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THE CASE FOR CELLULOSE PRODUCTION ON MARS

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From examining the consequences of not requiring that all wastes from life support be recycled back to the food plants, we conclude that cellulose production on Mars could be an important input for many non-metabolic material requirements on Mars. The fluxes of carbon in cellulose production would probably exceed those in food production, and therefore settlements on Mars could utilize "cellulose farms" in building a Mars infrastructure.

INTRODUCTION

Much scientific attention in recent years directed toward integration of plants into space life support systems has focused on the use of plants as sources of food, potable water and oxygen, and as sinks for carbon dioxide and metabolic wastes[1]. In other words, the metabolism of plants has been linked to the metabolism of the human body. In an ideal bioregenerative life support system, materials cycle in various loops between biomass production, food processing, the crew, and waste processing. In this work, we look specifically at the effect of a substantial reservoir of CO_2 in the atmosphere of Mars on the conceptual design of a life support system on Mars.

OPEN VS. CLOSED LOOPS IN MATERIAL FLOWS

To set the general stage for the following discussion, Figure 1 shows three system diagrams to compare two extremes: a completely open system with no internal material recycling and a materially closed system with total recycling. Somewhere between these two falls a system that is both partially open and partially recycling. These systems have been simplified to make certain points. First, a basic difference between the two end-points in this spectrum is that the functions of the intake and eject parts of the open system are replaced by the recycle part of the closed system. What would determine whether a system is open or closed? A first-order driver is the absence or presence of a needed material. For example, the paucity of hydrogen on the Moon, even though oxygen is abundant and extractable, would indicate the need for nearly complete water recycling, subject to economic costs of shipping water from the Earth. In other words, there always will be a trade-off between the cost of

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supplying a material external to the system and regenerating the material within the system. Furthermore, there will be varying costs to recycle different forms of a material or differing total fractions. Recycling 99% of water may cost more per unit mass than recycling 90%. Such differential costs lead into systems that are partially open and partially recycling, where what and how much is recycled is determined by some economic balance between what and how much is supplied externally. We see these trade-offs operate in our Earth systems today with the partially open systems used to supply metals, glass, and paper, to mention a few. Obviously the same principles will operate in our future systems on Mars, but the economic advantages will likely be more abrupt.

