Vizzavona

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1. INTRODUCTION

Fig.1. Vizzavona is a forest of mountain pines in Corsica.

The settlement of Mars represents such difficult technical and human challenges that its feasibility has been questioned. One of the most challenging problems is to be able to satisfy the needs of the settlers during the long period required for developing the settlement. How many rockets and how much is it going to cost to support such a settlement? Before presenting our project, let us define the context and clarify the statements that explain our choices. According to several authors, the cheapest way to send a cargo payload to Mars is to use an interplanetary re-usable vehicle that exploits solar electric propulsion (SEPV) [1,2]. The trip would be longer but there would be important mass savings for the propellant and the SEPV could be re-used several times. It is assumed in this proposal that this kind of SEPV will be developed and used in the future for sending payloads to Mars. In order to send some payload to LEO, a heavy launcher (at least 100 tonnes capability) will also be available (same capability as Saturn V, SLS etc.). If electric propulsion is used, up to 50% of the 100 tonnes LEO capability will represent the cargo payload to Mars. Obviously, another space vehicle will be used to send astronauts. All in all, let us assume with careful estimates that, at most, two heavy launchers will be built and launched each year (or 4 launches every 2 years to take the planetary configuration into account) in order to send:

- 1st rocket: 5 to 10 settlers to the surface of Mars (the mass is allocated to propulsion systems, life support systems and the landing module).

- 2nd rocket: 50 tonnes of payload to Mars (100 tonnes to LEO, but some mass is allocated to propellant for SEPV re-fueling and another part of the mass is allocated to the structure and EDL (Entry, Descent and Landing) systems of the landing craft).

Remark: In his plan to settle Mars, Elon Musk proposed a very powerful re-usable rocket with very high transportation capability. Such an interplanetary vehicle could be a game-changing technology. However, the testing and qualification of such a vehicle (especially Mars entry, descent and landing systems, which are supposed to be re-usable) might be very difficult and uncertain. In order to make sure that the constraints of the settlement problem are not underestimated, it is assumed in the proposed study that such a vehicle will not be available for the settlement process.
In order to better understand the difficulty of the settlement, we present a mathematical model in section 2, showing that the required mass of things that have to be sent to Mars each year to sustain the lives of the settlers during the growing phase is incredibly high. This model defines the economic constraints of the settlement and helps us in determining a global strategy for the settlement process. Section 3 presents the technical choices. Section 4 discusses social and cultural issues. Section 5 is dedicated to economic aspects of the settlement. Political issues are presented in section 6. Finally, well-being and aesthetic aspects are addressed in section 7. The name of our project is Vizzavona, a beautiful forest of mountain pines in the island of Corsica. These pines are able to grow on rocky terrain and survive in harsh environmental conditions.

2. MATHEMATICAL MODEL OF THE SETTLEMENT

2.1 Settlement equation

In order to better understand the difficulties of the settlement process, a mathematical model is proposed [3]. The idea is to determine the annual payload mass required to satisfy the needs as a function of the number of astronauts. See equation (1).

$$p(n)= k*n*(r/s(n) - w) \quad (1)$$

Where:

- p(n) is the required annual payload mass that has to be sent to the planet to sustain the lives of the settlers.
- w (in hours) is the average individual working time capacity per year. This parameter may vary according to the type of work, the organization of the society, habits, etc. In modern societies, a person works approximately 2000 hours per year.
- r (in hours) is the minimum individual working time requirement per year and on average (considering that the settlement could survive forever) to produce on the planet all objects and consumables that are necessary to sustain the life of one person during one year. It includes agricultural time to grow plants, industrial time to extract chemical elements from the atmosphere and ores from the soil in order to produce metals, plastics and then tools and complex objects,

as well as medical time, teaching time, administration time, etc. As all objects have a limited lifetime, the working time also includes the time to create or build each object divided by the lifetime of the object. The working time therefore includes a percentage of the construction time of buildings, cars, and all complex objects that are assumed to be required for living a decent life.

- s(n) is a function of n and is called the sharing factor. For instance, if for 4 astronauts, on average, each object is shared between 2 persons, s(4) = 2. It is expected that the number of shared objects grows with the number of persons. For instance, a kitchen may be shared by four or five persons of the same family and an electric power plant may be shared by a thousand people. Importantly, for a high enough value of n called n_t, $r/s(n_t)$ equals w, which means that a threshold is reached and that there will be enough people in the settlement to produce everything. In other words, the settlement would achieve full autonomy as soon as the number of persons is greater than n_t.
- Given w, r and s(n), the right part of the expression computes the time that is missing per person and per year to build all required objects to sustain the life of one person. It is multiplied by n to obtain the total missing time for all persons and by a coefficient called k to transform the missing time into tonnes.
- k is a mass conversion coefficient. If the missing time is greater than zero, it is necessary to compensate by sending objects from the Earth. A difficulty is to convert a time into mass. This is the role of the constant k. It is obviously not required to send all missing objects. It is possible to send only tools or to provide parts of the missing objects, with the objective of minimizing the total payload mass and therefore k. A method is proposed in section 3 to determine k.

It is difficult to estimate the values of the parameters. In a first trial, considering the needs of a modern society, the following values are proposed:

- w=2000 hours
- r = 10^6 hours. This means that 1 million hours of work per year would be required to produce all objects and consumables needed each year for a single person.
- $s(n) = n^{\alpha}$
  This an easy way to consider the sharing factor. This function is interesting because it starts as expected with n equal to 1 whatever the value of α and it regularly increases with n but in less proportion, which is also expected. Intuitively, as for 2 persons more than 50% of all objects would be shared (house, car, life support system, facilities, etc.), it is assumed that α is higher than 0.5. For the sake of simplicity, 3 examples are taken to illustrate the model with α equal to 0.52, 0.54 and 0.6, respectively. See Fig. 2.
- k = 0.00001
  It is proposed to determine k by looking at p(1), which is the expected payload for a single person. For n=1, the sharing factor is equal to 1, which simplifies the equation. A single person would not be able to produce large amounts of objects or consumables on the planet. As most objects would have to be sent from Earth, an estimate of the payload can be made by looking at the payload mass that is expected for the first manned missions to Mars, which is in the

order of 30 tonnes for 3 astronauts and a stay of 1.5 years on the planet. It is proposed here to determine k such that p(1) would be equal to 10 tonnes given the set of parameters already fixed. In an initial approximation, k can therefore be set to 0.00001.

