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**Roadmaps and Strategies for Crop Research
for Bioregenerative Life Support Systems**
**A Compilation of Findings from NASA's
Advanced Life Support Meetings**

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July 2009

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ABBREVIATIONS AND ACRONYMS

A	Ampere
ALS	Advanced Life Support
CDR	Critical Design Review
CEC	Controlled Environment Chamber
CEEF	Closed Ecology Experiment Facility
CELSS	Controlled Ecological Life Support System
CESRF	Controlled Environment Systems Research Facilities
CEV	Crew Exploration Vehicle
CO ₂	Carbon Dioxide
CPS	Crop Production System
CRAI	Capabilities Requirements Analysis Integration
ECLSS	Environmental Control and Life Support System
ELS	Exploration Life Support
ESA	European Space Agency
ESAS	Exploration Systems Architecture Study
ESM	Equivalent System Mass
ESMD	Exploration Systems Mission Directorate
FY	Fiscal Year
GMO	Genetically Modified Organism
HACCP	Hazard Analysis Critical Control Point
IALSWG	International Advanced Life Support Working Group
ICPS	Integrated Crop Production System
IMBP	Institute for Biomedical Problems
ISS	International Space Station
JAXA	Japanese Space Exploration Agency
KSC	Kennedy Space Center
LED	Light-Emitting Diode
LMLSTP	Lunar-Mars Life Support Test Project
LPC	Low Pressure Chamber
LSSC	Life Sciences Support Contract
NFT	Nuclear Film Technique

NRA	NASA Research Announcement
NRC	National Research Council
NSCORT	NASA Specialized Center for Research and Training
NSF	National Science Foundation
O ₂	Oxygen
PC	Physico-Chemical
PDR	Preliminary Design Review
PGBA	Plant Generic Bioprocessing Apparatus
PLM	Pressurized Logistics Module
SRO	System Requirements Document
SRR	Science Requirements Review
STOSA	Science, Technology, and Operations Support Accommodations
TAMU	Texas A&M University
TDP	Technology Development Project
TST	Technology Selection Team
VPU	Vegetable Production Unit

1 SUMMARY

Extensive testing with plants for bioregenerative life support systems has been conducted by NASA for nearly 40 years, both through university grants and work at NASA field centers. During this time, numerous meetings were held to develop strategies and roadmaps for implementing bioregenerative life support systems. Findings from several of these meetings are summarized in this report. In nearly all cases, the recommendations included an active ground-based research program and integration tests with other life support subsystems, followed by eventual spaceflight testing. The most recent roadmap of NASA's Exploration Life Support Crop Element suggests a sequence of first developing a modular vegetable production unit (VPU) to provide perishable foods to supplement the crew's diet. A similar system could then be used on the lunar surface, with additional modules added as the lunar outpost expands. Eventually, these modules could be transferred to a dedicated pressurized logistics module (PLM) for crop production. Experience from the lunar tests could then be used to conduct a similar buildup for Mars missions, where *in situ* food production and bioregeneration would be important for achieving outpost autonomy. To date, most trade studies of bioregenerative life support systems indicate that reducing the costs associated with crop lighting systems are key, and use of light-emitting diodes (LEDs) or direct solar lighting offers promising options. Likewise, sustaining high yields and high harvest index (% edible biomass) will be important for minimizing costs, and this can be achieved by optimizing growth environments and through selecting, breeding, and genetically engineering crops suitable for space environments. Collectively, these strategies and roadmaps suggest that a combined approach of fundamental research, hardware (plant chamber) development, and operational testing is required to achieve reliable bioregenerative life support systems.

2 BACKGROUND AND DISCUSSION

Following recommendations from the Exploration Systems Architecture Study (ESAS, 2005), NASA's research in bioregenerative life support was curtailed and redirected to more pressing needs in the newly formed Constellation Program. In particular, research on the use of higher plants (crops) for producing food and oxygen was terminated. The eventual need for plant-based life support system was still recognized (Griffin, 2006), with the notion that funding would be allocated when the mission needs were more appropriate. In contrast to NASA, other space agencies have continued plant and bioregenerative life support research at various levels. For example, bioregenerative life support research is underway in the European Space Agency (ESA) through the MELiSSA Project (Lasseur and Tan, 2004; Waters et al., 2004), the Italian Space Agency's CAB project (Lobasscio et al., 2008), the Japanese Institute for Environmental Science Closed Ecology Experiment Facility (CEEFF) Project (Tako et al., 2005; Arai et al., 2007), various Japanese Space Exploration Agency (JAXA) grants to universities (Kanazawa et al., 2008; Kitaya et al., 2008), the Canadian Space Agency's Devon Island analogue facility and research grants (Waters et al., 2004; Whekamp et al., 2007), the Chinese National Space Agency's activities at Beihang University and the Cosmonaut Training Center in Beijing (Guo et al., 2008; Qin et al., 2008), the Russian Institute for Biomedical Problems testing with the Lada Plant Chamber on ISS and their upcoming 500-day human test (Berkovich et al., 2005; Sytchev et al., 2007), and continuation of testing at the BIOS project for the Russian Institute of Biophysics in Krasnoyarsk (Tikhomirova et al., 2005).

