CR-171 853
c. 1

(NASA-CR-171853) MODULAR PLANT CULTURE SYSTEMS FOR LIFE SUPPORT FUNCTIONS Final Report (Phytoresource Research, Inc.) 35 p HC A03/MF A01 CSCL 06K

N85-21924

Unclas
G3/51 14454

# MODULAR PLANT CULTURE SYSTEMS FOR LIFE SUPPORT FUNCTIONS

**Final Report**

NASA Contract No.
NAS 9-16671

March 1, 1985

PhytoResource Research, Inc.
707 Texas Avenue, Suite 202-D
College Station, Texas 77840

## INTRODUCTION

This report summarizes the results of a study undertaken on the first phase of an empirical effort in the development of small plant growth chambers for production of salad type vegetables on space shuttle or space station. The overall effort is visualized as providing an underpinning of practical experience in handling of plant systems in space which will provide major support for future efforts in planning, design, and construction of plant based (phytomechanical) systems for support of human habitation in space. The assumptions underlying the effort hold that large scale phytomechanical habitability support systems for future space stations must evolve from the simple to the complex in an essentially operational mode. The highly complex final systems will be developed from the accumulated experience and data gathered from repetitive test trials of fragments or subsystems of the whole. These developing system components will, meanwhile, serve a useful operational function in providing psychological support and diversion or some modest contribution to the food supply.

The first phase, which is the subject of this report, had two technical goals: (1) an assessment of the current state of knowledge with regard to culture of higher plants in the zero-G environment; and (2) the evaluation of concepts for the empirical development of small plant growth chambers for use in the shuttle middeck area.

## PART I

## ASSESSMENT OF THE CURRENT STATE OF KNOWLEDGE

Operationally, the information collected has been used primarily in defining parameters of growth chamber design and, with the exceptions noted below, will not be presented in detail in this report or in derivative documents. Three areas were emphasized in the accumulation of the supporting data base for hardware concept development. All are considered to be continuing activities beyond the period of performance of the current effort. These areas of emphasis are:

(1) review and analysis of the literature and the current status of research in the basic gravitational biology of plants;

(2) review and analysis of the relevant results of previous and current U.S. flight experiments with plants; and

(3) review and analysis of Soviet efforts in the use of plants in space.

Of the three subject areas, the major emphasis is placed upon the Soviet activities because theirs has been, by far, the most extensive and has, moreover, emphasized the practicial aspects of plant culture on spacecraft.

### I. The Status of Gravitational Biology Research

It is useful to classify gravitational biology in terms of effects at three levels in the physiology of the organism: (1) Primary, or fundamental effects, effects at essentially the genetic level which have no particular relevance to the question at hand; (2) Secondary effects which are related to gravity directed growth response and are of some practical importance in setting approaches to orientation of growth and flight growth facilities; and (3) Teritary, or indirect-effects of gravity upon the organism's environment which could have considerable effect upon the growth and productivity of plants in a micro-G environment.

#### Primary Effects

The basic research question of whether gravity plays some essential role in the morphogenesis of biological systems, or whether the complete absence of gravity will result in the failure of some key sequence of developmental events is probably not of great consequence to this project. First of all, it will be impossible to critically test such hypotheses until some time in the relatively distant future when free-fall experimental facilities become available in which acceleration levels do not exceed threshold levels of less than .001 G. Current flight operations, into which this project is visualized as fitting, will always involve above-threshold accelerations associated with on-orbit maneuvering and crew activity. Moreover, the putative long-term or fundamental effects of gravity, or absence of it, will have minor impact upon the practical attempts with short-term plant growth in a manned operational mode. The Soviets (see later specific discussion), after many years of practical experience, with not a few failures which they may or may not understand completely, nonetheless appear not to give much credibility to the notion of fundamental effects.

## Secondary Effects

The primary relevance of gravitational biology research for the present project is in the guidance of efforts to understand and compensate for the secondary and tertiary effects of gravity. Secondary effects will have some impact from a practical aspect in terms of directing growth of roots and shoots; however, much of the field we call gravitational biology is concerned with 1-gravity environment oriented questions, explanation of the mechanisms by which organisms modify their architecture to compensate for gravity-induced stress, or utilize gravity as a reference stimulus for orientation. This kind of research has been an ongoing activity since the time of Darwin (Darwin, 1880) and has utilized a wide variety of organisms as illustrated in Table 1. The ability to eliminate gravity as a variable in such experimentation has the potential for providing valuable insights. Thus, space flight in this context can be viewed primarily as an experimental tool, a probe for understanding these mechanisms which are, of course, of considerable economic importance to terrestrial agriculture and horticulture.

## Tertiary Effects

NASA has spent a considerable sum of money over the years on the design and construction of apparatus and on the planning of systems for plant growth in space based upon two pre-conceived and somewhat inconsistent viewpoints:

1. That there may be some fundamental effect of gravity, or the lack of it, upon plant cells and that, except for this hypothetical effect, there is

2. No signficiant difference between the space environment and the earth environment in terms of the organism's interaction with it (accepting, of course, the obvious secondary or morphogenetic responses).

The major result of our survey of the literature is that we are led to take, for the purposes of this growth chamber development effort, a contrary view: that as a reasonable working hypothesis, there is <u>no</u> fundamental effect of gravity, or absence of it, upon living systems because in manned spacecraft, there will always exist a certain above-threshold G environment associated with on-orbit maneuvering and human activity. On the other hand, in terms of the practical functioning and growth of plants, there is a probably profound effect of the altered physical environment. This effect is mediated to a minor extent through such phenomena as the sensing and orientation response. Much more important; however, are the indirect effects of the physical environment, and it is these effects which will most probably have a major impact upon plant growth and growth chamber design. Neglecting direct sensing of gravity or its absence, the basic physical pheonomena most likely affecting plant growth in zero-G are altered fluid response and the absence of gravity driven convection. Whereas under gravitational influence, fluids will flow to the lowest point and drain from a soil matrix or run off the leaves, stems, or roots, in a zero-G environment the dominant force is surface tension and the molecular attraction of the water for itself and for other surfaces. Water will thus accumulate to a

TABLE 1 - Plants Used in Gravitational Biology and Space Research

| LATIN NAMES | COMMON NAMES | RESPONSES STUDIED | LITERATURE CITED |
|---|---|---|---|
| Aegopodium podagraia | Goat Weed | Rhizome Gravitropism | Bennet-Clark and Ball 1981 (in Tepfer and Bonnett 1972) |
| Agrotis nebulosa | Cloud Grass or Bent Grass | Gravitropic Response of Leaf Sheath Pulvinus | Dayanandan et al, 1982 |
| Arabidopsis thaliana | European Cress | Shoot and Root Response to Clinostat | Hoshizaki, 1983 |
| Arabidopsis thaliana | European Cress | Horizontal Clinostat | Brown, Dahl, and Chapman, 1976 |
| Arabidopsis thaliana | European Cress | Development Response to Gravitropism | Brown, 1983 |
| Arachis hypogaea | Peanut | Gravitropic Response | Waber, Williams, Dubin, and Siegel, 1975 |
| Artemisia Sp. | Sage Brush | Root Gravitropism | Iversen, 1969 |
| Artemisia Sp. | Sage Brush | Response of Roots to Garvitropism | Johnson and Pickard, 1979 |
| Asparagus officinalis | Asparagus | Epicotyl Gravitropism | Perbal, 1982 |
| Avena sativa | Oat | Gravitropic Response of Leaf Sheath Pulvinus | Dayanandan, Franklin, and Kaufman, 1981 |
| Avena sativa | Oat | Response to Gravitropism | Shen-Miller, Hinchman, and Gordon, 1968 & Shen-Miller, 1970 |
| Avena sativa | Oat | Gravitropic Response and Calcium in Cell Walls | Roux, Biro, and Hale, 1983 |
| Avena sativa | Oat | Response to Hypogravity | Slocum and Galston, 1982 |
| Avena sativa | Oat | Phototropic Response | Shen-Miller and Gordon, 1967 |
| Avena sativa | Oat | Phototropic Response | Pickard, 1969 |
| Avena sativa | Oat | Phototropic Response | Brigs, 1960 |
| Capsicum Sp. | Pepper | Response to Freefall | Gordon, 1972 |
| Caulerpa Sp. | Marine Algae | Stem Part Gravitropism | Westing, 1971 |
| Chara Sp. | Algae | Rhizoid Gravitropism | Buder 1961 |
| Clivia Sp. | Kaffer Lilly | Root Gravitropism | Westing, 1971 |
| Convolvulus arvensis | Field Bindweed | Root Gravitropism | Tepfer and Bonnett, 1972 |
| Cucumis sativa | Cucumber | Role of Shoot Apex in Gravity | Iwami and Masuda, 1974 |
| Cucumis sativa | Cucumber | Stem Lignification | Chen, Siegel, and Siegel, 1979 |
| Cucumis sativa | Cucumber | Seedling Lignification | Siegel, 1979 |
| Elodea Sp. | Water Fern | Cytoplasmic Streaming | Chen, Siegel, and Siegel, 1979 & Briegleb and Schultz, 1980 |

Table 1 Cont:

