Energy problems of terraforming Mars. Leszek Czechowski[1], [1]Centrum Badań Kosmicznych Polskiej Akadenii Nauk, Space Research Center of PAS, u.l. Bartycka 18 a, 00-716 Warszawa, Poland lczechowski@cbk.waw.pl

Introduction: The recent successes of astronautics bring us closer to the expedition to Mars. However, significant colonization is still a long way from the scientific expeditions of a few people. On Earth we still have uninhabited areas of Antarctica. There, potential settlers do not have to worry about breathing air and drinking water. This brings us to the idea of terraforming of Mars. Here we are considering versions of terraforming that would allow people to live without pressure suits.

Atmosphere of Mars: For the adopted reference level on Mars, the average value of atmospheric pressure is 610 Pa [1]. On Earth the avereage pressure is 101.3 kPa (at sea level). However average atmospheric pressure on Mars ranges from 72 Pa at the top of Olympus Mons (Mars' highest mountain) to 1.16 kPa at the bottom of Hellas Planitia (Mars' lowest lowland). Therefore, Hellas Planitia can be considered the natural home for colonists on Mars.

Water at a pressure below 6.25 kPa boils at human body temperature (Armstrong limit). However, we often have to operate at higher temperatures, it is worth adopting a higher minimum pressure, e.g., p_{50} = 10 kPa. Then the water will boil only at ~50ºC.

The current mass of Mars' atmosphere is $2.5x10^{16}$ kg [1]. The pressure is proportional to the mass of the atmosphere. We are considering the terraforming variants described in Table 1. The C parameter means how many times we must increase the mass of the atmosphere to obtain a given variant. The next column contains the mass. R_{1000} is the radii of the bodies of this mass (with density of 1000 kg m^{-3}).

Table 1
Variants of terraforming

Var.	Pressure	C	Mass [kg]	R_{1000} [m]
v1	p_{50} at Hellas	8.6	1.905E+017	35696
v2	p_{50} at h=0	16.4	3.848E+017	45123
v3	101.3 kPa at Hellas	87.3	2.1581E+018	80168
v4	101.3 kPa at h=0	166.1	4.1266E+018	99503

Possible sources of volatile substances: For the terraforming we should import the right elements. Celestial bodies orbiting far from the Sun have large amounts of volatile substances, including water, CO_2, nitrogen, CO, and some organic compounds (e.g., CH_4). Some of these compounds seem harmful to life. In the terraforming plans proposed here, we envision an interim stage in which (after sufficient amounts of the above compounds have been brought to Mars) specially bred (or genetically engineered) organisms will release oxygen from H_2O and CO_2. The energy source for these processes will be the solar energy.

There are three places where there are enough bodies for terraforming: the asteroid main belt (MB), the Kuiper Belt (KB), and Oort Cloud (OC) [3]. The closest collection of these bodies to Mars is the asteroid belt. Its mass is 2.39×10^{21} kg. However, MB bodies are significantly depleted in light elements [3]. Therefore, the MB is not a good source of material for us. The Kuiper belt (KB) extends from about 30 to 55 a.u. from the Sun. It consists of over 70,000 objects over 100 km in diameter. The mass of KB is large enough [3, 4]. In fact, one body with a diameter of over 100 km would be enough - Table 1.

OC is rather a hypothetical object. It contains, among others, billions of bodies with a diameter of over 20 km. The total mass is $\sim3\times10^{25}$ kg [5]. The chemical composition meets our goals, but the problem is the large distance from the Sun. In Table 2 we have given the approximate distance of the inner edge of the OC.

Table 2

1	2	3	4	5	6
Source	**[a.u.]**	**Time [yr]**	**v_{orb} [km/s]**	**v_{fall} [km/s]**	**Ionic engine 10000 s**
MB inner l.	2.2	3.86E-01	20.07	18.92	0.002044
KB. inner l.	30	2.90E+01	5.43	33.23	0.000554
OC. inner l.	2000	1.58E+04	0.67	34.10	0.000068

(1) Source of the matter. (2) semi-major axis [a.u.], (3) Time of falling [yr] from (1) to Mars' orbit. (4) orbital velocity v_{orb} [km/s]. (5) final velocity of falling v_{fall} from distance (1) to Mars' orbit [km/s]. (6) Relative mass of propellant used to reducing v_{orb} to 0.99 v_{orb} for ionoc engine.