Despite its current stand-down, NASA had one of the most active bioregenerative life support research programs of any space agency from the 1960s through the 2000s. Much of this was carried out through university grants, with a gradual increase in activity at NASA field centers such as Ames Research Center, Kennedy Space Center, and Johnson Space Center (Figure 1). Indeed, some of the earliest work on bioregenerative life support in the world was sponsored by NASA and the US Air Force (Eley and Myers, 1964; Bongers and Kok, 1964; Miller and Ward, 1966; Taub, 1974). These studies focused largely on *Chlorella* algae and *Hydrogenomonas* bacteria, with exploratory testing of higher plants for food production recommended at the Biologistics Symposium in 1962 (Boeing, 1962; Miller and Ward, 1966; Taub, 1974). Several NASA-sponsored panels were convened in the years following the Biologistics Symposium to reassess potential space crops and cover a wider range of nutritional needs, including producing sufficient protein, carbohydrate, fat, and micronutrients (Hoff et al., 1982; Tibbitts and Alford, 1982; Salisbury and Clark, 1996; Mitchell et al., 1996). Many crop species were common to these various lists, with the differences due largely to how complete the diet would be. For example, meeting all the micronutrient needs using only plants would require extensive plantings with multiple species, and it might be more practical to provide a portion of the food with crops and then import some dietary supplements and/or highly processed foods (Tibbitts and Alford, 1982; Masuda et al., 2005). Similar crop selection efforts for life support systems were undertaken by other space agencies, including the Russians for the BIOS projects in Krasnoyarsk (Gitelson and Okladnikov, 1994), the European and Canadian Space Agencies (Waters et al., 2002), the Japanese as part of the Closed Ecology Experiment Facility (CEEF; Masuda et al., 2005), and most recently the Chinese National Space Agency (Qin et al., 2008).

During the 1980s, several workshops and planning meetings were held at NASA's Ames Research Center to review activities in the Controlled Ecological Life Support (CELSS) Program and recommend future directions for ground-based research on designs for plant growth chambers, waste recycling, microbial ecology, and plant physiology (MacElroy and Bredt, 1985; MacElroy et al., 1986). A similar meeting near this same time focused on space flight experiments with plants (Wheeler and Tibbitts, 1984). The 1985 CELSS Workshop was perhaps one of the first meetings to bring together North American, Japanese, and European researchers in bioregenerative life support (MacElroy et al., 1986), setting the stage for the eventual formation of the International Advanced Life Support Working Group (IALSWG). Another meeting was held in 1989 in Orlando, Florida, to review CELSS research with plants, algae, waste recycling using both physical/chemical and biological approaches, tissue culture, a status report on the newly started CELSS Breadboard Project at Kennedy Space Center (Prince et al., 1989), and discussions of a "salad machine" concept, which involved developing a small-scale plant growing system to produce perishable vegetables and fruits as supplemental foods for a space station or transit vehicle (Kliss and MacElroy, 1990; MacElroy et al., 1992). At about the same time, NASA sponsored a conference in Houston, Texas, to discuss the challenges for developing agricultural life support systems on the lunar surface, including the potential for using *in situ* regolith as a growth substrate (Ming and Henninger, 1989). The readers should refer to these documents for an interesting glimpse of the early bioregenerative research efforts in NASA. It is impressive and somewhat humbling to see how creative and visionary these researchers were in identifying the key challenges and issues, which still remain today (Miller and Ward, 1966; Taub, 1974; MacElroy et al., 1985, 1990; and Ming and Henninger, 1989).

