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# AG-Pod - The Integration of Existing Technologies for Efficient, Affordable Space Flight Agriculture

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BioServe Space Technologies

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## ABSTRACT

Technology for microgravity plant growth has matured to a level which allows detailed gravitational plant biology and commercial plant biotechnology studies. Consequently, plants have been shown to adapt to the space flight environment, which validates their use in advanced life support applications. However, the volume available for plant growth inside pressurized modules is severely constrained, both in present and future spacecraft. Furthermore, the required power and heat rejection associated with the artificial lighting on existing systems, and the resulting weight and volume increases, affect the viability of these systems for life support. The Autonomous Garden Pod (AG-Pod), an inflatable module specifically for plants, resides outside the habitable modules and uses passive solar illumination. It's based on existing technologies including flight-proven plant growth subsystems, commercial satellite thermal systems, and off-the-shelf inflatable technology. AG-Pod will support low Earth orbit as well as planetary missions, including transit and surface operations.

## INTRODUCTION

The last decade has seen the maturation of technology for closed system plant growth during space flight. Several plant growth systems have been constructed and operated on orbit from days or weeks to months at a time [Hoehn, et al., 1998]. Much effort has been directed toward selecting and qualifying technologies for various subsystems that enable precise control over $CO_2$, temperature, humidity, and scrubbing of harmful contaminants from the atmosphere. The goal of these efforts is to maintain a proper physiological environment for the plants. The Plant Generic Bioprocessing Apparatus (PGBA), built and operated by BioServe Space Technologies at the University of Colorado, is the latest entry to the group of space flight plant growth chambers to demonstrate on-orbit operation. The design of PGBA has benefited from lessons learned on earlier plant hardware efforts such as Plant Growth Unit (PGU), Astroculture‰ (ASC), Plant Growth Facility (PGF), and even the Russian SVET greenhouse. These lessons will be further built upon by the Biomass Production System (BPS) and the Commercial Plant Biotechnology Facility (CPBF) that are currently under various levels of development at Orbitech, Inc., and the Wisconsin Center for Space Automation and Robotics (WCSAR), respectively.

Despite these advances in microgravity plant growth technology, the limitation that *all* of these units suffer is lack of plant growth volume. The volume limitations are a result of the constraints imposed on payloads residing within the interior of the pressurized modules of a spacecraft such as the Shuttle or the International Space Station (ISS). Pressurized volume is expensive, in terms of spacecraft mass, and is difficult to obtain given the numerous disciplines all vying for it. As a result, obtaining valid experimental results is difficult due to the small number of repetitions currently available within the latest and even next generation hardware. This constraint is slowing the progress of basic plant gravitational biology and life support application research and making it difficult to attract commercial plant biotechnology concerns to space research.

Table 1. Mission planning parametric infrastructure costs used to convert volume, power, and heat rejection resources into an Equivalent System Mass (ESM). [From: the Advanced Life Support and Technology Development Metric – Draft, 1998].

| Infrastructure Costs | Transit | Surface | Units |
|---|---|---|---|
| Pressurized Volume | 0.015 | 0.48 | m³/kg |
| Power | 12 | 18 | W/kg |
| Heat Rejection | 47.5 | 15 | W/kg |

Table 1 illustrates how expensive space flight system internal pressurized volume can become. It shows the mass penalty to payloads that use the pressurized volumes of Mars transit and surface habitats. For example, the original Advanced Life Support Mars Transit Baseline includes provisions for a small plant growth chamber with a physical mass of 120 kg and an allocated volume of 1.94 $m^3$. Using the pressurized volume infrastructure costs for a transit mission, the volume of the plant growth unit equals an Equivalent System Mass (ESM) of 129 kg, or more than the physical mass of the unit.

In addition to paying the high cost of pressurized volume, current space flight systems utilize artificial plant lighting. This further increases the mass costs with inefficient use of power and the need for excessive heat rejection. The plant growth chamber in the previous example is allocated 650 W of power and subsequent heat rejection. This further increases the ESM by 68kg, of which 80% can be allocated to artificial plant lighting.

Finally, the small size of these systems restricts efficient use of their volume. There is a lower limit to the miniaturization of plant growth subsystems; therefore, much of their total volume is devoted to subsystems and not actual plant growth. Also, these small volume systems can only support a crop grown in a single direction, which limits their ability to use a more volumetrically efficient planting surface geometry.

## THE AG-POD SOLUTION

A solution to these problems would be to grow plants outside the spacecraft pressurized modules in separate, specialized habitats for plants. The authors propose a cylindrical inflatable module, called the Autonomous Garden Pod (AG-Pod). AG-Pod is based on low risk technologies that are already in existence and, in most cases, flight proven. The unit can be stored in a small volume on launch or landing and once in orbit, be deployed outside the vehicle. This maximizes the growing volume while minimizing launch volume.

Growing plants outside of the pressurized volume of a spacecraft allows for greater growth areas and volumes as well as access to power- and mass-saving direct solar irradiance. The deployment of such units outside of the spacecraft conserves precious internal space for delicate experiments that need the pressurized environment and higher crew involvement.  If needed, these units can also be stored externally between crops. The bulk of an AG-Pod system - power, thermal, structure, and environmental - can remain outside without taking up precious internal experiment or habitable space.

Because mass is by far the primary driver in the cost of planetary missions, it is central to the only metric currently used to measure the progress of the NASA’s Advanced Life Support technology program [Anon., 1999a]. AG-Pod improves this metric for bioregenerative systems by lowering the ESM of plant growth systems by residing externally, using solar irradiance, and employing inflatable structures. This increases the viability of plant-based bioregenerative systems by lowering the break-even point for these systems and promoting their use on shorter missions.

