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TERRAFORMING MARS WITH (LARGELY) SELF REPRODUCING ROBOTS*

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The advent of self reproducing robots within fifty years will make possible the terraforming of Mars in a few decades. All schemes for terraforming should be judged against this likelihood, and we should think in terms of the next century rather than the remote future. Such robots can also help terraform the moon and many other bodies in the solar system.

INTRODUCTION

There are various schemes to provide Mars with a CO_2 atmosphere by causing the evaporation of the dry ice at the South Pole and in the regolith. Although no one knows how much is available from these sources, getting it to vaporize may not be too difficult and a reasonably thick atmosphere may be attainable in a hundred years or so. (1,2)

However the next step in terraforming, changing some or all of the carbon dioxide into breathable oxygen, is far more difficult. It inherently requires about twenty times as much energy to split a molecule into carbon and oxygen as to sublime and warm it. * Some terraformers hope to sow plants or bacteria to do the job by photosynthesis. But as Zubrin and McKay point out, plants turn less than 0.01% of solar energy into this chemical reaction, and would take over 100,000 years to complete the task. * They hope genetic engineering can improve this efficiency a hundred times, but even then 1,000 years would be needed.

Other terraformers suggest the use of nanobots, tiny self reproducing robots that will rip the CO_2 apart physically. But nanotechnology is so far in the future that no one can really guess its capabilities or limitations. Thus the plan is not provably wrong (or right) and simply amounts to saying that the human race will make vast improvements in technology sometime in the future, and make the new atmosphere using nanobots or some other form of "magic". Actually this is very likely, but it really says very little about *how* we'll do it.

THE PLAN

Here is a clearer plan. We do not need nanobots, only robots able to reproduce themselves. Presumably such machines will be roughly man-sized, not microscopic. Nor need they be able to

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reproduce every part of themselves, just the heavy parts. Light parts -- e.g. computer chips -- can easily be brought from earth. Even today a chip weighs half a gram, and two million of them weigh only a ton, so we can transport the brains for a robot army in a small space probe.

Once there are many robots on Mars they can make solar panels or reflectors enough to cover the planet, and the power can be used to run cracking plants to split the CO_2. Solar cells are 20% efficient, much better than the 0.01% efficiency of bacteria. So 100,000 years shrinks to 50. Solar cells of 75% efficiency are in the works (3), so the time could be shorter still.

Even more promising is the process of simply heating CO_2 until it dissociates, and then pulling the oxygen out through a zirconium membrane. This process and variants have been studied as a means of in-situ fuel production, with CO as a by-product or fuel component. (4) Carbon monoxide is poisonous and explosive though, and would not make a good component for an atmosphere. However, via a catalyst such as hydrogen-reduced magnetite, oxygen and pure carbon can be produced at just 300 C. (10) Using solar reflectors and "ovens" with heat exchangers, this method could approach 100% efficiency and produce a 120mb oxygen level in just ten years.

Of course we may wish to cover only a part of the planet and cannot achieve perfection, so these numbers are only approximate. Yet uncertainties should not obscure the critical, the absolutely salient point: even 20% efficiency is more than 0.01%. **Two thousand times more**.

We do not have manlike robots today, but our path to them is straightforward and one would expect them to exist before a thick CO_2 atmosphere on Mars (which will take at least 60 years from today to achieve). To understand why rapid progress is likely, see addendum. Here is a possible scenario for Mars:

The year is 2050. Robots have been designed and tested extensively on earth. Ten robots, 100kg each, are sent to Mars, where a scientific station or small colony already exists. (Note that 10 x 100 kg is one metric ton, which we surely can afford to send.) The colony is nuclear powered, and produces adequate hydrogen for the robot fuel cells. A couple of engineers will direct and maintain the robots, while hundreds of planners on earth send directions with a few minutes' time lag. Some robots are manlike and dexterous, while others are small earthmovers. At first humans help with much of the work.

