PERMANENT – Chapter 4 –

Industrial Processes in Space For Converting Lunar and Asteroidal Materials into Useful Products

Excerpts from a website developed by physicist Mark Prado on issues related to space transportation and resources. [www.permanent.com]

1 The Space Environment – Advantages and Disadvantages

The manufacturing environment in orbital space is much more flexible than on Earth, and more flexible than that on the lunar surface.

1.1 Zero-Gravity

With the exception of the lunar surface, the space environment offers zero gravity, which creates many options not available on Earth. However, if gravity is needed for a process, then artificial gravity can easily be made available by use of a rotating complex to produce a centrifugal force, which is equivalent and practically indistinguishable from gravity. Indeed, any strength of artificial gravity can be provided, whatever is ideal. A rotating industrial facility offers different strengths of gravity at different distances from its axis.

Zero gravity and the absence of wind facilitate the handling of very large components and their assembly into giant structures impossible to build on Earth. Zero gravity means no convection currents in molten material, which allows purer material separation processes, mixing of materials which would separate due to gravity on Earth, and perfect crystallization processes (e.g., for solar cells and microelectronics). Many alloys and crystals are easily producible in space which are practically impossible to make on Earth.

1.2 Vacuum

The pure vacuum environment in space offers many advantages in manufacturing. Vacuum prevents air contaminants. More importantly, however, it allows industrial processes which are difficult or completely infeasible on Earth due to interference by air and the expense and difficulty of producing vacuum in an industrial facility at the bottom of Earth's ocean of air. The space vacuum is much purer than what is feasibly producible on Earth at great cost, and it's abundant and free in space. Of course, if air is desired, a facility can be pressurized.

1.3 Solar Ovens

Giant solar ovens will introduce entirely new industrial processes undreamed of on Earth. It just isn't feasible to produce the temperatures on Earth which can be easily done with giant solar ovens and containerless processing in zero gravity. Even medium temperatures are easier to produce in space. Giant solar ovens can be built in zero gravity and with no wind. These can be relatively lightweight structures, e.g., foil mirrors. Zero-gravity containerless processing using very high temperatures will usher in a whole new field of materials science processing and manufacturing impossible on Earth. Thermal energy is cheap and clean in space.

1.3.1 The McDonnell Douglas Solar Oven

Experiments on Earth (not in space) in processing lunar soil simulants were performed in the early 1990s in a joint research effort by the McDonnell Douglas Space Systems Company (MDSSC), the Aluminum Company of America (ALCOA), and the Space Studies Institute (SSI). (Paper reference.) This was based on a solar oven MDSSC had built for previous research into solar power for producing electricity, a 75 kilowatt thermal solar collector made originally for a 25 kilowatt electric Stirling engine but reapplied to a simple oven for the lunar materials. This solar concentrator can achieve concentration ratios of 10,000 suns (i.e., 1400 Watts/cm2) over a 20 cm (8 inch) wide beam. The device is located at MDSSC's Solar Energy Test Facility in Huntington Beach, California. (MDSSC also developed a 10 megawatt Solar One power tower but that was overkill for lunar materials processing.)

The oven used lunar simulants to produce cast basalt rods, bricks and glass fibers. Standard ASTM tests found that the rods had compressive strengths of approximately 10,000 p.s.i., which is about two or three times greater than concrete. One experiment produced a 2 cm thick (approx. 1 inch thick) opaque glass plate of remarkable strength by heating lunar simulant with a moderate intensity of 60 W/cm2. Another welded two bricks together by putting lunar simulant between them and heating it, producing a weld depth of range 1.3 to 1.9 cm. It is thought this process could eventually be used to help produce closed, potentially pressurized structures exclusively from lunar resources (e.g., buried habitats under compression). Further studies were underway on crystallized cast basalt structures and glass composites. (There is quite a lot of experience in cast basalt on Earth, as eastern Europe countries have been producing pipes and other things from melted bulk basalt for decades.)

Together with the Shimizu Corporation (a huge, old Japanese engineering and construction company), MDSSC investigated breaking up rocks by thermal shock on the surface (much like a glass breaks if you pour hot water into a cold glass) for the purpose of enhancing lunar surface mining operations. Tests on rocks from the same quarry as Minnesota Lunar Simulant (MLS) found that the rocks broke up when hit with an intensity of 25 W/cm2, though the relevancy of this work was being studied in view of the potential effects of moisture in the rock on Earth used for these experiments.

Additional work was planned several years ago. If anyone has any information on this additional work, please send a message to info@permanent.com. For example, they had planned to implement some design changes to the melt crucible at this facility, and discussions were underway to perform similar research using a solar furnace at the University of Arizona which can achieve comparable solar concentrations over a smaller, 2 cm wide area.

1.4 Electrical Power from the Sun

Electrical energy will be abundant and cheap from solar cells. As the MIT report on manufacturing SPSs in space put it: "...the cost of energy for the SMF operations resembles the cost pattern of SPS's: a large initial outlay for the solar array, followed by a very low operating cost (due to the absence of need for fuel and the low maintenance requirement). Therefore, for long operating times, the cost of energy in SMF operations can be substantially lower than the cost of energy in earth manufacture; this is another potential cost reduction in the lunar material scenario over the earth-based construction scenario."

1.5 Heat Rejection

The vacuum environment does bring one drawback, however. Industry on Earth often rejects heat to the environment by smokestacks and cooling pipes in lakes. In space, plain infrared radiation must fulfill this task. Any processes requiring rapid heat rejection would require using large radiators (since infrared radiation rejects heat at a rate proportional to the fourth power of temperature, T4). Large radiators would be expensive to blast up from Earth, but they can be simple enough so that they are mass produced from asteroidal and/or lunar material for most applications.

Of course, not every application requires rapid heat rejection. Some applications will require insulation for slow cooling. However, some processes will be limited by the rate of heat rejection. It's worth mentioning that extremely cold temperatures are also readily available in the shadows of space. However, it takes time to achieve very cold temperatures. However, if you want to store something in the cold for a long time, it's cheapest to do it in space. Once it's cold, it doesn't take any refrigeration work to keep it cold. Just keep it in a shadow produced by a reflector.

1.5.1 Different designs of radiators in space

Many studies focus on making low mass, highly efficient radiators for launching up from Earth. However, in a PERMANENT scenario, many of these designs are inappropriate. It's important to understand that the mass of the radiator is not as big of a problem for radiators made from asteroidal or lunar material as it is for a radiator made on Earth and launched up. For manufacturing the radiator in space, simplicity of design for manufacturing it in space is an important factor. There are two kinds of radiators, "passive" (no moving parts) and "active" (with moving parts). Within these two types are a wide array of variations.

The simplest radiator is just a big metal hot plate with fins. No moving parts. It could be oriented perpendicular to another large object which casts a shadow. It would protrude away from the factory so that its radiation is not reflected by the factory and so it doesn't receive other radiation from the factory. Radiators are best made of metals which are good heat conductors and have a high rate of emissivity.

The most common active radiators pipe a fluid to materially move the heat from one place to another, usually a fluid that evaporates at the hot end and condenses at the other (called a "heat pipe radiator", utilizing heat of vaporization and fusion). Another concept is the "liquid droplet radiator" whereby a hot liquid metal is sprayed from the hot end towards a collector (no evaporation or condensation, just spray), the idea being that droplets have a higher surface area to radiate, per unit mass. Regarding radiators with working fluids, micrometeors could puncture them, or a large leak could cause a disaster, so the fluid must be protected some way. One interesting design has the working "fluid" in active radiators consist of tiny metal balls rather than a liquid. A fairly new design is a "moving belt radiator" whereby a drum is connected to the heat source and a long metal conveyor belt moves across the drum.

Passive radiators are generally much simpler and easily mass produced from asteroidal or lunar material. In any case, the radiators in space will be much bigger than radiators on Earth to perform the same amount of cooling.

1.5.2 Multiple uses of heat gradient in factory complex

Different industrial processes require different operating temperatures. It may be feasible to design an overall factory complex whereby one process utilizes the waste heat from another process, rejects its own waste heat to a third process, and so on. However, if too many processes are added, this results in a very complex factory design. The factory must be adaptable to the shutdown of a particular operation down the chain, as shutting down one operation could affect the operating temperature of the next process unless remedial measures are taken.