The primary goal of the AG-Pod program is to provide modular, low mass, highly reliable plant growth systems for orbital, interplanetary, and planetary surface missions. The initial configuration of AG-Pod will supplement the plant growth needs aboard the ISS, so special consideration will be given to the conceptual design of such a unit in this paper. However, the benefits of AG-Pod to future missions beyond low Earth orbit (LEO), both interplanetary transit and planetary surface operations, will be highlighted as well.

## SYSTEM CONFIGURATION

As currently envisioned, an AG-Pod unit consists of a cylindrical inflatable section with rigid, ellipsoidal end caps as shown in Figure 1. The aft end cap houses the environmental systems and interfaces to externally attached hardware such as radiators and gas storage devices.  The forward end cap provides plant lighting and interfaces to attached hardware such as solar panels or external light collectors or concentrators. Direct illumination can also generate onboard solar power for supplemental artificial lighting so AG-Pod can use direct solar illumination, artificial lighting or a combination of both.

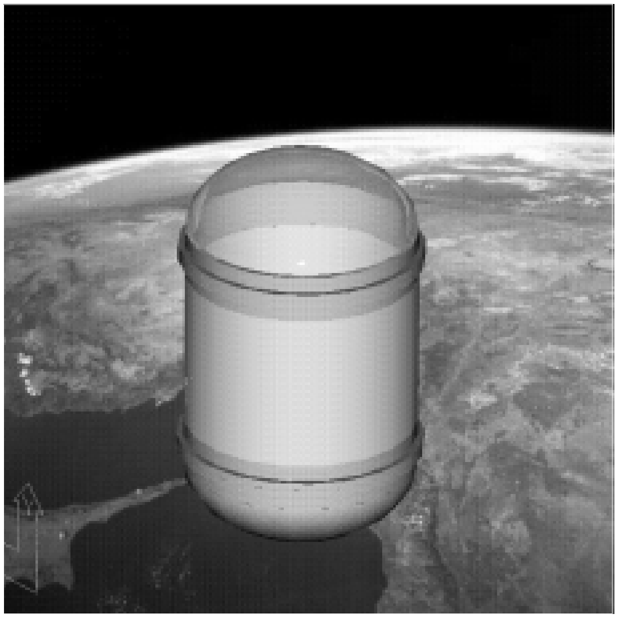

Figure 1.    The AG-Pod concept incorporates a simple, collapsable cylindrical structure  with rigid end caps.  The forward end allows for solar or artificial illumination while the aft end houses the command and control and environmental subsystems.

Initial sizing of a unit for use aboard the ISS depends upon its location outside of the pressurized modules, the commodities available, and the approach to its operational and service interfaces. There are a number of places designed to accommodate external payloads. Larger payloads can be mounted directly to the truss structure as an Attached Payload (AP), while smaller ones can be accommodated on the EXPRESS Pallet Adapter (ExPA) or the Japanese Experiment Module’s (JEM) External Facility (EF). Both of these small payload platforms, shown in Figure 2, can support experiments with power, heat rejection, and data that reduces the need for these subsystems on this first generation. The JEM EF standard payload is assumed to be 1.85m x 1.0m x 0.8m (6.2ft x 3.3ft x 2.7ft) and weighs 500kg (1110 lb.) [Anon., 1999b]. The ExPA's maximum single payload weight is 227 kg (500 lb.) and the payload envelope dimensions are shown in Figure 3 [Anon., 1999c].

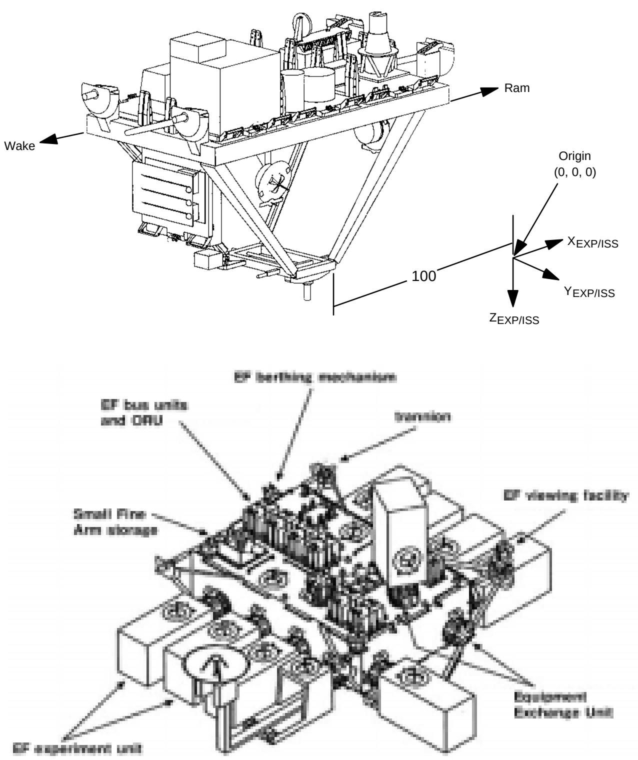

Figure 2. The EXPRESS Pallet Adapter (ExPA) (Top) and the Japanese Experiment Module (JEM) Exposed Facility (EF). Both platforms provide experiments with power, heat rejection, data, etc. [Anon., 1999b; Anon., 1999c].

The approach to operating and servicing the first generation AG-Pod, which primarily consists of planting, harvesting and routine maintenance centers on the crew. There are two options for crew access to AG-Pod aboard the ISS. One option would be to 'dock' AG-Pod to a common berthing port, similar to a Mini-Payload Logistics Module (MPLM). However, AG-Pod would then become part of the ISS pressurized volume and require a man-rating, which increases complexity, weight, and cost. An easier solution, for an initial configuration, is to take the unit into the pressurized habitats. However, this will restrict the unit's size and becomes the driver to sizing the outside diameter. The two available ISS airlock hatches are the EVA airlock crew hatch and the JEM airlock hatch. The EVA hatch, at 0.925 m diameter, is the larger of the two and will be used to size AG-Pod. A double ExPA payload platform provides ample room for a 0.9 m external diameter AG-Pod structure with additional room remaining for micrometeoroid/orbital debris (M/OD) protection, multi-layer insulation (MLI), and various commodities such as compressed gas storage. To maximize the plant growth volume, only the inflatable portion of the unit will be brought through the hatch while the M/OD and MLI will remain outside. A thin structure on the inside diameter of the M/OD and MLI blankets will protect them from repeated insertion and removal of the inner unit.

