SPACE COLONIZATION PROGRESS

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Editor's Note: The first two articles in this issue are summaries of papers presented last year at the tenth Princeton/AIAA/SSI Conference on Space Manufacturing. The Proceedings of the Conference are available from the American Institute of Aeronautics and Astronautics, The Aerospace Center, 370 L'Enfant Promenade, SW, Washington, DC 20024-2518

ADVANCED SPACE LIFE SUPPORT SYSTEMS

Somewhere in between the shuttle and a 10,000 population space colony lies a space station, spacecraft, or base in which some form of recycling of air, water, and wastes will be needed. Scientists studying controlled ecological life support systems (CELSS) are attempting to install a "mini-Earth" in a bottle to sustain space travellers on extended stays outside the atmosphere. These studies combine nature and technology in new ways as explained by Dennis Chamberland, a bioengineer at the Kennedy Space Center, Florida. His paper focuses on the seldom discussed topic of waste processing or, as NASA calls it, resource recovery.

In ecosystems on Earth nothing is wasted. Everything is a resource that is continuously recycled. This is also desired in a CELSS. It is very expensive to keep resupplying outposts in space with provisions that are not recycled. NASA has a baseline study underway which is attempting to link four processes together into a closed loop life support system. The four processes are biomass production, food preparation, crew habitation, and resource recovery.

The biomass production produces a wide variety of food for hungry space travellers. Grains, fruit, and vegetables are grown in carefully controlled environments and then harvested for food preparation. The oxygen liberated from the plants will be utilized for crew habitation while the carbon dioxide released by human respiration will be returned to the biomass production. The system even has the potential to produce fish through an aquaculture setup.

Several resources can be recycled from the food preparation and crew habitation modules. These include inedible plant materials, human and kitchen "wastes", and grey waters from several points in the system. An assortment of biological reactions are utilized to treat the liquid and solid materials for recovery.

Water recovery is accomplished through condensation of the evaporated moisture from plant growth. Studies have shown that this process is efficient at purification so no filtering or chemical treatment is required.

The plant wastes are the most difficult to break down. Soluble plant matter extraction begins with exposure to water. Next, an enzyme from a fungus called Trichoderma reese is used to further break down the insoluble material.

IN THIS ISSUE:

This enzyme produces glucose (sugar) which can be segregated, purified, and passed back to the food preparation module. The portion of plant matter remaining is transferred to an oyster mushroom bed producing still more food. The last fraction persisting to this point is fed into a block of bioreactors using different types of reactions to reduce the material even further.

Depending on the needs of the habitation module the reactor used will be either aerobic or anaerobic. Aerobic reactors utilize microbiological cultures that maximize the use of oxygen converting the wastes to CO_2 and water, leaving a biomass "sludge". The sludge can then be dried, pelletized, and fed to fish as a source of protein.

The anaerobic reactors minimize the use of oxygen by using biochemical reactions in a fluidized bath to rapidly dissolve most of the solids. These reactions result in methane and sulfide gas which can be further separated by a high temperature plasma possess to net CO_2, water, and sulfur in its elemental form.

Utilizing both types of reactors increases flexibility in the CELSS. If the biomass production facility has aquaculture the aerobic reactions can be emphasized to produce fish food. If oxygen is scarce or if rapid reduction is required the anaerobic reactor is chosen.

The remaining residue from both types of reactors can be heated to resulting in a small amount of ash containing primarily oxidized metals. This by-product is hard to reduce without the use of hazardous acids and would probably be the only throw away remnant in the system.

Human waste recycling is frequently misunderstood and feared. Most people would shudder at the thought of this system being coupled back into the biomass production and food preparation facilities. Chamberland suggests that a psychological safeguard be implemented like a sterilization procedure with ionizing radiation before the wastes are cycled through the reactors. Actually human waste processing is easier then the plant matter. Most is soluble and therefore amenable to microbiological reactions that are well understood. The insolubles that remain can be treated like the previous plant materials.