Transport of bodies: The above reasoning shows that, due to its composition, it is worth considering transport from two places: from KB and from OC. The simple method to transport body from distant US regions is to reduce its speed to almost zero (in the calculations we assume reduction to zero). The body will then start falling towards the Sun. The fall time and the velocity of the body (impactor) when it reaches the orbit of Mars are in Table 2.

The important result is the fall time. For KB bodies it ranges from 29 to 63 years, and for OC bodies it is over 15,000 years. The time scale for planning and implementing investments of several dozen years is acceptable. However, the time of 15,000 years exceeds possible scales. So, we should use KB bodies for terraforming.

To change the velocity, it is necessary to use rocket engines. Table 2 shows the consumption of the propellant (as the ratio of the mass of matter thrown out by the engine to the mass of the entire body) necessary to change the speed by 0.01 v_{orb}. Of course, a chemical engine requires huge amounts of fuel and oxidant. An ion engine would require a much smaller amount of working fluid, but a power plant would be needed to power it.

Gravity assist: The velocity change of 0.01v_{orb} introduced above, assumes that the main energy for the orbit change will be provided by the gravity assist. It is the maneuvering of a body so that it passes close to another body of large mass. This maneuver is now widely used in astronautics. It requires precise maneuvering. The maneuver can be used whenever impactor approaches a large celestial body. There are a number of bodies of considerable size in KB, and on the way to Mars the gravitational field of large planets can be used. Table 3 gives the ratio of the energy needed to reduce the impactor's speed by 50 m/s to the energy currently consumed by humanity in 1 year: E_{1yrE} [6]. It can be seen that for the poorest variant v1 the energy required is approximately 21% of E_{1yrE}, but for the most ambitious variant v4 it exceeds E_{1yrE} by almost 8 times.

However, gravity assist in our case is fraught with significant danger. KB bodies can be quite unstable, especially when they get close to the sun. It is also worth using gravity assistance to reduce the relative velocity of Mars and the impactor at the moment of impact. This is important because a strong heating of the atmosphere will lead to the escape of gases from the atmosphere. Moreover, a powerful impact on the surface of Mars may lead to cracks in the lithosphere, earthquakes and volcanism [7].

Table 3

Var.	Required mass [kg]	E_{50} [J] Energy for Δv=50 m/s	E_{50} / E_{1yrE}
v1	1.905E+017	2.381E+20	3.68E-01
v2	3.848E+017	4.810E+20	7.42E-01
v3	2.1581E+018	2.698E+21	4.16E+00
v4	4.1266E+018	5.158E+21	7.96E+00

E_{1yrE} energy consumed by humanity during 1 year: assumed here: 6.48e20 J/yr [6].

Tidal disruption: To calculate possible effects of gravity assist we used formulas developed in [8]. They describe a minor body consisted of two parts m_1 and m_2 moving close to a large body. Motion of the part m_1 of the minor body is descibed by:

$$m_1\, d/dt^2\, \mathbf{r'}_1 = \mathbf{F'}_1 + \mathbf{F'}_c + \mathbf{F'}_g + \mathbf{P'} - m_1\, d/dt^2\, \mathbf{r}_s,$$

where $\mathbf{r'}_1$=(x'$_1$,y'$_1$) is radius vector of the part 1 of the minor body in relation to non-inertial primed frame of reference, $\mathbf{F'_1}$ is gravity force acting (from the large body) on part 1 of the minor body**,** $\mathbf{F'}_c$ is the centrifugal forces and $\mathbf{F'}_g$ is the gravitational attraction of part 1 by part 2. Component P'_x and P'_y are friction and reaction forces, respectively. The $\mathbf{r}_s$ is the position of the center of the satellite in an inertial system. The results of our calculation indicates substantial problems. The effect of a gravity assist often depends on unstable behaviour of volatiles or on the low cohasive forces of the KB bodies.

Conclusions: Creating an atmosphere that would allow human life is possible by importing matter from other celestial bodies. The required amount of energy required for implementation is comparable to the current energy consumption of humanity within a few months to several years, depending on the selected terraforming variant. Due to the huge amounts of energy needed, a power plant based on a thermonuclear reactor (operating on local hydrogen) and an ion engine seems to be the most appropriate. However, there may be problems with using gravity assist.

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