ORIGINAL PAGE IS
OF POOR QUALITY

| LATIN NAMES | COMMON NAMES | RESPONSES STUDIED | LITERATURE CITED |
|---|---|---|---|
| Elodea Sp. | Water Fern | Lignification by Stimulated Hypogravity and Water Stress | Chen, Siegel, and Siegel 1980 |
| Helianthus annuus | Sunflower | Gravity Induced Growth | Firn, Digby, and Riley, 1977 |
| Helianthus annuus | Sunflower | Response to Autotropic Straightening | Firn and Digby, 1979 |
| Helianthus annuus | Sunflower | Response to Clinstat | Brown and Chapman, 1982 |
| Helianthus annuus | Sunflower | Response of Hypocotyls to Gravitropism | Johnson and Pickard, 1979 |
| Helianthus annuus | Sunflower | Auxin in Shoot Gravitropism | Rayle, Higliaccio and Watson, 1982 |
| Helianthus annuus | Sunflower | Role of Shoot Apex in Gravity | Firn, Digby, and Hall, 1980 |
| Helianthus annuus | Sunflower | Gibberellins in Gravitropically Stimulated Roots | El-Antably and Larson, 1974 |
| Hordeum vulgare | Barley | Coleoptile Gravitrpoism | Behl, and Jesihke, et al 1981 |
| Hordeum vulgare | Barley | Gravitropic Response of Leaf Sheath Pulvinus | Dayanandan, Franklin, and Kaufman, 1981 |
| Laelia Sp. | Orchid | Aerial Root Gravitropism | Westing, 1971 |
| Lens culinaris | Lentil | Root Gravitropism | Perbal, 1982 |
| Lepidium sativum | Garden Cress | Root Gravitropism | Iversen, 1969 & El-Antably, and Larson, 1974 |
| Lepidium sativum | Garden Cress | Root Response to Gravitropism | Hart and McDonald, 1980 |
| Lepidium sativum | Garden Cress | Graviperception in Cells | Hensel and Sievers, 1983 |
| Lolium multiflorum | Italian Rye Grass | Gravitropic Response of Leaf Sheath Pulvinus | Dayanandan, 1982 |
| Lupinus albus | Lupine | Root Response to Gravitropism | Lyon, 1961 |
| Lupinus albus | Lupine | Root Gravitropism | Dijman, 1934 |
| Lycopersicon esculentum | Tomato | Response to Clinostating | Salisbury and Wheeler, 1980 |
| Lycopersicon esculentum | Tomato | Response to Horizontal Clinostat | Lyon, 1970 |
| Lycopersicon esculentum | Tomato | Clinostating | Siegel, 1979 |
| Lycopersicon esculentum | Tomato | Stem Gravitropism, Seimotropism, Epinasty | Wheeler, and Salisbury, 1979 & Wheeler and Salisbury, 1981 |
| Phalaris Sp. | Canary Grass | Coleoptile Gravitropism | Darwin, 1880 (Fern, Digby, & Hall citation of Darwin) |
| Phaseolus Sp. | Bean | Response to Gravitropism | Salisbury, Wheeler, Salwinski, and Mueller, 1982 |
| Phaseolus vulgaris | Wax Bean | Stem Gravitropism | Chen, Siegek, & Siegel, 1979 |
| Phaseolus aureus | Mung Bean | Response to Hypogravity | Slocum and Galston, 1982 |
| Phaseolus coccineus | Scarlet Runner Bean | Root Gravitropism | Hartung, & Wolfram, 1981 |

| LATIN NAMES | COMMON NAMES | RESPONSES STUDIED | LITERATURE CITED |
|---|---|---|---|
| Phycomyces | Bread Mold | Sporangiophore Gravitropism | Dennison, 1961 |
| Physarum polycephalum | Slime Mold | Protoplastic Streaming | Briegleb & Schultz, 1980 |
| Picea abies | Norway Spruce | Root Response to Gravitropism | Iversen and Siegel, 1976 |
| Pinus ethitti | Black Pine | Lignification | Cowles et al, 1984 |
| Pisum sativum | Pea | Auxin in Root Response to Gravitropism | Lyon, 1972 |
| Pisum sativum | Pea | Root Response to Gravitropism | Lyon, 1961 |
| Pisum sativum | Pea | Auxin in Root Response to Gravitropism | Irvene and Freyere, 1961 |
| Pteris longifolia | Mangrove | Lignification of Seedling | Jones and Yokayama, 1983 |
| Rhizophora mangle | Mangrove | Lignification of Seedling | Siegel, 1979 |
| Ricinus communis | Castor Bean | Gravitropic Bending in Stems | Salibury, Mueller, Blotter, Harris, White, Gillespie, and Sliwinski, 1982 |
| Ricinus Communis | Castor Bean | Response to Clinostating | Salisbury and Wheeler, 1980 |
| Tagetes patula | Dwarf Marigolds | Hypogravity Peroxidase and Cell Wall Constituents | Siegel, Speitel, Shirari, and Fukumoto, 1978 |
| Tagetes patula | Dwarf marigold | Lignification | Siegel, 1979 |
| Tagetes patula | Dwarf marigolds | Leaf Epinasty | Waber, Williams, et al 1975 |
| Tagetes patula | Dwarf marigolds | Lignifaction | Seigel, Speitel, et al, 1981 |
| Tagetes patula | Dwarf Margold | Gravitropic Response | Waber, Williams, Dubin, and Siegel, 1975 |
| Tradescantia Sp. | Spiderwort | Response to Freefall | Gordon, 1972 |
| Triticum aestivum | Wheat | Clinostating | Siegel, 1979 |
| Triticum aestivum | Wheat | Gravitropic Response of Node | Bridges and Wilkins, 1973 |
| Triticum aestivum | Wheat | Response to Freefall | Gordon, 1972 |
| Triticum aestivum | Wheat | Root Gravitropism | Barlow, 1974 |
| Triticum aestivum | Wheat | Response to Gravitropism | Burstrom, 1971 |
| Triticum vulgare | Wheat | Response to Chronic Acceleration | Gray and Edwards, 1971 |
| Troparolum majus | Garden Nasturtiums | Root Response to Gravitropism | Lyon, 1961 |
| Vanilla planifolia | Vanilla Vines | Root Gravitropism | Irvine & Freyre, 1961 (in Tepfer & Bonnett 1972) |
| Vanilla planifolia | Vanilla Vines | Root Response to Gravitropism | Lyon, 1961 |
| Vica faba | Broad Bean | Root Response to Gravitropism | Lyon, 1961 |
| Vica faba | Broad Bean | Root Gravitropism | Hartung and Wolfram, 1981 |
| Xanthium strumarium | Cockelbur | Stem Gravitropism | Wheeler and Salisbury, 1981 |
| Xanthium strumarium | Cocklebur | Response to Clinostating | Salisbury and Wheeler, 1980 |
| Zea mays | Corn | Role of Shoot Apex in Gravity | Firn, Digby, and Hall, 1980 |
| Zea mays | Corn | Response to Gravitropism | Mulkey and Evans, 1981 |
| Zea mays | Corn | Response of Coleoptiles to Gravitropism | Hild and Hertel, 1972 |
| Zea mays | Corn | Root Response to Gravitropism | Pilet and Ney, 1981 |
| Zea mays | Corn | Role of ABA in Root Gravitropism | Evans and Mulkey, 1982 |
| Zea Mays | Corn | Phototropic Response | Brigs, 1960 |

ORIGINAL PAGE IS OF POOR QUALITY

## SELECTED REFERNCES ON GRAVITATIONAL BIOLOGY AND SPACE RESEARCH


Anderson, M., J.A. Rummel, and S. Deutsch (ed.). 1979. "biospex: Space Experiments. A compendium of Life S iences Experiments Carried on U.S. Spacecraft. NASA Techincal Memorandum 58217. Washington, D.C.

Barlow, P. 1974. "Recovery of Geotropism after Removal of the Root Cap." J. Exp. Bot.. 25(89):1137-1146.

Bennet-Clark, T.A. and N.G. Ball. 1951. "The Diageotropic Behavior of Rhizomes." J. Exp. Bot.. 2:169-203.

Bridges, I. and M.B. Wilkins. 1973. "Acid-induced Growth and the Geotropic Response of the Wheat Node." Planta. 114:331-339.

Briggs, W. 1960. "Light Dosage and Phototropic Responese of Corn and Oat Coleoptiles." Plant Phsyiology. 35:951-962.

Brown, A.H. and D.K. Chapman. 1982. "The First Plants to Fly on Shuttle." Physiologist Supplement. 25:S-5-S-8.

Brown, Allan H., A.O. Dahl and D.K. Chapman. 1976. "Limitation on the Use of the Horizontal Clinostat as a Gravity Compensator." Plant Physiology. 58:127-130.

Brown, A.H., A.O. Dahl, and D.K. Chapman. 1976. "Morphology of Arabidopsis Grown under Chronic Centrifugation and on the Clinostat." Plant Physiology. 57:358-364.

Brown, A. 1983. "Resistance of Mature Arabidopsis Plant to Mechanical Deformation in Relation to G-force During Development." Physiologist Suppl. 26:S-149-S150.

Burstrom, H.G. 1971. "Oreintation and Geotropic Reaction of Seminal Roots of Wheat". Physiol. Planta.. 25:283-293.

Chen, N., S. Siegel, and B. Siegel. 1980. "Gravity and Land Plant Evolution: Experimental Induction of Lignification by Stimulated Hypergravity and Water Stress." Life Science and Space Res.. 18:193-198.

Cowles, J., H.W. Scheld,, R. LeMay, and C. Peterson. 1984. "Growth and Lignification in Seedlings Exposed to Eight Days of Microgravity." Ann. Bot. (supplement). 3:33-48.

Cowles, J., H.W. Scheld, C. Peterson, and R. LeMay. 1982. "Lignification in Young Plants Exposed to the Near-zero Gravity of Space Flight." Physiologist Supple. 25(6):S-129-S130.

Dayanandan, P., C.I. Franklin and P.B. Kaufman. 1982. "Linkage Between Gravity Perception and Response in the Grass Leaf-Sheath Pulvinus." Physiologist Supplement. 25:S-102-S103.

Dennison, D. 1964. "The Effect of Light on the Geotropic Response of Phycomyces Sporangiophores." J. of General Physiol.. 47:651-665.

El-Antably, H. and P. Larson. 1974. "Redistribution of Endogenuos Gibberellins in Geotropically Stimulated Roots." Nature. 250:76-77.

El-Antably, H. and P. Larson. 1974. "Distribution of Gibberellins and Abscisic Acid in Geotropically Stimulated Vicia faba Roots." Physiol. Plant. 32:322-329.