Chamberland closes with some of the beneficial spin-offs from these studies. The obvious ones are technological advances in conservation and recycling systems. Less tangible philosophical spin-offs would be a better understanding by the public of waste processing in general and the importance of recycling to reduce pollution. By colonizing space we just may save the Earth. ★

AN APPROACH TO INTERSTELLAR TRAVEL

A general approach to interstellar flight has been suggested by Erik T. Paterson, an Assistant Professor at the University of British Columbia. Paterson bases his scheme on a set of ten axioms which he has devised to support a simple strategy to achieve interstellar travel. The scheme relies on experience gained from the use of space colonies in the solar system and may even provide an explanation as to why humans have not been contacted by alien civilizations.

Axiom 1 is: "No Planetary Civilization Can Marshall The Resources To Carry Out Interstellar Flight." At first glance, this statement seems to suggest that travel to the stars is hopeless. The key word in the statement, however, is *"planetary"*. The author recognizes that civilizations on the surface of planets are limited in that they must expend enormous amounts of energy to lift material off of their worlds. In addition, cultures confined to planetary surfaces have limited resources and fragile biospheres which would be damaged by attempts at interstellar travel.

The obvious corollary to Axiom 1 is: "Only Civilizations Firmly Based Upon The Use Of Extraplanetary Resources Can Carry Out Interstellar Flight." This statement is based on the same rationale used for space manufacturing and development. It is far more efficient to utilize resources and energy in space to build space colonies then to launch all of the materials from the bottom of a gravity well.

Another corollary is: "Only Extraplanetary Civilizations Can Make An Informed Decision About Where To Send Interstellar Colonies." This is saying that the only telescopes large enough to detect planets outside the solar system must be built in space where the distortion of the atmosphere is not a hinderance and the need for massive structural support hardware is not needed in microgravity. Such telescopes would be kilometers in diameter and could only be built using infrastructure firmly established in space.

Getting to the stars has been the subject of extensive research. Propulsion systems based on nuclear fission and fusion, antimatter, solar sails, lasers, and magnetic sails utilizing the solar wind have been studied in detail. Perhaps the system that will be utilized has not been invented yet. The propulsion concepts making the Starship Enterprise possible are based on breakthroughs beyond our current technology which challenge the known laws of physics. These propulsion systems have one thing in common: they all attempt to deliver their payloads has fast as possible. If time is not an issue, then interstellar flight takes little more energy then that required for interplanetary missions.

Assuming we could find a way to get to the stars, why should such a journey be attempted and which stars would be visited? It has been suggested that we go to study new life forms or colonize new worlds. Thus, stars with planets hospitable to life would be the most likely candidates for space telescopes. With obvious planetary chauvinism this suggestion ignores the fact that the people most likely to make the journey would be residents of space colonies totally adapted to life in space (Axiom 1). It is more likely that the trip would be made to harvest the bounty of cometary and asteroidal material orbiting other stars.

Within a sphere of about 12 light years centered on the sun, there are about six stars that are likely to have planets. By not limiting the destinations to stars with suspected planets, the number of possibilities increases to 26 candidates.

Propelling space settlements would not be difficult. Since moving the colony is presumed to benefit all the occupants, the thrusting force applied would be low enough so as not to damage the structure or disrupt the lives of the colonists. Paterson's Axiom 2 is: "The Upper Limit Of The Acceleration Of Any Flying Colony May Be 1/100 Of A Gravity."

With such a low acceleration, consequences result for the length of the journey, the size of the population, and the amount of supplies carried on board. Since each colony is limited in size, the capacity for supplies is similarly finite. If the journey becomes too lengthy, the population will grow (assuming no laws mandating birth control) to a point where the supplies will become depleted resulting in dire consequences for the mission. In planning the mission, an initial crew size should be chosen that will result in a tolerable population at the end of the mission. Paterson assumes that "The Population Doubling Time May Be 25 Years" as Axiom 3.

On the other hand, isolation during the journey and at the destination will require total self sufficiency. This fact favors a large population composed of people with as many different abilities and functions as possible. "The Larger The Initial Population, The Better" is Axiom 4. Although the colony will be physically isolated from the rest of humanity after leaving the solar system, it will still be able to communicate electronically. Axiom 5 is: "The Colonists In Flight Would Remain In Full Contact With The Wider, Human Culture."

The environment inside the colony will be much like that of a Mediterranean Village set among lush greenery and flowing streams. There will be teachers, doctors, farmers, entertainers, scientists, and shop keepers. In short, all talents of a diverse population will be utilized in a culture unaffected by the outside environment. Thus Axiom 6 is: "Any Flight

Will Have Little Effect On Most People Aboard."