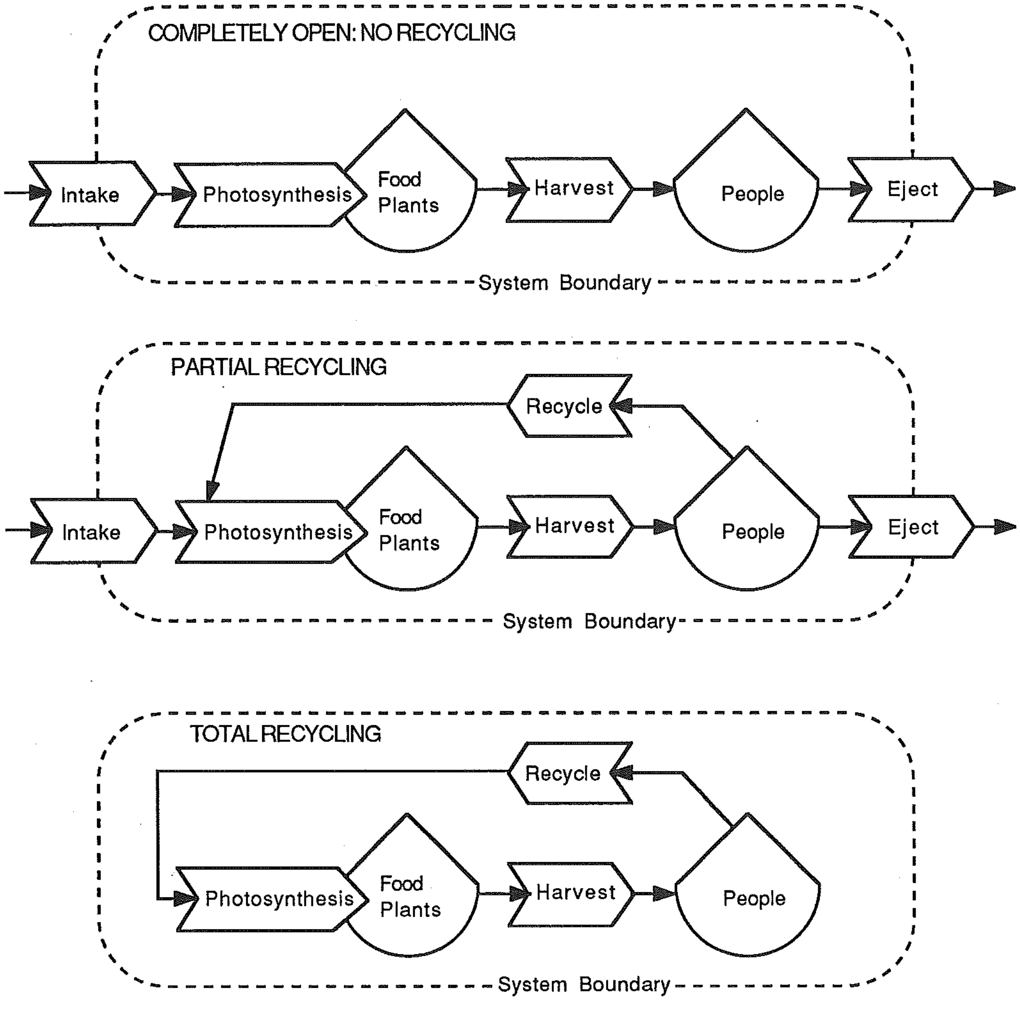

Figure 1. Three operating modes of a Martian life support system

The entire existence of the human species has depended on photosynthesis, directly or indirectly, for our food and oxygen; such also will be likely in the case on Mars. One necessity for photosynthesis, CO_2, is abundant on Mars. The CO_2 in the atmosphere of Mars alone is about 20 times that in Earth's atmosphere, about 20 times that in the living portions of Earth's biosphere (were all the reduced biosphere carbon to be oxidized), and about 33% that in Earth's ocean. Thus, if a Martian biosphere, equivalent in mass to that of Earth, could be constructed, the Mars' atmospheric CO_2 reservoir would be tapped only slightly, and there may be more carbon locked in carbonate sediments. Since it may be possible to grow plants in the Martian atmosphere (with some oxygen added, R. L. Mancinelli, personal comm., 1987), the energy and material requirements for an intake function on Figure 1a might be very low with respect to CO_2. We therefore will assume little drive for recycling the carbon-containing waste from humans back to the plants on Mars, since the CO_2 can be obtained rather inexpensively from the Martian atmosphere. What further concepts does this assumption lead to?

THE TYPES OF CARBON-CONTAINING WASTES

With all the carbon available on Mars, it would seem that recycling of carbon-containing wastes might not be necessary. The relative magnitudes of carbon in the three major carbon-containing wastes from humans, the exhaled CO_2, the fecal solids, and the urine solids, are approximately in the ratios of 22:4:1, respectively[2]. Most of the carbon is in the exhaled CO_2, and if this is removed from the air and the oxygen is separated, a carbon waste residue would remain. This carbon is a prime candidate for dumping, again assuming that using the Martian atmosphere as a supply for CO_2 is cheaper than recycling the exhaled human CO_2 back to the plants. The urine and feces solids are different than the exhaled CO_2 at least in the important aspect of containing fixed N. As in the case of CO_2, N is available in the Martian atmosphere as N_2, which could be fixed into an ammonia or nitrate fertilizer as a nutrient source for the plants by already-existing technologies[3]. Nonetheless, due to the energy costs, this fixed-N in the urine and feces will be a valuable resource and will inspire designs in which the fixed-N can be recycled back to the plants. Of course, if the fixed-N can be separated from the C in the urine and feces, this C will be a candidate for dumping, but CO_2 production could be a consequence of the fixed-N recycling.

Another major C-containing waste comes not from the humans, but from the plants: the non-edible plant parts that are grown along with the edible food. In wheat, for example, this includes the leaves, stems, and roots. Research efforts in the NASA CELSS program recognize these inedible parts could be utilized by other organisms, or could be further processed to yield fuels or other edible substances. But we will consider that some plant wastes also would be candidates for carbon-dumping.