The robots begin by building an aluminum smelter (basically vats to fuse martian ore, plus electrodes), surface-mining ore with earthmovers, and smelting it into big sheets of aluminum. These will be used to build the bodies of robotic scrapers and mining machines, to be completed with lighter parts from earth. From here out aluminum is plentiful.

Next the robots make dies and simple presses, and thus a stamping plant. Now they can turn aluminum sheets into the heavy structural parts of robots (perhaps exoskeletons like plate armor.) These parts are the heaviest single component of a robot, perhaps 60% of its weight.

The robots assemble these parts together with a ton of parts from earth, but this time the ton from earth is enough for twenty-five robots instead of ten...

And so it continues, with more robots building factories for assembly, for gears and tubing, for bearings and motors, until it takes only a kilogram of earth materials to build a robot; until it takes only a gram... There is no need for a fanatical insistence that the robots completely reproduce themselves on Mars, only that, in a practical way, most of their mass be produced there.

Soon there will be thousands, then millions of robots, and then they will set to work making solar panels and setting them up over much of the surface. A good atmosphere will be produced in decades. Thereafter they will remove the apparatus and oxygen will be maintained by plant life or just a few panels.

The advantage of this idea is that no magic is needed, just continued progress of the kind we are making now: better chips, better programs, and improved robots. We already have dexterous robots on assembly lines, and automated factories where robots completely assemble calculators and almost-completely assemble VCR's and even robots like themselves. We have experimental bipedal robots, autonomous rovers, experimental excavating and ore hauling robots and so on. (9) True, we must improve these devices before we'll have robots that can do *everything* we want, but such improvements appear fairly straightforward and require no nano-warp-drive breakthroughs.

DETAILS AND DOUBLING TIMES

Let us ask how many machines we need to cover half a planet with solar reflectors. Mars' surface is 1.4×10^8 Km^2, so we must cover $0.7\text{-}x10^{14}$ m^2. What do we have for a basis of comparison?

We can certainly carry to Mars a ton of chips, enough for 2 million machines, so let's use that as a baseline. Spreading the reflectors or cells, once they are produced, should be easy. We imagine a man pushing a lawnmower, moving at 1m/s, cutting a 1m swathe, covering $1m^2/s$. Now we imagine a farmer on a big tractor, going 10m/s (about 20mph), unrolling a 10m wide roll of cells, covering 100 m^2/s, (x 3600s/hr x 24h/d x 365d/y = 3×10^9 m^2/y). At this rate a machine would need 22,000 years to cover the area. Or we could do it in a year using 22,000 machines. This is just one percent of two million, leaving the other 99% to mine the materials, make the cells, etc. Furthermore, silicon, aluminum, and iron are among the most common elements on earth and Mars -- so common one might almost say they *are* Mars. If we must cover the surface of a large silicon body with a one-mm thick layer of silicon solar cells, we are not likely to run out of silicon, which extends to 4000 Km deep (from the surface to the center of the planet.) Nor should even thinner aluminum foil reflectors deplete the aluminum.

But two million robots, including man-like, tractor, and mining models, is a lot. How long would it take to make them by present day standards? The answer is surprising. In America today, a basic 1000-Kg car can be bought new for about $10,000. An automotive engineer has said that that just 43% of that is production (not just assembly, which takes only fifteen hours, but all production from mining the ore to polishing the nameplate.) At an industry average wage of around $43 per hour (counting fringe benefits) that's just 100 hours. Hence a 100-Kg robot should take 10 man-hours. (A tenth the weight of a car, a tenth the time.) The Fanuc factory in Japan produced a thousand robots per month, using what appears from illustrations to be about 100 to 200 robot workstations plus some human workers, all in 1988. This would give a doubling time of three to six days. (11) Allowing for the humans, let us assume seven days for argument. This means robots could reproduce themselves, doubling their numbers every week. In ten weeks ten robots would be ten thousand; in twenty weeks, 10 million, and so on.

