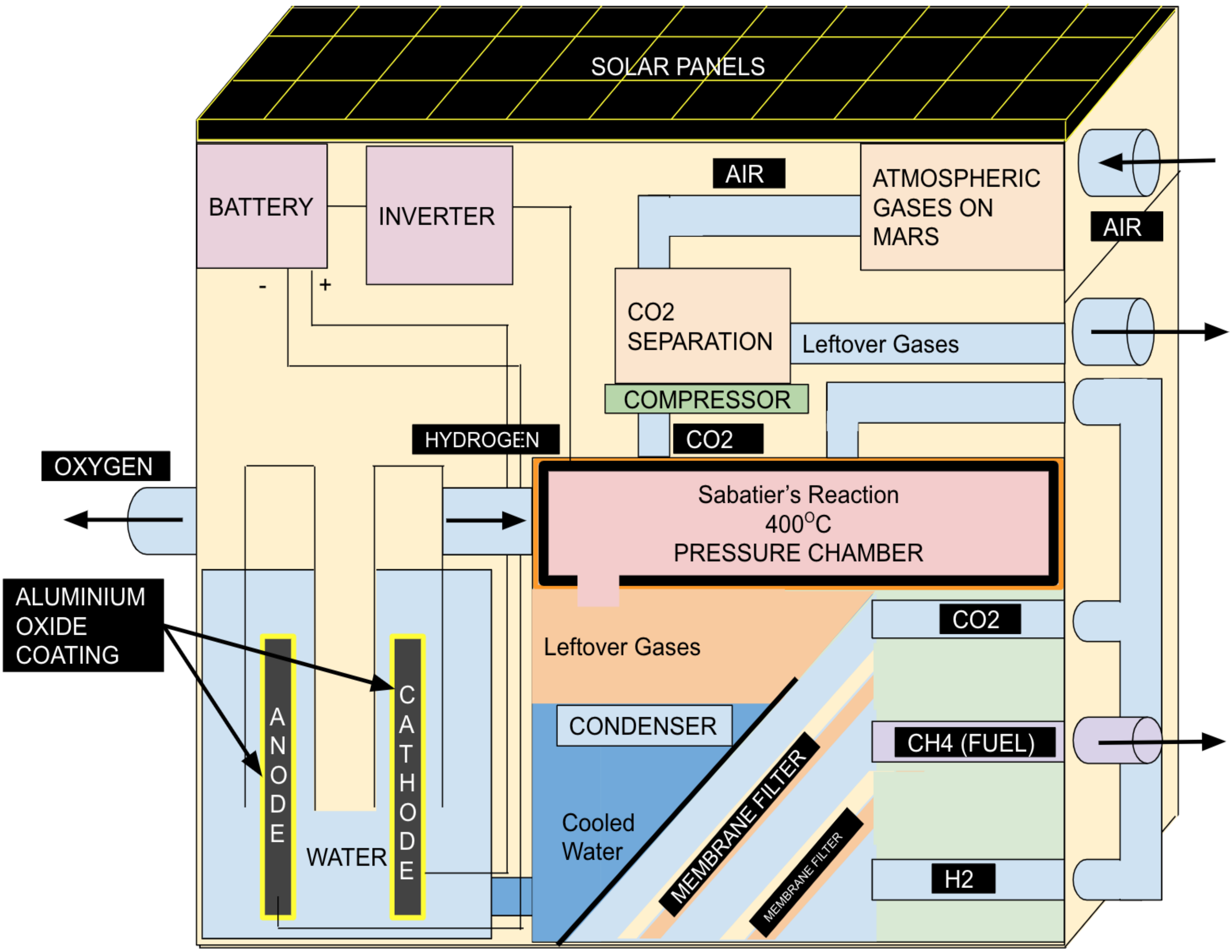
$$CO_2 + 4H_2 = CH_4 + 2H_2O$$

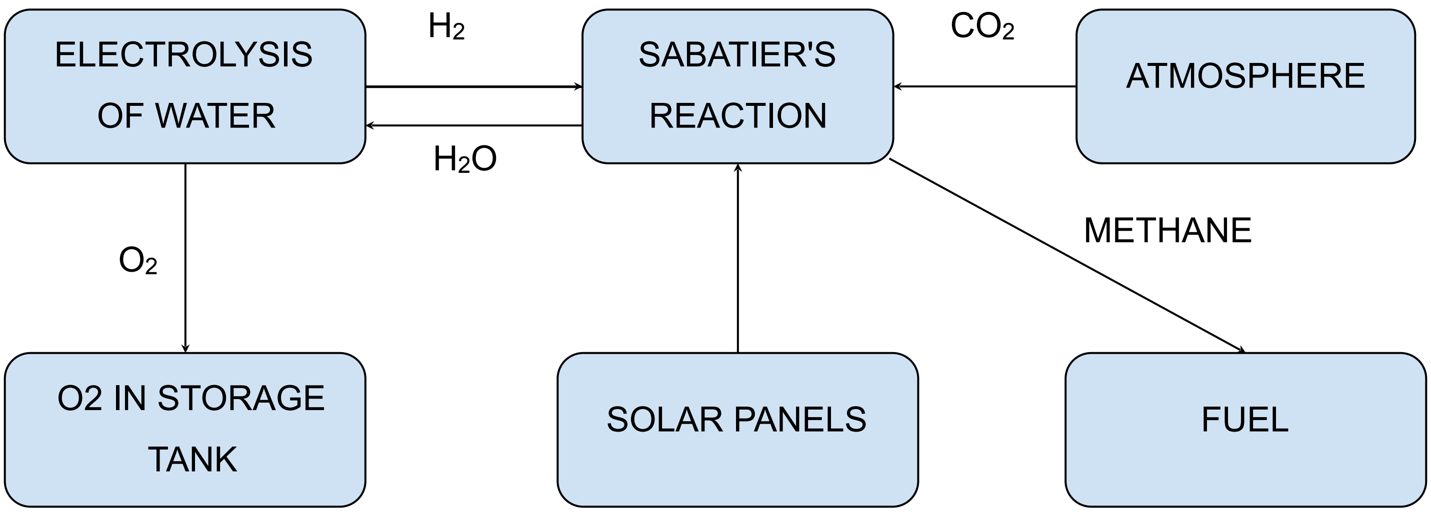
The heat will be generated with the help of the thin-film solar panels and the pressure will be generated using air compressors. I am using thin-film solar panels because they are newer and more efficient than the dated crystalline solar panels. The electricity generated by the solar panels will be stored and used to power the reaction. Some electricity will be used for electrolysis while the remaining can be used for the Sabatier reaction.

The output of the Sabatier reaction, methane and water vapour, are sent into another chamber where they are separated. Also, some unreacted carbon dioxide and hydrogen may be a part of the output. To separate the water, the gases will be cooled from $400^{o}C$ to below $100^{o}C$. This will turn the vapour into liquid water which can flow back into the electrolysis chamber. The leftover gases will be separated one by one via membrane filters. The carbon dioxide and hydrogen will again be passed into the Sabatier reaction chamber while the methane can be used as a fuel.

A good catalyst for the Sabatier reaction is nickel which has a great affinity for hydrogen. It can be used to coat the walls of the Sabatier reaction chamber. Also, the chamber would be made with aluminium because it can withstand pressure of up to six times atmospheric pressure. The chamber will also be insulated from outside to prevent the heat from escaping. The Sabatier reaction helps generate additional water by utilising the free hydrogen and taking the Oxygen from the Carbon dioxide.

5.2 Working Block Diagram





5.3 The Innovation

The proposed solution combines two separate process, Electrolysis of water and the Sabatier Reaction, to generate oxygen. This leads to recycling of 75% of the water. The only other output is methane which too can be used as a fuel. It is also better than MOXIE because it requires a temperature of only 400^{o}C in contrast to MOXIE's 800^{o}C and does not generate carbon monoxide.

6. Feedback from Industry Experts

6.1 Dr Anuj Thakar

Dr Anuj Thakar is a PhD in organic chemistry from Gujarat University. He heads process development for a company called Anupam Rasayan in Surat. He has 16 years of experience in the field working both at lab-scale and plant-level. He liked the solution and said that it could be improved in a few aspects.