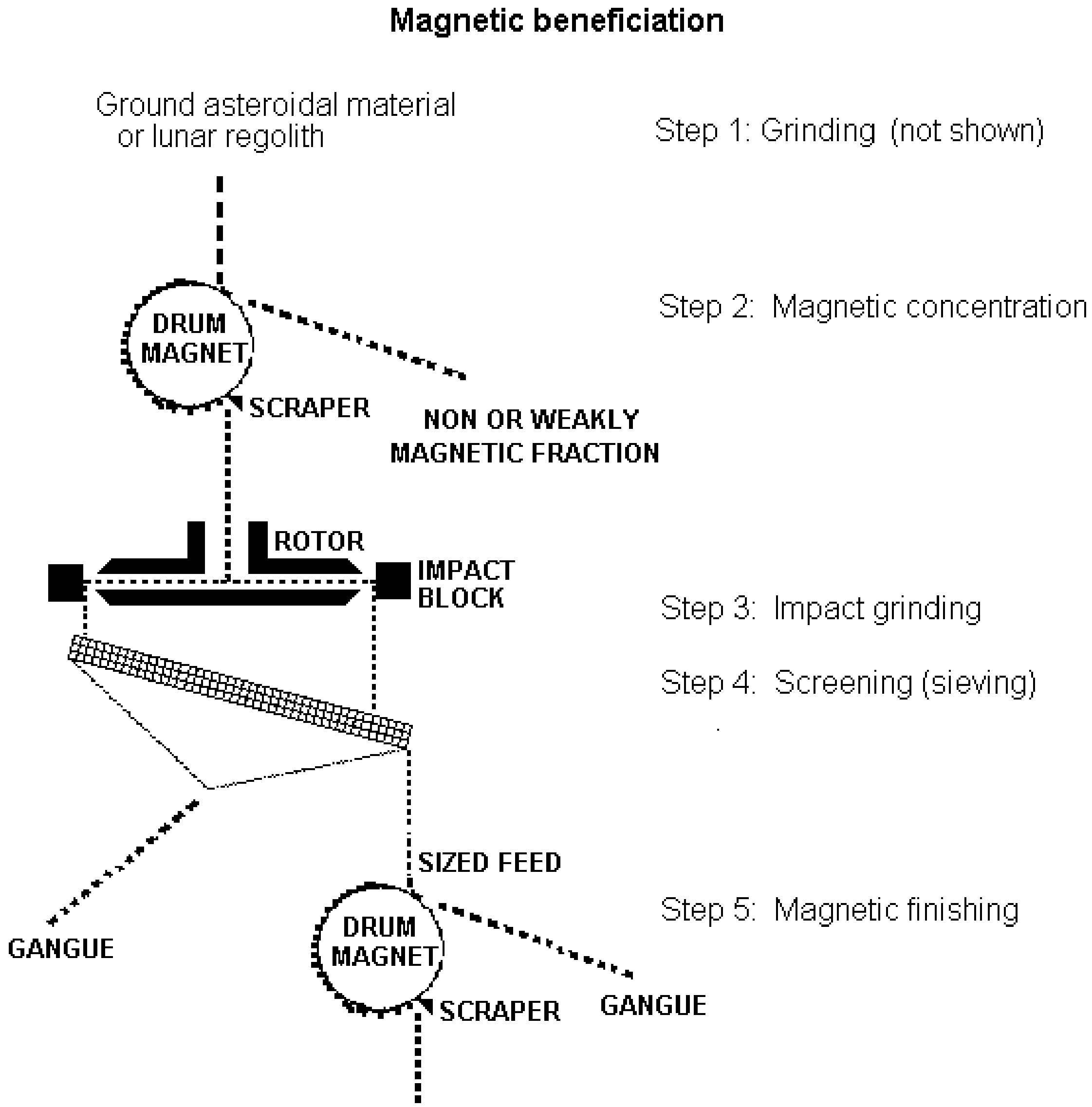
"Cogeneration" is a process whereby electricity is generated using thermal engines (e.g., Stirling, Brayton or Rankine engines) and their waste heat is used for thermal heat in factories. Likewise, the other way around, waste heat from high temperature materials processing could be used for electricity generation (thermal engines or solid state thermoelectric). The value of this in space is debatable in view of solar cells as an alternative electricity generation scenario. Indeed, a good place to put a radiator is in the shadow of the solar cell array.

2 Separating Elements and Minerals by Simple Methods

Instead of covering lunar mineral processing in the lunar section, it is better to cover it in an industrial section because it can be applied to processing asteroidal minerals as well. On the other hand, because asteroidal material has uniquenesses, i.e., free nickel iron metal and precious metals, which cannot apply to lunar materials, the simple processing of asteroidal materials with simple crushers, magnets and ovens was discussed in the section on asteroidal material. However, advanced processing of asteroidal minerals for other things besides free metals and volatiles was not discussed there, since it overlaps with lunar materials processing.

2.1 Magnetic Separation of Free Metals

As discussed in the section on asteroid resources, asteroids are rich in free nickel-iron metal granules. The Moon has trace but extractable quantities of these granules as well, left over from asteroid impacts and preserved on the waterless, rustless Moon. Though there are big differences in concentration and size of granules between the two sources, the basic process is the same. After grinding, the streams of material are put through magnetic fields to separate the nickel-iron metal granules from the silicate grains. Repeated cycling through the magnetic field gives highly pure bags of free nickel iron metal. One of several alternative ways is to drop a stream of material onto magnetic drums, as shown in the figure below. This method also shows an impact grinder discussed in the next paragraph. The silicates and weakly magnetic material deflect off the drum whereas the magnetic granules and material holding magnetic grains stick to the magnetic drum until the scrape off point.



Drawing by Mark Prado, based on concept by Dr. William Agosto

Figure 1:

An optional additional piece of equipment is an “impact grinder” or “centrifugal grinder” whereby a very rapidly spinning wheel accelerates the material down its spokes and flings it against an impact block. Any silicate impurities still attached to the free metal are shattered off. It’s feasible to have drum speeds sufficient to flatten the metal granules by impact. A centrifugal grinder may be used after mechanical grinding and sieving, and before further magnetic separation. In fact, most of the shattered silicate will be small particles which could be sieved out. Magnetic beneficiation can be used not only for separating pure nickel-iron metal granules, but also for minerals which have weak magnetic properties. This is done at Earth mines. In space, where gravity is lower and more sensitive processes are possible, magnetic beneficiation can play a significantly greater role. There are minerals that are attracted, repulsed, and unaffected by magnetic fields, based on their “permeability” to magnetic fields. This is often illustrated by showing a picture of magnetic field lines and grains which attract lines by bending them into the grain (concentrating), grains which repel the lines, and grains which aren’t affected. The degrees of magnetic permeability differ from mineral to mineral. Particles which concentrate the lines of force and become polarized and consequently attracted are called “paramagnetic”. Those which disperse the lines are called “diamagnetic”.

Based on magnetic behaviour, paramagnetic materials are sub-classified as ferro-magnetic and feebly magnetic. Magnetic separators are classified as drum, pulley, disc, ring and belt separators. They are all based on the same principle, and all use a provision for feed to run into and through the magnetic field and various means for discharging separately the magnetic and nonmagnetic portions. See also the PERMANENT section on electrostatic beneficiation, a similar process for separation of minerals based upon electrostatic, instead of magnetic, properties.

2.2 Thermal Extraction of Volatiles

Asteroids are rich in volatile elements such as water, hydrogen, carbon, sulfur, and other elements. Extracting these is easy. The material is channelled into a solar oven where the volatiles are cooked out. In zero gravity and windless space, the oven mirrors can be huge and made of aluminum foil. The gas stream is piped to tanks located in a cold shadow of space. The tanks are put in series so that the furthest one away is coldest. This way, water condenses more in the first one, whereas carbon dioxide and other vapors tend to migrate and condense in the tanks downstream. Notably, rocket fuel for the delivery trip to Earth orbit can be produced by separating oxygen and hydrogen gases from the mix, or by electrolysis of water. Alternatively, the hydrogen could be chemically bonded with carbon to produce methane fuel. Tanks for storing frozen volatiles for sending to Earth orbit can be manufactured by some of the free nickel iron metal, by use of a solar oven for melting the nickel iron metal. For example, a cast can be made from sand or glass-ceramic material from melted leftover ore. The tank doesn’t need to be a highly pressurized tank, as the volatiles will be frozen to a very cold temperature in space. Alternatively, thin tanks could be sent, remanufactured from spent fuel tanks used to get to orbit from Earth. Or the spent fuel tanks could be sent as-is. The re-use of spent fuel tanks in space is discussed in the chapter on products and services.

2.3 Separating Minerals by Electrostatic Beneficiation

Minerals come in grains. For example, a scoop of lunar dirt will typically contain a number of minerals, but the different minerals will come in the form of different grains, each grain being a glob of mostly one particular mineral. Usually two or more different mineral grains will be fused together into one, which requires grinding the material in order to separate the grains. However, like sand on a beach, you often see free pure grains beside different free pure grains, or grains predominantly of one kind or another, depending upon origins. The naturally pulverized lunar soil is like a fine sandy beach.

At the mine, it is easy to scoop up a mix of fine grains and separate pure grains of a particular mineral from the rest, and grains of predominantly one kind or another, using one or more of the following processes: The material will be initially sieved by screens to separate grains by size. Optionally, the grains of each given size can be passed through the appropriately sized mechanical grinders and sieved again for uniformity. The next step is to separate the mineral grains by a process called “electrostatic beneficiation”, which means charging them with static electricity and separating them by passing them through an electric field, as pictured in the next figure.

