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A COMPARISON OF IN SITU RESOURCE UTILIZATION OPTIONS FOR THE FIRST HUMAN MARS MISSIONS

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Abstract

The current plans of NASA for the first missions to Mars involve in situ resource utilization (ISRU). Goal of the six month study carried out at the Johnson Space Center(Ref. 1) was to obtain an independent assessment about whether ISRU can provide the advantages in mass and cost that are claimed by the approvers. Furthermore it was tried to obtain a non-biased comparison of the different ISRU options proposed for a human Mars mission in order to find the optimum option for such a mission. The study is based as far as possible on actually built production units and less on previous theoretical studies.

It is shown that estimations of the approvers of ISRU are very often too optimistic and that many options, which look good at first sight, have to be ruled out due to practical reasons during detailed review. Nevertheless, some options remain very promising and actually have the potential of decreasing mass and cost of such a mission.

Background

The Design Reference Mission (DRM)(Ref. 2) of the NASA Mars Exploration Study Team is the current "best idea" of NASA to fly humans to Mars. The DRM is not a final result - it is a documentation of the present research status and changes permanently as the development continues. If new ideas substantiate that they can improve the mission performance, the DRM is altered accordingly(Ref. 3).

The current design involves a split mission approach with predeployment of the hardware that is needed for the surface stay (about 550 days) and the return to Earth in the launch window prior to the launch of the first piloted flight. By means of the split mission approach and new technologies, such as aerocapturing, the size of the ships that have to be launched to Mars decrease significantly. Thus, excessive assembly operations in low Earth orbit can be avoided, which reduces risk and cost. Each flight can be lifted to orbit with not more than two launches of a Shuttle derived launcher with a payload of about 85 metric tons.

Another technology that is used to reduce risk and cost is the use of indigenous resources on Mars. This technology was already suggested in the sixties and in the seventies (by Ash & al)(Ref. 4), but was implemented in the planning as a mission critical element not until Zubrinâ€™s Mars Direct plans(Ref. 5).

Goal

Goal of the in situ propellant production (ISPP) on Mars is to fuel up an ascent vehicle that is able to deliver a payload of 6359 kg into a 1 sol Martian orbit (see Fig. 1). This number is taken out of the current Design Reference Mission (Ref. 3). For an ascent vehicle that uses a liquid methane / liquid oxygen propellant combination, this results in a propellant mass in an order of magnitude of 50 tons. For different propellants the engines, the specific impulse, the tank sizes, and basically the whole Mars Ascent Vehicle vary. All these parameters have to be taken into account to obtain a fair comparison between the options.

Fig. 1: Mars Ascent Vehicle with ISRU Plant (Ref. 2)

Apart from the in situ production of propellants, the DRM suggests a life support system cache. The idea is that in the case of the breakdown of primary and secondary life support system the survival of the crew can be assured with the help of an open loop system. The consumables in this case would be provided by the ISRU plant. This option has also be taken into account.

Furthermore, it was tried to estimate the effect of an in situ rover fuel production. During their stay on the Moon, the Apollo crews had only a very limited sortie radius and always stayed in walking distance from the ascent vehicle. For a human Mars mission with surface stays of over 500 days the mobility and the crew's radius of action has to be increased significantly. Battery powered rovers cannot provide this range, and the use of plutonium powered rovers is dwarfed by political issues. It is tried in this study to find out whether ISRU could be a way out of the dilemma.

Candidate ISRU Processes

A plethora of different processes has been suggested for ISRU. In this study options have been considered, which involve the utilization of the Martian atmosphere. The acquisition of atmosphere is relatively simple compared to drilling or collecting regolith. This was a handicap given by the Mars Exploration Study Team, because the feasibility of other options can hardly be estimated. But it must be kept in mind that the usage of indigenous resources is not limited to the atmosphere; ground ice and other resources could once be very useful, too.

The processes that were considered in this study are:

- Sabatier

- Water Electrolysis

- Carbon Dioxide Electrolysis

- Reversed Water Gas Shift

- Methane Pyrolysis

- Fischer / Tropsch

- Methanol Synthesis

- Ethylene Synthesis

- Bosch

The list is not complete; other promising ideas are currently under investigation (e.g. synthesis of higher hydrocarbons). But only little information about these new ideas is available up to now, so it was decided to limit the computer simulation to these processes.

With these processes, the following fuels can be produced on Mars:

- Methane (CH_4)
- Methanol (CH_3OH)
- Carbon Monoxide (CO)
- Amorphous carbon (C)
- Ethylene (C_2H_4)
- Hydrogen (H_2)

The oxidizer in all cases is liquid oxygen (O_2).

Acquisition of Data

To estimate the mass, power and volume properties of the mission elements, it was tried to base the estimation formulae as far as possible on actually built machinery and less on previous studies. Ref. 6 to Ref. 10 give only a very limited overview of the references used.