This last fact implies that very few individuals would be involved in piloting the craft. Those few people would be in a position of power over the colonists in that they control the destiny of the mission. To prevent a dichotomy of status developing in the culture, "The Powers Of The Flight Crew Should Be Described And Circumscribed In Detail Before The Start Of Any Flight" (Axiom 7). The flight crew would probably be prevented from altering course unless they had the consent of the entire colony.

What about the cost of the mission? Paterson maintains that this is irrelevant. The development of the space frontier will open up such vast resources for utilization that it boggles the mind. For example, a single five kilometer wide asteroid contains enough gold to extinguish the U.S. National Debt, not to mention all the other products that could be refined from its raw materials. And that is just one asteroid. When all the available asteroids, moons, and comets are considered, the wealth available for non-planetary cultures is truly enormous. With access to such riches, an extraplanetary society would probably harness fusion energy relatively quickly. In fact, the lack of sufficient solar energy in the outer solar system will accelerate this quest. This brings us to Axiom 8: "No Planetary Civilization Is Willing To Marshall The Resources Necessary To Develop Fusion Power."

The journey to the stars will require the colonists to adopt behaviors appropriate to survival in space. A mistake by one individual could mean disaster for all. There is not a possibility of a rescue mission in deep space. However, it is likely that the colonists will have traits forged from experience in interplanetary space. Each person will be interdependent on the others for their mutual survival. Thus, "The Interstellar Colonists Must Be Supremely Responsible And Moral Individually And As A Group" is Axiom 9.

With the development of fusion power, a non-planetary culture can take the equivalent of the sun to the outer reaches of the solar system. Current theories of solar system formation posit that there is a vast sphere of primordial material in the form of comets far beyond Pluto. This so called Oort Cloud extends far into interstellar space and may even intersect other similar clouds associated with neighboring star systems. Indeed, it may be difficult to tell where the solar system ends and interstellar space begins. This bounty of raw materials would be available for harvesting by space cultures. In fact the first interstellar journey may happen for economic reasons. One of the colonies may work its way to another star because of over utilization of the inner solar system. Thus, the final Axiom is: "Interstellar Flight Is Most Likely To Come About By Default."

This last premise raises the question of the Fermi Paradox: "If life is common throughout the Galaxy, and if it is so easy to bring about interstellar flight, where is everybody?" Ignoring the preposterous response that we are alone in the universe, the only viable solution is to invoke Axiom 9. To survive interstellar journeys, an alien culture would have to be extremely responsible and moral. There is no reason to believe that this behavior would not also carry over to their relationships with other cultures. Therefore, we have not seen evidence of alien civilizations because they choose not contact us, the result of which would surely cause cultural shock and interfere with our evolution. ★

SOLAR ENERGY FOR PROCESSING LUNAR RESOURCES

The feasibility of processing lunar resources using solar energy has been under study for quite some time by the Space Studies Institute in Princeton, New Jersey. A status report was given in SSI's publication *Update* for January/February 1992. The writers, John M. Garvey and Michael A. Magoffin are employees of McDonnell Douglas Space Systems Company

(MDSSC) of Huntington Beach, California, the subcontractor on the program.

Extraction of resources from lunar soil or "regolith" as it is often referred to, requires large amounts of energy. The only power sources capable of generating the required energy on the moon are concentrated sunlight and nuclear fission. Of these, solar energy systems are simpler to design and maintain while being environmentally benign.

The MDSSC work has focused on results from an existing 75 kilowatt solar concentrator developed for terrestrial solar studies in the early 1980s. The system focuses sunlight with a parabolic reflector on to a crucible containing simulated regolith. The assembly techniques could be based on similar concepts already under development. Some of the applications include oxygen extraction, casting bricks from regolith, glass/fiber production, Helium-3 extraction, metal extraction, and resource recycling. In addition, the concentrator could also be used to generate electricity as it was originally designed to do. A mobile concentrator could melt a top layer of regolith to create roads, stabilize launching pads, and fuse cast bricks together.

Experience gained from the 75-kW system indicated that the crucible or receiver at the focus of the concentrator should remain stationary for the fixed applications. This innovation does two things. First, the receiver is not attached to any moving mirrors tracking the sun allowing the feed systems bringing regolith to the furnace to be simpler. Second, there are no variations in reflector sun angles providing consistent illumination.