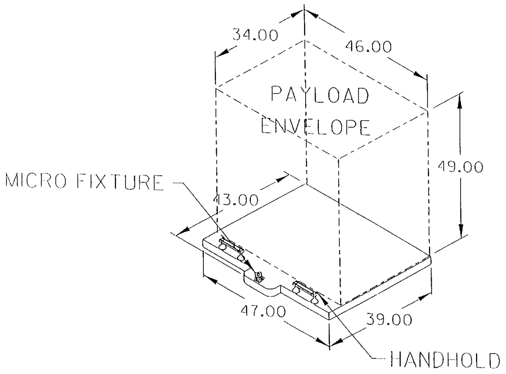

Figure 3. The ExPA payload envelope. Dimensions are in inches [Anon., 1999c].

The 1.2 m (49 in.) height of the ExPA payload allowance can provide up to 75 cm of shoot height with a flat crop area of around 0.5 $m^2$. Alternatively, using a convex cylindrical crop surface [Berkovich, 1998], the same size unit could provide a crop, with 42.5 cm of combined root/shoot height and an area of 2.67 $m^2$. This combination of shoot heights and crop areas accommodates most research crops, as well as all of those plants currently identified for vehicle and planetary surface food systems [Behrend & Henninger, 1998].

Even though AG-Pod eliminates the use of expensive internal pressurized habitable volume, its own volume will have to be used efficiently in order to ensure an overall lower ESM. Volumetric efficiency of plant growth systems can be developed in two separate ways. The first we can call Plant Payload Efficiency (PPE), which is how much of the entire plant growth system, or payload volume, that is devoted to plant growth volume. The second we'll call Plant Growth Chamber Efficiency (PGCE), which describes how efficiently the plant growth volume itself is used. PGCE is developed from results of Berkovich [Berkovich, 1998]. The aerial crop area for the volume of interest is compared to an equivalent area for a convex spherical crop surface of the same volume and root/shoot height. PPE is a function of payload size, subsystem technology, and engineering, while PGCE depends upon plant growth volume, crop selection, and geometry of the planting surface. PPE increases with payload size because the plant growth subsystem volumes do not scale directly with the plant growth volume. For example, computer systems volume should remain somewhat constant as payload size varies.

At its initial size, AG-Pod is about two times larger than the CPBF payload, which means both PPE and PGCE can increase. Initial calculations for AG-Pod indicate a PPE of 60-75%. Although existing units were not optimized for volumetric efficiency, AG-Pod is about two times more efficient in PPE than the best existing plant growth unit design as shown in Figure 4. The increase in volumetric efficiency also translates into increased specific plant growth volume, or plant growth volume per unit of mass.

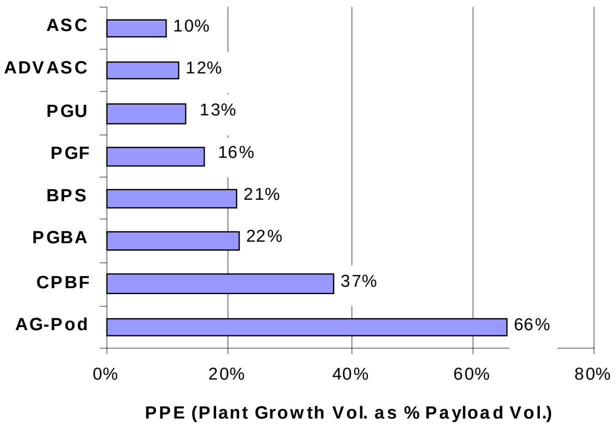

Figure 4. The volumetric efficiency, PPE, of current and proposed space flight plant growth units. Although not specifically designed for volumetric efficiency, the larger payloads are generally more efficient. Based on AG-Pod's size advantage alone, it will be much more volumetrically efficient.

Planting surface geometry can dramatically increase PGCE. For example, a spherical crop surface is up to three times more volumetrically efficient and cylindrical crop surfaces are up to two times more efficient when compared to the same size flat crop surface. However, there is a minimum plant growth chamber volume, dependent on crop selection, required to be able to take advantage of these efficiency increases. AG-Pod's cylindrical crop surface configuration can accommodate crops with a combined root/shoot height of 45 cm, similar to that proposed for CPBF. However, for the same crops, AG-Pod has more than ten times the growing area of the CPBF with only four times the plant growth volume and only two times the payload volume.

## STRUCTURE

Many of AG-Pod's advantages are due to its inflatable structure, which makes it lighter, easier to ship, easier to store, and faster to assemble than conventional structures. On Earth, inflatable structures are used to secure special environments, such as tennis courts and swimming pools, and to save lives, such as inflatable boats and rafts, and even hyperbaric chambers for the treatment of high altitude sickness. In space, the preeminent inflatable structure in regular use today is the spacesuit. Several other space inflatables have either been in service or proposed. Most recently, the TransHab demonstration program has highlighted the incredible benefits available from space inflatables such as reduced weight and increased packaging efficiencies [Dunn, 1999]. Like their terrestrial counterparts, these space inflatables provide a special environment for their occupant by offering delicate living organisms protection from the rigors of space. What the spacesuit and the TransHab are for humans, AG-Pod is for plants.