To be sure, we on earth already have the infrastructure, the steel mills and power plants and roads that make this possible. On Mars, ten robots will take a while to build aluminum plants (for structure and wires), a steel mill (for magnets and motors), a stamping plant and so on. But with those, production can take off. I would expect the infrastructure to take several years, but after that the doubling time might approach days. And even if each doubling required a year, we'd have our two million robots in under twenty years. If we needed more, an initial lot of ten would grow, in forty years, to eleven thousand billion ($10x2^{40}$, $1.095x10^{13}$.) This is an absurd number, nearly two thousand times the human population of earth, but it illustrates the point that we can quickly have as many as we could possibly need. Given self-reproduction and a reasonable doubling time, virtually anything is possible.

HOW MUCH ORE IS NEEDED?

Two million, 100kg robots represent about $2x10^8$ kg of aluminum, or, allowing for 40% ore, 5 $x10^8$ kg of ore (500,000 metric tones). The great Bingham open pit copper mine produces 320,000 tons/day, so this is under two days' production. Harder is covering half the surface of Mars with reflectors. Aluminum foil is "quarter mil", or .00025 inches thick. Covering .07 x $10x^{14}$ m^2 requires 4.4 x 10^8 m^3 ; 1.2 $x10^9$ tons, or 3.1 $x10^9$ tons of 40% ore, which is 26 years' production at Bingham. This is a large but reasonable task. The mine employs 800 men; there will be millions of robots.

WASTE DISPOSAL

Two hundred millibars of oxygen, the earth standard, represents 3 lb of oxygen in a column above every square inch of the surface. On Mars, with its lower gravity, 7 lbs would be required for the same pressure. Seven lbs of oxygen is contained in ten lbs of CO_2, the other three lbs being carbon. So if we produce seven lbs of oxygen above every square inch we'll have three lbs of carbon above the same area. At a density of .063 pci for solid carbon, this is a carbon column an inch square by 48 inches tall (1.2 m), or probably 2 m counting voids. That is, if we produce an earth-normal pressure of oxygen from CO_2, we'll cover the whole surface of the planet with two meters of carbon dust -- i.e. lamp black, a vile dirty substance that coats everything and shorts out electronics. This will not be Utopia. To avoid this coal miner's nightmare we must peletize the carbon as it is made and either bury it in ravines and low spots or pile it into hills. If these are 200m high or deep they will cover just a hundredth of the surface, which is reasonable. They will of course be sealed with soil to prevent the wind from eroding them and scattering lampblack, and to prevent their catching fire. Thus, just as so much carbon is stored on earth beneath our feet as seams of coal, so it can be stored harmlessly and neatly on Mars.

This dirty problem exists, by the way, no matter how oxygen is produced from CO_2. McKay et al note that "The limiting step in the production of any O_2... [may be] the necessity of sequestering the organic material in places (presumably deep sediments) where it is not reoxidized [which could be very difficult.]"(1) On earth, biology has made coal from CO_2. On Mars, biology would do the same, but it might be millions of years before coal formed and was buried, during which time carbon would continue to pollute everything. No matter what, we must dispose of the carbon.

HEAT BALANCE AND GOOD GLOBAL WARMING

If we use a lot of the solar energy striking Mars to break CO_2, there will be less left to warm the planet and it will grow very cold -- other things being equal. Fortunately, we don't have to leave those other things equal -- we can change them drastically for the better.

The temperature of an object in space is determined by three things: the amount of sunlight striking it, the percentage of visible light (sunlight) absorbed (="absorptance", a_s), and the emissivity in the infra-red (the percentage energy emitted by a surface compared to the amount a perfect emitter at the same temperature would radiate, "e") A perfect mirror (a_s=0) could grow very cold. An object with low emissivity would grow warm.