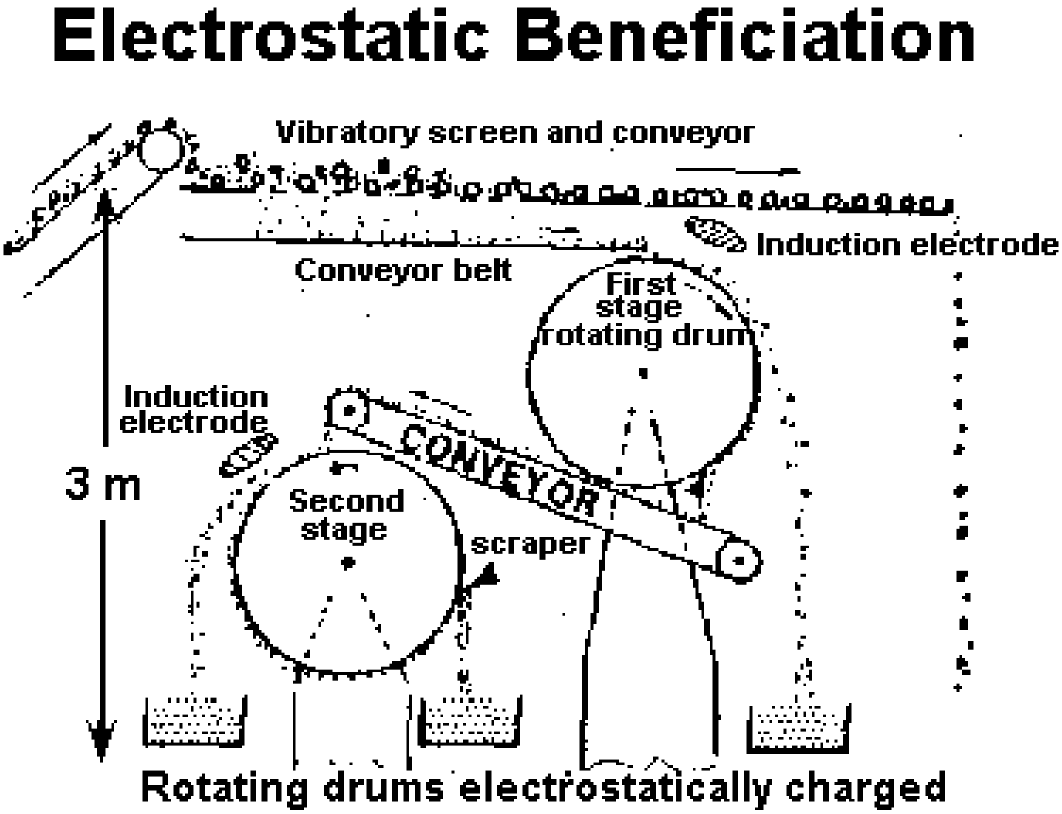


Figure 2:

An electrostatic beneficiator works because different minerals have different electrostatic affinities – will absorb different amounts of charge depending upon their composition, and hence are deflected different amounts by an electric field. After grains are sieved by size, they are placed through a beneficiator. After a few passes through beneficiators, we have separated different minerals fairly well. (There's no change in physical or chemical identity; there's only separation of minerals.)

Beneficiators typically use free-fall of grains through electric fields. However, some beneficiators slide the grains down a ramp, and some put them across a rotating drum with a certain electrostatic charge so that grains of a certain affinity will stick to the drum and others will fall to the ground due to gravity or the centrifugal force. Thus, beneficiation separates minerals according to their electrostatic affinity, as well as their different densities (with gravity or the centrifugal force).

The grains are charged by any of the following methods: charging the screen that sieves them, or charging another surface which they slide over, or a diffuse electron beam as they fall. The charging method can depend upon which minerals we want to separate, since different minerals have different responses to different methods (and indeed to different temperatures, too). The resultant material is collected in different bins whereby the enriched portion of the desired mineral is called the "concentrate" and the rest of the output is called the "gangue" or "tailings". While on Earth we're usually interested in just one mineral and one bin, on the Moon we will often be interested in using more of the material. With an electrostatic beneficiator we could have multiple bins at the bottom, as the mineral stream will split up into multiple streams depending upon the degree of attraction or repulsion of each mineral.

Whereas electrostatic beneficiation is commonly used at mines on Earth, it world work even better in orbital space or on the Moon, dramatically so. The vacuum of space and the Moon means no air turbulence in the drop chamber. Air does not tolerate electric fields as well as vacuum, and in fact electric fields can be ten times stronger in vacuum. In space and on the Moon, there is no moisture to make grains stick together. Moisture also changes minerals' electric conductivity and reduces the differences between minerals, hence on Earth we often have to roast the material before beneficiation. The one sixth lunar gravity dramatically slows the fall of the material through the electric field, thereby greatly enhancing the separation. If we beneficiate minerals in orbit (e.g., asteroidal minerals), the centrifuges could create artificial gravity of any sensitivity, which would be superior to the Moon's surface as well.

Notably, the naturally fine lunar powder on the surface of the Moon was of keen interest in the early days, as grains would stick to things, and sometimes show levitational properties such as gliding when kicked. This is due to the very high electrostatic affinity of some of the grains. Indeed, lunar dust was a nuisance. Experiments with simulated lunar soil have produced excellent results using beneficiators in a regular air environment. (Notably, there's also a lot of experience at Earth mines in separating the valuable mineral ilmenite, of particular interest and abundance on the Moon. Some engineering companies focus on ilmenite in their first lunar mission scenarios.) Metal-producing minerals are not the only targets of beneficiation. Quick production of some kinds of simple glass products are also of interest.

For the Solar Power Satellite (SPS), the General Dynamics report states: "The presence of large quantities of fine glass particles in lunar regolith is particularly relevant to the recommended use of foamed glass as primary structure for the SPS solar array and antennas. Foamed glass is commercially manufactured from fine particles of ground glass by the addition of small quantities of foaming agents and the application of heat. Thus, beneficiation of lunar regolith to recover the large amounts of fine glass particles may permit the direct production of all of the foamed glass needed for the SPS with few or no intermediate steps required to prepare the glass for foaming."

Beneficiation could occur either at a central processing area on the lunar base or at the mine. As is often the case on Earth, locating the beneficiator at the lunar mine could significantly reduce hauling of ore and hence the cost of bigger haulers and more energy, but would require that the beneficiator be mobile. Some designs in the literature have a mobile beneficiator as part of the mobile excavation equipment whereby the waste is left behind in the same spot it was dug up, as landfill.

2.4 Separating Minerals by Floatation and Vibration

It's possible to separate some minerals by their density, once we have a sieved collection of grains of the same size. Just vibrating a bed of same sized grains will separate mineral grains into layers fairly well based on their "weight" in a centrifuge or in lunar gravity. The denser grains fall to the bottom. Pouring material into a liquid of intermediate density will quickly separate a desired grain by floatation, though it must be dried thereafter and the fluid recycled. Floatation can be fine tuned based on the theory discussed below.

In orbital space, zero gravity helps in this process, as a centrifuge can provide different levels of artificial gravity as different minerals settle at different rates. Floatation is based primarily on surface phenomenon, not the specific gravity of the mineral. Different materials have different affinities to a selected liquid and the air bubbles introduced. The surface tension of the liquid is essential to fully understanding the process. Frothing reduces the surface tension of the liquid. Of interest is minerals' "wettability" or repellant properties, relative degree of readiness to adhere to bubbles, and affinity for certain types of chemical compounds or reagents. Sulphide minerals of all types and sizes are the most easily floatable.

On Earth, floatation is often opted because of its simplicity, selectivity and flexibility. Frothing and separation processes may be fairly interesting in low gravity. The downside in space is the need to stringently recycle the liquid used for the floatation, as long as volatiles remain in short supply in earth orbit.

2.5 Electrophoresis – Super Mineral Separation In Orbit

"Electrophoresis" for mineral separation can work only in zero gravity, but it is an extremely high performance process as well as a simple one. (Indeed, the use of the Space Shuttle for small medical purpose electrophoresis payloads has been and always will be a major program.) Electrophoresis works better than electrostatic beneficiation but is much slower. A tank is filled with a fluid, and an electric field is created across the tank, say, by charging two opposite walls or plates facing each other, one positive and one negative, as shown in the figure below. The mineral grains to be separated are put into the fluid, where they will be suspended due to the zero gravity environment.

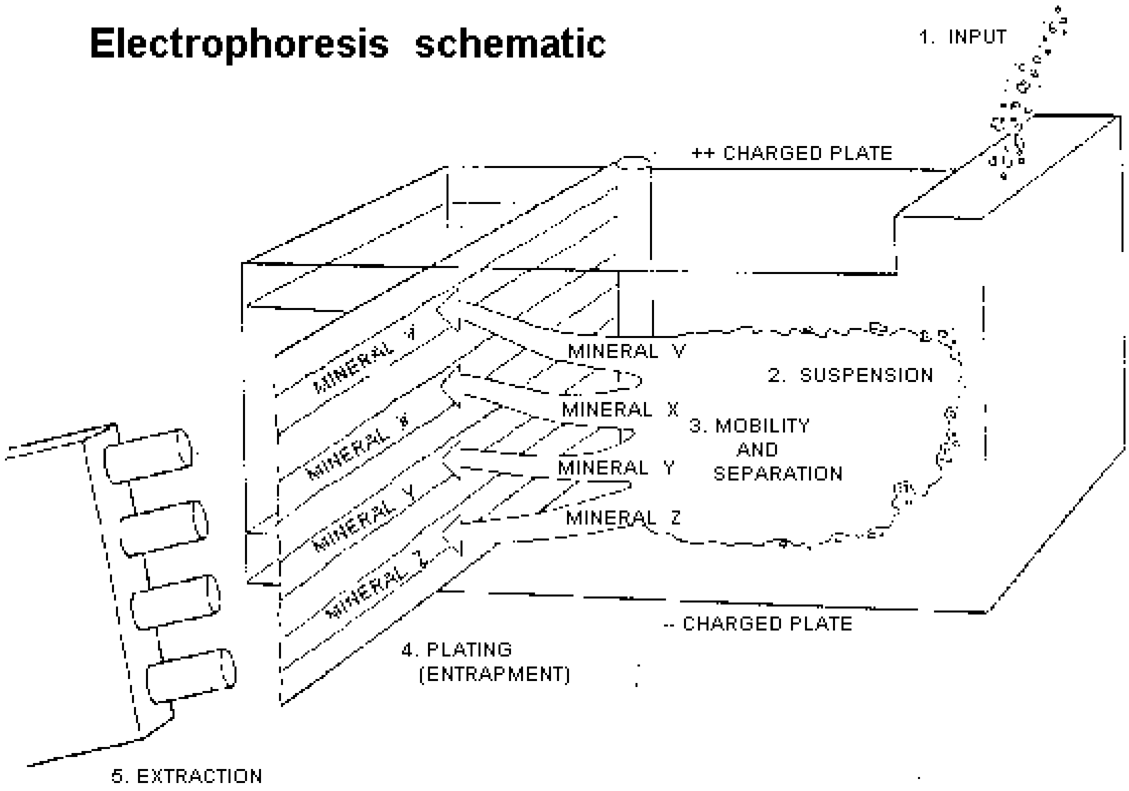


Figure 3:

Electric charges will pass through the fluid from one wall to the other, and the minerals will collect electric charges. Due to the differing molecular natures of the different mineral types, each will accumulate a different net electric charge with respect to the fluid. The different minerals will migrate through the fluid to a certain position between the two walls and between other types of minerals of higher and lower “isoelectric” values. Each type of mineral will form a plane of material parallel to the two walls and parallel to planes of the other mineral types.