Since AG-Pod's structure does not require it to be rated for human occupancy, only 'plant rating' will be required. This rating can reduce the cost of design, parts, and, most importantly, the qualification - even as part of a bioregenerative life support system. For example, plants do not require as much radiation shielding as humans do. Also, due to the built-in redundancy of a modular system, the loss of a single component should not adversely affect the overall system; therefore, a single unit can have less restrictive reliability margins, which generally reduces costs.

Inflatable technology minimizes system mass, which dramatically reduces launch costs. An inflatable structure is ideal for the vacuum of space because they are stiffened by a difference in pressure between the inside outside surfaces of the volume. This characteristic eliminates the need for stiffened structural supports. The TransHab program is the latest to demonstrate this aspect of inflatable structure benefits. On a per-cubic-foot basis, the TransHab weighs about 75% less than the ISS habitat module it is proposed to replace. Based on the design weights of the same materials used by the TransHab program [Kennedy, 1999], AG-Pod should weigh between 100-125 kg (220-275 lbm), or less than or equal to that proposed for CPBF. On a per cubic meter basis, the first generation AG-Pod could save between 25-60% in structural mass over current technology. Without the constraints of the ISS, future generations of AG-Pod will offer even greater advantage.

Because AG-Pod is located outside the crew habitable portion of the spacecraft, it could be operated at lower pressures, which may reduce structural mass and leakage rates. If this is needed, earlier work on reduced pressure plant growth has shown that plant dry mass was increased, by as much as 26% for the total plant [André & Massimo, 1992]. In contrast to André and Massimo, Daunicht and Brinkjans [Daunicht & Brinkjans, 1992] found a lower (-8%) dry mass at 400 mbar for tomato. These plants showed an increased (+26%) transpiration rate, smaller (-6%) leaf area, more (+10%) root and less (-21%) shoot mass. These plant responses are more likely to be affected by partial pressures of oxygen and carbon dioxide rather than absolute pressure. Consequently, some aspects of reduced absolute pressure may be counter-acted by changing the partial pressure composition. However, recent material developments within the space inflatable industry indicate that lower pressure may not be necessary. The feasibility of operating at atmospheric pressures has been demonstrated by the recent TransHab testing to 4 atmospheres [Dunn, 1999].

The collapsibility of inflatables increases their packaging efficiency, or the storage volume compared to the inflated volume. Relatively little volume is required to store the inflatable in a Space Shuttle for shipment to the ISS or to store one, or several, AG-Pod(s) aboard or outside the

ISS until needed. High packaging efficiency is also particularly useful during interplanetary transit missions. During transit, the units reside outside of the habitable volume allowing more volume for the occupants inside. For the short descent to the surface, the units could be collapsed and stowed inside the habitat volume. Once on the surface, the units could again be deployed outside of the habitat volume and begin producing food, fixing $CO_2$, and transpiring water for the long stay.

Historical packaging efficiencies for proposed inflatables have been quoted as high as 20:1, but a more realistic number is around 10:1 [Kennedy, 1999]. AG-Pod's packaging efficiency depends upon the length of the cylindrical section, which corresponds to crop height. The packaging efficiency for the ISS configuration AG-Pod can reach 3:1 or more. Further optimization of the structural configuration could offer significant increases in this efficiency as well. To "build" or assemble an AG-Pod on orbit, in transit, or on the surface, the crew simply inflates it.

ILC Dover, Inc., manufacturer of the current Shuttle space suit, has developed a structure that serves as an ideal analog to AG-Pod's intended size and configuration. Figure 5 shows a hyperbaric chamber designed by ILC for the US Air Force's Human Systems Program Office. A previous NASA study mission, The Human Lunar Return Concept, also employed an inflatable structure that is very similar to that proposed by AG-Pod, an inflatable mid section with rigid end caps [Drake, 1999]. Additionally, Aeroponics International has proposed an inflatable root zone concept that could be configured into the cylindrical crop surface discussed earlier and still maintain collapsibility of the unit [Stoner, 1999]. These existing designs and structures demonstrate the feasibility of the AG-Pod concept.

Soft-goods fabrication techniques are generally much less costly than those used for rigid structures, because of fewer types of operations and the flexibility of the raw material in the manufacturing cycle [Grahne, 1998]. There are a number of materials and material combinations that could potentially meet the requirements of the AG-Pod program. These materials already exist and pose little or no risk to the development of a flight-qualified unit.

Impacts from micrometeoroid and orbital debris (M/OD) pose one of the only threats to the integrity and reliability of AG-Pod's inflatable structure, particularly in LEO. Fortunately, the recent TransHab demonstration program included the development of a new concept for the protection of inflatable structures from M/OD impacts [Dunn, 1999]. This development effort combined with existing methods, used on Apollo and Space Shuttle era spacesuits, provides a range of existing technologies that are directly applicable to AG-Pod.

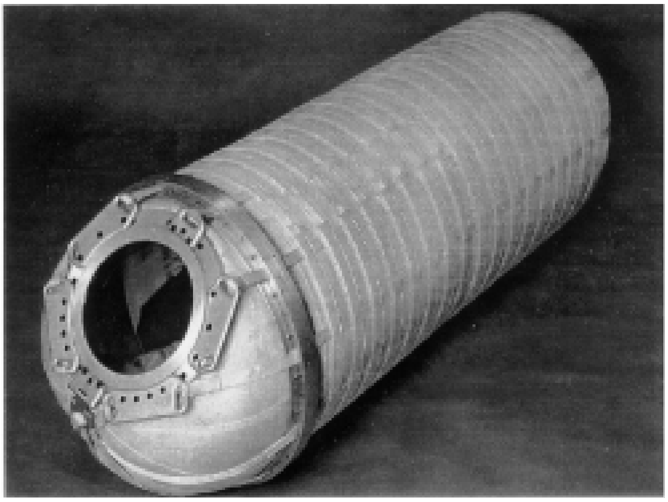

Figure 5. ILC Dover, Inc.'s inflatable hyperbaric chamber designed for the USAF. It was developed for the treatment of the 'Bends' and operates at 2.8 atm (41 psid). It is three feet in diameter and only two feet long when collapsed. [Photo courtesy of ILC Dover, Inc.]