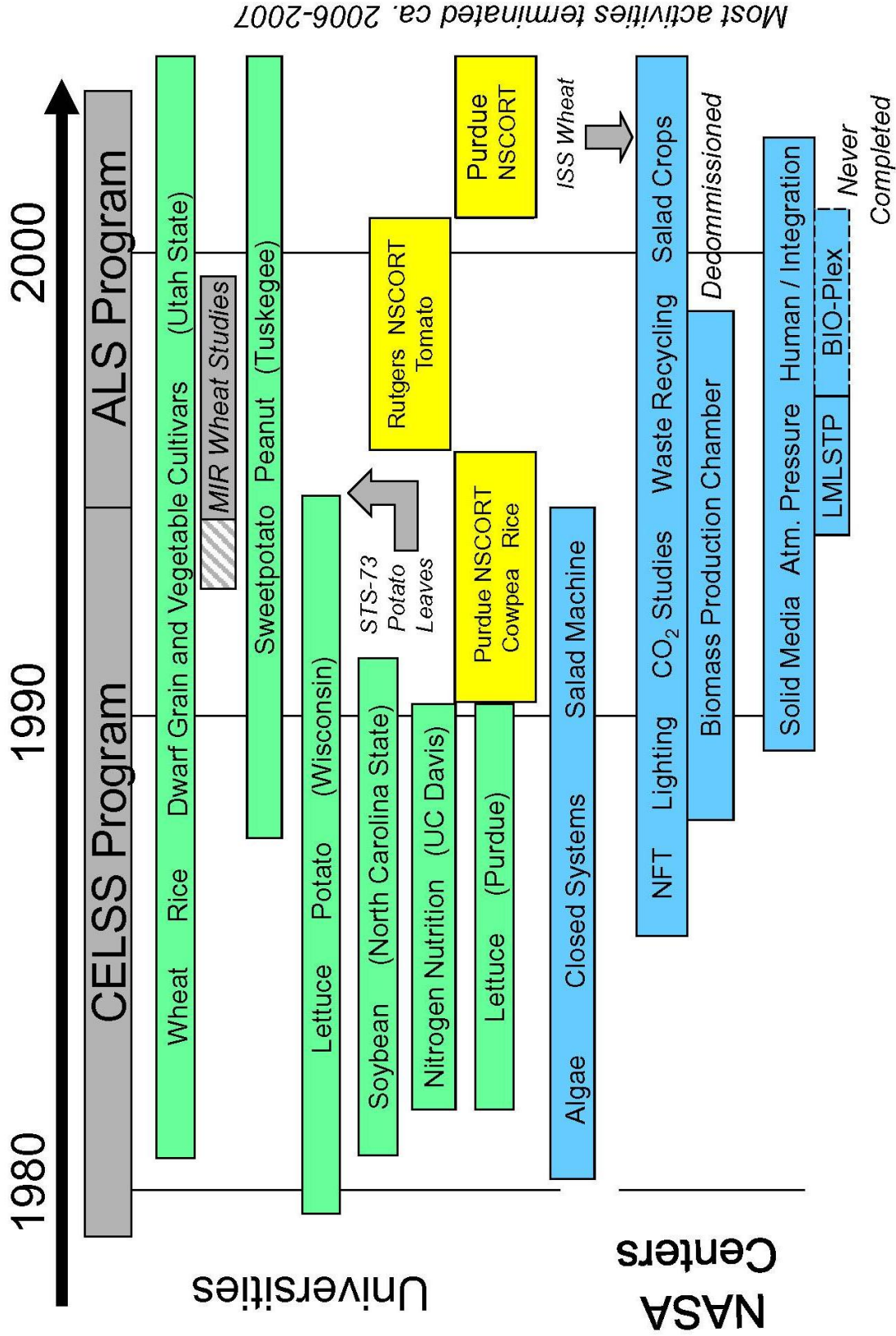


Figure 1. Timeline of crop research and testing for NASA Controlled Ecological Life Support System (CELSS) and later the Advanced Life Support (ALS) programs.

With the consolidation of the research in biological and physico-chemical approaches under NASA's Advanced Life Support (ALS) Program ca. 1994, an element of the program was established at NASA's Kennedy Space Center to focus on Crop Production Systems. This element provided coordination for NASA field center activities, while external grants in bioregenerative research were still managed directly by the ALS Program and NASA Headquarters. Beginning in the early 1990s, NASA funded a series of grants to support a NASA Specialized Center for Research and Training or NSCORT in the area of bioregenerative life support at Purdue, then at Rutgers, and then again at Purdue (Figure 1). Each of these NSCORT grants included significant crop research components (e.g., Volk and Mitchell, 1995; Gianfanga et al., 1998; Frantz et al., 2000), in addition to research on biological processes for waste recycling and water purification. Coinciding with this ground-based research, several space flight demonstrations of ALS concepts with plants and plant growth hardware were conducted. These involved demonstrations of plant watering and horticultural techniques for microgravity on the Space Shuttle using the Astroculture and PGBA plant chambers (Morrow et al., 1993; 1995; Hoehn et al., 2000), a series of experiments using the Russian SVET plant chamber on the Mir Space Station, where dwarf wheat plants were eventually grown from seed-to-seed (Salisbury, 1997; Levinskikh, et al., 2000; Salisbury et al., 2003), an experiment where small potato tubers were grown in the Astroculture chamber on the Space Shuttle (Wheeler, 1986; Croxdale et al., 1997; Brown et al., 1997; Tibbitts et al., 1999), and a test to measure wheat canopy photosynthetic rates on the International Space Station in the Biomass Production System flight chamber (Stutte et al., 2005 a, b). This does not include many other plant flight experiments looking at fundamental responses to μ -gravity and the space flight environment, which all served to advance the state of knowledge on using plants for life support in space; for example, Tripathy et al. (1996), Musgrave et al. (1997), Stout et al. (2001), Kuznetsov et al. (2001), and Jiao et al. (2004), just to mention a few.

In the late 1990s, several meetings and working groups were convened to develop recommendations on crop research for NASA. One of these was held at NASA's Kennedy Space Center in 1997 (Wheeler and Strayer, 1997). Discussions at this meeting also included the "readiness" levels of crops for inclusion in larger-scale integration testing in BIO-Plex, a human life support test bed being developed at NASA's Johnson Space Center (Barta et al., 1999). Minutes from that meeting are attached as Appendix A. Among the so-called staple crops, the knowledge and experience base for wheat, soybean, potato, and sweetpotato were considered well advanced, while for salad crops, knowledge and experience in growing lettuce, tomato, spinach, and radish were also considered well advanced (Appendix A). An additional recommendation from this meeting was to develop a handbook on the basic approaches for crop production on future life support. This specific objective was never completed but resulted a NASA Technical Memorandum entitled "Crop Production for Advanced Life Support System" (Wheeler et al., 2003), which summarized the findings and procedures used over 10 years of testing at NASA's Kennedy Space Center (KSC). Although the report focused on the KSC testing, in many ways it represented a broad sample of horticultural and physiological findings of the extended community of investigators, since many of the KSC horticultural procedures and protocols were based on recommendations from the university investigators. These investigators included Bruce Bugbee and Frank Salisbury at Utah State University for wheat; Cary Mitchell (Purdue), Ted Tibbitts (University of Wisconsin) and Bob Langhans (Cornell) for lettuce; Ted Tibbitts, Ray Wheeler, and Weixing Cao (University of Wisconsin) for potato; Walter Hill, Phil Loretan, Desmond Mortley, Conrad Bonsi, and Carlton Morris (Tuskegee University) for sweet

potato; and peanut; C. David Raper and colleagues (NC State University) for soybean; Bruce Bugbee and Cary Mitchell (Utah State and Purdue) for rice; and Harry Janes and colleagues (Rutgers) and Bruce Bugbee (Utah State) for tomato.