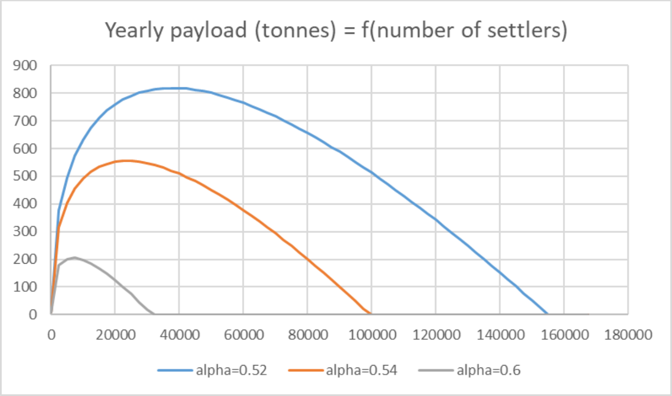


Fig. 2. Yearly payload for scenario 1.

The result is presented Fig. 2. According to our model, for α=0.54, approximately 100,000 people are required in the settlement to achieve full autonomy. Another important result is the peak payload requirement that is close to 550 tonnes and occurs when there are 20,000 people in the settlement. This number is 10 times as high as the annual payload capability that has been proposed in the introduction. This high payload requirement, which has to be maintained over a long period of time, is clearly a tremendous constraint that could discourage any public or private organization from investing in the settlement process. If important commercial exchanges are possible (tourism?), a settlement could become economically viable. However, according to us, it is doubtful that the ticket to Mars could become affordable anytime soon without significant technological revolutions and, therefore, that tourism could become economically viable (preliminary cost estimates from Elon Musk for one way tickets are assumed to be too optimistic). Based on these considerations, do we have to give up the idea of a Mars settlement? Not at all, let us see in the following chapters how difficulties can be overcome.

2.2 Appropriate parameters in the search space

Reduction of the needs

In order to make the settlement possible, a key idea is to reduce the needs. In our equation, reducing the needs means reducing r, which is the working time to produce all required objects. Let us consider two important examples.

- If robots are used in the settlement, robots will have to be imported from Earth as long as the settlers are unable to build their own robots. If only a small number of robots are needed, this would not be a big issue, but for a settlement of several thousand people, the mass of all robots might be very high and since the lifetime of robots is usually not greater than ten years or so, the annual importation of new robots might quickly become a problem. In addition, robots are typically complex objects that require many different industries and factories for their construction (metallurgy, manufacturing electronic components, plastics, computers, etc.), which means that the impact on parameter r is certainly high. On the other hand, if it is accepted to live on Mars without robots, the productivity would be lower, but all in all there would be a notable reduction of r.

- Surface vehicles will undoubtedly be used on Mars for the transportation of ores, goods, consumables, or astronauts. However, what sort of technologies will be involved in these vehicles? In modern cars, computers are everywhere, but fifty years ago, there weren't any computers at all and cars were almost as efficient as they are now. In other words, producing cars on Mars will be easier if it is decided to build simple old-fashioned cars rather than modern cars. In addition, in order to maximize the ability to repair or maintain old cars on Mars, it would be preferable to use simple technologies and simple materials.

Similar considerations can be made for other technologies. In order to reduce parameter r (and therefore the list of needed objects that have to be (re)sent to Mars), a kea idea is to rely as far as possible on simple objects that can be easily manufactured on Mars. It is important to notice that these considerations are only valid for the first stages of the settlement process. It is obviously expected that high-tech tools will also be produced on Mars one day, but probably not before human resources are numerous enough to support the industrial organization that would be needed to produce them.

Sharing factor

Another way to reduce the needs is to increase the sharing among the settlers. For example, instead of allowing individual belongings, all vehicles can be shared and used according to an appropriate policy. If it is desired and accepted to maximize the sharing, important reductions of needs can be made. Washing machines, ovens, showers, toilets, clothes, tools, etc., the list of possibly shared objects is potentially very long. The acceptability, however, is questionable. Such a society would clearly be closed to a kind of communism, which is considered by many people as inefficient and not adapted to human nature. It is not proposed here to maximize the sharing and to try a kind of full communism on Mars, but to look at what can be reasonably accepted to minimize the needs. For instance, it is probably acceptable to share the production of consumables, especially water and food, the vehicles and the main tools among all settlers without asking them to pay for them. In fact, another important issue is to minimize human resources for administration, education, health, justice, trade management, finance, entertainment, etc., which are not directly concerned with the production of consumables and goods for the support of the settlers. These services should be shared among the settlers with the strict minimum requirements. Once again, it does not mean that a local currency would not be created one day, as well as a justice department, a police department, etc., but as long as they can be reduced to the strict minimum and the resolution of problems can be shared by the community of settlers, it will help considerably to increase the sharing factor.

Time to mass conversion

In our model, the time required to produce consumables, goods or tools, is converted into payload mass according to a conversion coefficient. In order to reduce that coefficient, various strategies can be chosen. The first idea is to send missing objects. However, this is not an optimal strategy because it is often possible to send only an efficient tool that could make the production of that object possible. For instance, a 3D printer can help to produce complex plastic objects. Building a 3D printer from scratch on Mars might be very difficult. According to the recommendation made in previous paragraphs, we should try to avoid the construction of such complex objects to reduce industrial needs. However, there exist tools that allow important time savings in production processes and 3D printers certainly belong to that category. A trade-off has therefore to be found. Complex tools can be sent to Mars in the early stages of the development of the settlement if they are not too heavy and if they enable the production of numerous objects with little effort. In fact, 3D printers might help in reducing the mass conversion coefficient of our model, and therefore the peak payload requirement. When the number of astronauts becomes higher, as numerous industries will be available, it will be easier to avoid the use of 3D printers or at least to avoid the use of thousands of 3D printers.