To the extent that these plant wastes contain protein, they contain N, although in much smaller quantities relative to C, compared to the urine and feces solids. For example, assuming the inedible plant parts of the hydroponically-grown wheat contain about 2% N by mass, the urine and feces solids contain about 30% and 10% N by mass, respectively. Due to the abundant nutrient supply during the entire life of hydroponic plants, their inedible parts contain more protein than field crops, so it may be possible to lower the protein content of the hydroponic crops by careful adjustment. Furthermore, if the protein could be separated, N-free components, such as cellulose, hemicellulose, and lignin would remain as wastes, and these could be dumped without compromising the recycling of the nitrogen. Parts of the inedible plant wastes thus could be prime candidates for dumping, again subject to design trade-offs of costs of intake vs. recycling.

THE UTILITY OF CELLULOSE

The possibility of dumping either the exhaled CO_2 or the low-N plant waste requires that recycling be more expensive than intake of fresh CO_2 from the Martian atmosphere. However, this recycling might be relatively easy to accomplish. In the case of the exhaled CO_2, it could be as simple as using the crew atmosphere as feedstock for the plant growth. For the plant waste, the supercritical wet oxidation seems to be very efficient at taking organic carbon wastes of any sort and forming CO_2[4].

Let us now consider the following scenario: that in the total processes associated with life support, the intake and recycling of CO_2 will be relatively inexpensive compared to such processes as nitrogen fixation and recycling, water intake and recycling, etc. Therefore, although the plant waste could be recycled, there is no drive to do so, but this organic material could have other uses in the total material base of life on Mars.

One of the major components of plant waste is cellulose. For example, fibers composed of cellulose and hemicellulose constitute about 75% of the inedible parts of wheat. Wood also consists typically of 50% cellulose. While some similar arguments to those in the following paragraphs could be made for useful, non-cellulose components of inedible plant parts, such as resins and even lignins[5], we will confine the remainder of the paper to the utility of cellulose. Cellulose should be taken as representing any organic matter produced by plants that is non-edible and that may serve uses in the total picture of life support, including areas more widely defined than metabolic life support alone. Specifically, cellulose could be (and is) used in many areas of our habitations; why not use it on Mars, too? For example, desks, tables, chairs, shelvings, floorings, and interior wall coverings can all be made from wood products. One could imagine a Mars furniture factory processing cellulose into a variety of useful objects.

From tensional and compressional framing members to various types of boards and sheets, from heavy construction to finishing work, many construction materials could be (and are) based on cellulose. Martian construction systems will not necessarily look like Earth systems, but the utility of cellulose in Earth construction has been proven. There is a substantial historical base showing that cellulose products are comfortable to people in terms of touch and look, and can be manufactured in a great variety of shapes and sizes to suit a large number of needs.

There is also a family of plastics derived from cellulose, the cellulose ester plastics[6]. These plastics have a wide variety of uses, including lacquers for wood, metals, and plastics, names such as acetate, butyrate, and propionate. They can range from soft, extremely tough materials to hard, strong, stiff compositions. They can be transparent and virtually colorless, making it possible to manufacture them in almost any desired transparent, translucent or opaque color. Resistant to water and aqueous salt solutions, they are excellent for contact with food; Cellophane is a well-known trademark.

Other possible sources and uses of cellulose are obvious. Cotton is almost pure cellulose, and provides clothing and fabrics for rugs, furniture finishings, towels, etc. Rayon fibers from wood cellulose have been manufactured for decades, and cellulose fibers produced by new solvent technologies that are longer and stronger than those made with current technology could compete against the fibers now derived from petroleum[7]. Before leaving the production of fibers, it is worth just mentioning the widespread uses for paper products from information to hygiene.

Cellulose can be burned directly of course, or can be hydrolysized into glucose that can be made into ethanol for fuels. Wood alcohol, or methanol, and other distillates from the combustion of wood can be formed into fuel oils by use of a zeolite catalyst[7]. Once various methods of converting cellulose to glucose by hydrolysis have been perfected--chemical methods employ hydrochloric acid, calcium chloride and lithium chloride, biological methods use bacteria and fungi that secrete enzymes which dissolve cellulose--the ethanol manufactured from the glucose can serve as the feedstock for ethylene, itself a precursor for a variety of products, such as polyethylene and ethylene glycol[7].

We do not mean to imply the equivalence of all forms of cellulose, that wheat stalks would be as useful for structural beams, for example, as lumber. From the numbers discussed below, we estimate that cellulose will be grown intentionally on Mars, not just as a by-product of food production. Therefore the different types of cellulose--from waste by-products to intentional agricultural products--could be channeled into uses to which each is best suited. A survey[7] of current research into the potential for trees to be a major resource for plastics, textiles, and drugs in the next century looked at a variety of techniques that promise to give us great control in digesting and processing the many different components of wood.