Evans, M.L. and T.J. Mulkey. 1982. "A Reevaluation of the Role of Abscisic Acid in Root Gravitropism". Physiologist Supplement. 25:S-25-S26.

Firn, R., J. Digby, and A. Hall. 1981. "The Role of the Shoot Apex in Geotropism." Plant Cell and Envirn.. 4:125-129.

Firn, R., and Digby, J.. 1979. "A Study of the Autotropic Straightening Reaction of a Shoot Previously Curved during Geotropism." Plant Cell and Environ.. 2:149-154.

Firn, R., J. Digby, and H. Riley. 1977. "Shoot Geotropic Curvature - the Location, Magnitude, and Kinetics of the Gravity-induced Differential Growth in Horizontal Sunflower Hypocotals." Ann. Bot.. 42:465-468.

Gorden, S. 1973. "Effect of Free Fall on Higher Plants". COSPAR Life Sci and Space Res.. 11:155-162.

Gray, S. and B. Edwards. 1971. "Plant Responses to Chronic Acceleration." In: Gravity and the Oraganism (Gorden, S. and Cohen, M.) pg. 341-369.

Hart, J.W. and I.R. MacDonald. 1980. "The Influence of Light on Geotropism in Cress Roots." J. Exp. Bot.. 31:903-911.

Hensel W. and A Sievers. 1983. "Gravitropism in Plant Cells." Physiologist Supple. 26:S-60-S63.

Hild, V. and R. Hertel. 1972. "Intial Phase of Gravity Induced Lateral Auxin Transport and Geotropic Curvature in Corn Coleoptiles." Plant. 108:245-258.

Hoshizaki, T. 1983. "Clinostat Effects on Shoot and Root of Arabidopsis." Physiologist Supple. 26:S-151-S-152.

Irvine, J. and R. Freyre. 1961. "Diageotropism in Vanilla Roots." Science. 134:56-57.

Iversen, Tor-Henning. 1969. "Elimination of Geotropic Responsiveness in Roots of Cress (Lepidium sativum) by Removal of Statolith Starch." Physiol. Plant. 22:1251-1262.

Iversen, Tor-Heening and K. Siegel. 1976. "The Geotropic Curvature in Roots of Norway Spruce (Picea abies) Containig Anthocyanins." Physiol. Plant. 37:283-287.

Iwami, S. and Masuda, Y.. 1973. "Hydrogen Ion-induced Curvature in Cucumber Hypocotyls." Plant and Cell Physiol.. 14:757-762.

Johnsson A. and Pickard, B.. 1979. "The Threshold Stimulus for Geotropism." Plant Phys.. 45:315-319.
Krikorian, A.D. and S.A. O'Connor. 1984. "Karyological Obseravtions." Ann. Bot. (supplement). 3:49-63.

Krikorian, A.D., and S.A. O'Connor. 1982. "Some Karyological Observations on Plants Grown in Space." Physiologist Supple. 25(6):S-125-S-126.

Lyon, C. 1972. "Auxin Control for Orientation of Pea Roots Grown on a Clinostat or Exposed to Ethylene". Plant Physiology. 50:417-420.

Lyon, C. 1970. "Choice of Rotation Rate for the Horizontal Clinostat". Plant Physiology. 46:355-358.

Lyon, C. 1961. "Measurement of Geotropic Sensitvity of Seedlings." Science. 133:194-195.
Mulkey, T. and M. Evans. 1981. "Geotropism in Corn Roots: Evidence for Its Mediation by Differtial Acid Effux." Science. 212:70-72.

Perbal, G. 1982. "The Mode of Gravity Sensing in Plant Cells." Physiologist Supplement. 25:S-99-S100.

Pickard, B. 1969. "Second Positive Phototropic Response Patterns of the Oat Coleoptile." Planta. 88:1-33.

Pilet, P.E. and D. Ney. 1981. "Differential Growth of Georeacting Maize Roots." Planta. 151:146-150.

Rayle, D.L., F. Migliaccio and E. Watson. 1982. "Role of Auxin and Protons in Plant Shoot Gravitropism." Physiologist Supplement. 25:S-33-S35.

Roux, S.J., R.L. Biro and C.C. Hale, II. 1983. "Calcium Movements and the Cellular Basis of Gravitropism." Adv. Space Res.. 3(9):221-227.

Salisbury, F., R. Wheeler, J. Sliwinski, and W. Mueller. 1982. "Plants, Gravity, and Mechanical Stress." Utah Sci. 43:16-21.

Salisbury, F. and R. Wheeler. 1981. "Interpreting Plant Responses to Clinostating." Plant Physiology. 67:677-685.

Salisbury, F.B., W.J. Mueller, P.T. Blotter, C.S. Harris, R.G. White, L.S. Gillespie, and J.E. Sliwinski. 1982. "The Mechanics of Gravitropic Bending in Leafy Dicot Stems." Physiologist Supplement. 25:S-111-112.

Shen-Miller, J. and S.A. Gordon. 1967. "Gravitational Compensation and the Phototropic Response of Oat Coleoptiles." Plant Physiology. 42:352-360.

Shen-Miller, J., r. Hinchman, and S.A. Gordon. 1968. "thersholds for Georesponse to Acceleration in Gravity-compensated Avena Seedling." Plant Physiology. 43:338-344.

Shen-Miller, J. 1970. "Reciprocity in the Activation of Geotropism in Oat Coleoptiles Grown on Clinostats." Planta. 92:152-163.

Siegel, S. 1979. "Gravity as a Biochemical Determinant." Life Science and Space Res.. 17:147-160.

Siegel, S., Speitel, T., Shirali, D., and Fukumoto, J.. 1978. "Effects of Experimental Hypogravity on Peroxidase and Cell Wall Constituents in the Dwarf Marigold." Life Science and Space Res.. 16:105-109.

Siegel, S., B. Siegel, and J. Chen. 1981. "Lignification and Land Plant Evolution." In: Billingham, Life in the Universe, NASA Symposium, NASA-Ames Research Center, MIT Press, Cambridge. pg. 307-316.

Siegel, S., T. Speitel, D. Shiraki, and J. Fukumoto. 1978. "Effects of Experimental Hypogravity on Peroxidase and Cell Wall Constituents in the Dwarf Marigold." Life and Space Res.. 16:105-109.

Slocum, R.D. and A.W. Galston. 1982. "A Comparative Study of Monocot and Dicot Root Development in Normal (Earth) and Hypogravity (Space) Environments". Physiologist Supplement. 25:S-131-132.

Slocum, R.D., J.J. Gaynor, and A.W. Galston. 1984. "Cytological and Ultrasturctural Studies on Root Tissues." Ann. Bot. (supplement). 3:65-76.

Waber, J., B. Williams, J. Dubin, and S. Siegel. 1975. "Changes Induced in Peroxidase Activity under Simulated Hypo-gravity." Physiol. Plant. 34:18-21.

Wheeler, R. and F. Salisbury. 1980. "Gravitropism in Plant Stems May Require Ethylene." Science. 209:1126-1127.

Wheeler, R. and F. Salisbury. 1979. "Water as a Convenient Means of Imparting Mechanical Stimulation to Plants." HortScience. 14:270-271.

Wheeler, R. and F. Salisbury. 1981. " Gravitropism in Higher Plant Shoots. I. A role for Ehtylene." Plant Physiology. 67:686-690.

considerable layer thickness and cling to surfaces for which it has an affinity, while the maximum diameter of pores for which capillary action is an effective filling mechanism, is increased dramatically.

As a general principle, mass flow and gravity driven air convection constitutes a major mechanism of heat exchange between the plant and its environment as well as for movement of metabolic gases. In a micro-gravity environment, heat exchange through transpiration and the exchange of $CO_2$ and $O_2$ with the atmosphere will be severely hampered or perhaps reduced to a process of pure diffusion. The effects upon plant function are of very basic interest and such data could provide significant observations from the basic science point of view.

It is well recognized that excessive moisture in tight soils or growth media reduces air movement often with deleterious effects. In a micro-G environment, this problem will be accentuated. Any soil matrix, unless subjected to mechanical force to effect drainage, will become water-logged. Fluids, because of the dominance of surface tension or molecular attraction will tend to deposit themselves in unexpected and inconvenient places on the plant surfaces in growth media thus greatly impeding air movement and the supply of oxygen to plant cells.

Although the foregoing discussion has been couched in terms of certainty, and while there are sound theoretical reasons for believing that the picture just presented represents the truth, there has been, as far as we know, no actual characterization of the effects of the micro environment upon the plant in micro-G and, in fact, no careful study by biological or physical scientists of the more general phenomenon of absence of convective air flow in zero-G. All discussions of botanical experiments in micro-G either ignore the possibility or assume that the effects would be insignificant or non-existant. In fact, there is apprently no way of predicting _a priori_ what will be the precise nature of the convective environment in micro-G and it has been suggested by various people that the general phenomenon of behavior of air masses of different densities might be of a very great basic interest to some physical scientists, and hence, deserving of careful consideration without reference to its importance to plant growth (G. Brueckner - personal communication). There is, however, reasonable circumstantial evidence that such effects are real and have a significant impact. Altered areation and gas exchange in plant root appears to constitute the best explanation of a normal cell structure, cell division, and mitochondrial development in recent U.S. flight experiments (Cowles _et al._, 1982, 1984; Krikorian and O'Connor, 1982; Brown and Chapman, 1982; Slocum _et al._, 1984).

It logically follows from this discussion that if we are to design plant growth systems either for basic science experiments or for practical functions in providing food or atmospheric recycling on future spacecraft, it is of great importance to derive data for design of such hardware from a carefully planned characterization of the micro-G environment with respect to its interaction in the phenomena of interest. In a word, if we are to design micro-G rated plant culture systems, we will need ultimately to base such systems on micro-G derived data.

