SCIENTIFIC TASKS FOR HUMANS: PLANT GROWTH EXPERIMENTS

Ken Corey

Biographical Sketch

Ken Corey, former University of Mass/Amherst professor, received his M.S. and Ph.D. at North Carolina State University in plant physiology with minors in statistics and soil science. His research has involved the study of physiological processes and responses of a wide range of agronomic and vegetable crops. As a teacher, he has developed and taught numerous courses in plant, soil, and environmental sciences, including a special topics course in advanced life support systems. For the past 11 years, Corey has been involved with advanced life support systems research for NASA with an emphasis on the use of plants for bioregenerative purposes. Recently, his work has focused on plant responses to rarified atmospheres with applications to the design of atmospheres for extraterrestrial plant growth systems and structures.

Summary

The bioregenerative functions performed by plants are vital to the sustainable management of human life in extreme environments and will require development of new methods and technologies for plant cultivation on Mars. Such methods will likely involve scenarios for cultivating plants in their own atmospheric environments and those directly integrated with human habitats. It will be desirable to use low-pressure atmospheres to reduce structural loads and start-up and maintenance masses for plant growth. Provision of human life support requirements by bioregenerative methods, engineering constraints for construction and deployment of plant growth structures on the surface of Mars, and in-situ resource utilization all suggest the use of hypobaric pressures for plant growth. Past work demonstrated that plants will likely tolerate and grow at pressures at or below one-tenth of sea level pressure on Earth. The use of atmospherically-isolated structures also enables the regulation of plant growth with atmospheric compositions tailored to the plant species. Geometric configurations of those structures will also influence resource requirements, light interception, and function of engineering designs.

There are two broad categories of scenarios for the use of reduced pressures. First, there are scenarios that include direct integration of plants with human habitats or that permit ease of human entry to those habitats. Those habitats would involve the use of moderately low atmospheric pressures (40 to 70 kPa) and relatively high partial pressures of oxygen (14 to 21 kPa). Second, there will be a need for isolated plant growth habitats that will employ very low atmospheric pressures (5 to 40 kPa) potentially with a full range of oxygen partial pressures (1 to 21 kPa) and carbon dioxide partial pressures (0.1 to 10 kPa). The second set of conditions will involve the use of inflatable structures that will employ relatively thin, lightweight materials, capable of transmitting a maximum of ambient photosynthetically active radiation on the surface of Mars. Very few studies have been conducted in either area, but available literature strongly suggests the feasibility of the first (moderately low pressures) and hints at the feasibility of the second, though evidence at this point is scant.

A ***general scientific objective*** driven by a long term presence of humans on Mars is to ***determine the atmospheric limits for normal plant growth and development***. Specifically, limits of interest are low pressure, low partial pressure of oxygen, and partial pressure of carbon dioxide. As a corollary to this objective, it is of interest to answer the following question. ***Can***

plants grow and develop normally at or slightly above the boiling point of water? This question arises from the constraints of materials resupply, material engineering, and the available photon flux available for plant growth on the Martian surface. It also arises from experimental evidence that clearly demonstrates the ability of plants to tolerate low atmospheric pressures. Very low pressures (<5 kPa) are associated with the boiling point of water near temperatures suitable for plant growth. Answers to this question may also be accompanied by the use of tools of genetic engineering to select traits and design plants for adaptation to low pressure and low oxygen extremes. From a long-term perspective, it is of interest to answer the following questions related to the ***technological path*** by which humans choose to explore, settle, and develop the Mars landscape. ***How do we choose to provide people with life support requirements? Do we wish to develop and build a highly sustainable system of Martian agriculture to accompany human exploration and research efforts?***

Plant research efforts on Mars will require further Earth-based testing with a combination of vacuum chambers and Mars analog environments. Analog studies could make use of a Mountain Analog Project (MAP) that would involve controlled plant growth experiments in a High Altitude Plant Production Environment Network (HAPPEN). High altitude balloon flights (stratosphere) would enable short-term plant growth experiments that test and screen genotypes for adaptation to very low atmospheric pressures; those lower than the terrestrial analog limits. During future missions to Mars, it will be helpful to obtain additional information that characterizes the Mars environment. Particularly useful will be a knowledge of the range of photosynthetically active radiation incident on the Martian surface as a function of time, latitude, and atmospheric conditions (e.g. dust storms). Also, plant growth experiments on Mars provide unique opportunities to test plant responses directly to three-eighths gravity and for cultivation in Martian soil. The direct roles of humans in such experiments will be crucial to ensure success and the rapid technological development of sustainable bioregenerative systems. The following is a partial list of important human roles in plant growth experiments. While one can envision many of these roles also being served robotically, most would be better served directly by people.