## LIGHTING

There is a wide variety of available lighting schemes, from natural solar illumination via transparent materials to artificial illumination powered by externally mounted solar arrays, that AG-Pod could accommodate. For advanced life support applications, the use of direct natural sunlight via transparent materials can save considerable mass, power, and heat rejection resources that would otherwise be required for artificial lighting systems.

To illustrate, LEDs [Barta, 1992] typically operate at maximum of ~10% efficiency, and fluorescent lamps operate at ~20% efficiency [Sager, 1994]. When solar power electric generators, operating at ª10% efficiency, are used to power the already inefficient artificial lights, the overall system mass becomes excessive and very expensive. These systems achieve an overall light-to-light energy conversion as low as 1-2%. Additionally, up to 99% of the originally available solar energy has to be rejected as waste heat (in solar cells, power conditioning equipment, light sources, etc.). Even for large terrestrial systems, the power for artificial lighting requires approximately 45% of total system power, while cooling (heat rejection, humidity control) uses another 35% of the total electrical power [Ikeda, 1992]. Using the values in Table 1, for 1000 $W/m^2$ of electrical power required for plant lighting, artificial systems are burdened with power generation and heat rejection inefficiencies of 104 $kg/m^2$ for transit and 122 $kg/m^2$ for surface systems.

Moving ‘outside’ the pressurized modules provides an attractive, passive means for acquiring both efficient and reliable sunlight and equally attractive heat rejection capability to deep space. Photosynthetically Active Radiation (PAR) (400-700 nm) in LEO is approximately 70% higher than that experienced on the Earth’s surface and is constant. Moving the “greenhouse” outside can provide potential energy savings of greater than 80% in electric power.

There are two ways that space flight plant growth units can use natural sunlight: 1) employing the use of a collection mirror or lens with a transmission and distribution system such as fiber optics, or 2) employing the use of a transparent material. Light collectors could reduce concerns of transparent material fracture from micrometeoroid impacts and could combine artificial with natural sunlight distribution into one system. They also have the ability to harvest light from a larger area than the crop area, thus concentrating the available light. Collection schemes have been investigated in the past [Himawari design, Lockheed: Lunar CELSS study], but were found to have too much transmission loss for space flight plant growth applications. New studies are in progress [Cuello, et al., 1998, NASA STTR 97-03-970025, 1997] to further improve the light collection & distribution technology, but is not expected for flight applications in the near term.

The technology for transparent, inflatable materials suitable for space application is in its infancy. It is not expected that materials to handle such large pressure differentials will be available in the near term. The baseline AG-Pod will use a rigid transparent material similar to that used for the Shuttle Extravehicular Mobility Unit (EMU) helmets. The inner shell of these helmets is formed from high-strength, UV-stabilized polycarbonate and is attached to the spacesuit by a pressure-sealing neckring. A polysulfone, gold coated sun visor assembly mounts to the exterior of this inner shell to maintain proper thermal/optical properties for the astronauts. AG-Pod uses an external sun “visor” as well with flight proven coatings that provide the appropriate spectral filtering for the plants. The “visor” is interchangeable so that different ones can be used depending on research goals and/or mission location, be it Earth orbit, interplanetary transit, or planetary surfaces.

Particularly in Earth orbit, the transparent material may be affected by micrometeoroid / orbital debris (M/OD) and transmit too much radiation both in bandwidth and intensity. It is likely that some sort of attenuation of the PAR present in space may be required to avoid photoinhibition. Also, potentially harmful infra-red and some UV light can be filtered by reflection before it becomes a problem to the plant facility. The admission of some UV light, however, may prove beneficial for some functions such as trace gas control and/or a means of passive sterilization.

For Space Station, due to its inclination and speed, a directly illuminated AG-Pod would operate on a short, day / night cycle, or orbital photoperiod [Hurtl, 1990]. Relatively little research has been focused on the effects of an orbital photoperiod. Hurtl [Hurtl, 1990, also Sacher and Burian, 1994] tested Mung bean, soybean and millet under orbital light / dark cycles. Soybean was the least affected by these conditions (25% reduced dry weight, 12% reduction in yield). The limiting factor in the light activation of C-fixation in plants lies in the light activation of the premiere $CO_2$-fixing enzyme, Ribulose-1,5-bisphosphate carboxylase/oxygenase (RUBISCO). All other enzymes of the Calvin Cycle possess rapid light-activation/dark-deactivation kinetics [Salvucci, 1989, Sassenrath-Cole et al., 1994]. Crops such as soybean, however, exhibit RUBISCO inhibition due to a metabolite formed in the dark known as CA-1-BP [Servaites et al., 1985; Seeman et al., 1990]. The sluggish kinetics could lead to the observed reduction in yield. Salad crops, however, should not suffer this RUBISCO inhibition and their yields should not be as affected by orbital photoperiod. The authors are currently investigating orbital photoperiod affects on spinach.

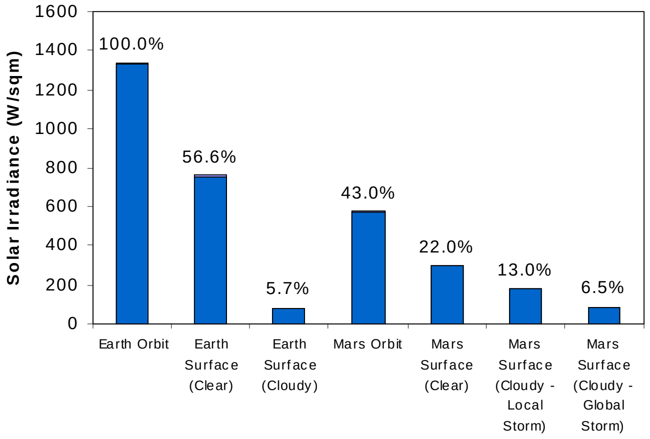

Figure 6. Relative total solar intensity of the Mars environment, including orbital and surface, compared to Earth orbit and surface. [Adapted from Reference Mission Version 3.0, 1998, with additional data from Bjorn, 1976].