Mars' soil surface absorbs visible light well. Its a_s varies from .75 to .85. (5) We could achieve a little by darkening the light areas by spreading dark soil over them, but a_s is already so high that we cannot do great things here.

For emissivity the story is different. Soil emissivity is nearly 1.0--100%, the maximum possible. But emissivities as low as 2% are achievable, meaning that at the same temperature, the surface could radiate away just one-fiftieth the energy it now does.

The situation is complicated somewhat by the atmosphere, which radiates weakly itself and also insulates the ground via the greenhouse effect. The author has discussed the matter with a planetary-atmospheres scientist, who confirms that a low-e surface on Mars would raise the temperature of both the surface and (by contact and convection) the atmosphere. But the effective emissivity of the atmosphere is only a few percent over the entire IR band (high at the 15-micron wavelength of CO_2 but low everywhere else.) Thus the atmosphere would not radiate much. However, a dust storm would make the atmosphere look like the surface, with an e of 1.0. (So dust storms would have to be avoided by covering dusty areas with foil and rocks.) As the atmosphere becomes like earth's, with many gasses radiating at many wavelengths, the emissivity will approach the earth's level of 50%. (But this is still only half the present 100% level of the surface, and the greenhouse effect of such an atmosphere would keep the planet tolerably warm by itself.) In any event, under present conditions, the atmosphere can be ignored and we can base calculations on lowered surface emissivity. (12)

If, then, we covered the ground with low-e material and used most of the sunlight for making oxygen, then just a fiftieth of the solar energy could keep the ground and air at their present temperatures. Actually, various thermal losses in the CO_2 cracking process will exceed 2% and the excess will go to warm everything above present norms.

Thus one may imagine thin aluminum mirrors covering the surface and focusing on high temperature retorts in which the CO_2 is cracked. The absorptance (a_s) of the mirrors is 8%, so they reflect 92% to the retorts. The emissivity is just 2%, so they radiate almost nothing to space -- just a fiftieth of the current loss. The backs of the mirrors, facing the ground, are treated for high emissivity, so the excess heat is coupled to the soil and warms it.

Of the incoming solar energy, 8% is absorbed and turned to heat by the mirrors, and perhaps 24% is lost from the O_2 process, so overall only 32% of solar energy goes to heat (vs. about 80% today). But only 2% as much energy is lost. We go from today's a_s/e of (.8/1.0 =) 0.8 to (.32/.02 =) 16.0 -- a factor of twenty improvement. We net about 30% of the incoming solar energy for warming soil and air, and still have 68% to break CO_2.

McKay et al (1) calculate that to warm a 1 bar atmosphere from 150-288 K requires four years of martian solar insolation, while to warm the top ten meters of soil will need 0.3 years. (1) That is, a total of 4.3 years of sunlight is needed to warm Mars to earthlike temperatures. If we use only 30% of the energy for warming, it will take 17 years. If we cover only enough surface to capture half the sunlight, 34 years is required. Conveniently, that is about the time needed to make the oxygen (at 68% efficiency and catching 50% of the total insolation, 29 years is needed for 120 mb.). So in 29 years, we can have a warm wet Mars with breathable atmosphere.

OTHER USES

Given as many robots as we want, we can do many things besides split CO_2. Nitrogen may be locked in chemical compounds on the martian surface. We can split those compounds and produce a nitrogen atmosphere. CO_2 thousands of meters deep in the regolith may take thousands of years to warm and evaporate, because heat transfer through kilometers of soil is poor. (14) But we could sink heat pipes at small intervals and get it in decades. We can produce other greenhouse gasses, per Lovelock and Allaby(15), and speed warming. We can build many fission or fusion power plants and obtain energy in addition to solar, perhaps far surpassing it. We can build the giant orbital reflectors also envisioned to heat the planet, and build mass drivers or slingatrons to launch them.