Firstly, he said that using solar panels was a very good idea. He explained that there were two types of solar panels, thin-film solar panels and crystalline solar panels. He also said that crystalline solar panels were being used for 40-50 years whereas thin-film solar panels were a recent development but produced more energy. He suggested using thin-film solar panels because they produced more energy. Also, he said that it was important to store the energy produced by solar panels by using an inverter. This would allow usage of the stored energy at night too.

He also said that the efficiency could be improved by using catalysts for electrolysis and the Sabatier reaction. For electrolysis he suggested dissolving sulphuric acid in the water and suggested using aluminium oxide to cover the electrodes. This he said would make the electrolysis faster and more efficient.

He also highlighted that some carbon dioxide and hydrogen would remain unreacted in the Sabatier reaction. These unutilized gases would need to be separated them from the methane and water vapour, for which one could use a membrane filter.

6.2 Dr Paul Menacherry

Dr Paul Menacherry a PhD in Heterogeneous Catalysts from Yale University. He is the Managing Director of a company called Anthea Aromatics. He really liked the solution and said that it could surely be implemented. He gave very helpful insights on how to improve the solution.

He recommended that the surfaces of the electrodes be made rough so that the surface area would increase. He also said that nickel or ruthenium would be a good catalyst for the Sabatier Reaction because it has an affinity for hydrogen. He also suggested ways to increase the efficiency of the Sabatier reaction by passing the gases through a winding pipe.

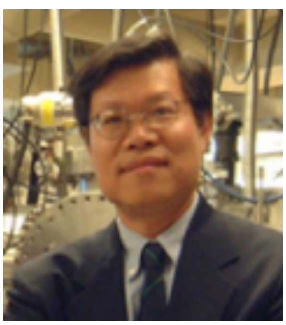
Dr Menacherry provided insights for separation of gases using a membrane filter. He suggested using multiple membrane filters to separate all three gases. Finally, he highlighted that the solution would require a large amount of insulation to prevent the heat in the Sabatier reaction chamber from escaping.

7. Research and Learnings from Experts and Mentors

7.1 Dr Snehangshu Patra

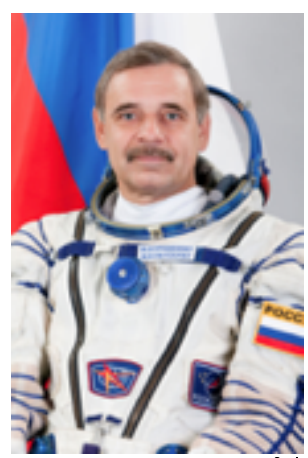
Dr Snehangshu Patra is an expert in Artificial Photosynthesis. Since he lives in Kolkata, I did a video chat with him. He told me that it was very difficult to do Artificial Photosynthesis in space. He also showed me an apparatus of his which had chlorophyll and could do Artificial Photosynthesis.

7.2 Prof. Cheuk-Yiu Ng



Prof. Cheuk-Yiu Ng is professor at the University of California, Davis and has developed a machine which actually splits carbon dioxide into oxygen using vacuum ultraviolet light. I exchanged emails with him. He liked my idea but questioned the feasibility and the costing because it would be difficult to set up a machine at such a large scale.

7.3 Cosmonaut Mikhail Kornienko



We met Cosmonaut Mikhail Kornienko as part of the Rosatom Festival held in Mumbai. He told us that anti-gravity felt like deep sea diving and that he found both launch and landing to be stressful but exciting. He also said that he had never fallen sick aboard the ISS and had eaten salads made of vegetables grown on the ISS itself. He had spent one year in space as part of a test mission to see the impacts of microgravity on the human body. He said that it wasn't very difficult to adapt back to

Earth’s surroundings and did not face too many social issues because he had companions aboard the ISS.

7.4 Aastha Patel

Aastha Patel, a graduate of the Birla Institute of Technology and Science, Pilani and a Graduate Research Assistant at IIT Bombay, was my mentor through this research. She helped me set-up the criteria to evaluate various problems and navigate through the technicalities of each of them. Her help and support was invaluable.

8. Conclusion

The proposed solution is only an idea. It will require for space research agencies to believe in its viability before one can dream of making it a reality. It will require a lot of work which I am keen on doing so as to progress this idea into a working prototype of this model. This will also require the help and support of various experts in related fields, which will give me an opportunity to learn from them.

I am quite excited at the prospect of taking this forward.

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