Another consideration should be to have the ore irradiated directly instead of the beam heating the body of the crucible. This allows for higher temperature applications and gravity feed valves in the bottom of the receiver.

With these factors in mind, a three-mirror design was selected based a small scale system in use at the University of Arizona. One flat mirror is mounted on a motorized stand that tracks the sun. This mirror directs sunlight horizontally to a second flat mirror which is fixed at 45°. The second mirror diverts the beam straight up to the third parabolic mirror which then concentrates the light down to a focus into the crucible suspended between the second and third mirrors.

The reflecting surface of the parabolic mirror is composed of seven panels arranged in a ring. The panel size, constrained by the width of the space shuttle cargo bay, is 4.2 meters in diameter. The seven panels together result in a total reflecting area of 80 square meters. The flat mirrors are identical in design. Larger than the parabolic mirror, they are composed of 2 rings of 19 panels.

Tests with the 75 Kw system have indicated that an 80 square meter furnace would be capable of producing 108.2 kW and process 123 kilograms/hour of regolith. Using data from a space based mirror study called the Precision Segmented Reflector (PSR), the mass of the total system is estimated to be 4500 kilograms. These estimates indicate that the system could process its own weight in lunar material in just 35 hours and begin paying for itself during the 1st lunar day.

PSR studies show that it would take about two days of extra-vehicular activity to assemble the system. The use of remotely controlled robots could reduce this estimate. An assembly test of the PSR system is planned in an underwater test facility to gather more data. Soon a solar power furnace will be tested and ready to begin refining lunar regolith into building materials for a lunar base ★

AUTOMATED CONSTRUCTION OF GRAVITY PROPELLED SPACE STATIONS

An innovative plan for exploration and colonization of Mars has been conceived by Michael A. Minovitch, President of Phaser Telepropulsion, Inc. located in Los Angeles, California. Writing in the December Issue of the *Journal of the British Interplanetary Society*, Minovitch makes use of the "gravity assist" maneuver made famous by Voyager spacecraft when they used the gravity of each planet visited to sling shot them to the next on a grand tour of the solar system. Once launched on the initial leg of a journey and regardless of the initial mass, very little energy is required to propel a spacecraft to its destination, significantly reducing on-board fuel requirements and therefore cost. Minovitch's strategy further reduces costs by automating assembly in space. The scheme even has the potential to pay for itself in the long run.

Current state of the art propulsion systems can get us to Mars no faster than about 150 days. Any plans for trips to Mars must consider the health risks of the resulting long exposure to the space environment. Namely, exposure to weightlessness and radiation. In addition, the only reason for going to Mars should be to establish a permanent presence for long term exploration and eventual colonization. An expensive, throw-away, Apollo-type mission makes no sense in today's political climate. The ideal spacecraft for a manned Mars mission should be large enough to carry plenty of equipment and be designed to spin to provide artificial gravity. It should be made from the proper materials and massive enough to provide shielding against cosmic rays, and it should be reusable and mass producible.

Assuming size and mass are not limitations (would if we could!) the ideal spacecraft, as envisioned by Minovitch, would be more like a space station that shuttles between the Earth and Mars using a never ending series of gravity assists. The station would be toroidal in shape, similar in form to the giant pinwheel orbital hotel in the classic 60s sci-fi flick 2001: A Space Odyssey.

Never stopping at a planet, this interplanetary transfer vehicle (ITV) would carry a fleet of orbital transfer vehicles (OTV) which could be dispatched to rendezvous with space stations of the same design as the ITV in orbit around each of the planets. The initial transportation system could be established with just one ITV, however more could be added to the system to take advantage of different launch windows there by reducing the waiting period between planetary fly-bys.

With gravity propulsion, mass is not a limitation. Once launched on its journey, the ITV would receive a "boost" from the planets on either end of its route. Up until now size *has* been a limitation based on our launch vehicle technology. This has forced space station designers to think in terms of modules that would fit in the Space Shuttle cargo bay. The modules would then be assembled by astronauts in risky EVAs. The human presence in this system makes it very expensive. Not only do engineers need to design safety margins into everything but all the equipment and provisions for life support (food, air, water, recycling equipment, etc.) must be boosted into orbit.