TERRAFORMING OTHER BODIES

The Moon

Oberg (6) tells of various schemes to heat moon rocks and liberate oxygen, producing a thick atmosphere that would last but a moment in geological time -- but a geological moment is 10,000 years, or forever in terms of human history. Clearly, robots plus solar concentrators (reflectors or Fresnell lenses) could heat the rocks this way. The Moon would still be deficient in hydrogen and nitrogen, and still have too long a day, but providing even a partial atmosphere would be a good start towards terraforming.

The Moons Of Jupiter

Jupiter is so far from the Sun that light is weak and the moons are very cold. However, the temperature of an object in vacuum is proportional to both light intensity and a_S/e, and an increase in one can compensate a decrease in the other. If we could cover the moons with thin layers having a high a_S/e, we might warm them to earthlike temperatures. Gasses would sublime creating thicker atmospheres and greenhouse effects would warm the bodies further. (Again the gasses are only weak emitters so though they will be warm they will not radiate away much energy.)

Sunlight at Jupiter is only 1/27th as strong as at earth. For earth, a_S/e is about .6/.5= 1.2. To increase that 27 times we would need an a_S/e of 32. The best artificial surface for high a-over-e is vapor deposited gold, a_S=.19, e=.02, a_S/e=9.5. This falls short, yet close enough to suggest that an adequate material might be developed. (7) Or, reflecting sunlight from vapor deposited aluminum (a=.08, e=.02)onto a high absorptance material arranged to heat only atmosphere (and not radiate directly to space) will raise effective a_S to 1.0 while not changing e at all, so a_S/e goes to 50, more than enough.

Again we have a good start, though other problems remain: long days and mostly-ice surfaces that might melt to produce universal oceans.

(Saturn's moons cannot profit from this method -- all are too small to hold an atmosphere, except for Titan which already has a thick atmosphere whose emissivity sets the temperature, making surface emissivity irrelevant. An a/e of 108 would be needed at Saturn, above the maximum shown here, and far better ratios would be needed for more distant planets.)

Mercury

Mercury gets 6.7 times the sunlight of earth, but if its a_S/e were much less than earth's it could have the same temperature. Earth's 1.2 divided by 6.7 gives 0.18 required. The white coating of Barium Sulphate with Polyvinyl Alcohol has an a/e of .06/.88= .068 -- much better than required and enough to make the planet icy. (Obviously we could use a different material or cover only parts of the surface.)

If robots then built slingatrons and threw off material to increase the spin rate and shorten the day, if volatiles could be found in the crust (perhaps methane brought by comets during the original accretion as proposed by Thomas Gold for earth (8)), and if these could be released to form an atmosphere, then even Mercury, most daunting of all the planets, might be fully terraformed. (However this is meant more as a vision than a suggestion; speeding the rotation of a planet is a stupendous undertaking.)

CONCLUSION

We can *today* build robots for mining and assembly, and will soon be able to make largely-self-replicating robots that can increase their numbers to any desired level at little cost to us. Cheap robot armies give us a powerful new tool for terraforming whose uses have barely been touched on here. Others should consider the possibilities that this idea opens up.

For Mars we should have sufficient capabilities in fifty years, though it could be more or less. But surely we will have macrobots before nanobots, and whether it takes fifty years or a hundred and fifty we *will* have them, and be able to turn Mars' CO_2 to O_2 in a few decades.

We should therefore abandon the idea that it will take a hundred millennia to terraform Mars, and turn our thoughts to a livable O_2 atmosphere in a century or less. In the event, we may find a better way, but this believable scenario should be taken as an outside limit.

Let us explore Mars soon, and then make it a garden.

ADDENDUM: ADVANCES IN TECHNOLOGY AND NASA WORK

Is it somehow "cheating" to assume we will have robots in fifty years? Is it wrong to base estimates on anything besides today's technology?