Smoothing the curve

In order to reduce the peak payload of our model, another important idea is to split the settlement process into several steps. In the first step, the objective would be to accumulate assets and resources when the number of astronauts is kept low (5 astronauts for instance). In the second step, the number of astronauts could rapidly grow, but as the resources would be abundant, the peak payload would be more easily passed. In other words, it means that the variables of our model can be dynamically adjusted to cope with the 50 tonnes payload per year constraint. Then, as it is desired in the long term to build more complex objects, a new industry can be started but only when there are some margins for the payload.

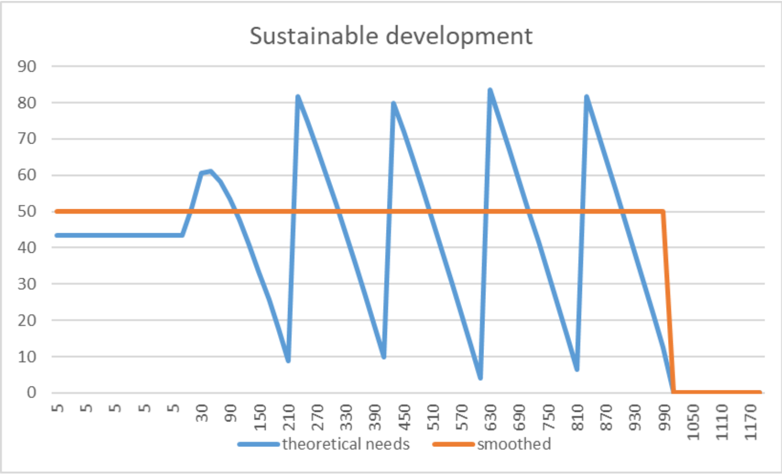


Fig. 3: Smoothing the payload requirement curve. Horizontal axis: number of astronauts. Vertical axis: mass imported from Earth in tonnes per year.

For example, concretely, at the beginning of the settlement, many greenhouses can be built, as well as many houses, facilities, etc., which could sustain a large settlement. Then, many settlers come and benefit from the numerous infrastructures. When the peak payload is expected, the needs are reduced because more facilities and resources are available (see Fig. 2). Later on, the number of settlers continues to increase and a new autonomy phase is reached (low importation requirement). This would be the right moment to start a new industry and to release the constraints on complex object requirements and also on the sharing factor. Once again, the new peak payload can be passed thanks to the accumulation of resources before it is reached. And so on, and so forth. This process is illustrated in Fig. 3.

All in all, providing that significant efforts are made to reduce the needs (very few modern complex objects), to increase the sharing factor and to optimize productivity, it might be possible to achieve the first autonomous phase on Mars with a very low number of astronauts, perhaps a few hundreds. By doing so, there are two advantages:

- First, obviously, we cope with astronautics constraints (50 tonnes of importation per year) and the project remains feasible.
- Secondly, if support from Earth is sudden abandoned, temporarily or definitively, the impact is low and the settlement process is only delayed, since the settlement is close to autonomy.

3. TECHNICAL DESIGN

3.1 Main principles

The mathematical model of the settlement process provides important cues for technical choices. It is proposed here to derive 4 important guidelines from the model, as follows:

Preliminary version

a) **Make it simple**: The settlement can use complex objects, but must not rely on them in order to reach an autonomous phase as quickly as possible with the smallest number of settlers. In addition, whenever possible, the simplest objects or tools have to be chosen so that they can be produced/maintained/repaired on Mars with a minimum of energy/industrial effort.

b) **Develop step by step:** New habitats and new industries have to be introduced step by step, as illustrated in Fig. 3.

c) **Accumulate resources**: In order to pass a "payload peak", the best strategy is to accumulate resources and assets when the settlement is close to an autonomous phase and before the development of any new industrial process.

d) **Maximize sharing:** The sharing factor has a large impact on the organization of the settlement and therefore also on technical choices. For instance, as energy distribution has to be shared, it is preferable to have a large power plant rather than multiple small ones.

3.2 Energy

3.2.1 General considerations

Energy production capability is probably the most important parameter driving the settlement process. Large amounts of energy are indeed required for growing plants, for mining, for industrial production, for life support, etc. As there is no oil on Mars, energy must primarily come from the sun. It might also be possible to use thermal energy from underground, but at the moment the feasibility of that option is not clear. Nuclear energy might also be used with nuclear power plants and uranium imported from Earth. Nevertheless, the "make it simple" principle suggests that the settlement should not rely on that capability. According to the "accumulate resources" principle, it should be possible to increase energy production or storage with little effort, especially when the settlement is close to an autonomous phase and before the start of any new industry.

3.2.2 Solar arrays

Solar arrays are chosen because very thin and light solar arrays already exist (easy to import from Earth), and they can be easily deployed and maintained [4]. There are, however, two difficulties. The first is to be able to build solar panels from local resources. As silicates are already required for the production of glass (see next sections), we propose to try to implement a factory for photovoltaic cells to produce solar arrays. Other resources like copper may not be available and producing pure silicon might be very difficult. Nevertheless, even if the efficiency of locally produced solar panels is below 5%, it is worth doing because, in case of an abandon from Earth, it would be difficult to find alternatives. The second problem is to provide energy at night and during dust storms.

3.2.3 Energy storage

Energy can be stored in many different ways (e.g., thermal energy, mechanical energy, gravitational energy, chemical energy, biomass, etc.). The "make it simple" principle suggests the use of biomass. It is indeed very easy to grow plants (energy storage) and to burn plants to obtain energy. However, though it can be recommended to use plants as a backup energy source, it is not possible to convert electricity into plants for energy storage. Fuel cells or batteries are typically proposed in combination with solar arrays but they are complex systems that will be difficult to produce on Mars using local resources [4]. Another important element of the problem is the way vehicles are powered. The simplest solution is to use chemical energy, for instance methane or ethanol, which is also suggested by Zubrin [5]. If it is agreed to use methane, then methane might also be chosen as energy storage to be used in combination with photovoltaic arrays. This is what is proposed here - see Section 3.3 on chemistry.
Remark: In case of dust storms, some energy would still be collected, in the order of 10% of the array capacity. The simplest solution is therefore to multiply the size of solar arrays by a factor of 10.