At this same time, the overall performance of NASA's bioregenerative research and other "Advanced Technology for Human Support in Space" was assessed by a panel commissioned by NASA through the National Research Council (NRC) and the US National Academy of Science. The panel's findings were positive regarding NASA's work and scientific output in the area of bioregenerative life support and recommended NASA's scientists, (1) stay engaged with professional societies and committees, (2) initiate studies of off-nominal performance and potential system failures, including the build-up of toxins or microbial pathogens, (3) conduct testing on situations of intermediate food closure, which would be encountered on early missions (as compared to efforts on more full closure), (4) conduct research to prepare for space-like environments, including studies of crop tolerance to very high CO₂ levels (up to 1%) and managing fluids in micro- and hypogravity, and (5) perform integration tests with crops and waste water to process ammonium nitrogen, sodium, and constituents of graywater, such as surfactants (National Research Council, 1997).

In response to the NRC recommendation to understand "intermediate" food closure situations, the large lists of crops from the 1997 and previous meetings were narrowed to focus on salad crops for augmenting the diet on early missions and initial BIO-Plex tests. This shorter list included tomato, lettuce, spinach, cabbage, radish, carrot, chard, green onion, and herbs such as dill, basil, chive, and spearmint (Appendix B). The list was modified later through informal discussions to include pepper, strawberry, and other leafy *Brassic*as, such as mizuna, which is popular with Russian investigators (Sytchev et al., 2007). This list provided a framework for baseline environmental tests with radish, lettuce, and onion conducted at Kennedy Space Center ca. 2001-2006, where plants were grown under three temperatures (22, 25, and 28°C), light levels (150, 300, and 450 $\mu\text{mol m}^{-2} \text{s}^{-1}$ PPF), and CO₂ concentrations (400, 1200, and 4000 $\mu\text{mol mol}^{-1}$). The intent of these studies was to straddle a range of conditions that might be encountered in early space missions, with 25 °C, 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$, and 1200 $\mu\text{mol mol}^{-1}$ being the central set. All the studies were conducted at 50% relative humidity, which is somewhat low for crop production but common for space cabin environments (Wheeler et al., 1993; Goins et al., 2003; Richards et al., 2004, 2005; Edney et al., 2007). Additional studies with onion were conducted at Texas Tech University in support of this, including variety trials, CO₂ responses testing, and development of horticultural techniques (Jasoni et al., 2004; Thompson et al., 2005).

At the biennial Bioastronautics Investigators' Workshop held in Galveston, Texas, in January 2001, crop research discussions were held in breakout session for NASA's Advanced Life Support Program. Findings from the session addressed both near- and long-term considerations for bioregenerative systems, as well as mission opportunities for plant research. Key among the recommendations was the development of a Vegetable Production Unit (VPU) that might be used in BIO-Plex (ground-based demonstration) and then modified for testing aboard the International Space Station (ISS) (Wheeler and Bugbee, 2001). In essence, this was a reaffirmation of the suggestion to develop a "salad machine" by Bob MacElroy and colleagues nearly 15 years earlier (MacElroy et al., 1992; Kliss et al., 2000). Experience with the VPU in the μ -g setting of ISS would be directly applicable to Mars transit missions and provide valuable experience for operating plant chambers in a space setting. Other recommendations included: (1)

developing concepts for deployable surface greenhouses (plant growth systems) (Wheeler and Martin-Brennan, 2000), (2) cultivar selection, with emphasis on dwarf, high-yielding lines, (3) horticultural studies with salad crops, (4) improving the efficiency of lighting systems, (5) use of genetic modifications (engineering) to improve crops, (6) conducting long-term production tests for reliability assessments, (7) studies on the psychological value of plants in confined environments, and (8) quantifying the water purification capacity of crop systems. A copy of the findings is attached as Appendix C.

Subsequent strategic planning meetings were held at regular intervals as part of the Exploration Life Support (ELS) Crop Element activities (note, Advanced Life Support was changed to Exploration Life Support to be consistent with NASA's newly formed Exploration Systems Mission Directorate). The minutes from a meeting held in 2005 compiled by Gary Stutte of Kennedy Space Center are shown in Appendix D. The meeting reviewed the ongoing activities of the ELS crop research, including environmental testing (temperature, CO₂, and light intensity), simultaneous production trials with multiple species, cultivar trials with strawberry, food quality assessments, hypobaric research, and testing with LEDs for plant lighting. Other discussions included future priorities for plant research, including exploring opportunities for robotic landers for the Moon and Mars to conduct preliminary plant growth tests using automated or remote operation, and developing the capabilities for surface production systems for the Moon by 2020 and for Mars by 2030 (Appendix D). The group also recommended reconvening a team to update the candidate crop list based on recent findings.

Following a reorganization of NASA that merged the Office of Biological and Physical Research in the Exploration Systems Mission Directorate (ESMD), research and development objectives for a wide range of human lift support technologies were assessed as part of the Human Health and Support Systems Capabilities Roadmap (March 2005) and the Capabilities Requirements Analysis Integration (CRAI) reviews. For both efforts, Dan Barta of the ELS Project Office served as a key advisor for life support technologies. At that time, NASA's overall space exploration plan was broken out into discrete but linked steps called "Spirals".