To obtain a fair comparison, the theoretical specific impulses of the different propellants were calculated with computer codes and then multiplied with the same engine efficiency for all options.

Computer Model

The model consists out of the following modules, as shown in Fig. 2:

- Mars Ascent Vehicle
- Atmosphere Acquisition
- Power Supply
- Processing Data
- Combination of Processes
- Propellant Data
- Liquefaction
- Comparison

Fig. 2: Structure of Computer Model

The elements of the computer model are described in the following paragraphs.

Mars Ascent Vehicle

As mentioned before, the modeling of the Mars ascent vehicle is of crucial importance for the overall simulation. Different fuels lead not only to different propellant masses, but also to different tank masses, cooling requirements, etc. Thus, an accurate vehicle modeling that takes into account all these aspects is essential. The numbers of other ascent vehicles (like the Apollo Lunar ascent stage) are not automatically transferable to a Mars ascent stage.

The ascent vehicle was modeled by means of assumptions, taking in account the results of sizers used by Johnson Space Center and the Marshall Spaceflight Center. The results of the modeling of ascent vehicles that use different propellant combinations is summarized in Fig. 3. The calculations consider a 20% dry mass margin and residual propellants at burnout.

Fig. 3: Mars Ascent Vehicle Model

Atmosphere Acquisition

For small missions, a new atmosphere acquisition technology proved its usefulness: the sorption pump. Instead of compressing the Martian atmosphere by means of mechanical compressors this technique uses molecular sieves to adsorb the carbon dioxide. Unlike a mechanical compressor, a sorption pump does not contain moving parts, but achieves the densification of carbon dioxide by alternately cooling and heating a sorbent bed material. Because of the lack of moving parts, it has a significant potential for long lifetime, reliability and robustness. This material (for example zeolite) adsorbs low pressure gas at low temperatures and releases high pressure gas at higher temperatures. Accordingly, the Mars ISPP Precursor (MIP) experiment onboard the 2001 lander uses this technology to acquire the Martian atmosphere. Nevertheless, the simulation shows that the system mass of a mechanical compressor increases less with the mass flow than the system mass of a sorption pump. At a production rate of about 50 kg per day the masses are about equal. For human missions with almost one order of magnitude higher mass flows, the sorption pumps are heavier than mechanical compressors. As promising as the sorption pumps may appear for small missions, they are probably the wrong way for human missions.

Other technologies, like for example batch freezers that try to acquire the carbon dioxide by cooling it down below its freezing point, have still to prove their viability.

The baseline of the modeling of the pumps was hardware built for the International Space Station respectively for the 2001 Mars Lander.

Power Supply

The Design Reference Mission assumes a nuclear power plant on the surface of Mars. The reactor design is based on the work done in the fifties, the sixties and the seventies during the NERVA project (Nuclear Engine for Rocket Vehicle Application). A reactor of the required size of some 100 kW_e was designed by the NASA Lewis Research Center. The results of this research work is the baseline for the modeling of the nuclear power source. The graphs shown in Fig. 4 are an example of how the masses of the power source were estimated. Similar relations are derived for all subsystems.

Fig. 4: Mass of Power Supply

Fig. 4 shows, that the mass of the nuclear reactor changes only little with the increasing power demand. Thus, saving of energy is not as crucial as it is with a solar power source. Political issues (like the question of ground testing of these nuclear devices on Earth) and the issue of site contamination on Mars have still to be answered.

Preliminary results of an ongoing study of the Exploration Office show, that only for keeping the crew alive, some 3000 m^2 of solar array area are needed. It is questionable whether the power need of the outpost could be satisfied with solar energy. That is especially a problem for the first cargo mission, where the solar arrays would have to be deployed and operated automatically. For later missions, humans could assist the deployment and cleaning of the solar arrays, but the needed areas are still huge.

Other resources like wind energy or geothermal energy were suggested by James & al (Ref. 11) and Zubrin & al (Ref. 5), but the feasibility of these options has still to be proven. Thus, the computer model only involved the simulation of nuclear and solar energy.

Process Data / Combinations of Processes

With the nine processes listed above, a plethora of process combinations can be obtained. Not every combination makes sense; the combination must be able to produce fuel, oxygen and water. The selection of the process combinations was based on the following two requirements:

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- The combination must be able to produce fuel, oxygen and water (for life support system cache). This is

necessary only for the first mission - for the follow-on missions cache production is not required.

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• The number of processes must not exceed three, to limit the complexity of the ISRU-plant.