Roles of Humans

***** Site Selector	* Data Collector	* Interactor
***** Initiator	* Sampler	***** Analyst/Statistician
***** Monitor	* Interpreter	***** Explorer
***** Variable Manipulator	* Evaluator	***** Discoverer
* Adjuster/Tweaker	***** Reporter	
* Diagnostician	***** Designer/Planner	

Reduced Pressure Rationale

* Structural Considerations
  Minimize Pressure Gradient
  Maximize Transparency of Material
  Decrease Launch Mass or In-situ Processing Mass

* Atmosphere Considerations
  Decrease Start-up Mass for Habitat Atmosphere
  Minimize Leakage and Maintenance Mass

* Crop Performance Considerations
  Photosynthesis
  — Diffusion
  — Photorespiration
  Respiration
  Transpiration
  Gene Expression
  Other?

Key Design Decisions

One Very Large Atmosphere vs. Many Small Atmospheres

A. One Very Large Atmosphere

- Buffering – thermal, atmospheric, chemical
- Minimize atmospheric manipulations or adjustments (control events)
- Large start-up mass, mostly water and carbon dioxide
- Disaster prone — e.g., particle impacts, disease
- Degree of autonomy?

B. Many Small Atmospheres

- Prelude to ecosynthesis
- Modular
- Scaleable
- Adaptable
- Penetrations
- Truncones provide thermal and atmospheric buffering
- Lends itself to extreme environments
- Creates resource caches
- Tailored to plant (crop and noncrop species) requirements
- Degree of autonomy?

C. Combinations of A & B

Concept of multiple barriers
Light transmission/attenuation — Could be used to provide different light environments, e.g., grow lettuce at lower light

Experimental Variables for Plant Growth Experiments on Mars

* ***Atmospheric Pressure***
- With human integration (moderately low pressures)
- Without human integration (very to extremely low pressures)

Possible range for plants isolated from people: 5 to 25 kPa

* ***Partial Pressure of Oxygen***
- Anoxia tolerance
- Intermediate range of tolerance

* ***Partial Pressure of Carbon Dioxide***
- Upper tolerance limit
- Importance of $ppO_2/ppCO_2$

* ***Genotype***
- Food plants (e.g., rice, wheat, lettuce)
- Non-food plants (e.g., *Arabidopsis*, algal species)

* ***Growth Medium***
- Martian regolith
- Solid substrate shipped from Earth
- Hydroponics of some form (several options)

* ***Irradiance***
- Time and site-dependent
- Should the PPF for plant growth experiments be controlled?
- Materials, thermal control, nature of barriers, light attenuation

* ***Gravity***

Three-eighths G has not been the focus of much work.

Reduced Pressure Categories

There are two broad categories of scenarios for the use of reduced pressures. First, there are scenarios that include direct integration of plants with human habitats or that permit ease of human entry to those habitats. Those habitats would involve the use of moderately low atmospheric pressures (40 to 70 kPa) and relatively high partial pressures of oxygen (14 to 21 kPa). Second, there will be a need for isolated plant growth habitats that will employ very low atmospheric pressures (5 to 40 kPa) potentially with a full range of oxygen partial pressures (1 to 21 kPa) and carbon dioxide partial pressures (0.1 to 10 kPa). The second set of conditions may involve the use of inflatable structures that employ relatively thin, lightweight materials, capable of transmitting a maximum of ambient photosynthetically active radiation at an extraterrestrial site. Very few studies have been conducted in either area, but available literature strongly suggests the feasibility of the first (moderately low pressures) and hints at the feasibility of the second, though evidence at this point is scant.

Categorization of atmospheric pressure ranges and generalized adaptations of organisms to those conditions.