## II. American Flight Experience

The most notable characteristic of the U.S. program in plant biological experimentation is its small size in terms of either number of tests or number of species tested. Table 2 summarizes the totality of U.S. flight experimentation from its earliest trials to the present. Excluded are the so-called student experiments or other tests such as the Get-Away Special seed exposure experiments of the Park Seed Company which were primarily public relations efforts with no appreciable science content or technical validity. As of the fall of 1984, only two full scale botanical experiments have been carried into orbit and successfully completed on American spacecraft: the STS-3 plant lignification experiment in the spring of 1982, and the Spacelab I Heflex experiment on sunflower nutation. Although both produced results with practical implications, both were oriented primarily toward testing hypotheses in basic gravitational biology. Neither paid especial attention to the possible confounding tertiary effects of the space environment.

The major practical result of both the Heflex and the lignification experiments was in the results of tests peripheral to the main science objectives, which examined the growth and health of the roots. The general result was the observation that such roots exhibited unexplained anomalies in cell division and mitochondrial development (Cowles et al., 1982, 1984; Krikorian and O'Connor, 1982; Brown and Chapman, 1982; Slocum et al., 1984). Similar observations have been reported from a number of Soviet experiments. The most reasonable explanation for this phenomenon lies in the obvious fact that none of the experimental root systems were maintained under conditions that would allow circulation or aeration by convective flow equivalent to standard 1-G conditions. These observations thus point to the need for careful examination of indirect effects of the micro-G environment in any practical use of plants as well as in the planning of basic science experiments.

## III. Soviet Flight Experience

This effort, which has formed the major portion of the total information gathering effort, is part of the continuing survey of Soviet pronouncements upon, or reference to, their space activities with special attention to the use of plant systems in support of their specific flight activities. The results of research of the Soviet literature have been compiled into an extensive document which is primarily of interest to scholars and is beyond the scope of the present report. It is being prepared for publication, as a separate document. The general findings of this work are summarized here.

While American experience with cultivation of plants in space is negligible, the Soviets have been continuously engaged in a variety of tests with plant systems since the earliest days of their space flight program. By comparison to the American interest, limited to science only, the Soviets have maintained a continuous and intensive effort of practical plant growth testing on orbit for over ten years. Since 1975, every manned mission has carried as a minimal compliment, onions growing in small pots, and often other plants such as orchids and tulips; primarily for the purpose of entertaining the crew. In addition, a variety of experiments utilizing several hardware items, ranging up to relatively complex small growth chambers, has been flown routinely. These experiments range in objectives from basic

TABLE 2 - Plants Used in U.S. Flight Experiments*

| SPECIES | COMMON NAME | PLANT NAME | FLIGHT | PART USED | PHENOMENON STUDIED |
|---|---|---|---|---|---|
| Pinus elliottii | Pine | Gymnosperm, Woody Plant Timbertree | STS-3 | Germinating seeds → seedlings | Gravitropism, lignification |
| Avena sativa | Oat | Monocot, Grass, Field Crop, Grain | STS-3 | Dry seeds → seedlings | Gravitropism, lignification, cytological damage |
| Oryza sativa | Rice | Monocot, Grass, Field Crop Grain | Skylab | Dry seeds → seedlings | Phototropism |
| Triticum aestivum (vulgare) | Wheat | Monocot, Grass, Field Crop Grain | Biosatellite II | Dry seeds → emerging roots | Gravitropism, cytology, biochemistry |
| Zea mays | Corn | Monocot, Grass, Field Crop Grain | Discoverer XVII ASTP | Dry seeds | Radiation and HZE damage |
| Phaseolus aureus | Mung bean | Dicot, Legume Garden Vegetable | STS-3 | Dry seeds → seedlings | Gravitropism, lignification, cytological damage |
| Vicia faba | Broad Bean | Dicot, Legume Garden Vegetable | ASTP | Dry seeds | Radiation and HZE damage |
| Nicotiana tabacum | Tobacco | Dicot, Field Crop Recreational Drug Herb | ASTP | Dry seeds | Radiation and HZE damage |
| Helianthus annuus | Sunflower | Dicot, Field Crop Oilseed | STS-2 STS-3 Spacelab 1 | Whole seedlings | Gravitropism (nutation) Cytological damage |

* Data Complied from:
Anderson, et al. 1979.
Brown, et al. 1982.
Cowles, et al. 1982.
Cowles, et al. 1984.
Slocum, et al. 1984.

Table 2 Cont:

| SPECIES | COMMON NAME | PLANT NAME | FLIGHT | PART USED | PHENOMENON STUDIED |
|---|---|---|---|---|---|
| Capsicum annuum | Bell pepper | Dicot, Garden Vegetable | Biosatellite II | Whole immature plants | Gravitropism |
| Arabidopsis thaliana | House-ear cress or European water cress | Dicot, miniature plant Laboratory Organsim | ASTP & Apollo 16, 17 | Dry seeds | Radiation and HZE damage |
| Tradescantia paludosa | Spiderwort | Dicot, ornamental flower Laboratory Organism | Biosatellite II | Excised flower stems | Genetic damage |
| Daucus carota (Tissue Culture) | Wild carrot | Dicot, Weed, Garden Vegetable in the Domesticated Form | Kosmos 782, 1129 | Cells and embryoids | Embryonic development |
| Elodea densa | Elodea | Monocot, Aquatic Herb, Aquarium Plant. | Skylab | Excised leaves | Cytoplasmic streaming |
| Spirodela polyrhiza | Duckweed | Dicot, very small vestigal water plant | OV1-4 | Whole plants | Growth |
| Chlorella ellipsoidea | green alga | Unicellular plant | Discoverer XVII | Cells | Growth, radiation |
| Chlorella sorokiniana | green alga | Unicellular plant | OV1-4 | Cells | Growth |

science, aimed at evaluating effect of gravity upon such phenomena as cell development and ultrastructure and the ability of test tube plants (such as Arabidopsis thaliana) to flower and form seeds, to the very practical problems of plant growth for food production.

The Soviets have never been noted for elegance or sophistication in their undertakings; typically, they accomplish their aims by massive and concentrated effort. Their approach to space biology is no exception. They have done their experiments, often crudely, but in very large numbers. In spite of anomalies, unexplained results and downright failures, they have moved forward and out of all their efforts, they have observed enough successes or have understood the reasons for their failures to the point that they have convinced themselves that space presents no real biological barriers. This is true with respect to plants as well as human or animal systems. They have in the past explained their inability to grow plants reliabily in space by saying that plants need gravity to grow. This is probably more related to political expedience than actual belief. It may not be wise to complain about the very poor conditions of the spacecraft or their inability to engineer adequate environmental control systems.

It is obvious, from much of what they write, that no one in the controlling faction of the space biology establishment believes that there are any fundamental effects of weightlessness upon living systems. Their goals, of course, are quite different from those of the U.S. While we in the U.S. tend to vacillate quite a lot about why we are going into space, and often attempt to justify our going into space as a means of doing science, the Soviets care relatively little about science itself as a goal. They are frankly interested in more practical aspects. Whatever they might lack in the finesse with which they pursue their space program, one can never criticize the Soviets for their ambitions nor for the imagination and far reaching vision which guides their efforts in space. From the earliest days of their interest in space, their effort has been guided by a common vision, no doubt held to a greater or lesser degree by the national leaders as well, that of the extension of the Soviet domain into space not only in the exploratory and scientific sense, but in the occupation and large scale use of space as an extension of the national borders. They have not been reticent in proclaiming these goals. Thus in their efforts with plant experiments in space, the Soviets are very frankly problem-focused in their approach. The problem is simply this: how to use plants, higher or lower, in systems which will support their efforts to explore and conquer the Cosmos.

## PART II

## PHYTOMECHANICAL SYSTEM CONCEPT DEVELOPMENT

This section outlines an empirical approach to the development of plant systems for support of space activities. Such an approach appears entirely justified based upon our quite limited knowledge of the space flight environment and the responses of plants in that environment. It is well to remember that the basis of what we consider to be modern terrestrial agriculture and horticulture was laid over the centuries in empiricism and art. Modern science and engineering have produced some remarkable advances, but none of these would have been possible without the ability to build upon the ancient foundation. That same foundation of experience is not yet available to those who wish to culture plants in space. We, therefore, will only be able to make appreciable progress if we have some reasonable body of empirically derived data upon which to build.

### I. Habitability Support System Characteristics

In initiating this effort, we began to consider the characteristics and components of a program which would be necessary to develop a habitability system, or systems, for support of major orbital space activities or of activities on other planetary surfaces. The general approach taken was to define, based upon current knowledge, what was considered to be a final system in terms of its major characteristics in order to establish a target; and, then, to visualize the program necessary to arrive at that target system. In Table 3 are listed the general characteristics of this target system visualized as being appropriate based upon current knowledge.

Table 3. Characteristics of Target Phytomechanical Habitability Support Systems

1. They will be very large, but comprised of relatively small, individual units.

2. They will not be self-regulating biological systems and, in fact, by definition will be a combination of biological and mechanical systems.

3. They will incorporate redundancy from both organic and chemical systems and their capacity will be lightly stressed in order to enhance reliability.

4. They will be largely isolated from the human habitations.

5. They will utilize growing conditions for plants which are radically different from conditions ordinarily utilized in terrestrial plant culture.

6. They will initially emphasize atmosphere and waste recycling over food production as a primary function because of the probable difficulties of large scale food conversion.

7. They will develop incrementally through space flight experience with small fragments and components of the overall system.

8. They will retrofit with minimum modification of in-place physicochemical systems.

---

The general scenario for the long-term development of plant culture systems for space is depicted in Figure I. There is nothing about the currently defined target system or the pathway to its development that specifies precise configurations or technologies employed. We are, in effect, deferring specific questions related to the selection of final system concepts and approaches until we have gained sufficient data and operational experience in the handling of plants in space to support rational decisions. The present report summarizes the results of our efforts in defining the first empirical plant growth systems which will provide the needed operational experience and data in handling plant systems in space as well as some practical support of the general flight food system.