Electrophoresis has been employed by medical and biological fields since the 1930s for separation and identification of enzymes, proteins, lipids, and blood cells. Electrophoresis has also been used as a separation technique for dissolved clays and limestones.

However, electrophoresis on Earth is limited to very lightweight materials. When it is used, it is performed with difficulty and limited effectiveness because of Earth’s gravity, which causes convection currents, as well as gravitational settling. Some medical applications of electrophoresis which were exceedingly difficult, elusive or practically impossible on Earth due to convection currents proved quite easy on the Space Shuttle.

A NASA-supported research report states “One of the most promising properties of lunar soil is the wide range of isoelectric points of the minerals. No two minerals have the same isoelectric point or, in practically all cases, even similar isoelectric points ... [This property of lunar soil] makes it an ideal candidate for electrophoretic separation; it means that for a given suspension material each mineral phase will separate and form a discrete band within the electrophoretic chamber.”

An experimental series of studies were supported at the NASA Marshall Space Flight Center to test and develop the concept of electrophoresis of simulated lunar soil, and the results were very encouraging, including separating minerals with close isoelectric points. Electrophoresis is simple, takes little energy and is highly automatable. Electrophoresis can also be highly effective for separating trace minerals.

3 Materials from Minimally Processed Bulk Lunar/Asteroidal Soils

3.1 Overview of Lunarcrete, Astercrete, fiberglass, ceramics and Glasses

Perhaps even more commonly than metals, we will use fiberglass, “lunarcrete” concretes, ceramics, glass, foamed glass and clear glasses. These will be used to make structural beams, walls, floors, sinks, pipes, electrical insulators, waveguides on SPSs and communications antenna farms, and substrates to mount things on. Clear glass will be used for windows and solar cell covers. Ovens, metal casting molds, and other industrial refractory needs can be satisfied by sintered calcia (CaO), silica (SiO_2), magnesia (MgO), alumina (Al_2O_3) and titania (TiO_2). Of course, these stable materials are commonly used on Earth for the same purposes, due to their great resistance to heat, oxidation (they are already fully oxidized), corrosion and abrasion. Some ceramics have low thermal expansion and are attractive for space environments where a wide range of temperatures are experienced.

Glasses and ceramics generally work well in compression but not well in tension. Foamed glass structural beams could be reinforced with asteroidal nickel-iron steel so that they withstand a wide range of both tension and compression. However, many researchers think that steel reinforcement will usually not be necessary. For example, NASA-sponsored experiments using simulated Apollo 12 soil has produced glass-ceramics with “superior mechanical properties ... with tensile strengths in excess of 50,000 p.s.i.” which can be “used as structural components of buildings in space or on the Moon.” Clear, pure silica glass (SiO_2) is readily manufacturable from lunar materials, as are other clear glasses that are made of simply beneficiated lunar soil.

Free natural glass is more common on the lunar surface than on Earth. The lack of water on the Moon has preserved these glasses from their volcanic inception billions of years ago, in contrast to Earth where “devitrification” (*i.e.*, decomposition by the chemical action of water in the environment) breaks down natural glass over the period of millions of years. Notably, lunar-derived clear glass can be made optically superior to that produced on Earth because lunar glass can be made completely “anhydrous” – lacking in hydrogen. “With the possibility of containerless melting plus the ready availability of ultra high vacuum, the processing of high purity glass fibers [for fiber optics, *e.g.*, on large communications satellite platforms] can probably be achieved at much reduced costs in space...” Using a simpler process, we can produce bulk fiberglass. “The manufacture of glass filaments is a standard, highly developed process and no problems are foreseen in transferring this process to the lunar surface or to [an orbital based facility].” The conservative General Dynamics study designed a 4 ton fiberglass plant that would produce 750 tons per year of fiberglass assuming operation 91% of the time, though Darwin Ho and Leon E. Sobon have followed up on this work to improve the design of the plant.

Hard ceramics used for industrial processes, called “refractories”, *e.g.*, calcia, magnesia, titania, silica and alumina, are used for casting molds and other high temperature, high pressure and highly abrasive processes, as well as contact with highly reactive chemicals without being corroded. On Earth, ceramic ball bearings are even used in special aircraft engines. These refractory ceramics are produced by “sintering”, whereby powdered material of the same composition (e.g., CaO) is put together and melted at a very high temperature then cooled slowly to a solid and held for long periods of time at that temperature. While this is a routine process on Earth, it’s easy in orbital space with large solar ovens, and works better in vacuum where there is no oxygen, water, or other molecules to create impurities, poison the pristine surfaces and decrease molecular attraction within the desired pure material.

3.2 Sintering of Lunar and Asteroidal Minerals

Sintering is a simple process whereby bulk basalt or a particular mineral or set of minerals in powder form are heated to a high temperature less than the melting point, whereby the particles bond to each other, producing a porous (on a microscopic scale) material. The material usually shrinks significantly, and often the sintering process occurs in a die with a compaction pressure. The vacuum in space generally helps this process. The heat can come from either direct solar energy and/or microwave. Microwave heating allows quicker uniform heating. The result is a fairly low density material which can be cut and shaped fairly easily, can hold small loads in compression, and provides good thermal insulation, but cannot take much stress in tension and is brittle. Sintering allows production of parts without melting and liquid casting processes, *i.e.*, dealing with only powder or fine sand.

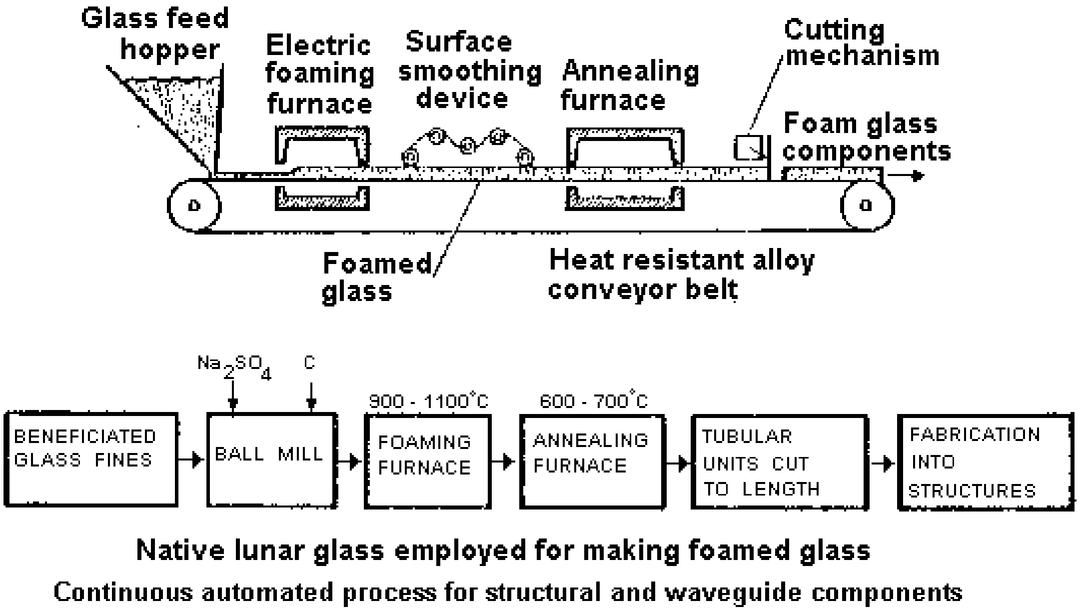


Figure 4: Source: General Dynamics/Convair report for NASA and US Dept. of Energy on making solar power satellites from lunar materials. Slightly reworded by Mark Prado for PERMANENT.

3.3 Glass-Ceramics from Lunar Material

Lunar regolith or basaltic rock can be simply melted and cast to form products with greater mechanical properties than sintered materials. The resultant material is called a glass-ceramic. Additional properties of this material include high resistance to abrasion and chemical elements, and fairly good thermal shock resistance. There has been an entire “cast basalt” industry common in some countries (mainly Eastern European) for at least 50 years, used to manufacture basaltic pipes, tiles and other industrial products from Earth basalt rocks which have very similar properties to lunar basalt. To fully melt basaltic rock, the required temperature is around 1350°C. The material may be poured at around 1200°C into sand or metallic molds, and will solidify at around 900°C to 1000°C. Much like concrete is reinforced with steel rods, the flexural and tensile strengths of this glass ceramic, and ductility and fracture toughness, may be improved by adding fiber reinforcements, either glass or metal fibers. Preparation and testing of samples from ALS (Arizona lunar simulant) were underway by Desai et al. (1993) and a review of the subject is given in Desai et al. (1992).