Finally, we would like to highlight the possibility of combining the cellulose in construction materials and plastics to build greenhouse structures. This would amount to feeding the products of plant growth back into the structures that can grow more plants. The cellulose industry could become self-maintaining and expanding in this way, and could constitute a base for the growth of the Martian economy independent from input from Earth. Due to the presence of CO_2 in the atmosphere of Mars, there is a resource not just for growth of food plants, but also for providing carbon-containing materials that can permanently move into human systems on Mars. These various possibilities for the pathways of carbon are diagramed in Figure 2.

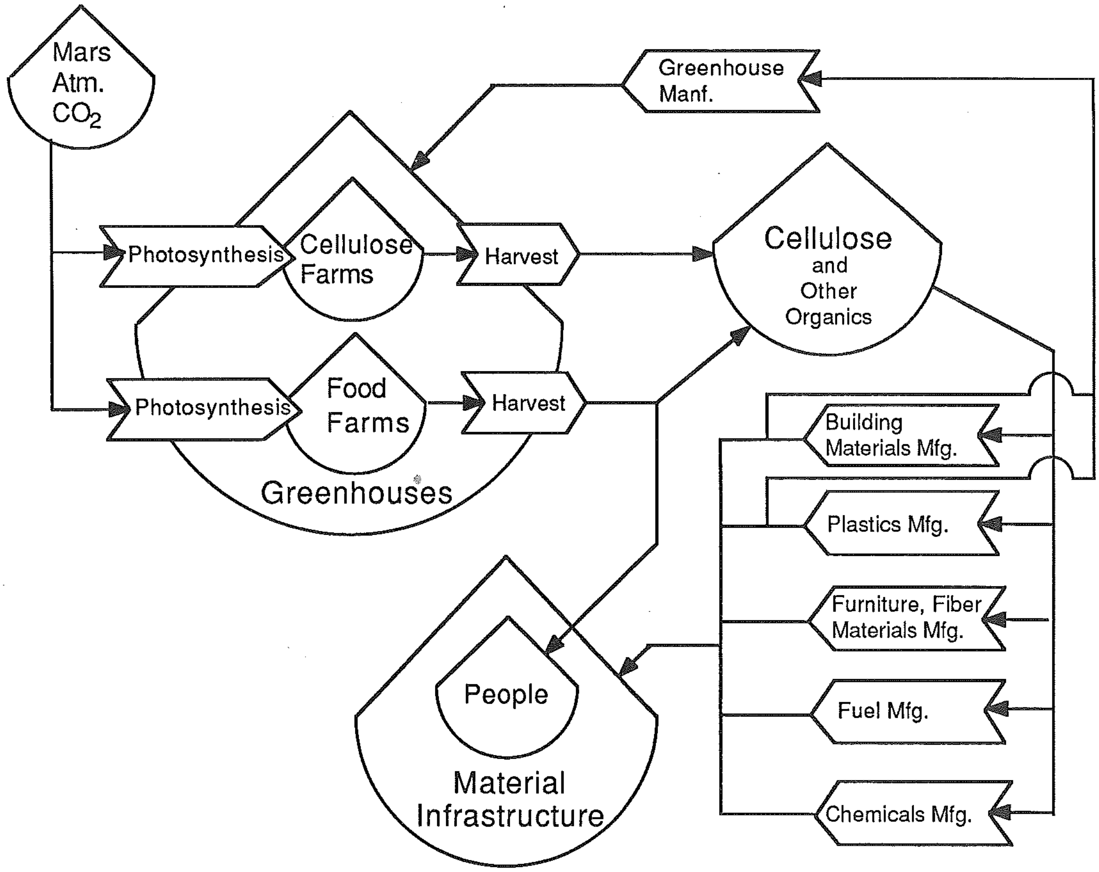

Figure 2. Possible flows of carbon "fixed" from the Martian atmosphere

HOW MUCH CELLULOSE?