3.2.4 The case for plants

It is important to include plants in the energy category. The photosynthesis process is indeed an energetic process allowing plants to grow. Then, plants are the primary source of food (energy for humans), and can also be used as biomass for energy accumulation. More importantly, provided that they are integrated in an appropriate ecosystem, plants grow on their own with little human intervention, and the growing process does not depend on the use of complex objects. In addition, plants are also very interesting for the production of oxygen, trees are interesting for the construction of objects made of wood (tables, chairs, etc.) and can also be used for other functions (glue, paper, etc.). For these reasons, it is proposed in this project to increase the role of plants and trees. The idea is to create a huge number of greenhouses and to use plants as energy and resource accumulators that will help attaining the first autonomous phases. This idea suggested the name of the project called "**Vizzavona**" (see Fig.1). Such trees can grow almost everywhere on rough rocky terrain with very limited organic soil.
Greenhouses: Ideally, plants will be able to grow in greenhouses without human intervention. However, there are several important technical challenges:

- <u>Brightness</u>. On the surface of Mars, the light of the sun is weaker (Mars is further than the Earth from the sun). How to increase the illumination? The first idea is to settle not too far from the equator, for instance 10° north. As a complement, it is proposed to add mirrors behind the greenhouse to reflect more sunlight towards the plants. It is expected that this strategy will avoid artificial lighting.
- <u>Transparency</u>. Greenhouses have to be as transparent as possible to maximize illumination from the sun. It is proposed to use glass supported by an iron structure. Glass and iron can be produced using local resources - see industrial section.
- <u>Plants need an atmosphere</u>. It is proposed to maintain in all greenhouses a

pressurized atmosphere in the range 350 to 400 mb with approximately 25% N_2, 70% O_2, other elements being mainly CO_2 and H_2O. Such an atmosphere is breathable by humans and animals and the pressure is relatively low in order to minimize structural constraints (glass thickness reduced).

- Plants need water. There are huge amounts of water ice on Mars and sometimes very close to the surface. However, extracting ice, transporting ice and converting ice into water will be quite difficult and will require lots of energy. As it is desired to "make it simple" and to maximize autonomy, it is proposed to create an ecosystem, in which water is recycled. The idea is to grow plants on an impermeable terrain. Two options are possible to recover water. On a flat terrain, after watering, water can be collected on the side and pumped back to the reservoir. On the slope of a mountain, water drops will penetrate the first centimeters of the soil but will then follow the slope. At some point, all water is concentrated in the same place and is filtered by a sandy/rocky conglomerate. Below that point, water is collected and pumped back to the highest point of the greenhouse. The pumps will be alimented by solar panels placed outside the greenhouse.
- Plants need carbon dioxide and nutriments. There are two main options to satisfy these needs. The first option is intensive hydroponic cultures, and the second would be creating acceptable soils and growing plants on them. As there are advantages and disadvantages in each case, the choice is not easy. Hydroponic cultures are often suggested because they enable an accurate monitoring of plant feeding. However, the difficulty is to be able to produce the nutriments using *in situ* resources. As the number of plants will be huge (the requirement is to feed 1000 people and to carry on increasing the number of settlers), the mass of nutriments, pumps, sensors, and other hydroponic accessories would quickly represent a non-negligible part of the payloads sent from Earth. More importantly, it would be very difficult to build all facilities allowing the production of local nutriments using *in situ* resources because it would require mining different ores, extracting very specific minerals, and controlling mineral concentrations accurately. Creating soils for plants would also be difficult. However, numerous tests have been conducted using simulated Martian soil and it has been demonstrated that it is possible [7]. It is therefore proposed here to avoid hydroponic cultures and to grow plants on Martian soil, with the addition of fertilizers and decomposers that can be imported from Earth at the beginning and, later on, produced on Mars. Carbon dioxide can be extracted from the Martian atmosphere (compressor) and pumped into the greenhouse. Worms, insects, bees and other animals also have to be introduced to help recycling organic waste and stabilizing ecosystems. Different ecosystems will have to be implemented, as has been suggested for Biosphere II experiments that were conducted in Arizona a few years ago.
- Dust storms. Thanks to the greenhouse effect, it is expected that temperatures will easily increase above 20°C. At night, as external temperatures will drop below -50°C, inside temperatures might drop below 0°C. In order to avoid freezing, big black rocks can be inserted into the greenhouse to collect the heat during the day and release it at night. The main problem, however, is to be

resilient to dust storms, which would be equivalent to winters on Earth, with very weak sunlight and very low temperatures. The proposed strategy is twofold. On the one hand, it is possible to accumulate food resources in normal sunlight periods. During dust storms, plants would simply wait for the sun to come back as they do on Earth. Though some plants do resist low temperatures (pines for instance), in most greenhouses, it will be preferable to keep temperatures above 0°C. To make sure that this constraint is respected, it is proposed to heat up greenhouses using solar panels and heaters. During dust storms, solar panels would not be very efficient, but the idea is to dimension them so that 10% efficiency would be sufficient to warm the greenhouse to acceptable temperatures.

Remark: It is important to make sure that the proposed greenhouses will work properly. Tests have therefore to be carried out in the first phase of the settlement process, with very few people on Mars and the growing phase will only take place in a second phase, when numerous greenhouses have been built and checked.

3.3 Chemistry

There are two good reasons to develop a chemical industry on Mars. First, it will be fundamental to control the composition of the atmosphere, keeping O_2, N_2, CO_2 and H_2O at acceptable levels. Secondly, it will be necessary to produce methane (CH_4) for vehicles and other engines. Let us present here the main chemical reactions that will help the settlers:

- Water electrolysis:

$$2\,H2O \rightarrow 2\,H2 + O2 \qquad \text{(180 MJ/kg)}$$

  Water will be an important resource. Water electrolysis will be used to produce O_2, which is required in habitats, spacesuits, pressurized vehicles and also in numerous industrial processes. It will also produce H_2, which is a key element of the Sabatier reaction.