- Spiral 1 (CEV mission to Moon)
- Spiral 2 (Extended Duration Lunar Mission)
- Spiral 3 (Long Duration Lunar Surface)
- Spiral 4 (Mars Vicinity)
- Spiral 5 (Initial Mars Surface)

As part of the capabilities assessments, roadmaps and research plans were developed for the different elements of NASA's Exploration Life Support efforts, including crop production. A version of one roadmap for the crop systems testing and development is shown in Figure 2. Although the dates are no longer accurate, the development sequence is still relevant, showing a typical approach of first going through preliminary design reviews (PDRs) and then critical design reviews (CDRs) several years prior to the actual mission. The term "spiral" has since fallen from the NASA vernacular and been replaced with more specific program and project titles, such the Crew Exploration Vehicle or Orion, the Lunar Lander or Altair, and the Lunar Surface Systems Project.

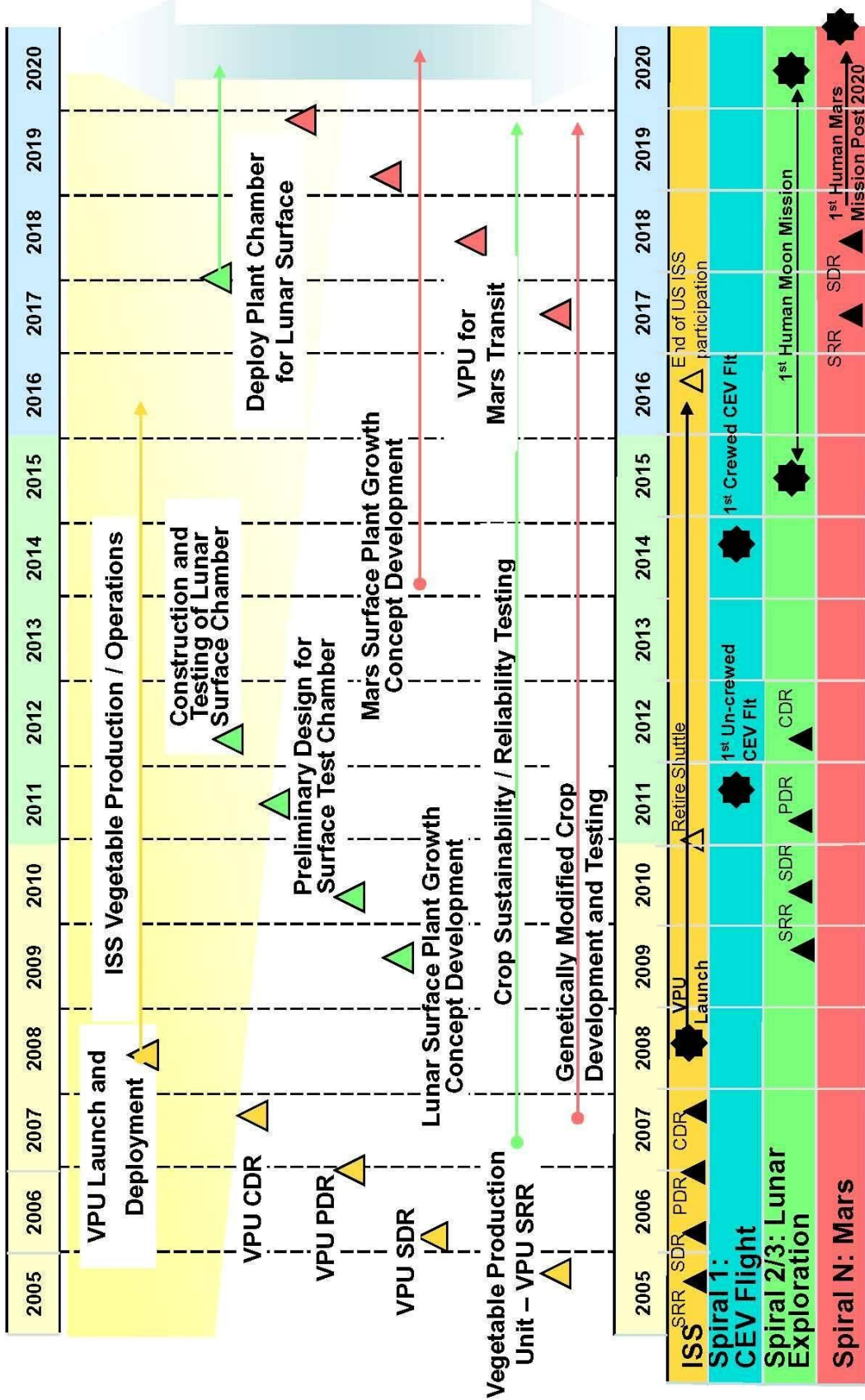
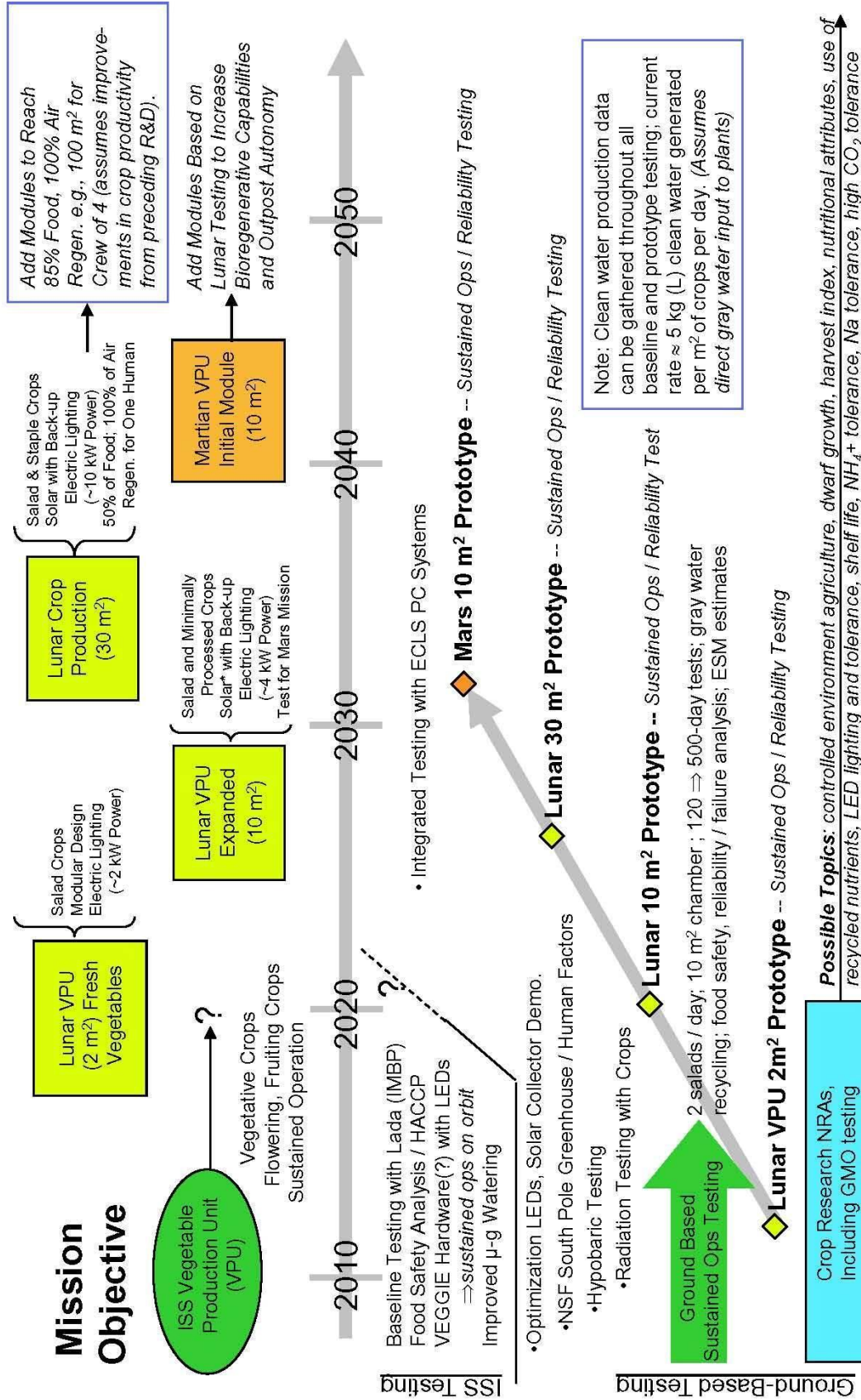