Before turning to the possible magnitude of cellulose production, we note that cellulose production requires water, as well as CO_2 and energy (simplest formula: $6CO_2 + 5H_2O \Rightarrow C_6H_{10}O_5 + 6O_2$). From this formula, it is clear that a little more than 0.5 gm water is required for each gm of cellulose. The water available in the atmosphere of Mars as water vapor (equivalent to about 1 km^3 of condensed water) could be extracted at a cost of 100 kwhr per kg H_2O[8]. At an photosynthetic efficiency of 0.10 (below that currently achieved with hydroponic wheat), about 45 kwhr of energy is required to produce 1 kg of cellulose. About the same amount of energy would be needed for extracting the water from the atmosphere. Of course, if water is available from the subsurface of Mars, water delivery costs could be less, depending upon location, transportation costs, depth and quality of the water--all unknowns at this point. So the acquisition of water for cellulose production warrants further consideration, since it is a cost in addition to the assumed low cost of CO_2. We also have not mentioned the additional benefit of O_2 production; producing 1 kg of cellulose would produce 1.2 kg of oxygen. Producing this amount of oxygen from zirconium cells would cost about 7 Kwhr (Frisbee, this volume), which is not an insignificant savings over the energy used in photosynthesis. Nevertheless, photosynthetic energy may come directly from the sun, not requiring electrical energy as is required for the zirconium catalysis process, so the two energy amounts are not directly comparable.

Typical daily human requirements for food are on the order of 700 g dry matter. The magnitude of plant waste associated with this food production varies among cultivars, and is usually defined by the harvest index, the ratio of edible mass to total production. The harvest index for wheat and soybeans is about 50%, for potatoes and lettuce, about 80%. Taking 50% as an assumed harvest index, then, about 700 g dry matter per person-day is produced as plant waste. Incidentally, this total production would yield about twice the amount of oxygen needed per person-day; if not required to oxidize the plant waste, some of this excess oxygen could be make-up gas for the habitat atmosphere that is lost through air-locks and other unavoidable leaks. All of this waste may be useable as feedstock for chemicals, fuels, building materials, etc., but if only one-half is cellulose (a typical figure), then cellulose production will be about 350 gm per person-day.

Each inhabitant of a highly industrialized country consumes on average per day about 4 kg of wood and wood products[9]. If we assume that the carbon content of food and wood per gram is approximately the same, the amount of fixed carbon "consumed" as wood and wood products is about 5 to 6 times greater than the carbon required nutritionally, and about 10 to 12 times higher than the carbon in the cellulose of the inedible waste parts of food plants. These ratios are shown in Figure 3.

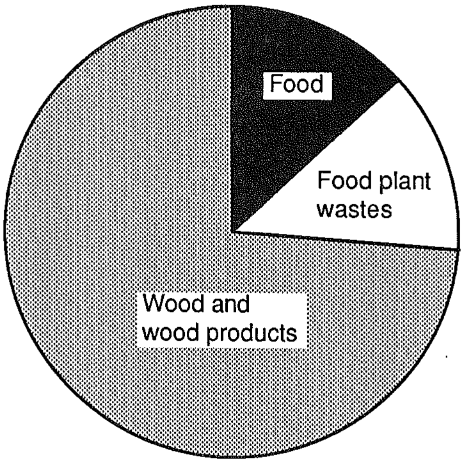

Figure 3. A comparison of the magnitudes of fixed-carbon fluxes on Earth, assuming similar carbon fractions for food, for inedible parts of food plants, and for wood and wood products (see the text)

If on Mars the cellulose requirements matched those of an industrial nation on Earth (trade newspapers on Earth for air filters on Mars), then the need for fixed carbon in cellulose substantially exceeds that for fixed carbon in food. Furthermore, the cellulose needed as an input into the non-metabolic life support needs discussed above may be of a different nature than plant waste associated with food production. These calculations imply that as a Mars settlement matures, cellulose production will eventually be differentiated from food production. In other words, there will be "cellulose farms" on Mars in the way there are managed forests and cotton farms on Earth. One can imagine the Martians requesting that the shipment from Earth be changed from tables and floorings to chocolate and lobster, and that they will be able to say "send us the luxury foods, we will grow and build our own furniture".

CONCLUSIONS

As a Martian settlement develops, non-food plant production could contribute significantly to the Martian economy, with cellulose production surpassing the food production in magnitude, as it does on Earth. The incorporation of fixed carbon materials as buildings, plastics, and fabrics, etc., is only possible when there can be a one-way flow of carbon from a reservoir in the environment into the human-controlled system. Given a source of water on Mars, such flow is possible because of the abundance of CO_2 in the Martian atmosphere. In the future as much, if not more, consideration should be given to plant production providing various material products associated with society as is now given to food production for the direct metabolic needs of people.

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