- Sabatier reaction:

$$CO2 + 4H2 \xrightarrow[400°,pressure]{} CH4 + 2H2O$$

  CO_2 can easily be extracted from the Martian atmosphere and H_2 can be obtained with water electrolysis. Methane will be used as fuel. The Sabatier reaction has been proposed by several authors to produce methane for Martian vehicles [5,6]. It can be used in combination with the reverse water-gas shift reaction to simplify the production of methane. Remark: There is no oxygen in the Martian atmosphere. In order to use methane as a fuel for surface vehicles, it will be necessary to bring also oxygen.

- Oxidative coupling of methane

$$2CH4 + O2 \xrightarrow[900°]{} C2H4 + 2H2O$$

  Methane and oxygen can be obtained thanks to the previous chemical reactions. The result of the proposed equation is ethylene, which is a key molecule for plastics and organic chemistry, including polymerization. The transformation rate of the proposed equation is not optimal - some CO_2 may also result - but the result is very promising for the future of the settlement. Very complex objects can be manufactured if the production of ethylene is mastered.

3.4 Industry

As suggested by Zubrin, several industrial processes can be implemented on Mars [5]. It is proposed here to manufacture in priority ceramics, glass, iron and silicon. Glass can be manufactured using Martian sand. Sand is abundant on Mars. A selection of the best sandy terrains will be required but not sufficient to avoid a filtering stage to obtain appropriate silicate proportions. Specific chemical elements also have to be added to obtain transparent glasses. An important issue is to build ovens to melt silicates. A possible solution is to bring ovens from Earth, but as it is required to reach autonomy as quickly as possible and to minimize Earth importations, an interesting option is to build a solar furnace. See Fig. 4 for an illustration. This is what is proposed here for ceramics and glass production.
Iron can be manufactured on Mars from hematite, which is abundant on Mars. The process is not simple, because ore quality will probably be poor. However, even if iron production is difficult and not optimized and if the product is not as robust as it is expected on Earth, it will be sufficient to support many of the metallic structures that are needed, especially for greenhouses and domes. The idea is strengthening the structures wherever it is necessary to make sure that it will be resistant to the large difference in pressure between inside and outside.
Some sand can also be used to produce silicon that can be exploited for solar array production. Simplified photovoltaic cells can be manufactured, as already proposed by several authors for lunar settlements.

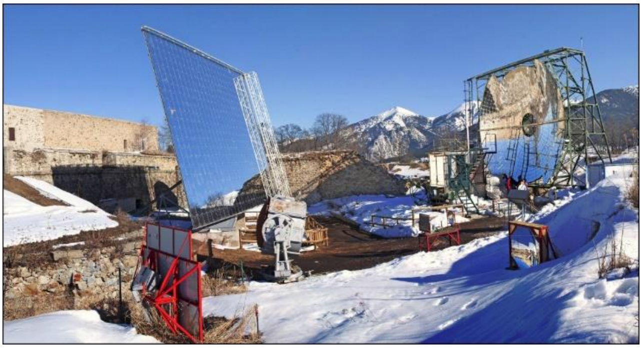


Fig. 4. Solar furnace with double reflexion in Mont-Louis, France.

4. ECONOMIC ISSUES

4.1 Main principles

In the long term, it is expected that there will be a rocket industry on Mars, interplanetary trade and several launches per year to export goods from Mars to Earth. However, in the context of the proposed study, with no more than 1000 settlers, there will be very limited industrial capacity and it is quite unrealistic to believe that there will be a rocket industry on Mars. For that reason, it is assumed here that the rocket going back to Earth must first arrive from Earth. If it is a kind of shuttle, bringing some goods back to Earth might be possible and not so expensive. Before examining that option, let us consider first the economic issue of shipping goods from Earth to Mars in the first stages of the settlement.

4.2 Shipping goods from Earth to Mars

As already highlighted in earlier sections, there are two important organizational challenges:

a) To be able to maintain interplanetary transportation (astronauts and cargo) on a regular basis over a long period of time.
b) To pass the peak payload requirements (Figs. 2 and 3).

In the astronautics industry, it is well known that the annual rate of rocket construction must be as stable as possible. It is very difficult to increase that number because it takes a long time to design and integrate all parts. If it is required to double the production rate, new facilities have to be built and new teams have to be hired to achieve that goal with a tremendous cost impact. Ideally, as illustrated in Fig. 3, the best way to minimize the cost is to impose that the payload mass is always the same during all the settlement process, as long as there is no paradigm change in interplanetary transportation. This is what is assumed here.

In 2017, the cost of launching 1 kg into orbit with a Falcon 9 was $1,891. In 2020, it is expected that the cost will drop to $951 using a Falcon Heavy. Further reductions might be achieved with another rocket, but it is not yet proven. For the sake of simplicity, let us assume that the cost of sending 1kg to a low Earth orbit is $1,000.

The objective is to send the payload to the surface of Mars, not to a low Earth orbit. As suggested in the first chapter, in terms of energy, the most efficient way to send a payload to Mars is to use solar electric propulsion. If that vehicle can be re-used multiple times, the main cost is associated with the cost of sending the propellant to a low Earth orbit. In a first approximation, considering ΔV calculations, let us assume that the mass of that propellant is equivalent to the mass of the payload (see NASA Design Reference Architecture 5.0 [1]). The cost of 1kg to a Mars orbit is therefore $2,000. Then, the payload has to be sent to the surface by means of entry, descent and landing systems. Such systems generally are heavy. In the last NASA study as well as in Salotti's architecture [8], the entry mass is on the order of the double of the payload mass. A kind of re-usable shuttle might be used to minimize the cost but the qualification and the re-qualification for the next flights might be very difficult and impractical in the early stages of the settlement process. In order to avoid possible criticism of such an estimate, it is assumed here that the cost of sending 1kg to the surface of Mars is once again doubled at $4,000.