3.4 Glasses

A great variety of glass products can be produced from lunar and asteroidal materials, including fiberglass, clear glass, and materials for items such as walls, pipes and some kinds of structural members. Free natural glass is more common on the lunar surface than on Earth. The lack of water on the Moon has preserved these glasses from their volcanic inception billions of years ago and from asteroid impacts, in contrast to Earth where “devitrification” (*i.e.*, decomposition by the chemical action of water in the environment) breaks down natural glass over the period of millions of years. This glass can be separated using simple electrostatic beneficiation. On Earth, glass isn’t used for structural applications because glass produced on Earth is heavily contaminated by water vapor present in the atmosphere which makes the material brittle, weak and prone to cracks. “Anhydrous” glass, *i.e.*, glass produced in the absence of hydrogen or water, has significantly better mechanical properties. This has led some researchers to analyze the potential use of glasses for structural components, *e.g.*, the General Dynamics report endorses use of foamed glass in solar power satellites, Blacic covers wider uses, and Carsley, Blacic and Pletka report on the mechanical properties of these materials produced from lunar simulants.

Soils rich in iron oxide (FeO) produce dark but mechanically strong glass-ceramics, whereas "colorless glass windows can be produced from basically anorthite alone or with small additions of CaO and/or SiO_2. The expansion coefficient of such glasses is likely to be less than that of common window glass. This should be an asset for windows which will esperience large changes in temperature." Clear, pure silica glass (SiO_2) is readily manufacturable from lunar materials. Due to the lack of hydrogen, superior optical fibers can be readily produced. Glasses, as opposed to glass ceramics, are produced by cooling the melted material faster to create a different crystalline structure. There has also been discussed the prospects of foamed glass structural beams reinforced with asteroid nickel-iron steel so that the structural members could withstand a wide range of both tension and compression.

PERMANENT – Chapter 6 – Space Colonies

4 Colonies in Orbit vs. Colonies on Planetary Surfaces

Colonies in orbital space are superior to colonies on other planets and moons, contrary to popular belief. "Planetary chauvenism" is the tendency for people to think that colonies in space would preferably be located on planetary surfaces like Mars or the Moon instead of in orbital space. Consider the advantages of a habitat based in orbit:

- A habitat based in orbit can be wheel-shaped and rotated to produce artificial gravity by the centrifugal (centripetal) force. Choose the healthiest gravity you want. Earth-normal gravity may be needed for good health for long-term stays.
- A habitat based in orbit has access to sunshine 24 hours/day. No nights. Crops can grow faster by varying sun (but not sunlit 24 hours/day since many plants need nights, but opening/closing sunshades or mirrors for optimal sunlit periods), for more economical output per unit of habitat and time. Year-round growing season. Orbit-based habitats will be very green, glassy structures with some very exciting architectural and recreational features, including areas for human flight.
- Products and services for selling to Earth economies will be manufactured and assembled in orbital space, and operated there. So, the suburbs in space will be located where the demand is, namely, next to the factories, like it or not. (Why the manufacturing facilities will be located in orbital space instead of on the Moon is discussed elsewhere.)

There will eventually be settlements on other planets as well, as there will be all kinds of people with diverse preferences, but settlements on other planets and moons will be feasible only after we have settlements in orbital space and the economic support and physical infrastructure to support them.

4.1 Space Settlements – How Realistic in Our Near Future?

Certainly more realistic than most people realize. Reason: large space habitats will not be blasted up from Earth. Instead, we will use materials already in space to make them, *i.e.*, material from asteroids near Earth and/or the Moon. After all, when the settlers of America came, they didn't bring their bricks, cement, wood and all their needed food with them. As reported in numerous engineering papers and reports, we can utilize construction materials derived from Earth-crossing asteroids and/or the lunar surface as construction materials to make habitats and large, valuable space products for use in orbit around Earth, as discussed in other sections.

The 20th century has been revolutionary beyond the greatest imaginations. Now, we are poised for another great leap. Oxygen for habitats is abundant – lunar soil averages 42% oxygen, chemically bound as silicon dioxide and metal oxides (just like the dirt under your feet). The oxygen can be extracted using simple solar ovens. Asteroids near Earth are rich in all life elements, as are certain permanently shadowed lunar polar craters.

Agriculture would benefit from 24 hour sunlight in orbit, no unwanted insect pests, no pesticides, and perfectly controlled weather. Many kinds of people will be needed there – not just engineers, technicians, and robot teleoperators, but also administrators, cooks, agronomists, doctors, nurses, sociologists, factory and construction laborers, cleaners, ... and reliable people who just do the diverse odd jobs that need to be done. It will be a business-friends atmosphere. The most important skills needed are the ability to get along with others positively, a resourceful, can-do attitude, and a willingness to do without many conveniences that one would have on Earth during the initial years in space. It may be awhile before Dominoes or Pizza Hut deliver a pizza.

Huge, spacious habitats and colonies will be located in orbits around Earth, and small outposts will be maintained at near-Earth asteroids being mined, maybe as far away as Mars' two asteroidal moons. One or more lunar bases may also be operated to supply the orbital manufacturing facilities with semi-raw materials. The wheel colony is what PERMANENT calls a "second generation" space colony. "First generation" space colonies will most frequently be made from spent fuel tanks and tunneled-in habitats on asteroids and the Moon and will be much smaller than the wheel colony; whereas "third generation" space colonies will be much larger than the wheel colony.

4.2 Ecological Issues and CELSS

To date, when humans have gone to space, they have brought with them all the air they needed to breathe, their water and their food. All wastes created were either flushed into space or returned to Earth in their original form. (The water astronauts drank was often a byproduct of electric power generation by chemical means - hydrogen-oxygen fuel cells.) Gaseous wastes were recycled by machines – carbon dioxide was processed to produce oxygen, by "physical-chemical" processes.

In order to become self-sufficient in space – independent from Earth – we will need to grow our own food in space. We can use machines to recycle urine and water vapor in the air to produce drinkable water, but it will eventually become more desirable and economical to recycle our human wastes naturally rather than only by machines, and to do so naturally in conjunction with food production. Machines would be used only to sterilize and purify water that has already been cycled through the artificial biosphere.

On Earth, animals breathe in oxygen (O2) from the air and breathe out carbon dioxide (CO2) as a waste. Plants absorb this carbon dioxide from the air, and using the energy of sunlight plus water and materials from the soil and air produce sugar, starch and other things – based on a process called photosynthesis. Plants emit oxygen as a waste. That completes the animal-plant cycle. In this cyclic manner, animals and plants are mutually dependent upon each other. Plants produce both food and oxygen for animals. In turn, animals produce carbon dioxide for plants. In addition, animals produce excrement wastes which enrich the soil. Dead plants also enrich the soil and are not wasted. This natural cycle can be moved to space, in whole or in part.

Early experiments in the 1950s and 1960s focussed on recycling air using algae, not food crops. Flat tanks of algae were put under artificial light in order to absorb carbon dioxide that humans had exhaled in closed chambers, and emitted the oxygen for the humans to breathe. It was found that each human required about 8 square meters of algae for equilibrium. (The algae tanks were generally stacked as shelves so that they took much less than 8 square meters of floor space.) More recent research has expanded this to include production of edible food, and recycling of human excrement wastes and dead plant wastes in the food cycle.

In the early years of space colonization, we will use a combination of natural systems and machines. We can always import pure oxygen and water from asteroidal materials, as well as carbon dioxide if we wish. It's not necessary to produce a completely closed system. However, it is important to maintain healthy and highly productive crops, which requires waste management and recycling skills. The technologies required may be broken down as follows:

- Exchange of oxygen and carbon dioxide between plants and animals (aka air revitalization)
- Production of food (aka edible product production)
- Breakdown of human wastes (aka wastewater treatment)
- Composting of plant wastes

- Purification of water for drinking
- Elimination of pollutants from air

This field of study – regenerative life support systems – is called “Controlled Ecological Life Support Systems (CELSS)” (also called Closed... instead of Controlled... though “closed” is probably not attainable for awhile). There is a wealth of information from various institutions around the world on this topic, including papers presented at conferences dealing with lunar and asteroidal materials utilization.

In some circles, the word “biosphere” is used instead of CELSS to refer to large closed systems. However, just as frequently, the word biosphere refers to Earth or one of Earth’s ecosystems, not to space based CELSS systems. For example, if you search databases for the word “biosphere” you will get a lot of hits on remote sensing of the environment on Earth by NASA satellites, and the Mission to Planet Earth (MTPE) program. But you will also get hits on Biosphere 2, Bios-3, and Biosphere J, all CELSS experiments for space colonization. A better database search word is “CELSS” (for Controlled Ecological Life Support Systems ... or alternatively Closed Ecological Life Support Systems).

4.3 NASA BioHome

In 1989, NASA completed a small facility called BioHome, which integrated “biogenerative” components for recycling air, water and nutrients from human wastes – into a single, integrated habitat. Maximum air closure was achieved, and experiments were begun, which continue to date. A little larger than a mobile home, the facility put living quarters in a compartment beside the crops and waste processing facilities, circulating air and water between them. Drinkable water was taken from air condensate.

The facility initially focussed on wastewater treatment. Aquatic and semi-aquatic plants known for their ability to process sewage were studied. These were not edible plants, but were instead aquatic and semi-aquatic plants chosen for their history in making excellent compost material for food plants, after they grow based on the sewage. After growing to a certain size, they are harvested, cleaned and composted. This compost has been used as a complete growth media for tomatoes, sorghum, corn, potatoes, cucumbers and squash. The facility grew edible plants, though that information was not available on the web at the time of this writing.