## II. Considerations in Concept Development

It is virtually impossible, within a document of less than textbook length, to present in detail the large number of inputs and sources of information and the complex thought process involved in the sifting of information and weighing of possibilities for a plant culture chamber for space use, particularly one which is to have a more practical emphasis. A number of efforts have been published relating to plant growth facility design. These have ranged from the somewhat grandiose and superficial discussions of space greenhouses (Modell, 1977; Phillips, Leggett and Fielder, 1984; Crawley 1977; Phillips, 1979) to the relatively specifically focused documents emanating from the CELSS program (Mitchell et al., 1984; Hoshizaki and Hansen, 1981; Meissner and Modell, 1979; Moore et al., 1982; Raper et al., 1979) to the various efforts aimed at development of specialized hardware for basic science experimentation. Two such instruments have been built and flown in Shuttle (Brown and Chapman, 1982, 1984; Cowles et al., 1982, 1984; Maine et al., 1979) and more complex units have been considered. All of these as well as a considerable body of experience and information regarding conventional plant culture systems and art were incorporated into the effort summarized here.

The focus of this effort, however, has been quite different from the published work. As indicated in Table 3 and Figure 1, it has begun to examine the practical problem of space plant growth systems at the simplest useful level. It began with a given set of constraints and requirements and explored the possiblities within the envelope of these requirements. A relatively large number of dead-ends were explored and while these are useful to know, a detailed account will largely detract from a discussion of the concept development. The discussions and diagrams which follow outline the major steps in the process of developing approaches to small plant growth systems for Shuttle.

### Constraints in Design Envelope

The following are the constraints placed on the plant growth system:

FIGURE 1 - Time Course for Development of Space-Borne Plant Culture Systems

| | Stage 1<br>Concepts/Baseline Data | | Stage 2<br>Operational Testing of Hardware Concepts | | Stage 3<br>Operational Use |
|---|---|---|---|---|---|
| CHARACTERISTICS | - small fragmentary systems designed to yield data on:<br>- physical properties of materials<br>- plant reactions to space environment<br>- properties of space environment | | - minor contributions to food supply and habitability<br>- modular apparatus<br>- integration into spacecraft structure or habitable space<br>- major uses:<br>a) aesthetic/psychological support<br>b) operational development of data on capacities and mechanical/biological problems | | - major contribution to life support<br>- large apparatus or aggregates of modules<br>- exterior to, or seperate from, human habitations<br>- dichotomy based on function:<br>a) orbiting ØG<br>b) planetary surface |
| MAJOR ACTIVITIES | - small tests routinely carried on shuttle flights<br>- collection and analysis of test data<br>- synthesis of design concepts<br>- design and fabrication of hardware components | | - routine carry-on of single modules<br>- collection of operational data<br>- de-bugging, modification, or redesign | - expanded use-multiple modules, space station mounted<br>- food production<br>- diversion for crew<br>- data collection<br>- planning exercise for major operational use | - construction, external to the habitats, of specialized modules for growth<br>- modules are gradually brought on line to take up increasing proportions of the life support load |
| MAIN PRODUCTS | - engineering test data for hardware design | - small test hardware module | - expanded data base<br>- tested and operational growth hardware | - significant support of space habitability<br>- design data for major support systems | - large scale habitability and life support systems |
| TIME SCALE | 1984 1986 | 1988 | 1990 | 1992 1994 | 1996 ———— |

A. Functional Requirements

1. to provide useful contributions to the food system - prime requirement;
2. to test empirically the "best guess" of what a growth system should be;
3. to provide a test bed for acquisition of experience and data.

B. Hardware Configuration

1. must fit into a standard slot in the orbiter; the bulkhead storage locker system;
2. must have simple, low cost construction;
3. must use least complex growth systems consistent with adequate function; and
4. must be configured to grow salad-type vegetable plants.

## II. Approaches to Salad Production

After an examination of the various possibilities within the constraint envelope, two general approaches were adopted and pursued. The first, and simplest, was in the use of seed sprouts as a low cost, low technology means of producing fresh salad vegetable material. The second was, more conventionally, the use of standard garden vegetable plants in a small, lighted growth chamber.

### Sprouting Systems

Seed sprouts offer a number of advantages both as a quick and easy way of providing fresh vegetable material and in short Shuttle flights and as a more routine food for much longer duration space flights (Figure 2). Seeds of the various vegetables and field crop can be stored dry for considerable periods of time. When fresh sprouts are needed, water is the only needed input to bring about a five to seven-fold increase in fresh weight. The most important characteristic is the marked increase in food value associated with sprouting. Vitamin content increases dramatically, fat and carbohydrate content are reduced while relatively little protein is lost, fiber content increases, and many of the inhibitors and toxicants associated with seeds are lost.

Apparatus necessary for seed sprouting is minimal. Light, soil, and the containers necessary for whole plant cultivation are not necessary; water and a well drained, aerated container are the major requirements. The space environment with the altered conditions of fluid movement, as discussed in Part I, places some constraints on the process, but once recognized the elimination of the constraints is merely an engineering problem.

A number of potential issues was addressed and resolved during the development effort. These will only be listed here:

1. microbial contamination;
2. toxicant content of seeds and sprouts;
3. selection of species for use in flight conditions;
4. sources of water and water addition schedules particularly as they related to flight conditions; and

**FIGURE 2 - Comparative Characteristics of Seed Sprouts and Mature Salad Vegetable Plants as Candidates for Testing and Use in Small Inflight Fresh Food Systems**

| CHARACTERISTIC | SPROUTS | MATURE PLANTS |
|---|---|---|
| Time to Maturity | 4 - 6 Days | Up to 90 Days |
| Complexity of Apparatus | Simple and compact: necessity only for water and aeration; orientation not problematic. | More complex and larger: provision for soil and nutrients, light and temperature control, orientation of plant parts. |
| Variety of Food Items | Limited - A single type of item with limitations in taste texture and range of uses | Variety large - limited only by ability to contain and grow the plant. |
| Popularity/Aesthetic Appeal | Limited because of food habits of general population. Not especially appealing from an aesthetic point of view. | Wide popularity; high aesthetic appeal both during growth and at consumption. |
| Nutritional Value | Adequate. Limit on amount which can be consumed raw without complications. | Adequate. |
| Processing/Use | Very simple. No waste, no mess. | Not complex but with significant waste disposal problems. |
| Experimental Value | Useful for development of fluid/air handling technology. | Useful for development of soil, nutrient and microbiological technology. Useful for light and energy technology development and for study of air/gas handling. |

5. storage and/or pre-germination of seeds.

None of these were seen as having an appreciable impact upon the use of seed sprouts in Shuttle or extended flight systems.

The system depicted in Figure 3 represents the end point of an exercise which considered several different approaches to the problem of routinely producing salad sprouts on Shuttle. It utilizes the storage locker and the configuration of the standard half-locker tray as a structural envelope. A number of issues related to operation remain to be worked out; many will depend upon flight testing for resolution.

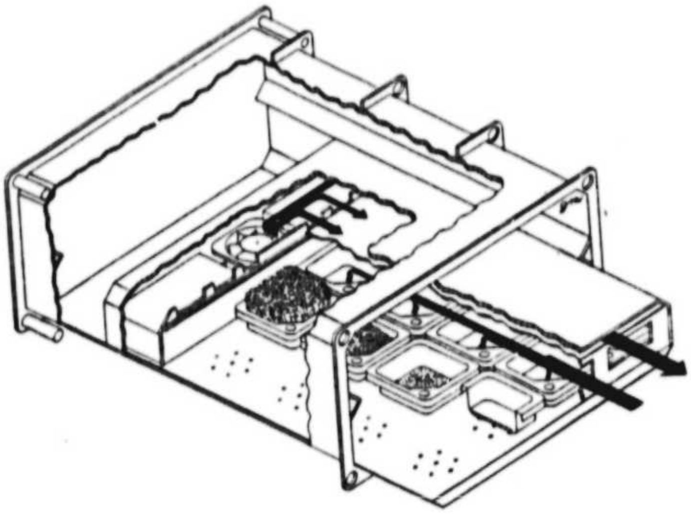


FIGURE 3 - Configuration of Shuttle Middeck locker based seed sprouting system. Unit is sized to half-locker tray.

The general features of the system are as follows:

1. The seed sprout container is the standard six ounce Shuttle food system pack. Seeds are packaged and stored dry under vacuum in the same manner as dehydrated foods.

2. The dry packs are installed in the system using a tool which perforates the bottom of the food pack, and the flexible cover is either perforated or removed.

3. Water is added to the dry seeds to initiate germination and is added periodically, as required, to maintain sprouting. Watering could be accomplished by hand, but a system for sensing moisture content and adding water as needed could be utilized.

4. In operation at micro-G, the system fan pulls a low flow of air down through the seeds into the space below and then forces it out through a channel separated from the compartment containing the seed packs. This small air flow serves to aerate the seeds

and in micro-G, theoretically, should be adequate to prevent the seeds or sprouts from floating out into the cabin environment.

The configuration shown in Figure 3 has been built and operated on the ground as a nonflight-qualified item. Issues such as watering practice, air flow, and general workability of the apparatus in micro-G will only be resolved by flight experience.

Whole Plant Chambers

The more conventional approach to growth has taken, as a starting point, the space envelope of one middeck foreward bulkhead locker, the exterior middeck dimensions of which are 21.062 in. x 10.757 in. x 18.125 in. A detailed description of the locker is included in the NASA Orbiter Middeck Payload Provisions Handbook. Because of the practical approach taken in this effort, many of the orientation and space constraints of an earlier effort (Maine et al, 1979; Cowles et al., 1982, 1984) were not necessary (see Figure 4) and thus more optimal use could be made of the available space.