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The combinations considered in this study are:

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1. No ISRU (as reference)
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3. Sabatier & Solid Oxide Electrolysis Cell
4. Sabatier & Water Electrolysis
5. Sabatier & Electrolysis & Pyrolysis
6. Sabatier & Electrolysis & Reversed Water Gas Shift
7. SOEC & Fischer-Tropsch & Pyrolysis
8. SOEC & Reversed Water Gas Shift (CO)
9. RWGS & Methanol Synthesis Reactor & Electrolysis
10. RWGS & Ethylene Synthesis Reactor & Electrolysis
11. Sabatier & Electrolysis & Pyrolysis (Hybrid C)
12. Solid Oxide Electrolysis Cell & Bosch (No ISRU Fuel)
13. Water Acquisition & Electrolysis (WAVAR)
14. Water Acquisition & Electrolysis & Sabatier
15. Water Acquisition & Electrolysis on Phobos

Most of the processes do not produce their products in the ratio that is needed for later applications (e.g. combustion). For the first mission, three substances are needed: the fuel (e.g. methane), water for the LSS and oxygen as oxidizer for the engines and for the LSS-cache. In this case, three different amounts must be produced. Therefore, three different variables - three “regulators” are needed. The first variable is the reactant input mass. The other variables have to be provided by the processes.

For the follow-on missions (the second and the third mission to Mars) things get easier, because no water has to be produced and therefore the number of variables is reduced from three to two.

Fig. 5: Sabatier / Electrolysis / Pyrolysis Flowchart

For a first estimation of mass, power and volume properties of the plant, the mass flows through the different subsystems of the plant must be calculated. This is done as shown in Fig. 5 at the example of the option 9 (“Sabatier & Pyrolysis & Water Electrolysis”). For a detailed calculation of the overall mass, power and volume properties, a more detailed design (see Fig. 6) of the ISRU plant is necessary.

Fig. 6: Sabatier / Electrolysis / Pyrolysis Plant Design

Liquefaction and Storage

Apart from the amorphous carbon all propellants must be liquefied. In the case of methanol, this is no big technical problem. Other fuels like hydrogen for example require more finesse, not only in terms of liquefaction but also in terms of storage (active cooling). Reliquefaction of hydrogen is difficult, currently it is preferred to reduce boiloff as far as possible instead of trying to reliquefy the hydrogen. New technologies like gelling hydrogen or nanotubes could have the potential of reducing the overall mass.

Evaluation

For the downselection of options the following metrics come into question:

- Cost
- Mass
- Power
- Volume
- Mission Performance
- Human Health and Safety
- Risk
- Level of Technology Readiness
- Complexity
- Political / Public Appearance

As shown previously, the power requirement of the ISRU plant plays no role if the power source is a nuclear one. For a solar power source the required power levels are probably too high for all options. Thus, power seems not to be a metric suited for the downselection process.

The volumes of the ISRU plant and the feedstock are only of importance regarding the accommodation into the cargo lander shroud.

The mission performance is the same for all options. The human health is not effected by any method.

To estimate the risk level respectively the level of safety is difficult, since the amount of long-term experience is very diverse for the different options. A good benchmark in this situation is a comparison of the level of technology readiness (LTR) and the complexity of the different options (see Fig. 12). The political / public appearance of the different option does not vary very much the options.

At the beginning of the thesis it was planned to downselect the best mission(s) by means of the metric cost. Unfortunately, the NASA cost estimation database was not available until the end of the six months study. Since mass is the most important input for a cost estimation program, it seems to be appropriate to use this variable instead for downselecting. However, it must be said that mass does not automatically equal cost.

After two months of investigation, the number of options was reduced to six by means of the preliminary results shown in Fig. 7. This figure shows the â€žticket home mass" for the first mission. This is the sum of the masses of everything that is needed to return crew and payload to the Earth Return Vehicle in Mars orbit. This includes not only the ISRU plant, but also the Mars ascent vehicle, the power supply and the mass of the imported hydrogen. A comparison of only the ISRU plant mass alone definitely would not be fair since for example a lightweight plant that produces propellants with a bad I_{sp} can still debase the mission mass budget.

The remaining options after the downselection were:

- Sabatier & Solid Oxide Electrolyte Cell
- Sabatier & Water Electrolysis
- Sabatier & Water Electrolysis & Pyrolysis
- Reversed Water Gas Shift & Methanol Synthesis & Water Electrolysis
- Reversed Water Gas Shift & Ethylene Synthesis & Water Electrolysis
- Solid Oxide Electrolyte Cell & Bosch

Fig. 7: Preliminary Comparison of ISRU Options

Results

In the further progress of the study, the models of the different subsystems became more and more detailed. The final results of the mass estimates after the downselection are shown in Fig. 8 to Fig. 11. For a human Mars mission, carbon monoxide and amorphous carbon are not feasible options, since the specific impulse is too low and would result in a huge mars ascent vehicle.