PVC pipes slowly moved sewage downstream. The pipes had holes cut in them in which the plants were emplaced. Experiments measured the effectiveness of several plants, each of which can utilize raw human sewage as a complete growth media. Samples of the water were taken at different points in the flow and studied. In the end, the effluent water flowed through an ultraviolet unit to assure complete kill of all microorganisms, especially those pathogenic to humans. This water was then suitable for use in toilets and watering plants.

Drinking water came from condensate from the air (*e.g.*, dehumidifier and air conditioner condensate), which was also disinfected by ultraviolet equipment. The plant leaves emitted quite ample supplies of water vapors. It was also found that the plants purified the air of many manmade substances such as formaldehyde, benzene, toluene and other undesirable organics. Foliage plants were placed throughout the living quarters for absorbing the gases from the newly constructed and furnished facility.

4.4 Russian CELSS Studies

The Russians were the initial pioneers into the field of CELSS. The concept started with the great visionary Konstantin Tsiolkovsky, and the more detailed analyses of biospheres by V.I. Vernadsky advanced this scientific field. The first experiments into closed, unmanned ecosystems were performed by the Russians in the 1950s and 1960s. This work expanded, culminating in the manned closed Bios-3 facility, a 315 cubic meter habitat located at the Institute of Biophysics, Krasnoyarsk, Siberia.

The first sealed manned experiment occurred in 1965 when algae was used to recycle air breathed by humans in a closed facility in Krasnoyarsk, Siberia. The algae was chlorella (a photosynthesizing unicellular organism). It absorbed the carbon dioxide that the humans breathed out and replenished the air with oxygen. The culture of chlorella was cultivated under artificial light, needing eight square meters of exposed chlorella per human to achieve a balance of oxygen and carbon dioxide. However, the water and nutrients were stored in advance, and

Figure 5: Biosphere 2 – Oracle Arizona

work started into recycling those as well. By 1968, the overall system efficiency had been raised to 80-85% by recycling water and other gases.

Next, the Russians started adding regenerative food crops to the system, *e.g.*, wheat and vegetables. The Bios-3 facility has conducted a number of long duration two-people and three-people CELSS experiments. Crews have inhabited the sealed facility for periods of up to six months. Their only contact with the outside world was via telephone, television and the windows. Bios-3 is divided into four equal quarters. One quarter provides the housing for the crew – three single cabins, a kitchen, a toilet, and a control room with various equipment for food processing, measurements, and repairs, as well as systems for additional purification of air and water when necessary. The other three quarters of the facility are where the wheat, vegetables, and other food plants are grown, as well as the cultures of chlorella. The crews plant the food, cultivate it, and harvest it – managing the entire system and processing the harvest. In these experiments, natural air and water recycling met most of the crew's needs, and the crops produced over 50% of the food needs of the crews.

Notably, the plants could not clear all the excess organic gaseous emissions, and a thermo-catalytic filter was employed to achieve this. Drinking water was additionally purified by ion-exchange filters. Water for other uses was simply boiled. "Crew who stayed inside the complex for six months, did not manifest any signs of deterioration to their health, including no harmful effects to the microflora of their skin and mucous membranes, nor the contractions of any allergies from contact with the plants. Tests also reveal that the air, water and vegetable parts of the food did not lose their qualities while inside the complex." (ref: Gitelson)

One of the main challenges has been achieving equilibrium of the ecosystem and a higher degree of autonomy – human interaction in the system has been critical to the health of the system, and we haven't come close to an autonomous system. Another challenge is creating and maintaining a sufficiently diverse and efficient collection of plant species capable of supplying man's nutritional needs while also recycling all of man's excretions.

4.5 Biosphere 2

"Biosphere 2" is a well known experimental complex (thanks to their public relations efforts) with a closed ecological system. Funded by Texas multimillionaire Edward P. Bass, Space Biospheres Ventures built an airlock-sealed habitat in Arizona, USA, initially stocked with over 3000 species (since nobody could predict which ones would survive as food chains evolved) - food producing and other plants, fish, trees, etc., and a crew of eight people. It is the largest closed ecological system ever built, at 2.3 acres - about 13,000 square meters. In Mission 1, the facility was closed and sealed, and the crew lived inside for two years from 1991 to 1993.

Biosphere was heavily instrumented for research, safety and operations management, with over 2000 points of data collection. The 3000 species were separated into several different miniaturized biomes based on different earth ecosystems, land systems ranging from rain forest to desert, and marine systems ranging from marsh to coral reef. The diet was nutritious and diverse, utilizing over 80 crops along with goat's milk, eggs and some animal meat, with average daily caloric intake of approximately 2200 calories, including 70 grams of protein and 32 grams of fat.

There were some small leaks in the facility, but air exchange was kept to less than 10% per year. In the second year, the oxygen level hit a low point (14%, as compared to 20% in earth's atmosphere) and carbon dioxide a high point in the winter (9.5 hours of sunshine) due to less sunlight plus unusual cloudiness due to an "El Nino" weather event in the region that year (the cloudiest winter in more than 50 years – worst case scenario bad luck!). The carbon dioxide level varied between 1000 parts per million (ppm) in June 1992 (14 hours sunshine) and 2700 ppm in December 1991, with sunny daily/nite fluctuations on summer days resulting in 600 to 800 ppm changes. (In the continuous sunshine of orbit, exchanging carbon dioxide and oxygen between plants and animals shouldn't be a problem at all, with mirror controls increasing either to any reasonable level. Of course, there's plenty of oxygen in the dirt of the Moon and asteroids, and plenty of carbon in asteroids, but it would be nice to have a naturally balan

After an initial shaking out of some species, the ecosystem reached a fairly stable overall equilibrium with careful human management. The facility produced 90% of the crew's dietary needs over this time. (With more sunshine in space, food self-sufficiency should be readily attainable.) Most of the other 10% came from foods grown in the facility before the crew arrived, and from seed stock. (There was also some fudging, as discussed in a moment.) Many lessons were learned about managing a small closed ecological system in Mission 1, and there were proposed changes in the species stocking in preparation for a Mission 2. Facility sealing to give an air leakage of just 1% per year was anticipated for Mission 2.

As one of the live-in researchers wrote: "As we prepare to eventually test and deploy preliminary, small biological life-support systems in space, and then move on to biospheric systems constructed of space-available materials, we may feel constrained by the limitations and requirements which life systems impose. But we may also be surprised, as we have been in Biosphere 2, by the adaptability of nature and by its resourceful self-organization into viable systems. As we create mini-worlds for space exploration and habitation, the prospect beckons that we will create a profusion of new and beautiful worlds never before seen on Earth. And as these worlds mature in their unique metabolic linkages ? we can expect that we and they will continue to adapt and evolve in response." (Ref: Princeton conference below)

A good report entitled "Biosphere 2 and Its Lessons for Long-Duration Space Habitats" (ref.) was given at the SSI/AIAA Princeton conference in 1993. A vast bibliography of papers and books on "biospherics" is given at the WWW home site of the managers who worked on this initial Biosphere.

However, a Mission 2 will apparently never happen in Biosphere 2, and indeed, Biosphere 2 has been retreating into oblivion as regards application to space habitats. Its financier has apparently reacted to criticism by not only changing the management but also changed the purpose of Biosphere 2 along the lines of interest of a new joint venture.

4.5.1 What Happened?

During the course of Mission 1, the management of Biosphere 2 installed a carbon dioxide scrubber and also provided some supplies from the outside without reporting these actions to outsiders observers. To make matters worse, two of the managers took a defensive stance when criticisms were raised regarding the degree of self-sufficiency and the lofty claims of the project. (We're not sure whether it was dishonest or misleading actions.) It would have been understandable (though a little bit disappointing) if the managers had reported unforeseen problems with Mission 1 and reported the measures they had decided to take. If they had been open, the project would have been seen as a great learning experience nevertheless, though not a complete success. Surely, some journalists and egotistical scientists would still have taken shots and sought high profile publicity by criticisms in any case, but it would not have been such sensational criticism, and there would have been due respect by the low key portion of the scientific research community which truly matters. There almost certainly would have been a Mission 2 based on the lessons of Mission 1.

Instead, the press had enough justification to engage in a feeding frenzy. Understand that before Mission 1, the press built up Biosphere 2 as one of the greatest ongoing projects on Earth, e.g., Discover magazine called it “the most exciting scientific project undertaken in the U.S. since President Kennedy launched us toward the Moon”, and Phil Donahue did a live on-site broadcast, calling it “one of the most ambitious man-made projects ever”. Once something becomes that famous, it attracts egotistical journalists and upwardly mobile scientists who rely on criticisms of others to raise themselves up - the bigger the target, the greater the benefit to one’s self if they can land a valid punch. Before long, practically nobody would defend the elements of Biosphere 2 that were worth appreciating, and the stories focused only on its misgivings. Indeed, the focus quickly migrated to sensational, juicy personal matters, e.g., characterizing the group as a cult. In terms of sociopolitical trends, Biosphere 2 had g

When the above issues were raised, the scientific merit of the project also came under a media microscope. While the project collected valuable scientific data and practical experience, it was never set up as a proper scientific laboratory according to certain standards. (Indeed, it’s difficult to take on such a large and complex task as Biosphere 2 with a near-term schedule and stick to the stringent scientific standards of academia and the slow, one step at a time process of exact science.) When the project’s openness and honesty was called into question, the value as well as the integrity of the scientific data was also called into question by some elements of the popular science media as well as hard science media analysts.