Despite the advantages of direct solar illumination, a stay on the Martian surface may require supplemental artificial light sources because of the degradation in solar irradiance resulting from surface storms as shown in Figure 6. Artificial light sources may also have their place in LEO as well, such as supplementing the orbital photoperiod or for more controlled research-based plant growth. For these reasons, the AG-Pod baseline design will be scarred to accommodate artificial lighting hardware. The hardware itself is not an expensive penalty in terms of mass, but the inefficiencies associated with additional power and heat rejection would need to be accommodated in the mission baseline. Nevertheless, even with severe degradation of solar irradiance, such as by Martian global storms, any amount of direct solar illumination can help to decrease the burdens of artificial lighting. For example, using the data in Figure 6, the Mars surface irradiance during a local storm is about 175 W/m$^2$ or 23% that of Earth's surface on a clear day. Most plants are generally saturated somewhere between 200-300 W/m$^2$ [Bjorn, 1976]. So, even when correcting for spectral differences between Earth surface and Mars surface, as much as half of the plant lighting requirements can be met with direct illumination.

## POWER & THERMAL

The greater reliance on solar illumination reduces AG-Pod's power and heat rejection needs by as much as 80% over existing plant growth systems. Still, both of these systems are critical to AG-Pod's operation. The initial ISS configuration will utilize the power and thermal commodities provided by the ExPA; however, later configurations will be able to operate autonomously by generating onboard solar power and employing radiators for thermal control. This will provide the greatest flexibility for accommodating units on both transit and surface missions.

We can estimate the power needs for a directly illuminated AG-Pod if we consider the earlier example of the proposed transit mission plant growth chamber. Both units have a flat crop area of 0.5 m$^2$. If we assume 80% of the baseline plant growth system power is used for artificial lighting and heat transfer, then, out of the total allocated 650 W, only 20%, or 130 W, is used for plant growth subsystems. This should also be the estimated power need for AG-Pod, which can be satisfied with less than 0.7 m$^2$ of solar cells in LEO.

Thermal control will be critical for AG-Pod, as plants live in a relatively narrow temperature range. Overall thermal rejection from AG-Pod will be minimal compared with the use of artificial lighting systems. Most of the non-photosynthetic radiation will be reflected away from AG-Pod using available coatings applied to the window. Options will be studied which permit some IR through the window to be absorbed in a water buffer that could conduct heat back into AG-Pod to aid in thermal control during the night periods. Internally, the AG-Pod uses highly efficient environmental control technologies derived from those used in existing flight-proven plant growth systems such as PGBA. These techniques will minimize the 'waste' heat to be rejected from the AG-Pod's avionics systems and unused radiant energy.

## RADIATION

Since AG-Pod will reside in LEO, in deep space during interplanetary transit, or on a planetary surface with presumably little atmosphere, it will not only be exposed to a broader and more intense electromagnetic spectrum, but also to an increased ionizing radiation environment. The ionizing radiation environment has always been of concern in low earth orbit and in deep space missions. For human-rated habitats, this requires the addition of a carefully designed radiation shield with low mass, adequate protection, and suppression of secondary radiation, or Bremsstrahlung. However, plants show a lower susceptibility to ionizing radiation than humans do [Casarett, 1968]. A number of experiments have demonstrated the ability of plants to tolerate this environment. Plant seeds have been exposed to cosmic radiation on LDEF for 6 years [Eckart, 1996] and plants have been successfully germinated and grown, even from seed to seed, in the space environment aboard several spacecraft including Skylab, Shuttle, and Mir. Most of the plant growth problems experienced during space flight can ultimately be attributed to environmental conditions other than space radiation. Table 2 demonstrates that the radiation dose that produces observable effects is much higher for plants (377 REM for onion, to 9,137 REM for Kidney beans) than for humans (25 REM ). Lethal doses for plants are also higher (from 1,500 REM for onions to 36,100 REM for Kidney beans) than for humans (450 REM). So, the shielding for a 'plant only' habitat could be minimal compared to a human rated facility.

Table 2. Effects of Ionizing Radiation on Selected Plants [A.P. Casarett, 1968]. Plants show lower radiation sensitivity than humans. Extra-terrestrial greenhouses that are not continuously human-tended (like AG-Pod) could use minimal or no radiation shielding.

| Organism | Observable Effects | Lethal Dose |
|---|---|---|
| Human (Annual Limit < 5REM) | 25 REM | 450 REM |
| Onion | 377 REM | 1,491 REM |
| Wheat | 1,017 REM | 4,022 REM |
| Corn | 1,061 REM | 4,197 REM |
| Potato | 3,187 REM | 12,608 REM |
| Rice | 4,974 REM | 19,677 REM |
| Kidney Beans | 9,137 REM | 36,149 REM |
| Potential Dose: | Solar Minimum: | 40 REM |
|  | Solar Maximum: | 120 REM |
|  | Proton Flare: | 500 REM |

The radiation environment in the orbit of the ISS includes protons and some electrons from the trapped radiation belts. The protons are capable of introducing a small amount of radioactivity through inelastic reactions on atomic nuclei. The average ionizing radiation dose rate due to galactic cosmic rays is around 10 mrad/day in $55^{o}$ orbit at 370 km, with fluctuations related to the solar activity cycle. Trapped electron and proton radiation add about 10-50 mrad/day to this level based on daily trips through the South Atlantic Anomaly [Curtis, 1974]. These very rough estimates, based on thinnest possible shielding, suggest a maximum of 50 mrad/day received by the plants. This sums to 2.5 rads (cGy) over an 8-week growth cycle. AG-Pod's location outside of the human rated facilities allows possibilities for research as well. Simple modifications to AG-Pod's shielding could further help investigate the effects of broad-band cosmic radiation and high energy particles on plant material and the effects of radiation that could help alleviate concerns over consumption of space grown food.