 

Fig. 8: Mass with Cache / without Roverfuel

Fig. 9: Mass without Cache / without Roverfuel

 

Fig. 10: Mass with Cache / with Roverfuel

Fig. 11: Mass without Cache / with Roverfuel

Methanol was seen as a promising fuel in many sample return studies. Its advantages are that it is not cryogenic and can be stored easily. The disadvantage though is a comparatively low I_{sp}. For small missions (such as sample return) with solar power production, the reduction of power requirements is of vital importance. For missions with a nuclear reactor as power source, the mass can only be reduced very slightly by reducing the power requirement. The computer simulation has shown that the power consumption has a very small effect whereas the specific impulse is a very important player.

Methane seems to be a very good choice. Methane engines are a relatively simple compared to for example hydrogen engines. Russians are currently testing their RD-169 methane engine which will by the engine for the new Riksha-1 launcher that will have its maiden flight within the next two years (Ref. 12).

An ethylene option was also considered in this study. It seems that the advantages of methane over methanol are outmatched by this fuel; the amount of hydrogen that has to be imported is considerably decreased, the specific impulse is about the same as for methane. The problem is, however, that this is a comparatively young idea; the application of ethylene fuel in rocket engines has still to be proven.

Fig. 12: Level of Technology Readiness / Complexity

Conclusion

One conclusion of the study is that the ratio of plant mass to produced propellant mass decreases with increasing mass flows. Thus, for a human mission it makes more sense to invest in a heavier plant to produce more efficient propellants - even if they are cryogenic. The importance of the specific impulse increases compared to small missions. The optimum choice of ISRU options for a small mission (like Mars sample return missions) is very likely different from the optimum options for large missions (human Mars mission). This rises the question whether it makes sense to see sample return missions isolated or whether it could be more reasonable to see them as dress rehearsals for human missions and to choose the processes that are optimal for the big missions.

Redundancy and margins are very likely to be underestimated. Three redundant units in every subsystem with each providing 50% of the total required mass flow with an opportunity of cross-linking seems to be a reasonable approach.

It is questionable whether the idea of a life support system cache out of water and oxygen on the Martian surface instead of a second backup system as proposed in the Design Reference Mission makes sense.

Fig. 13: Backup Strategy of DRM

Three redundant systems are not only needed on the Martian surface, but also on the way towards Mars. The production of rover fuel could avoid the need of plutonium powered rovers as well as the need of huge amounts of rover fuel. In case of a major malfunction the rover fuel depot could provide the crew with oxygen, water, heat, and electrical current.

Another open issue is the storage of hydrogen over extended periods of time and on the surface of Mars. Storing cryogenic fuels will never be easy, but progress has been made during recent years and new technologies, e.g. gelled hydrogen or nanotubes, seem to be promising. If it turns out that hydrogen storage is to difficult to realize, then the propellant production will probably be limited to oxygen.

Outlook

All the testing that has been done up to now must not give the impression that this is already sufficient. No testing on Earth, no matter how sophisticated, can ultimately assure that the systems will work in the Martian environment. Thus, before human missions can be launched, several robotic precursors will be sent towards the Red Planet, to prove the reliability of new technologies such as ISRU. NASA is planning to send a number of different probes with ISRU-experiments to Mars, starting with the MIP experiment onboard the 2001 Lander. In this experiment the feasibility of oxygen production out of the Martian atmosphere will be demonstrated. In the next launch window (2003), the first end-to-end in situ propellant production unit will be established where fuel is not only produced, put also stored and used. The 2003 Lander will also be the first lander of a new generation of landers which are larger than the landers of previous years. This type of lander will also be the basis for the first 2005 Mars Sample Return (MSR) Mission. It is very likely that this mission (and a similar mission in 2007) will be based on the ISRU concept. If the new technologies that are involved by the design reference mission prove their reliability in these missions, a first human Mars mission could take place in 2014.

One reason to go to Mars is the fact that with results obtained with the help of comparative planetology can help us to solve our problems here on Earth. The greenhouse effect was discovered on Venus by NASA scientists - the Martian atmosphere consists almost purely of a greenhouse gas (CO_2) and Mars has a “global ozone hole”. Mars was once a planet with less harsh conditions, and it could be of crucial importance to understand why that changed.

The Design Reference Mission also comprises the research in the use of solar energy and the storage of hydrogen over long periods of time. Most processes that were under investigation in this work convert a greenhouse gas into fuel and oxygen. All these techniques could be very well used here on Earth, too.

It seems likely that the human exploration of deep space is not feasible without in situ resource utilization. This is especially true for permanent outposts. If humans want to explore deep space, they have to learn to use indigenous resources. Mars seems to be the break-even point, where the ISRU approach becomes more advantageous than the classical approach.

The question whether ISRU will be used for the first human Mars mission has still to be answered. But there is no question that humans will explore the Red Planet in the next century. Humans have never stopped to push back the boundaries. Mars is the next step.

Fig. 14: Inevitable Descent (Pat Rawlings)

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