Finally, the payload itself has a cost. A pressurized rover, for instance, might cost several million dollars which, as a first order approximation, is as expensive as the cost of its payload mass. As it is necessary to send very robust objects and tools with strict qualification procedures, such costs will not be negligible. All in all, it is assumed that shipping 1 kg to the surface of Mars will cost around $5,000.

Remark: In the document describing the contest, a cost of $500 per kilogram is suggested. At the same time, it is asked to cost it out. Considering that the goal is to propose a realistic settlement project, it is proposed here to take our own estimate into account at $5,000 per kilogram.
Finally, as 50 tonnes of payload are expected each year, the annual cargo cost is about $250,000,000. Since it is also desired to send people to Mars, the recurrent annual cost will be at least twice as expensive, thus about $500,000,000.
Such a cost is high for private investors but it is easily affordable for nations such as the United States, Russia, China, etc., even if these efforts have to be maintained a long time. More importantly, as illustrated in Fig. 3, it is proposed here to develop the settlement step by step, trying to reach an intermediate autonomous phase as soon as possible. The key idea is to make sure that the settlement does not decline in case of a sudden abandon of investment. It must be resilient. Ideally, if resiliency is high enough, even in the case of a definitive stop of interplanetary travels, the Martian settlement should be able to slowly develop itself on its own.

4.3 Shipping goods from Mars to Earth

If it is required to send objects from Mars to Earth, the SEPV can be used but there will be an impact on the mass of propellant at departure from Earth. The problem is that it will be important to maximize the payload sent from Earth to Mars. As a consequence, there will be no margin for additional propellant. A possible option is to bring propellant from Mars, but it is highly impractical because ion thrusters generally use gases that cannot be produced on Mars.
Another idea is to send other vehicles to Mars to bring some objects back to Earth. Nevertheless, as mentioned in the previous section, it will be very difficult to increase the number of annual launches.
All in all, it would be very expensive to send goods from Mars to Earth. Occasionally, when the settlement is close to an autonomous phase, some people and some objects might be sent back to Earth, but it will be difficult to generalize and to make substantial benefits arising from such opportunities.
Remark: In the document describing the contest, shipping goods from Mars to Earth is considered possible at low cost ($200/kg). Though it might become affordable in a distant future, it is assumed here that the cost will be much higher and impractical for interplanetary trade in the early stages of the settlement process. The same conclusion applies for interplanetary tourism. With a ticket to Mars in the order of $100,000,000 (assuming 10 tonnes per person), tourism seems unaffordable.

4.4 Return on investment (ROI)

There is no direct ROI. However, there is considerable indirect ROI. As highlighted by several authors [9], space exploration brings huge ROI in many different domains:

- Technology: It is difficult to know *a priori* what technologies will be developed for the settlement process. It might be for instance in the domain of energy. As there is no oil on Mars, renewable energy systems have to be chosen from the start. It might also be in the domain of ecology with new air control systems, new paints that do not pollute the air or new water purification systems, etc.

- Arts: Many science fiction books and movies have been inspired by the early stages of the space conquest. No doubt that a Martian settlement will continue to stimulate imagination and creation in all countries.
- Education: Many children are curious and love space because space is full of incredible things like microgravity, planets, moons, stars, etc. Many of them want to work in the space domain and work hard for that.
- Psychology: Many people are depressed because they do not have a project or they feel that the world is dull and the future is not interesting. A settlement project will stimulate many people. It might help mitigating psychological depressions and violent reactions, which have a tremendous cost on productivity, health and security.
- Other ROI: There will be also books, games, toys, clothes and other objects derived from the settlement process as there was for the Apollo program.

All in all, the ROI is difficult to estimate, but it is probably huge. To end this section, we propose the famous quote from Walter Peeters, when he was teaching economics courses at ISU (International Space University): “The best ROI ever has been made by Christopher Columbus in 1492” [10].

5. SOCIAL AND CULTURAL ISSUES

5.1 Main principles

There are several important and difficult social and cultural issues:

- Will it be an international settlement or a national one?
- Do we have to select the settlers? And if yes, what criteria will be used? Do we have to impose constraints on the age and sex of the new settlers? Do we also have to send kids? Do we have to favor families or singles?
- Do we have to foster having children on Mars? And if so, how to care for them and how to educate them?
- After some decades on Mars, many settlers will be old. How to care for the elderly?
- It is not possible to avoid accidents. Some people might die and others might become disabled. How to face the death and how to care for handicapped people?
- How to take religion into account?

It is not possible to address all questions in this document. We propose to focus on the age pyramid and the role of families and children. Importantly, over time, adults grow old and can no longer work or, at least, not with the same effectiveness. If many settlers are getting old at the same time, the labor force rate would drop and the settlement might collapse due to insufficient human resources. In addition, if there are too few persons in the same age group, there is a risk of not finding a compatible sexual partner. In order to avoid these difficulties, it is important to select the settlers according to their age group and sex such that the age pyramid is

globally homogeneous.
As the objective is to settle on Mars without compromising well-being, people will like to live on Mars like people on Earth, looking for a partner and having children. If the age pyramid is balanced at the beginning of the settlement, new children are expected at a reasonable rate and will contribute to the expansion of the settlement.

5.2 Habitats

One of the most important parameters of the settlement is the “sharing factor”. As already suggested, the idea is to maximize the number of shared objects without compromising with comfort. The family level will be emphasized. Habitats will be sized for families or groups of 2 to 10 persons, possibly including grandparents a few decades later to avoid leaving old persons alone. They will be built in giant greenhouses (domes) and will be the property of the family/group living inside. All furniture (tables, chairs, beds, etc.) and all personal belongings will also be the property of the family/group. However, in order to maximize the sharing factor, it is proposed to share the management of life support systems (energy, air, food, water, including showers and toilets) and the management of household waste among all habitats of a village (see next section).