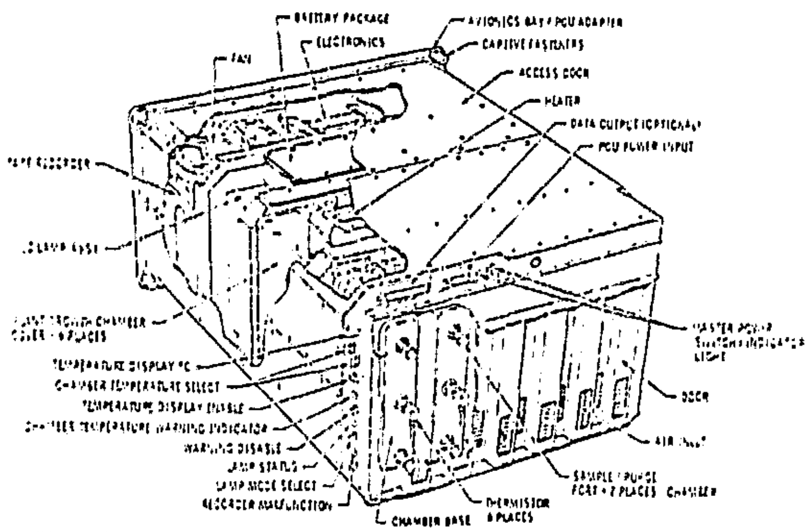



Figure 4 The Plant Growth Unit (PGU) of the STS-3 and SL-2 Lignification Experiments.
Dimensions - 51 x 38 x 27 cm and sized to fit a standard mid-deck locker space
Weight as used on STS-3, approximately 24 Kg
Average Power as used on STS-3 - 52 W at 28 Vdc
Power interface by single power cable to an outlet in the ceiling of the Shuttle Mid-deck.

Source: V.S. Clifton, 1982. Spacelab Mission 2 Experiment Descriptions-Second Edition. NASA TM-82477. NASA George C. Marshall Spaceflight Center.

The general effort had two thrusts:

1. A study of optimized configuration for the envisioned use; and

2. Consideration of the general array of technology to be taken into account in development of a growth system.

Figure 5 schematically summarizes the various issues as outlined below:

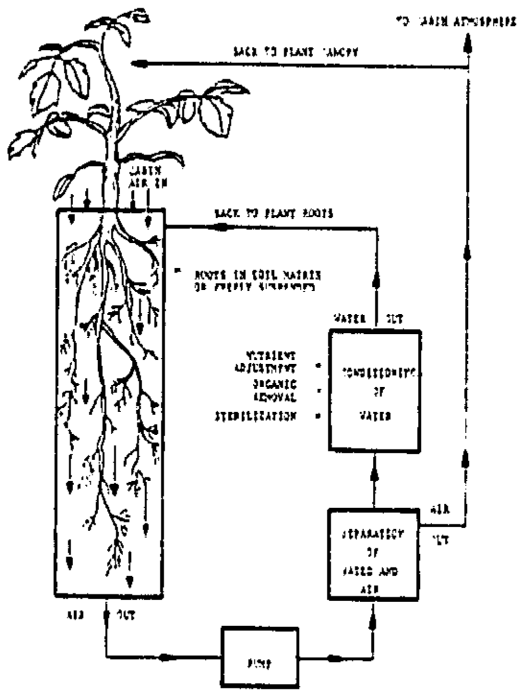



FIGURE 5 - Concept for Control of Watering and Aeration in a Zero-Gravity Environment.

1. Optimal configuration of the container.

    a. Geometry - which may be very dependent upon tests in a zero-G environment.

    b. Volume of contained area - related to plant size and species.

2. Composition of the growth/support medium.

    a. Synthetic, versus natural materials, versus a modified hydroponic/aeroponic system.

    b. Porosity and affinity for water.

    c. Fertilizer delivery system - slow release, versus ion exchange, versus hydroponic solution.

3. Operating parameters.

    a. Air and liquid movement rates.

    b. Temperature regulation of the root zone.

    c. The role of microorganisms - important because of disease, human and plant, but also because microbes could function in atmosphere scrubbing.

4. Mechanical systems.

    a. Air and water handling, zero-G separation of the two being the main problem.

    b. Water cleanup and conditioning.

        i. Nutrient adjustment.

        ii. Removal of root and microbial metabolites.

5. The adaptability of various plant species to the system.

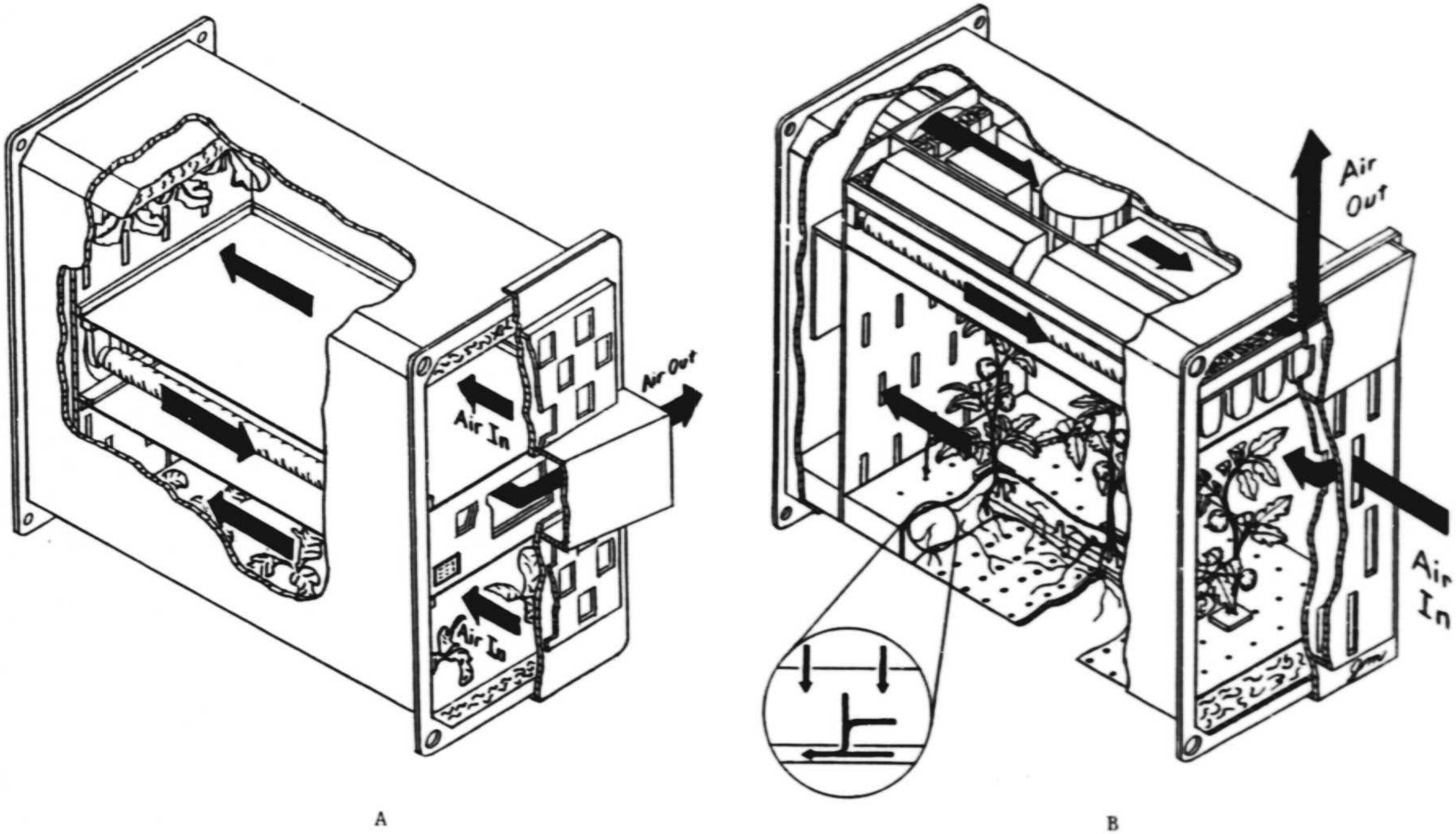
All of the points listed are subjects of continuing efforts. This report and the growth chamber concepts it presents are merely single frozen moments in an evolving field. Much of what we add will depend on flight test data and experience.

Most of the points have been addressed, at least briefly, in discussions of Part I. Point 5 needs a brief, philosophical note. The whole business of species selection can get out of hand. It is one of those projects which can easily generate much apparent result without any real progress. Several lists have been generated formally by NASA. The writer has informally assembled one on a more limited scope and knows of several unpublished lists which have been generated in a different context by other agricultural researchers. The main point we need to make is that species selection is a kind of activity undertaken when no one is really certain as to what should be done next. The approach we take here presumes that we know enough about the properties of plant systems and the specific requirements of the several functions they must perform to select species which are adequate for a particular function at this early stage of development. The ultimate selection of plant species will very likely, as indicated in Table 3, take into consideration and select for optimal performance in an environment very different from the one encountered by the standard horticultural and field crop varieties now in use.

## Growth Chamber Concepts

The growth chamber shown in Figure 6 embodies most of the issues listed above. Figure 6-B depicts a configuration appropriate for dwarf varieties of small, bush-type plants such as tomatoes or peppers. Figure 6-A depicts the configuration more appropriate for a low profile leaf or root vegetables such as lettuce, onions, or radishes. All exterior dimensions of the chamber shown are the dimensions of the Shuttle locker. Materials are yet to be determined by flight configuration. In the models depicted, all

FIGURE 6 - Configuration of Shuttle Middeck Locker Based Growth Chambers for Salad Vegetables. A - Dwarf fruit bearing plants. B - Leaf and root vegetables.



materials are off-the-shelf plexiglas or lexan, standard light and electronical components, and foamcore for the frames and shells.