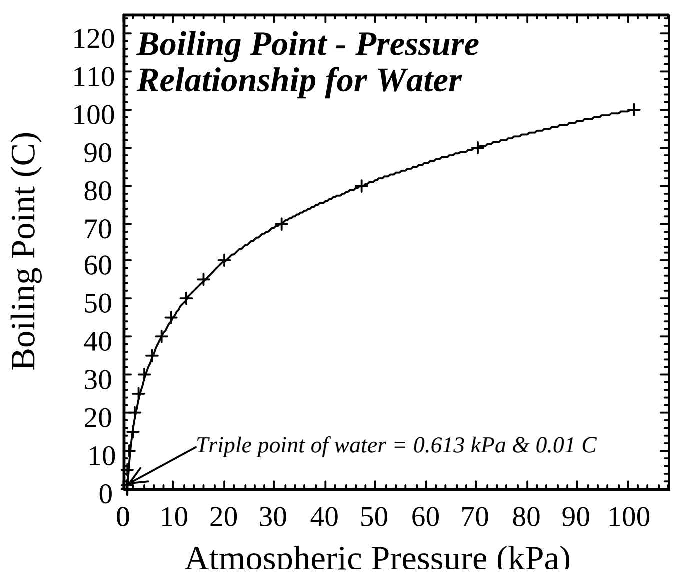
Pressure Range (kPa)	Fuzzy Description	Reference Altitudes (m)	Comments
101 – 75	slight	0 - 2500	* abundant terrestrial analogs * human adaptation easy
74 – 50	moderate	2500 – 5500	* many accessible terrestrial analogs e.g., White Mt. Res. Sta. – 4343 m (59 kPa) * human adaptation difficult, but possible over entire range
49 – 25	very	5500 – 10400	* terrestrial analog limit: Mt. Everest - 8,848 m (~ 31 kPa) * humans require supplemental oxygen
25 – 0.7	extreme	10400 – 27000	* stratosphere, lower Mars atmosphere (0.7 kPa) * plants & microbes can survive and grow, depending upon temperature and atmospheric composition

Can Plants Grow at the Boiling Point?

The surface pressure of the Martian atmosphere is about 7 mb or less than one-hundredth the sea level surface pressure of Earth. At this pressure, free water would boil off or sublime rapidly at temperatures where most organisms exist on Earth. However, if one were able to remove the thermal constraint to life on Mars, what would be the atmospheric limits at which plants can survive or even grow?

Recent interest in a human mission to Mars has captivated the public. However, if a long-term human presence is to develop in such a harsh environment, it will be necessary to establish limits for maintenance and growth of other organisms, especially plant life. Plant life will provide other heterotrophs with essential functions of oxygen evolution, carbon dioxide absorption, water recycling, and food. However, until a stage as advanced as terraformation occurs, it will be necessary to grow plants in thermally controlled environments. What then will be the atmospheric design for such a controlled habitat? What are the lower limits of atmospheric pressure for plants? Recent experiments at NASA's Kennedy Space Center strongly suggest that lettuce plants will at least be able to tolerate pressures at or below one-tenth atmosphere pressure for several hours, provided that sufficient water vapor is maintained in the atmosphere. Since plants do not wilt, it is reasonable to presume that they would be capable of long-term growth if provided with carbon dioxide, suitable temperatures, and sufficient photon flux. The limit suggested on the basis of pure water vapor would suggest that pressures of 2 to 5 kPa are likely possibilities, since saturated vapor pressures at normal growth temperatures are in the range of 1 to 4 kPa. Such pressure limits may necessitate the use of plants that would tolerate low partial pressures of oxygen. Such a scenario is well within the realm of possibility. An examination of the boiling point curve for water reveals that at a pressure of 3.2 kPa, water boils at a temperature of ~ 25 C. Thus, it is conceivable that plants will be capable of growth at temperatures at or very near the boiling point. Capability of plant growth at such low pressures would enable the use of lightweight, transparent structures that would minimize launch masses required to establish extraterrestrial plant growth facilities. Given suitably engineered habitats, early Martian travelers and settlers would then have plants as a foundation and life boat for the necessary consumables of oxygen, water, and food.

Figure 1. The relationship of boiling point of water with total atmospheric pressure.



Pathway to Early Martian Agriculture