Figure 2. Example of a proposed timeline for development activities for NASA's Exploration Life Support Program's crop research element (taken from the Capabilities Roadmap Exercise 2002-2004).

In 2007, I put together a more generic roadmap (Figure 3) consolidating some ideas from the CELSS and ALS programs, the capabilities assessments exercises, and inputs from the Kennedy Space Center crop research team, which included Gary Stutte, Greg Goins, Neil Yorio, Oscar Monje, Sharon Edney, Jeff Richards, and John Sager, and University of Florida researchers Rob Ferl and Anna-Lisa Paul. In this roadmap, research and development tasks were first directed at developing a small vegetable production unit (2 m²), followed by 10 m² and larger modular systems that would be tested for a long-duration lunar outpost. Experience with this system would provide information for implementing a similar sequence for Mars missions (Figure 2). Concomitant with the engineering and development activity, fundamental research in selection and genetically engineering plants for space environments was recommended, along with operational testing to assess long-term reliabilities and risks for crop production systems. Subsystem research and development related to plant lighting was also recommended to improve energy efficiencies of electric lighting systems and explore concepts for capturing and using solar light. Other key areas of research included crop tolerance to hypobaric pressures (e.g., the 54 kPa cabin pressure projected by NASA's Constellation Program), crop tolerance to high energy radiation, and assessing the psychological / sociological value of having live plants and fresh foods in isolated space habitats, particularly using terrestrial analogues such as the plant production chamber at the US South Pole Station (Patterson et al., 2008) (Figure 3). The Roadmap also suggested using ISS to conduct operational tests of a salad machine or vegetable production unit in a flight environment. Throughout the entire research and development sequence, system costs in terms of mass, energy, volume, and crew time would be updated to assess improvements in equivalent system mass (ESM) (Drysdale et al., 1999). Ultimately, the expansion of lunar testing at a sufficient scale (~10 m²) would provide experience for Mars missions, which could be expanded to larger bioregenerative systems that provide 100% of the atmospheric regeneration and perhaps 85% of the food needs for the crew, while being co-utilized for recycling liquid and solid wastes.