Air flow is set to move across the plant from the Shuttle environment and to exit across the lamps to provide cooling. Growth media and roots are aerated and water is controlled by positive movement of air down through the growth substrate area aided by a small vacuum pump. Water is metered into the growth substrate area under control of a sensing system that limits over watering and movement of excess fluid.

Working models of both configurations have been built and tested in the 1-G configuration with orientation of the lights, and other components, 90° to the flight orientation as the instruments would be mounted in a shuttle locker. These configurations thus form a base line and starting point for an effort aimed at flight development and testing of small growth systems.

## SELECTED REFERENCES ON SEED SPROUTING


Adkins, D.M. 1920. "LVI. Digestibility of Germinated Beans." Biochem. J. 14:637-641.

Ananda, S. 1982. Love the Sunshine in With Sprouts. A Better Health for Life Publication, John Becker, Corvallis, Oregon.

Bagley, B.W., J.H. Cherry, M.L. Rollins, and A.M. Altschul. 1963. "A Study of Protein Bodies During Germination of Peanut (Arachis Hypogaea) Seed." Amer. J. Bot. 50:523-539.

Baker, E., and E. Baker. 1980. The UNcook Book. Communication Creativity, Sagauche, Colorado.

Banerjee, S., and R. Banerjee. 1950. "Studies on the Biosynthesis of Nicotinic Acid. Part I. Biosynthesis of Nicotinin Acid by Germinating Pulses." Ind. Jour. Med. Res. 38:153-160.

Banerjee, S., A.R.G. Roy, and P. Kumar Ghosh. 1959. "Folic Acid Metabolism in Germinating Seeds." Food Research. 24:332-334.

Banerjee, S., K. Rohatgi. 1955. "Pyridoxine Inositol and Vitamin K Cotents of Germinating Pulses." Food Research. 20: 545-547.

Banerjee, S., N.C. Ghosh, and N. Nandi. 1951. "Studies on the Biosynthesis of Nicotinic Acid. Part III. Effect of Germination on the Nicoticic Acid, Nicotinuric Acid, N1-Methyl-Nicotinamide, and Trigonelline Values of Pulses and Cereals." Ind. Jour. Med. Res. 39:447-451.

Beauchene, R.E. and H. Mitchell. 1957. "Effect of Temperature of Dehydration on Proteins of Alfalfa." Agricultural and Food Chemistry. 5:762-765.

Bernstein, L. 1943. "Amylases and Carbohydrates in Developing Maize Endosperm." American Journal of Botany. 30:517-526.

Berrang, B., K.H. Davis, Jr., M.E. Wall, C.H. Hanson and M.E. Pedersen. 1974. "Saponins of Two Alfalfa Cultivars." Phytochem. 13: 2253-2260.

Bhagvat, K. and K.K.P. Narasinga Rao. 1942. "Vitamin C in Germinating Grains." Ind. Jour. Med. Res. 30:493-504.

Blauer, S. 1981. The Miracle of Sprouting. Green Grown Publications, Boston, Massachusetts.

Bogart, R. and J.S. Hughes. 1935. "Ascorbic Acid (Vitamin C) in Sprouted Oats." J. Nutr. 10:157-160.

Catsimpoolas, S., T.G. Campbell, and E.W. Meyer. 1968. "Immunochemical Study of Changes in Reserve Proteins of Germinating Soybean Seeds." Plant Physiol. 43:799-805.

Chattopadhyay, H. and S. Banerjee. 1951. "Studies on the Chlorine Content of Some Common Indian Pulses and Cereals both Before and During the Course of Germination." Food Res. 16:230-232.

Chattopadhyay, H. and S. Banerjee. 1953. "Effect of Germination on the Biological Value of Proteins and the Trypsin-Inhibitor Activity of Some Common Pulses." Ind. Jour. Med. Res. 41:185-189.

Cheeke, P.R. and J.E. Oldfield. 1970. "In Vitro Inhibition of Succinate Oxidation By Alfalfa Saponin." Can. J. Anim. Sci. 50:107-112.

Chick, H. and E.M. Delf. 1919. "XXII. The Anti-Scorbutic Value of Dry and Germinated Seeds." Bioch. 13:199-218.

Chien, T.F. and H.L. Mitchell. 1970. "Purification of a Trypsin Inhibitor of Alfalfa." Phytochemistry. 9: 717-720.

Choate, H.A. 1921. "Chemical Changes in Wheat During Germination." Botanical Gazette. LXXI: 409-424.

Cooperman, J.M. and C.A. Elvehjem. 1944. "The B Vitamin Content of Groats and Rolled Oats." J. Nutr. 27: 329-333.

Crocker, W. 1916. "Mechanics of Dormancy in Seeds." Amer. J. Bot. 3:99-120.

Davis, A. 1954. Let's Eat Right to Keep Fit. Harcourt, Brace and Company, New York.

De, H.N. and S.C. Barai. 1949. "Study of the Mechanism of Biosynthesis of Ascorbic Acid During Germination." Ind. Jour. Med. Res. 37: 101-111.

Dotzendo, A.D. and J.G. Dean. 1959. "Germination of Six Alfalfa Varieties at Three Levels of Osmotic Pressure." Agron. J. 51: 309-309.

Drennan, D.S.H. 1962. "Physiological Studies of Germination in the Genus Avena. II. Changes in some Metabolites During the Germination of Grains of A. Sativa." New Phytology. 61: 261-265.

Dunn, M.S., M.N. Camien, S. Shankman, and H. Block. 1948. "Amino Acids in Lupine, Soybean Seeds, and Sprouts." Arch. Biochem. 18: 195-200.

Evans, C.R. 1922. "Effect of Temperature on Germination of Amaranthus retroflexus." Bot. Gaz. 73:213-225.

Evans, R.J. and S.L. Bandemer. 1967. "Nutritive Value of Legume Seed Proteins." J. Agric. Food Chem. 15:439-443.

Everson, G.J., H. Steenbock, D.C. Cederquist, and H.T. Parsons. 1944. "The Effect of Germination on the Stage of Maturity and the Variety Upon the Nutritive Value of Soybean Protein." J. Nutr. 27: 225-229.

Gestetner, B. 1971. "Structure of a Saponin From Lucerne (Medicago sativa)." Phytochemistry. 10: 2221-2223.

Gilbert, S.G. and H.M. Sell. 1957. "Biochemical Changes During Germination of the Tung Seed." Plant Physiology. 32:668-674.

Hall, G.S. and D.L. Laidman. 1968. "The Pattern and Control of Isoprenoid Quinone and Tocopherol Metabolism in the Germinating Grain of Wheat (Triticum vulgare)." Biochem J. 108:475-482.

Hayward, J.W., H. Steenbock, and G. Bohstedt. 1936. "The Effect of Cystine and Casein Supplements Upon the Nutritive Value of the Protein of Raw and Heated Soy Beans." J. Nutr. 12:275-283.

Hegdecker, W. 1973. Seed Ecology. Penn State University Press. University Park.

Hesterman, O.B., L.R. Teuber, and A.L. Livingston. 1981. "Effect of Environment and Genotype on Alfalfa Sprout Production." Crop Science. 21:720-726.

Holman, R.T. 1948. "Lipoxidase Activity and Fat Composition of Germinating Soybeans." Biochem. J. 17:459-466.

Horner, H.T. and H.J. Arnott. 1965. "A Histochemical and Ultrastructural Study of Yucca Seed Proteins." Amer. J. Bot. 52: 1027-1038.

Howell, R.W. and J.L. Carter. 1958. "Physiological Factors Affecting Composition of Soybeans. II. Response of Oil and Other Constituents of Soybeans to Temperature under Controlled Conditions." Agron. J. 50: 664-667.

Hymowitz, T. 1970. "On the Domestication of the Soybean." Economic Botany. 24: 408-421.

Iengar, N.G.C., V. Jayarman and Y.V.S. Rau. 1955. "Thiamine Contents of Some Indian Foodstuffs. Part II. Studies on Thiamine Contents of a Few Leguminous Seeds During Germination." Annals of Biochemistry and Experimental Medicine. 15:49-54.

Jackson, H.D. and R.A. Shaw. 1959. "Chemical and Biological Properties of a Respiratory Inhibitor from Alfalfa Saponins." Archives of Biochemistry and Biophysics. 84: 411-416.

James, A.L. 1940. "The Carbohydrate Metabolism of Germinating Barley." New Phytology. 39: 133-144.

Johnston, F.A. and H.M. Sell. 1944. "Changes in Chemical Composition of Tung Kernels During Germination." Plant Physiology. 19: 694-698.

Jones, M. and F.C. Elliott. 1969. "Two Rapid Assays for Saponin in Individual Alfalfa Plants." Crop Science. 9: 688-691.

Kahn, A.A. 1977. The Physiology and Biochemistry of Seed Dormancy and Germination. North Holland Amsterdam.

Kaiser, S. and H.G. Albaum. 1939. "Early Root and Shoot Growth in Two Varieties of Avena sativa in Relation to Growth Substances." Amer. J. Bot. 26:749-754.

Kakade, M.L. and R.J. Evans. 1966. "Effect of Soaking and Germination on the Nutritive Value of Navy Beans." Research Note. 24: 781-783.

Knuckles, B.E., D. de Fremery, and G.O. Kohler. 1976. "Coumestrol Content of Fractions Obtained During Wet Processing of Alfalfa." J. Agric. Food Chem. 24(6):1177-1180.

Kozlowski, T.T. 1972. Seed Biology. Vol. I, II, & III. Academic Press. New York.

Krober, O.A. and J.L. Carter. 1962. "Quantitative Interrelations of Protein and Non-protein Constituents of Soybeans." Crop Science. 2: 171-172.

Liener, I.E. 1980. Toxic Constituents of Plant Foodstuffs. Academic Press. New York.

Macleod, A.M. 1956. "Raffinose Metabolism in Germinating Barley." New Phytology. 56: 210-220.