In order to deal with this overwhelming pressure and dramatic loss of face, the financier of Space Biospheres Ventures fired the management of Mission 1 and replaced it with highly respected scientists of the most impeccable credentials. After almost two years, a different project had taken a life of its own, albeit much drier, less ambitious and lower profile. The later project benefitted from the publicity and support of the former project, but without the corresponding ambition and risk. According to a press release by Columbia University, Biosphere 2 started working closely with Columbia University’s Lamont-Doherty Earth Observatory in 1994, one of the world’s leading institutions on studying Earth’s complex systems, in a joint venture named Biosphere 2 Science Consortium, which included scientists from many leading universities and institutions around the world. For example, scientists from Harvard, Yale, Stanford and Australian National universities, the Smithsonian Institution and others have been working as part of the consortium on issues ranging from biogeochemistry to ecology. (I don’t know where the income for all this came from, but they are apparently pulling it in.)

In late 1995, Biosphere’s entrepreneurial backer, Edward P. Bass, announced a 5 year agreement to extend this joint venture whereby Lamont-Doherty manages and directs the Biosphere’s scientific, educational, and visitors center operations, and will share rights to the commercial application of all new technologies and inventions. The Biosphere 2 WWW home page is quite nice. The purpose of the facility is no longer habitats for space, but is for studying earth’s ecosystems. There will be no more sealed missions of people inside the habitat, and the work does not look directly applicable to space habitats any more. Space Biosphere Ventures is out, and Biosphere 2 Science Consortium is in.

5 Artificial Gravity and the Effects of Zero Gravity on Humans

Zero gravity has many effects on the human body, some of which lead to significant health concerns. It is clear that it would be much healthier for crews to provide artificial gravity for long duration space habitation. This means rotating the habitat to produce artificial gravity by the centrifugal (centripetal) force. Deleterious effects of zero gravity on astronauts to date are well documented. Because this is a long topic, and a topic of frequent inquiry, we have started a separate page – the PERMANENT page on the adverse effects of weightlessness.

One issue regarding space settlements rotating for artificial gravity is the beginning of the “comfort zone” as regards the radius of the rotating structure. For example, if we want to connect two fuel tanks by a cable and rotate them to produce artificial gravity as strong as Earth’s gravity, how far should we put them apart? Some people ask how much artificial gravity we need in order to stay healthy and live in space for the rest of our lives. We could assume Earth-normal gravity and design accordingly, but less might be found to be acceptable. There’s literature on this but it’s not covered here yet.

For very small habitats, rotating them to produce artificial gravity results in some very noticible differences with real gravity due to the coriolis effect. When you drop an object, it does not fall straight now, but falls by a curve (according to the perspective of the person inside the rotating habitat). Likewise for objects bouncing up.

When you stand up, your upper body will find itself significantly leaned over if you are in a small habitat rotating fast. For larger habitats, these effects are diluted to where they are humanly unnoticable. If we want artificial gravity in spacecraft or small habitats (including industrial ones) and strive for a most economical design, then we need to understand the significance of rotation on humans. The analogy to the comfort of sailors on ships at sea is appropriate. Large, steel hulled ships are more comfortable than small, fiberglass hulled ships.

Based on experiments on people in centrifuges and slow rotation rooms, it appears that the minimum radius for an artificial gravity habitat is about 20 meters (*i.e.*, diameter 40 meters). This is not very long. Secondly, the maximum rotation rate appears to be around 4 revolutions per minute. If a gravity of about one third Earth's is permissable, then a short radius habitat may be comfortable. The main reason for lowering radius would be simply economics in an early space habitat in that lower radius means less material needed, including designs for stress. However, in a scenario using asteroidal or lunar material whereby the costs of material in orbit is much lower, we will probably opt for larger habitats and perhaps even Earth-normal gravity.

There are numerous technical designs for small spacecraft with artificial gravity, *e.g.*, for missions to Mars. Space stations in low Earth orbit to date have not used artificial gravity for several reasons: so that they could be smaller and cheaper; many of the experiments to be conducted by the station were in microgravity (where gravity is undesirable), and docking systems are simpler when the station is not rotating. For connecting spent fuel tanks to produce a space station situated in orbit, we can just put a long cable between them and rotate the structure. People in space will start to move away from an entirely "up vs. down" sense of reference, and start to integrate the circular elements into their frame of reference as opposed to rectangular elements on Earth.

5.1 Artificial Gravity and the Comfort Zone

"Much of the research into the human factors of rotating habitats is twenty or thirty years old. Since the 1960s, several authors have published guidelines for comfort in artificial gravity, including graphs of the hypothetical "comfort zone". The zone is bounded by values of acceleration, head-to-foot acceleration gradient, rotation rate, and tangential velocity. Individually, these graphs depict the comfort boundaries as precise mathematical functions. Only when studied collectively do they reveal the uncertainties. "With regard to the rotation rate, perhaps the most enlightening commentary on human adaptation was published by Graybiel in 1977 [30]:

In brief, at 1.0 RPM even highly susceptible subjects were symptom-free, or nearly so. At 3.0 RPM subjects experienced symptoms but were not significantly handicapped. At 5.4 RPM, only subjects with low susceptibility performed well and by the second day were almost free from symptoms. At 10 RPM, however, adaptation presented a challenging but interesting problem. Even pilots without a history of air sickness did not fully adapt in a period of twelve days. "The comfort graphs described above are succinct summaries of abstract mathematical relationships, but they do nothing to convey the look and feel of artificial gravity. Consequently, there has been a tendency in many design concepts to treat any point within the comfort zone as "essentially terrestrial", although that has not been the criterion for defining the zone. The defining criterion has been "mitigation of symptoms", and authors differ as to the boundary values that satisfy it. This suggests that the comfort boundaries are fuzzier than the individual studies imply. Comfort may be influenced by task requirements and environmental design considerations beyond the basic rotational parameters.

"Perhaps a more intuitive way to compare artificial-gravity environments with each other as well as with Earth is to observe the behavior of free-falling objects. Figure 1 shows, for Earth-normal gravity, the trajectory of a ball when launched from the floor with an initial velocity of 2 meters per second, and when dropped from an initial height of 2 meters. Of course, both trajectories are straight up and down. The "hop" reaches a maximum height of 0.204 meters, indicated by a short horizontal line. The "drop" is marked by dots at 0.1-second intervals. In an artificial gravity system, the ball trajectory is not straight up and down, but curves relative to the observer. The larger the habitat, or the longer the cable in a tethered habitat, the less curve there is.

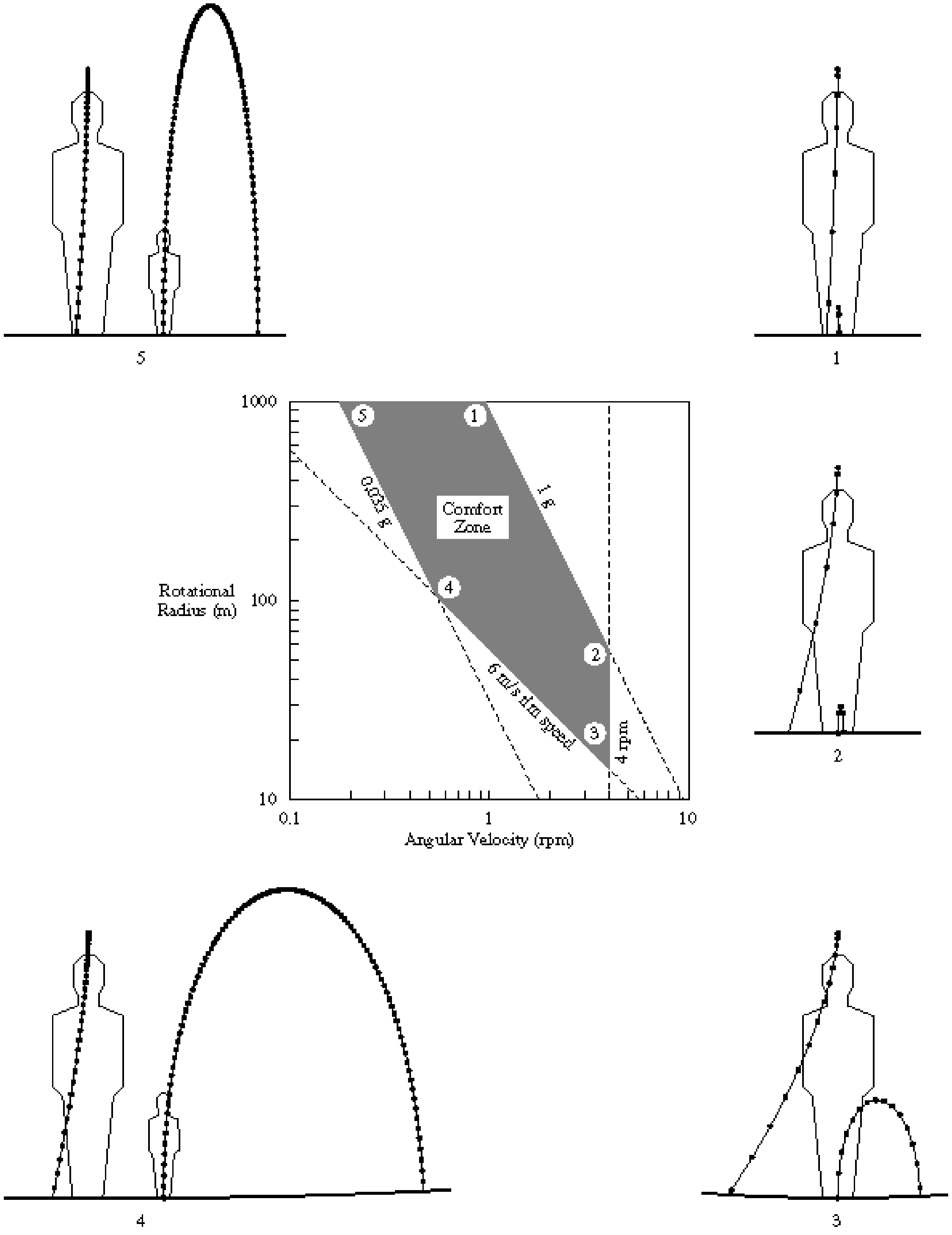


Figure 6: In this figure, the five "hop and drop" diagrams correspond to five different sizes of habitat and rates of rotation, corresponding to a typical comfort chart for artificial gravity, after that of Hill and Schnitzer - one for each boundary point of the comfort zone. The twisting of the free-fall trajectories in artificial gravity reveals the distortion of the gravity itself.