Martin Fogg describes a Freeman Dyson idea to place a fully self-replicating robot factory on Enceladus and comments:
" ... Dyson's reason for indulging in [this thought experiment] was to show just how unbounded the future might be. However most terraforming researchers leave von Neuman machines alone, as one of those tools of the "arbitrarily advanced civilization" mentioned in Section 3.1. Once such capability is attained, all bets are off and almost anything not ruled out by physical law is possible." (14)

The author agrees as regards full replication, though the partial replication described seems quite likely in the near term. But in a broader sense, is it wrong to assume *any* capability we do not have today?

No. Practically our whole civilization was invented in the last hundred years. Far more scientists and engineers will work in the next fifty years than in the last fifty, and it is widely remarked that knowledge is increasing exponentially, so our capabilities will increase more rapidly during this time than in the past.

There is opposition to terraforming Mars before it has been studied in its natural state, and since people will not even walk on Mars for twenty years it will probably be fifty before studies are complete and terraforming can begin. Fifty years ago we had no robots (nor even any computers); now we have Mars rovers, assembly line robots, and vehicles that can move off-road through obstacle fields at six miles an hour (9). In a few years we should have robots for strip mining and smelting. (Robotics students say a major equipment company could introduce robot mining trucks within five years, provided union opposition can be overcome, though the company itself is reluctant to discuss the matter -- in spite of having demonstrated the hauler at a major mining equipment show in 1996, and having run it 8,000 miles in a strip mine!(9)) In a few decades, we could have the more complex models here assumed. Thus these prognostications are not unreasonable. By the time we're ready to start changing Mars, the technology will be there to let us.

Previous Nasa Work

After this paper was completed it was found that in 1980 NASA had held a summer workshop to examine the idea of a self-replicating "seed" factory: a 100-ton factory that would reproduce itself in about a year. (13) They too considered use of some outside materials, or "vitamins" as they called them. Based on the average composition of the lunar soil (no ore bodies were postulated) and a reasonable ratio of material processed to material output, they found a "closure ratio" of 90-95% was feasible -- i.e. only 5-10% of mass would be imported.

Their 146-page report is comprehensive and thorough. They examined terraforming, finding 100mb of oxygen on Mars was possible through reduction of SiO_2 in the soil in about sixty years (with power from a giant solar satellite, existence assumed.) The moon, Venus and more could be achieved. They found it possible from a machine shop viewpoint (producing mainly molded parts finished with laser cutters.) They postulated front-end loaders to bring in soil. A 4400 kg loader running a 40km round-trip could deliver $4x10^6$ kg per year. (Incidentally, this is all that is required to make the robots in the current scheme, and if the smelter were located next to the ore deposit and the round-trip were only 1km, then just one 100-kg loader would be required. Of course, more and bigger loaders would be needed for the reflector material.)

They mapped the steps needed to develop such a factory. They estimated it would take eighteen years. Although nothing was done with the idea, the past twenty-two years have seen great progress in allied fields, as computers have shrunk from the refrigerator-size shown in one of their sketches to the latest single-chip models of today.

It is odd that this work has been forgotten, but obviously it has -- else why do we continue to talk in terms of a thousand centuries to terraform Mars?

In any event, it is not unreasonable to assume that we can do fifty years in the future what this serious NASA study concluded we could do twenty-two years in the past.

$CO_2 + H_2O >> CH_2O + O_2$.

Zubrin & McKay show that with this reaction 200 mb of O_2 requires 17 years of the total solar energy striking the planet. Sublimation and warming of 1000 mb of CO_2 require only four years' worth of sunlight. The reaction above is shown to require 8x106 J to produce 540g (both per cm2 of Mars' surface), which works out to 4.74 x 105 J per mole of O_2 .(1) The reaction here proposed, CO_2>> C+ O_2, uses slightly less energy, 3.94x105 J/mole(16). For this paper it has been assumed these numbers are the same and the numbers in (1) have simply been ratioed to obtain required times, because the values are close and it is not known what reaction would ultimately be used.

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