Not only can the human element be taken out, but the cargo bay size restraint can be eliminated as well with an innovative robotic assembly technique conceived by Minovitch. In this method, an inflatable torus made of high strength Kevlar fabric is boosted to orbit where it is inflated to provide a semi-rigid core. A specially designed wrapping machine uses the core structure as a guide to wrap the surface with long sheets of aluminum stored on specially constructed spools. The wrapping machine contains four of these spools which deposit interleaved layers into a very strong laminated skin on the outside of the torus. In this manner a very large continuous wall structure can be constructed in a fraction of the time and expense of the space station modular approach.

The large toroidal structure is designed to contain crew quarters and is rotated to provide Earth normal gravity. The torus is connected to a central hub with three cylindrical spokes. The hub contains flywheels which can store the energy of the rotating torus. The spin rate can be gradually decreased on the trip to Mars to allow the crew to adjust to Martian normal gravity. Then, on the return trip, the flywheels gradually release their energy into the torus to rev it back up to Earth normal gravity upon returning home.

On either end of the hub, non rotating column sections provide a large weightless environment for laboratories, materials research, and a mounting for astronomical telescopes. This section also carries a propulsion system for the initial launch of the space station as well as storage space for OTVs. Power for the station and propulsion system is provided by a circular thin film solar array attached to the outer edge of the torus.

The propulsion system is solar electric in which electricity from the solar array is converted to microwave energy which is then fed into two superconducting accelerators used to expel nitrogen gas as a propellant. For a typical orbital transfer from low Earth orbit to Mars, the acceleration period is 63 days, a leisurely pace but not a concern since fast trip times are not important in this system.

The automated construction technique mentioned previously can be used to build space stations to be put in orbit around Mars. The same technique can be utilized to construct pressurized toroidal habitats and fuel storage tanks to be utilized on the Martian surface (some propellent needs to be synthesized from indigenous Martian atmospheric gases to power the Mars landers, rovers, and the OTVs).

Minovitch estimates that one space station could be built for about the same price as Space Station Freedom - but providing a comfortable environment for a crew of *100 to 200 people* and microgravity research facilities *50 to 100 times larger*. The current cost estimate by NASA for a manned Mars mission which would be little more than an Apollo-type sprint to the planet, is $400 billion. Three fully instrumented toroidal space stations could be constructed for this amount, one each in orbit at Earth and Mars, while one serves as the cycling ITV. This strategy would establish a permanent presence on Mars generating a higher scientific return as well as establishing the foundation for colonization.

The use of inflatable core automated wrapping techniques to produce continuously cycled gravity propelled space stations will make the exploration and colonization of Mars cost effective. There is no reason that space stations could not be put in orbit around the Moon, Jupiter, or fly freely in the asteroid belt. The vast ore deposits in the Martian moons and asteroid belt could be mined and generate revenues far exceeding the capital invested to build the space stations. ★

IN THE NEXT ISSUE:

Strategy For Investment In Space Development
The Key To Becoming A Spacefaring Country
Advanced Base Made From Lunar Materials
Estimating The Number Of Earth-like Planets In The Galaxy

BACK ISSUES:

Vol. 1 No. 1 ($5.00)
- Lunar Manufacturing
- Space Infrastructure
- Interstellar Solar Sail
- Negative Matter Propulsion

Vol. 1 No. 2 ($5.00)
- Space Station: Teacher's Aid
- Biosphere 2
- Lunar Helium Power Source
- Nuclear Rockets

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- NASA's Lunar Outpost
- Solar Power Satellites
- Antimatter Electric Rockets

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- Rocket For Space Tourism
- Space Industry And SDI
- Lunar Power System
- Solar Photon Thruster

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- Two-Launch Mars Mission
- First Colony On Mars
- SPS From Space Materials
- Rationale For Colonization

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- Alternate Space Program
- Farming On The Moon
- Model Of Lunar Colony
- Multiple Propulsion Starship

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- Lunar Construction Methods
- Innovation In Space Tech.
- SPS - The Strategy

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- Accelerated Terraforming
- Culture Changes In Space

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- Magnetic Solar Sail
- 21st Century Space Economy

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- Conference On Bioastronomy
- Pulsed Fusion Starships

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- Space Tethers - Free Ride
- Design For Asteroid Colony
- Mining Uranus For Fusion Fuel

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