3 CONCLUDING THOUGHTS

The use of plants for life support systems in space is one of oldest and most enduring research themes within the US space program (Myers, 1954). In fact, the notion of using plants for life support in space can be traced back to the writings of Tsiolkovsky in the 1920s (Tsiolkovsky, 1926) and novelists such as Percy Greg in the 1880s (Greg, 2006). The US National Aeronautics and Space Administration has maintained an active research program with plants for bioregenerative life support throughout much of its existence, with the 1980s and 1990s being especially active. During this time different roadmaps and strategies were developed for bioregenerative life support systems in space. Several of these are reviewed in this document, but others are not, and I encourage the readers to study these related documents for further insights. Currently NASA has deferred its research on the use of plants for bioregenerative life support to meet more immediate technology needs for the Constellation Program and, in particular, the Orion vehicle and its launch system. But I am convinced that bioregenerative technologies, including plants, will come back into NASA's life support research and development efforts, particularly as the efficiencies of lighting systems and crop productivity improve, and crops specifically engineered for growing in space become available. Future studies may also show positive effects of living with plants and having continuous supply of fresh food (rather than just preserved foods) on the crew's physiology and well being. When that time comes, the plant



Technology Development and Testing

Figure 3 Bioregenerative Life Support Technology Development Plan for the Crop Systems Element, NASA Exploration Life Support Project (2007)

growing systems will need to be integrated with other life support subsystems, both physico-chemical and biological, and their associated costs and reliabilities assessed to choose the appropriate combination for the mission. Photosynthetic organisms provide the basis for much of the life as we know it on Earth, and I am convinced the same will be true as humans explore space.

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APPENDIX A. MINUTES FROM ALS PLANT/FOOD PRODUCTION RESEARCH MEETING

Date: 24 June 1997

To: Advanced Life Support (ALS) Program Management and Attendees

From: R.M. Wheeler, Kennedy Space Center, FL

Re: Minutes from ALS Plant/Food Production Meeting

On May 5 and 6, 1997, a meeting was convened at Kennedy Space Center (Hangar L) to discuss issues related to Food and Plant Production activities for NASA's Advanced Life Support (ALS) Program. Two primary topics were addressed: 1) development and maintenance of an ALS plant production database, and 2) candidate crops and support research for BIO-Plex I.

Questionnaires on the growth of crops for bioregenerative life support were mailed out to most of the attendees prior to the meeting by Frank Salisbury (Utah State Univ.). Frank and Mary Ann Clark (Utah State) are currently compiling inputs from these questionnaires to develop a database on controlled environment crop production for ALS. During the Monday morning session, the structure of the questionnaire and the types of data needed for ALS were discussed, and manipulations with the software were demonstrated. Frank also presented an overview of rules and proper usage of SI units for ALS research and reporting.

The Monday afternoon session included a discussion of systems-level considerations for food/plant production by Alan Drysdale of McDonnell Douglas Corp. Following this, Ted Tibbitts (Univ. of Wisconsin) and Ray Wheeler (KSC) led discussions on the types of testing and environmental measurement needed for thorough assessment of ALS crops. Key questions included: Has the crop been grown in recirculating nutrient delivery system? Are there short or dwarf cultivars available? Has the crop been grown under high-pressure sodium lighting? Cheryl Mackowiak (Kennedy Space Center) then presented the concept of developing workbooks or experiment protocols from the database; such protocols would be used to provide guidelines for ALS projects and mission planning involving plants.

Frank Salisbury is retiring from Utah State in July of 1997 and maintenance of the database following his retirement was discussed. The group thought it worthwhile for the program to maintain the database (current funding is provided by a contract through JSC). Options for maintaining the database were discussed. A preliminary recommendation was for Ted Tibbitts to act as the database curator through funding to the University of Wisconsin. Protocols for different crop studies for the program could be developed utilizing the database as needed.

On Tuesday morning, Dan Barta (JSC) provided an overview of the plant activities associated with the Lunar/Mars Life Support Test Project (formerly EHT) phase III and plans for the BIO-Plex project. Dan noted that the first phase of BIO-Plex would strive for a 90% crop-derived diet

(crew of four), with 45% produced within the system, and 45% stowed. The remaining 10% would be noncrop-related foods. The BIO-Plex food production module would provide about 80 m² growing area in a 185 m³ volume and use horizontally mounted 400-W HPS lamps providing up to 1500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ PPF. Plants would be grown in shallow trays on shelves 9.8 m long by 1.4 m wide with a nutrient solution reservoir for each shelf. For the “staple” crops requiring large growing areas, an entire shelf would be planted at once (i.e., no mixed ages of plants on a shelf).

Yael Vodovotz (JSC) followed this with an overview of food concerns for BIO-Plex as they might relate to plants. Some of the issues discussed included: finding a lipoxygenase-free soybean cultivar (to reduce processing requirements), considering adding dry beans (as a protein and Ca source), adding fruits and other salad crop varieties (for nutrition and dietary diversity), and continuing to search for dwarf rice and sweetpotato cultivars (to include them in as staple crop selections). Useful measurements to consider for ALS plant research include: edible tissue moisture content, proximate composition, protein and non-amino acid N content, micronutrient content, presence of anti-nutritive factors (e.g., tyrosin inhibitors, phytic acid), and the presence of any human-associated organisms in the foods.