5.2 How much artificial gravity do we need?

Many researchers think that one-third Earth-normal gravity is sufficient to prevent practically all the significant biological changes associated with zero gravity. However, we don't know for sure because we haven't put humans into artificial gravity situations and studied the effects. What we do know for sure is that artificial gravity prevents physiological changes associated with zero gravity. Humans adapt very well to space. However, there's a lot we don't know about the long term effects of weightlessness on humans. We can, however, eliminate that concern entirely by using artificial gravity with rotating space habitats.

5.3 Adverse effects of weightlessness

The entire following text is extracted from a paper by Dr. Theodore W. Hall entitled "Artificial Gravity and the Architecture of Orbital Habitats", and is Copyright 1997 by Theodore W. Hall, All Rights Reserved. Reprinted by PERMANENT with permission. "It is ironic that, having gone to great expense to escape Earth gravity, it may be necessary to incur the additional expense of simulating gravity in orbit. Before opting for artificial gravity, it is worth reviewing the consequences of long-term exposure to weightlessness.

1. fluid redistribution: Bodily fluids shift from the lower extremities toward the head. This precipitates many of the problems described below.

2. fluid loss: The brain interprets the increase of fluid in the cephalic area as an increase in total fluid volume. In response, it activates excretory mechanisms. This compounds calcium loss and bone demineralization. Blood volume may decrease by 10 percent, which contributes to cardiovascular deconditioning. Space crew members must beware of dehydration.

3. electrolyte imbalances: Changes in fluid distribution lead to imbalances in potassium and sodium and disturb the autonomic regulatory system.

4. cardiovascular changes: An increase of fluid in the thoracic area leads initially to increases in left ventricular volume and cardiac output. As the body seeks a new equilibrium, fluid is excreted, the left ventricle shrinks and cardiac output decreases. Upon return to gravity, fluid is pulled back into the lower extremities and cardiac output falls to subnormal levels. It may take several weeks for fluid volume, peripheral resistance, cardiac size and cardiac output to return to normal.

5. red blood cell loss: Blood samples taken before and after American and Soviet flights have indicated a loss of as much as 0.5 liters of red blood cells. Scientists are investigating the possibility that weightlessness causes a change in splenic function that results in premature destruction of red blood cells. In animal studies there is some evidence of loss through microhemorrhages in muscle tissue as well.

6. muscle damage: Muscles atrophy from lack of use. Contractile proteins are lost and tissue shrinks. Muscle loss may be accompanied by a change in muscle type: rats exposed to weightlessness show an increase in the amount of "fast-twitch" white fiber relative to the bulkier "slow-twitch" red fiber. In 1987, rats exposed to 12.5 days of weightlessness showed a loss of 40 percent of their muscle mass and "serious damage" in 4 to 7 percent of their muscle fibers. The affected fibers were swollen and had been invaded by white blood cells. Blood vessels had broken and red blood cells had entered the muscle. Half the muscles had damaged nerve endings. The damage may have resulted from factors other than simple disuse, in particular: stress, poor nutrition, and reduced circulation – all of which are compounded by weightlessness; and radiation exposure – which is independent of weightlessness. There is concern that damaged blood supply to muscle may adversely affect the blood supply to bone as well.

7. bone damage: Bone tissue is deposited where needed and resorbed where not needed. This process is regulated by the piezoelectric behavior of bone tissue under stress. Because the mechanical demands on bones are greatly reduced in micro gravity, they essentially dissolve. While cortical bone may regenerate, loss of trabecular bone may be irreversible. Diet and exercise have been only partially effective in reducing

the damage. Short periods of high-load strength training may be more effective than long endurance exercise on the treadmills and bicycles commonly used in orbit. Evidence suggests that the loss occurs primarily in the weight-bearing bones of the legs and spine. Non-weight-bearing bones, such as the skull and fingers, do not seem to be affected.

8. hypercalcemia: Fluid loss and bone demineralization conspire to increase the concentration of calcium in the blood, with a consequent increase in the risk of developing urinary stones.

9. immune system changes: There is an increase in neutrophil concentration, decreases in eosinophils, monocytes and B-cells, a rise in steroid hormones and damage to T-cells. In 1983 aboard Spacelab I, when human lymphocyte cultures were exposed in vitro to concanavalin A, the T-cells were activated at only 3 percent of the rate of similarly treated cultures on Earth. Loss of T-cell function may hamper the body's resistance to cancer – a danger exacerbated by the high-radiation environment of space.

10. interference with medical procedures: Fluid redistribution affects the way drugs are taken up by the body, with important consequences for space pharmacology. Bacterial cell membranes become thicker and less permeable, reducing the effectiveness of antibiotics. Space surgery will also be greatly affected: organs will drift, blood will not pool, and transfusions will require mechanical assistance.

11. vertigo and spatial disorientation: Without a stable gravitational reference, crew members experience arbitrary and unexpected changes in their sense of verticality. Rooms that are thoroughly familiar when viewed in one orientation may become unfamiliar when viewed from a different up-down reference. Skylab astronaut Ed Gibson reported a sharp transition in the familiarity of the wardroom when rotated approximately 45 degrees from the "normal" vertical attitude in which he had trained. There is evidence that, in adapting to weightlessness, the brain comes to rely more on visual cues and less on other senses of motion or position. In orbit, Skylab astronauts lost the sense of where objects were located relative to their bodies when they could not actually see the objects. After returning home, one of them fell down in his own house when the lights went out unexpectedly.

12. space adaptation syndrome: About half of all astronauts and cosmonauts are afflicted. Symptoms include nausea, vomiting, anorexia, headache, malaise, drowsiness, lethargy, pallor and sweating. Susceptibility to Earth-bound motion sickness does not correlate with susceptibility to space sickness. The sickness usually subsides in 1 to 3 days.

13. loss of exercise capacity: This may be due to decreased motivation as well as physiological changes. Cosmonaut Valeriy Ryumin wrote in his memoirs: "On the ground, [exercise] was a pleasure, but [in space] we had to force ourselves to do it. Besides being simple hard work, it was also boring and monotonous." Weightlessness also makes it clumsy: equipment such as treadmills, bicycles and rowing machines must be festooned with restraints. Perspiration doesn't drip but simply accumulates. Skylab astronauts described disgusting pools of sweat half an inch deep sloshing around on their breastbones. Clothing becomes saturated.

14. degraded sense of smell and taste: The increase of fluids in the head causes stuffiness similar to a head cold. Foods take on an aura of sameness and there is a craving for spices and strong flavorings such as horseradish, mustard and taco sauce.

15. weight loss: Fluid loss, lack of exercise and diminished appetite result in weight loss. Space travelers tend not to eat enough. Meals and exercise must be planned to prevent excessive loss.

16. flatulence: Digestive gas cannot "rise" toward the mouth and is more likely to pass through the other end of the digestive tract – in the words of Skylab crewman-doctor Joe Kerwin: "very effectively with great volume and frequency".

17. facial distortion: The face becomes puffy and expressions become difficult to read, especially when viewed sideways or upside down. Voice pitch and tone are affected and speech becomes more nasal.

18. changes in posture and stature: The neutral body posture approaches the fetal position. The spine tends to lengthen. Each of the Skylab astronauts gained an inch or more of height, which adversely affected the fit of their space suits.

19. changes in coordination: Earth-normal coordination unconsciously compensates for self-weight. In weightlessness, the muscular effort required to reach for and grab an object is reduced. Hence, there is a tendency to reach too "high".

"Many of these changes do not pose problems as long as the crew remains in a weightless environment. Trouble ensues upon the return to life with gravity. The rapid deceleration during reentry is especially stressful as the apparent gravity grows from zero to more than one "g" in a matter of minutes. In 1984, after a 237-day mission, Soviet cosmonauts felt that if they had stayed in space much longer they might not have survived reentry [3]. In 1987, in the later stages of his 326-day mission, Yuri Romanenko was highly fatigued, both physically and mentally. His work day was reduced to 4.5 hours while his sleep period was extended to 9 hours and daily exercise on a bicycle and treadmill consumed 2.5 hours. At the end of the mission, the Soviets implemented the unusual procedure of sending up a "safety pilot" to escort Romanenko back to Earth [22].

"Soviet cosmonauts Vladimir Titov and Moussa Manarov broke the one-year barrier when they completed a 366-day mission on 21 December 1988. Subsequent Russian missions have surpassed that. These long-duration space flights are extraordinary. They are milestones of human endurance. They are not models for space commercialization."