Macleod, A.M. and H. McCorquodale. 1957. "Water-Soluble Carbohydrates of Seeds of the Gramineae." New Phytology. 57: 168-182.

Miller, C.D. and D.B. Hair. 1928. "The Vitamin Content of Mung Bean Sprouts." Journal of Home Economics. 20:263-271.

Morton, R.K., B.A. Palk, and J.K. Raison. 1964. "Intracellular Components Associated with Protein Synthesis in Developing Wheat Endosperm." Biochem. J. 91:522-528.

Nada, I.A.A. and A. Rafaat. 1955. "Carbohydrate Changes During Germination of Vicia faba Seeds." Ind. Jour. Agric. Sci. 25: 271-280.

Naik, M.S. and N. Narayana. 1960. "Biosynthesis of Riboflavin in Bengal Gram Seedlings." Annals of Biochemistry and Experimental Medicine. 20:237-242.

Oliver, M.H. 1975. Add A Few Sprouts. Keats Publishing Inc. New Canaan. Connecticut.

Pederson, M.W. and L.C. Wang. 1971. "Modification of Saponin Content of Alfalfa Through Selection." Crop Science. 11: 833-835.

Pederson, M.W., B. Berrang, M.E. Wall, and K.H. Davis, Jr. 1973. "Modification of Saponin Characteristics of Alfalfa by Selection." Crop Science. 13:731-735.

Peterson, D.W. 1950. "Some Properties of a Factor in Alfalfa Meal Causing Depression of Growth in Chicks." J. Biol. Chem. 183: 647-653.

Peterson, D.W. 1950. "Effect of Sterols on the Growth of Chicks fed High Alfalfa Diets or a Diet Containing Quillaja Saponin." J. Nutr. 42:597-607.

Pieterse, P.J.S. and F.N. Andrews. 1956. "The Estrogenic Activity of Alfalfa and Other Feedstuffs." Journal of Animal Science. 15: 25-36.

Pieterse, P.J.S. and F.N. Andrews. 1956. "The Estrogenic Activity of Legume Grass and Corn Silage." J. Dairy Science. 39: 81-89.

Pudelkiewicz, W.J. and L.D. Matterson. 1960. "A Fat-Soluble Material in Alfalfa that Reduces the Biological Availability of Tocopherol." J. Nutr. 71:143-148.

Ramirez, J.S. and H.L. Mitchell. 1960. "The Trypsin Inhibitor of Alfalfa." Agri. and Food Chem. 8(5):393-395.

Rhine, J.B. 1926. "Translocation of Fats as Such in Germinating Fatty Seeds." Bot. Gaz. 82:154-169.

Rogler, G.A. 1954. "Seed Size and Seedling Vigor in Crested Wheatgrass." Agron. J. 46:216-220.

Rose, M.S. and E.H.F. Phipard. 1937. "Vitamin B and G Values of Peas and Lima Beans Under Various Conditions." J. Nutr. 14: 55-67.

Santos, F.O. 1922. "Some Plant Sources of Vitamins B and C." American Journal Physiology. 11: 310-334.

Schopfer, W.H. 1943. Plants and Vitamins. Chronica Botanic Co. Waltham, Massachusetts.

Shaw, R.A. and H.D. Jackson. 1959. "Isolation of a Respiratory Inhibitor from Alfalfa." Archives of Biochemistry and Biophysics. 84:405-410.

Smith, D. 1955. "Influence of Area of Seed Production on the Performance of Ranger Alfalfa." Agron. J. 47:201-205.

Stark, O. 1927. "The Protein Metabolism of the Soybean." Amer. J. Bot. 14:532-547.

Tombs, M.P. 1967. "Protein Bodies of the Soybean." Plant Physiology. 42:797-813.

Toole, E.H. 1924. "The Transformations and Course of Development of Germinating Maize." American Journal of Botany. 2: 325-350.

Trelease, S.F. and H.M. Trelease. 1943. "Sprouted Soy and Mungo Beans." New York Botanical Garden Journal. 23 254-260.

Tremazi, S.A. 1957. "Ascorbic Acid in Some Oleiferous brassicas Cultivated in Pakistan." Britain Journal of Nutrition 2: 1-4.

Van Atta, G.R., J. Guggolz, and C.R. Thompson. 1961. "Determination of Saponins in Alfalfa." J. Agri. Food Chem. 9(1): 77-79.

Van Parijs, R. 1965. "Quantitative Changes of Ribonucleic Acid, Desoxyribonucleic Acid, Protein, and Dry Matter in Different Organs of Pea Seedlings During Germination." Archives Internationales de Physiologie el de Biochimie. 75: 125-138.

Varner, J.E. and G. Schidlovsky. 1963. "Intracellular Distribution of Proteins in Pea Cotyledons." Plant Physiol. 38: 139-144.

Von Ohlen, F.W. 1931. "A Microchemical Study of Soybeans During Germination." American Journal of Botany. 18: 30-49.

Waggoner, H.D. 1917. "The Viability of Radish Seeds (Raphanus sativus L.) as Affected by High Temperatures and Water Content." Amer. J. of Bot. 4:299-313.

Wai, K.N.T., J.C. Bishop, P.B. Mack, and R.H. Cotton. 1947. "The Vitamin Content of Soybeans and Soybean Sprouts as a Function of Germination Time." Plant Physiology. 22: 117-126.

Wats, R.C. and C.M.E. Eylies. 1932. "Some Sources of Vitamin C in India. Part II. Germinated Pulses, Tomatoes, Mangoes, and Bananas." Ind. Jour. Med. Res. 20: 89-106.

Weiss, M.G., C.R. Weber, L.F. Williams, and A.H. Probst. 1952. "Correlation of Agronomic Characters and Temperature with Seed Compositional Characters in Soybeans as Influenced by Variety and Planting Time." Agron. J. 44: 289-297.

White, H.B. Jr. 1958. "Fat Utilization and Composition in Germinating Cotton Seeds." Plant Physiology. 33: 218-226.

Zimmer, D.E., M.W. Pedersen, and C.F. McGuire. 1967. "A Bioassay for Alfalfa Saponins Using the Fungus Trichoderma Viride Pers. es Fr." Crop Science. 7:223-224.

## LITERATURE CITED


Bowman, G.H. and P.D. Sebasta. 1978. "Support System Consideration for STS Biological Investigations." ASME Publication. ENAs 37:1-5.

Brown, A.H. and D.K. Chapman. 1982. "The First Plants to Fly on the Shuttle." The Physiologist. (Supplement). 25:S5-S8.

Brown, A.H. and D.K. Chapman. 1984. "A Test to Verify the Biocompatibility of a Method for Plant Culture in a Microgravity Environment." Ann. Bot. (Supplement). 3:19-31.

Cowles, J.R., H.W. Scheld, R. LeMay, and C. Peterson. 1984. "Experiments on Plants Grown in Space: Growth and Lignification in Seedlings Exposed to 8 Days of Microgravity." Ann. Bot. (Supplement). 3:33-48.

Cowles, J.R., H.W. Scheld, C. Peterson, and R. LeMay. 1982. "Lignification in Young Plants Exposed to the Near-Zero Gravity of Space Flight." The Physiologist. (Supplement). 25(6):S129-S130.

Crawley, E. 1977. "Designing the Space Colony ." Technology Review. July/Aug 79:45-50.

Darwin, C.R. 1880. The Power of Movement in Plants. (J. Murray, London.)

Darwin, C.R. 1875. The Movements and Habits of Climbing Plants. (J. Murray, London.)

Hix, M. 1984. Orbiter Middeck Payload Provision Handbook. Crew Station Branch Man-Systems Division. Revision C. NASA. pg. 1-32.

Hoshizaki, T. and B.D. Hansen, III. 1981. "Generic Waste Mangement for a Controlled Ecological Life Support System (CELSS)." AMSE Publication. ENAs 23:1-7.

Leggett, N. and J.A. Fielder. 1984. "Space Greenhouse Design." J.B.I.S. 37:495-498.

Maine, R.B., P.A. Wagner, T.M. Olcott, and R.S. Luce. 1979 "Development of a Space Shuttle Plant Growth Unit." ASME Publication. ENAs 19:1-11.

Meissner, H.P. and M. Modell. 1979. "Recycling Plant, Human, and Animal Wastes to Plant Nutrients in a Closed Ecological System." ASME Publication. ENAs 29:1-5.

Mitchell, C., S. Knight, and T. Pappas. 1984. "Photosynthesis Productivity and Vibration/Acceleration Stress Considerations for Higher Plants in Bioregenerative Systems." The Physiologist. (Supplement). 27(6):S-29-S30.

Modell, M. 1977. "Sustaining Life in a Space Colony." Technology Review. July/Aug 79:36-43.

Moore, B., R. Wharton, Jr., and R.D. MacElroy. 1982. Controlled Ecological Life Support System. First Principal Investigators Meeting. NASA Conference Publication #2247 pg. 1-83.

Phillips, J.M. 1979. "Controlled-Environment Agricultural System as Food Source for Large Space Habitats." AMSE Publications. ENAs 30:1-7.

Raper, C.D., Jr., T.A. Pollock, and J.F. Thomas. 1979. "Using Phytotrons in Assessing Environmental Requirements for Plants in Space Habitats." ASME Publication. ENAs 28:1-5.

Salisbury, F. 1984. "Acheiving Maximum Plant Yield in a Weightless, Bioregerative System for a Space Craft." The Physiologist. (Supplement). 27(6):S31-S34.

Schwartzkopf, H. and P.E. Stofan. 1981 "A Chamber Design for Closed Eco-olgical Systems Research." ASME Publication. ENAs 37:1-5.

Yakut, M.M., D.L. Magargee, and E.N. Tell. 1978. "Life Support Systems for Biological Specimens in the Shuttle/Spacelab." ASME Publicaton. ENAs 38:1-8.

Workshop on Closed System Ecology. 1982. NASA / JPL Publication #82-64. pg. 1-15.