5.3 Villages

A small village will be a group of 50 to 200 persons living in 10 to 20 habitats located inside a giant dome (50 meters wide). If possible, the dome will be located inside a small Martian crater. Each village will be in charge of several important life support systems:

- Energy production and supply (mainly electricity production using solar panels and methane production for vehicles).
- Exploitation of greenhouses for agriculture (vegetables, fruit), farming (mainly chickens and rabbits) and other needs (wood, etc.).
- Air production, supply and revitalization.
- Water extraction from ice (assumed to exist underground close to the base), transportation and recycling.
- Spacesuits, pressurized vehicles, quads, as well as 3D printers, general tools (hammer, saw, etc.), will also be shared at the village level.

In addition, some villages will be in charge of a specialization, which will be implemented at some distance from the main greenhouse of the village.

- Ore mining.
- Iron industry.
- Glass industry.
- Chemical industry.
- Wood industry.
- Maintenance and repair, mechanics, electronics, etc.

If possible, all places will be accessible from the center of the village thanks to pressurized tunnels and some villages can also be interconnected if they are not too far from each other.

5.4 Radiation risks and acceptability

High radiation levels are expected on the surface of Mars. According to scientific studies on the subject, such radiations are not strong enough to create immediately observable injuries but, in the long term (several years), the cancer risk is increased by a few percentage points. The risk can be decreased if the settlers hide deep underground during the most important part of their life. Obviously, all settlers will know the risks before the trip to Mars and the trip itself is very risky. If they nevertheless decide to go, they already have a high risk acceptability level. Are they willing to live underground in small habitats all the time or will they rather live in large spaces, exploring Mars as they want, even at the expense of a few years of life expectancy? It is assumed in this proposal that most settlers will have the psychological profile of adventurers and will accept the risks. They will go to Mars to be part of a great project and will prefer the second option. Eventually, a tradeoff can be chosen: At night, the settlers can sleep at the lowest level of their habitat with important shielding. During the day, however, depending on their activity, they might have to stay under the dome or in a greenhouse with relatively low shielding. But they will certainly prefer these conditions rather than staying underground all the time, never seeing the sky and the sun.

5.5 Behavioral competency

On Earth, the selection process will take psychological profiles into account. In addition, as for NASA astronauts [11], there will be behavioral training activities to improve communication, problem solving and team performance. These behavioral competencies will help a lot to get the settlers collaborative and constructive in their everyday activity, finding solutions to unexpected problems and avoiding interpersonal conflicts. It will certainly also impact the culture of the settlers, favoring the development of new social activities.

6. POLITICAL ISSUES

6.1 On Earth

It is assumed in this proposal that the settlement will be implemented by a state or multiple settlements by multiple states. Private companies might eventually propose launchers and interplanetary vehicles but a commitment to a long and expensive investment is required and can be supported only by nation states. Then, once a state is committed to the settlement project, there needs to be a group of persons - we can call it the Mars Settlement Organization Committee (MSOC) - in charge of the organization of the settlement:

- Technologies to be developed.
- Organization of the settlement process.

- Selection of settlers. For political, economic and pragmatic reasons, all settlers will probably belong to the same state. The advantage is the sharing of the same language and culture. Different nations might eventually invest in their own Martian settlement.
- Planning of launches.

Once the first base is built, the settlers will be in contact with the MSOC in order to adjust the payload according to the needs of the settlement.

6.2 On Mars

During the first development phase, it will not be possible to implement a complex political organization with different groups of persons in charge of executive tasks, legislative tasks, justice issues, etc. As the objective is to maximize the sharing factor and to optimize human resource allocation, it is rather proposed to manage the settlement using simple management principles:

- At the level of villages, a Village Direction Council (VDC) of 5 to 10 persons will be elected every 4 years and will be in charge of all decisions linked to life support systems and organization of the village. One person will be the Village Chief, one person the assistant and other persons will represent different activity domains. The exact number and the exact role of each VDC member will be determined by the VDC itself. The idea is to maximize the flexibility of the system in order to adapt the decision process to the difficulties that are going to be encountered and to allow quick re-organizations.
- At the settlement level, as long as the number of settlers is lower than 1 thousand (10 villages), each village chief will participate to a Settlement Direction Council (SDC). The SDC will be in charge of the development of the settlement, assigning industrial development tasks and production objectives to each village and organizing the sharing of all resources.

The VDC and the SDC will function as most organizations function in western societies. Each important decision will require the vote of each member of the committee and a decision is taken only if the number of positive votes exceeds the number of negative ones (or abstentions).

6.3 Conflict management

It will be important to minimize the risks of interpersonal conflicts on Mars. Behavioral competencies (see Section 5.5) will help a lot, but it is not possible to avoid all conflicts and, inevitably, there will be a person injured or even killed by another person. If the conflict involves several persons of the same village, and providing that they are not members of the VDC, it is the role of the VDC to address the problem and to find a solution, for instance a work punishment. If the conflict involves several persons of different villages, it is the role of the SDC to find a solution.

7. WELL-BEING AND AESTHETIC ISSUES

Preliminary version

Although there exists a wide variety of landscapes, Mars is a desert with no vegetation, no ocean or lakes and no rivers. In addition, going out for a walk or for exploration will require complex procedures with spacesuits, pressurized vehicles and safety concerns. As a consequence, if nothing else is proposed, many settlers will have to live in the same small place during long periods of time with very few changes. Important efforts have therefore to be made to increase the well-being of settlers and to avoid cases of depression:

- First, a village should be as beautiful as possible. Ideally, we should have large spaces and numerous gardens. It is proposed here to build a village under a transparent dome made of glass with an iron structure. The dome will be 10 to 20 meters high and 30 to 50 meters wide, allowing the presence of numerous houses and gardens inside. This concept has several advantages:
    - The width and transparency of the dome allows the feeling of freedom and wide-open spaces.
    - The presence of gardens brings nature into the village.
    - The sharing of the dome increases social relations and avoids isolation.

A drawing of our concept is presented in the appendix to the document. The dome is deeply incrusted in the rocks of the crater to resist external pressure forces.