With regards to radio-activation, proton-induced reactions produce neutron-poor isotopes of C, N and O in living matter, and these have half-lives of a few minutes. This means there is little radioactivity, a maximum of 700 pCi/kg, at steady state [Todd, 1962]. Furthermore, following harvest, this level falls below 1 pCi/kg in about one hour, which is less than one ten thousandth of the permissible level. Exposure of plants to space radiation will therefore not produce a hazard condition by making the plants ‘radioactive’. This safe condition is reflected in new FDA approval for the use of food irradiation for the stabilization of food products. In conclusion there is no obvious need to associate radiation-effects with AG-Pod-grown plants.

## ATMOSPHERE MANAGEMENT

One of the key life support functions of plants, in addition to providing food, is to convert metabolically produced carbon dioxide ($CO_2$) into oxygen ($O_2$) for use by humans. Through photosynthesis, plants are a biological “single process” system that can convert low concentration $CO_2$ and water directly into $O_2$. In the case of AG-Pod, the carbon dioxide gas will be supplied from pressurized, $CO_2$-enriched cabin air and/or injection of $CO_2$ concentrated by a molecular sieve from the Environmental Control and Life Support System (ECLSS) aboard the ISS. Logistically, the gas is supplied via high pressure gas Orbital Replacement Units (ORUs) similar to those used to resupply the ISS with $O_2$ and nitrogen ($N_2$).

As $CO_2$ is introduced, the internal pressure can be maintained by either venting the photosynthetically produced $O_2$ to space or by returning it to the habitable modules. Returning it to the habitation modules could be accomplished by either an umbilical or another high pressure gas ORU. The separating and concentrating of the $O_2$ produced in the AG-Pod will be investigated as part of the program. Separation of $O_2$ from the AG-Pod atmosphere can be accomplished by semi-permeable membrane technology or solid amine systems. Alternatively, a variable absolute pressure scenario may allow plants to start with a low $O_2$, low pressure atmosphere. As the plants grow and produce $O_2$, the inert gas $N_2$ would be injected to keep the $O_2$ concentration within an acceptable range. This, however, requires the plants to be subjected to a wide range of absolute pressures, the effects of which need to be further understood.

Humidity control is a critical function within the AG-Pod volume or any plant chamber with large transpiration rates. Initially, humidity control will be managed with an existing porous plate dew-point controller design that has been successfully used in PGBA and Astroculture‘ space flight applications. Collected transpiration water could either be stored and used as a potable water supply for the astronauts, but would more likely be circulated back to the plants for water/nutrient delivery to the roots.

Trace volatile organic compounds (VOC) contaminant control will be performed by using the proven Astroculture‘ photocatalytic conversion technology currently employed in PGBA as well. Of special concern is the build-up of ethylene, a plant hormone, which is easily oxidized using a titanium oxide catalyst and UV excitation. The use of the enhanced UV output available from extraterrestrial solar radiation might be useful as a passive means to prevent ethylene from accumulating. Additionally, the breakdown of methane and nitrous oxide in BioSphere2 was disabled by the lack of UV-light transmission through the glass panes [van Haren, J., 1998]. The possibility of using this “free” source of UV radiation to control all of these trace gas contaminants is part of the AG-Pod baseline.

## NUTRIENT DELIVERY

Tremendous effort has been expended in the development of nutrient delivery systems (NDS) for space flight plant growth [Dreschel, Sager et al. 1988; Morrow, Bula et al. 1994; Goins, Levine et al. 1997; Heyenga 1994]. AG-Pod is not limited to any one of these; rather, it will accept different modules depending on mission or crop requirements. For the flat crop configuration, any number of NDS approaches could be employed without sacrificing packaging efficiency when the unit is deflated. To maintain packaging efficiency in the cylindrical crop surface configuration, AG-Pod could employ Aeroponics International’s inflatable root zone concept based on their aeroponic technology [Stoner, 1999].

## COMMAND & CONTROL

The fast pace of computer technology development has offered smaller, less expensive, and more capable command & control options for space flight plant growth systems. The existing plant growth chamber command & control systems provide an excellent platform on which to base a system for AG-Pod. However, AG-Pod’s sensing and health monitoring capabilities will have to be somewhat more extensive since it resides outside of the habitable modules away from routine physical interaction with the crew. Several technologies are currently being studied to meet these demands such as machine vision and chlorophyll fluorescence measurements [Li, et al., 1998]. These types of direct plant health measurements can be used as feedback to command & control systems that can then alter the plant growth environment to keep the crop healthy.

## CONCLUSION

The recent advances in space flight plant growth technology have demonstrated the promise of space agriculture. Although useful for small pilot studies, the current systems lack the volume to conduct thorough scientific or commercial experiments. AG-Pod integrates these and other complimentary technologies into an optimized space flight plant production system that provides a platform to greatly expand plant gravitational biology, commercial plant biotechnology and advanced life support research. AG-Pod fills the existing void between the large scale ground operational test facilities, such as the Biomass Production Chamber (BPC) or the agricultural module of the Bioregenerative Planetary Life Support Systems Test Complex (Bio-Plex), and the current small space flight plant growth technology demonstrators.