- Secondly, it is proposed to build numerous refuges far from villages in order to provide safe backup habitations and to facilitate exploration and excursions. These refuges will provide minimum resources for settlers: air, water, food and a place to rest. However, as resources have to be saved, refuges will not be a place in which to live for long. All resources will be stored in containers. Such refuges will allow long distance trips on the surface of Mars.
- Thirdly, as already suggested, it might be possible to build greenhouses with robust ecosystems and very limited use of artificial systems to maintain living conditions. Such greenhouses will provide abundant plant and wood resources and will mobilize low human resources. Furthermore, they will also play the role of refuges and gardens for all settlers.

All in all, everything is done to provide comfort, well-being, exploration capabilities and development opportunities on the surface of Mars.

8. CONCLUSION

The settlement of Mars will not be easy. However, it is deemed feasible, providing that an adequate organization is implemented and appropriate efforts are made to achieve that goal. As resiliency is probably the key capability required of the settlement project and, as the step by step approach towards a modern Martian society will take a long time, we propose to end this document with a quote from Sheryl Sandberg, which could become the motto of the settlers:
“To fight for change tomorrow we need to build resilience today.”

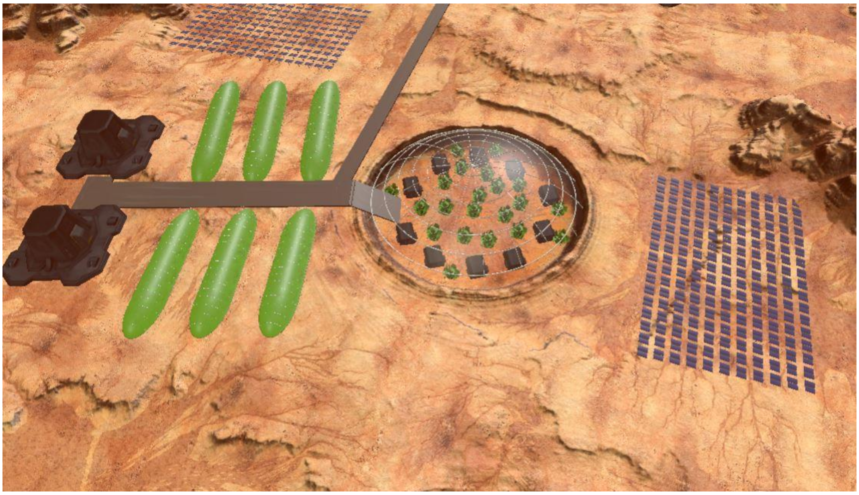
REFERENCES

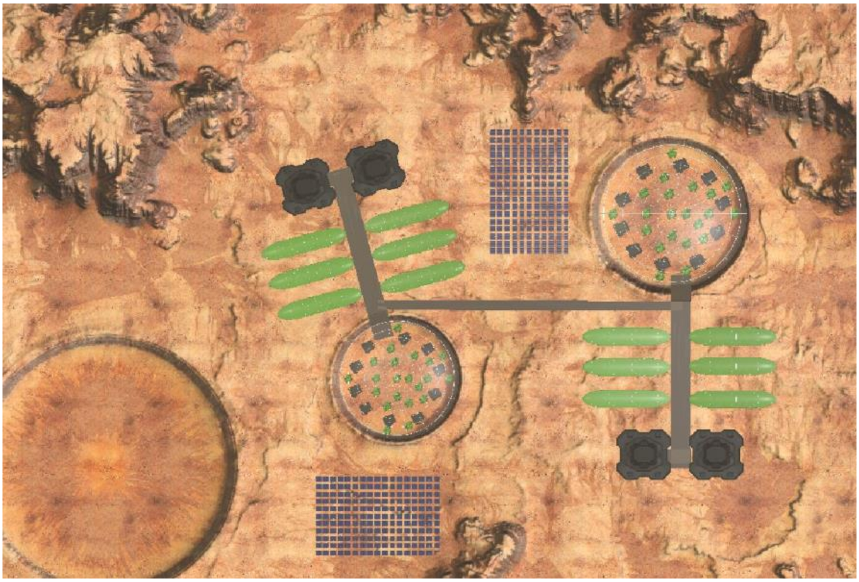
[1] G. Drake ed., Mars Architecture Steering Group, 2nd Addendum of the Human

Exploration of Mars, Design Reference Architecture 5.0, NASA Johnson Space Center, 2014.
[2] G. Genta and J.M. Salotti (ed.), Global Human Mars System Missions Exploration, Goals, Requirements and Technologies, Cosmic Study of the International Academy of Astronautics, January 2016.
[3] J.M. Salotti, Parametric equation for the settlement of Mars, proceedings of the 70th Internatioanal Astronautical Congress, IAC-19,A5,2,7,x49674, Washington D.C., 21-25 October 2019.
[4] C. Cooper, W. Hofstetter, J. A. Hoffman, E.F. Crawley., Assessment of architectural options for surface power generation and energy storage on human Mars missions, Acta Astronautica, vol. 7-8, pages 1106-112, 2010.
[5] R. Zubrin and R. Wagner, The Case for Mars, The Plan to Settle the Red Planet and Why We Must, Free Press, Touchstone Ed 1996.
[6] R. Zubrin, A. Muscatello and M. Berggren, Integrated Mars In Situ Propellant Production System, Journal of Aerospace Engineering. 26: 43–56, 2012.
[7] Cartier, K. M. S. (2018), Tests indicate which edible plants could thrive on Mars, Eos, 99, https://doi.org/10.1029/2018EO090749
[8] J.M. Salotti, Robust, affordable, semi-direct Mars mission, Acta Astronautica, vol. 127, pp.235-248, 2016.
[9] N. deGrasse Tyson, Space Chronicles: Facing the Ultimate Frontier, W.W. Norton, 2012.
[10] W. Peeters, International Space University, Economic course of the Master of Space Studies, 2002.
[11] NASA (2008), International Space Station Human Behavior and Performance Competency Model, NASA/TM–2008–214775, Vol. 2, Langley, USA.

APPENDIX

Illustrations of the settlement. Two domes are built above Martian craters. Under each dome, there is a village of ten houses and numerous trees. From each dome, there are corridors to reach greenhouses and industrial facilities. The next village can also be reached using a pressurized underground corridor. Large arrays of photovoltaic cells provide energy to villages.





Preliminary version