The AG-Pod concept, however, promises to be more than just an advancement of experimental capabilities. A modular food production system is possible with the use of multiple, size-optimized units. Such a system is flexible enough to serve a number of mission possibilities from ISS food production to Mars transit and surface operations as depicted in Figure 7.

This modular approach has many advantages over a single large greenhouse concept. The inherent redundancy of an interchangeable modular system decreases cost, improves reliability, and adapts to meet varying system demands. With multiple units, the loss of a single unit by either crop infection or mechanical failure is not as critical to the overall system. For example, despite the elaborate disinfecting and quarantine protocols sometimes used in preparation for space missions, microorganisms have flourished aboard spacecraft. These organisms pose a moderate threat to the use of plants as part of an advanced life support system. Schuerger [Schuerger, 1998] suggests isolating plant production systems into separate modules to mitigate the risk of crop loss due to pathogen infections. AG-Pod's modular approach isolates various crop elements from each other to avoid cross contamination. It also allows for customization of the growth environment to the particular part of the crop's growth cycle. Further, a fleet of units lends itself to continuous harvesting, which can eliminate the need for long term crop storage that can lead to spoilage. Finally, a system consisting of a number of similar or identical units with interchangeable parts decreases unit cost by allowing more economical processes and amortizing nonrecurring costs over more units.

Even though the inflatable AG-Pod greenhouse will not be human rated, it can still be a crucial pathfinder for establishing both an initial performance record and an historical record of performance (leak rates, radiation effects, thermal control) for future space inflatables which may support living organisms for extended periods. AG-Pod could be a modest, initial on-orbit demonstrator of such structures. It could be the ancestor for future inflatable human-rated structures for use on existing and future orbital platforms, additional living space on missions of planetary discovery, and for "base housing" on the Moon, Mars, etc. In this role AG-Pod would join the ranks of a progression of space inflatable technology from the space suits to the Mars Pathfinder's impact attenuation air bag system and future inflatable technology for life support applications such as the proposed TransHab module for the ISS and Mars Transit Vehicle.

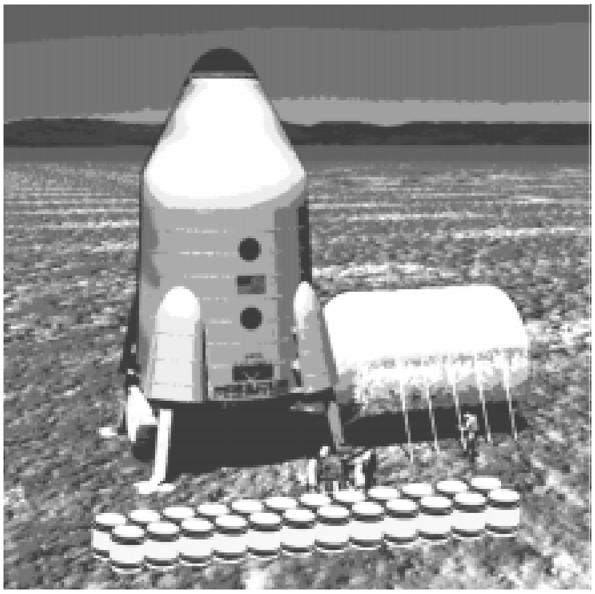

Figure 7. An array of AG-Pods could serve as a food supplementation/production system for Mars transit (Top) and surface operations (Bottom). [Background images from Reference Mission Version 3.0]

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

| | |
|---|---|
| ASC | Astroculture‘, designed and operated by WCSAR under Code UX grant. |
| ATS | Atmosphere Treatment System. |
| ALS | Advanced Life Support. |
| AP | Attached Payload. |
| Bio-Plex | Bioregenerative Planetary Life Support Systems Test Complex. |
| BPC | Biomass Production Chamber, located in Hanger L, KSC. |
| BPS | Biomass Production System, designed by Orbitec under NASA KSC contract. |
| CELSS | Controlled Ecological Life Support System. |
| $CO_2$ | Carbon Dioxide. |
| CPBF | Commercial Plant Biotechnology Facility, designed by WCSAR under Code UX grant. |
| ECLSS | Environmental Control and Life Support System. |
| EF | Exposed Facility. |
| EVA | Extra-Vehicular Activity. |
| ExPA | EXPRESS Pallet Adapter. |
| EXPRESS | Expedite the Processing of Experiments to Space Station. |
| FDA | Food & Drug Administration. |
| $H_2O$ | Water. |
| IR | infrared light. |
| ISS | International Space Station. |
| JEM | Japanese Experiment Module. |
| KSC | NASA Kennedy Space Center. |
| LDEF | Long Duration Exposure Facility. |
| LED | Light Emitting Diode. |
| LEO | Low Earth Orbit. |
| MLI | Multi-Layer Insulation. |
| M/OD | Micrometeoroid / Orbital Debris. |
| MPLM | Mini-Payload Logistics Module. |
| $N_2$ | Nitrogen. |
| NASA | National Aeronautics and Space Administration. |
| NDS | Nutrient Delivery System. |
| OEA | Oxygen-Enriched Air membranes. |
| $O_2$ | Oxygen. |
| PAR | photosynthetic active radiation (measured between 400-700 nm wavelength). |
| PGBA | Plant Generic BioProcessing Apparatus. |
| PGC | Plant Growth Chamber. |
| PGCE | Plant Growth Chamber Efficiency. |
| PGF | Plant Growth Facility, designed by Arthur D. Little and NASA KSC, under NASA KSC contract. |
| PGU | Plant Growth Unit, designed by Lockheed under NASA Ames / NASA KSC contract. |
| PPE | Plant Payload Efficiency. |
| TEC | Thermoelectric Controller or Cooler. |
| UV | Ultraviolet. |
| VOC | Volatile Organic Compound. |
| W | Watt. |
| WCSAR | Wisconsin Center for Space Automation and Robotics. |