On Tuesday afternoon, the initial crop list for BIO-Plex I and other possible crops was discussed (Hoff et al., 1982; Tibbitts and Alford, 1982; Salisbury and Clark, 1996). The crops fell into two general categories: 1) staple crops, which could supply significant amounts of carbohydrate, protein, and/or fat, but could require substantial processing, and 2) supplemental crops (vegetables and fruits), which are generally perishable but would add dietary variety. The following criteria were used to assign readiness levels of 0 - 3 for the use of the crops in BIO-Plex: 0 = little knowledge of the crop in controlled environment conditions; 1) limited testing of the crop in controlled environment conditions and limited published results; 2) extensive testing in controlled environment conditions with several papers published in the scientific literature; 3) extensive controlled environment testing, published results, and large scale (> 10 m²), closed system (i.e., pre-integration) testing conducted.

The crops and their current readiness ratings for use in BIO-Plex:

<u>Staple</u>		<u>Vegetables and Fruits</u>			
Wheat	3.0	Lettuce	3.0	Kale	1.0
Soybean	2.5	Tomato	2.0	Quinoa	1.0
Potato	2.5	Spinach	2.0	Onion	1.0
Sweet potato	2.0	Radish	2.0	Carrot	0.5
Peanut	1.5	Strawberry	1.5	Broccoli	0.5
Rice	1.0	Chard/Beet	1.0	Cabbage	0.5
Dry Bean/Pea	1.0	Chufa	1.0 ^b	Melon	0.5
Cowpea	1.0 ^a				
Sugar Beet	0.5				

^a not discussed but used in previous CELSS studies; ^b nutsedge.

Because time was limited, thorough assessment of readiness levels was not possible. Assessment should continue in conjunction with the database development to refine ratings for BIO-Plex and related efforts. There was a general agreement that staple crops, which require a large planted area, reach a readiness level of ~ 3.0 for inclusion in BIO-Plex. Supplemental crops might be expanded to include other salad crops or cvs., and readiness levels might be relaxed because the area investment would be substantially less for these species. Food / diet development staff should provide approval of the tentative crop list prior to integration testing. If possible, the crew might also be canvassed for supplemental crop suggestions.

Following the crop discussions, an outline of pressing research needs for BIO-Plex I was discussed briefly. Issues fell into four general categories: (1) nutrient delivery systems (e.g., growing mixed species and ages of crops on one solution, allelopathy, recycling of minerals from treated waste products, sodium chloride build-up, iodine removal, phytopathogens, and sanitation procedures); (2) cultivation and environmental effects (e.g., propagation, starting media for seedlings, transplanting, spacing, mixed crops in the same environment, volatile organic contaminants, automated planting and harvesting); (3) lighting (e.g., acceptability of HPS lamps for crops, light leakage during dark cycles, improved thermal management, use of LEDs and microwave lamps, and use of native sunlight), and (4) crop and cultivar selection (e.g., dwarf cultivars, lipoxygenase-free soybeans, and dry bean cvs.).

Following discussions of BIO-Plex issues, Yuri Syniak presented an overview of life support related activities at the Moscow Institute for Biomedical Problems (IMBP). IMBP activities include the development of flight hardware for producing salad crops (“Vitamin Greenhouse”) for the Russian module of the International Space Station. Following this, Bernie Grodzinski presented an overview of bioregenerative research at the University of Guelph, Ontario. Guelph activities are currently focused on carbon metabolism of whole crop stands using tightly closed chambers. The chambers utilize microwave lighting systems and have no plastic components, which allow tracking of volatile organic compounds. The group is also investigating the use of water/biological filtration approaches for removing atmospheric contaminants in closed buildings and has a working system in the Canada Life Insurance Building in Toronto.

The last topic scheduled was a discussion of inputs on plant/food production research for NASA Research Announcements (NRAs), but time did not permit a dialogue on this topic.

The meeting was adjourned at about 5:00 pm on Tuesday, May 6, 1997.

Attendees:

Mike Alzaraki / Kennedy Space Center
 Dan Barta / Johnson Space Center
 Maynard Bates / Ames Research Center
 Yuli Berkovitch / IMBP
 Doug Britt / Kennedy Space Center
 Dave Bubenheim / Ames Research Cen.
 Bruce Bugbee / Utah State Univ.

Bob Langhans / Cornell
 Colleen Loader / Kennedy Space Center
 Howard Levine / Kennedy Space Center
 Bill Little / Kennedy Space Center
 Phil Loretan / Tuskegee University
 John Lu / Tuskegee University
 Cheryl Mackowiak / Kennedy Space Center

Peter Chetirkin / Kennedy Space Cen.
Mary Ann Clark / Utah State Univ.
Dave De Villiers / Cornell Univ.
Mike Dixon / University of Guelph
Tom Dreschel / Kennedy Space Cen.
Alan Drysdale / McDonnell Douglas (KSC)
Barry Finger / Kennedy Space Center
Gene Giacomelli / Rutgers Univ.
Greg Goins / Kennedy Space Center
Bernie Grodzinski / Univ. of Guelph
Jill Hill / Tuskegee University
Ross Hinkle / Kennedy Space Center
Bill Knott / Kennedy Space Center

Desmond Mortley / Tuskegee University
John Sager / Kennedy Space Center
Frank Salisbury / Utah State University
Greg Schlick / Ames Research Center
Lisa Siegriest-Ruffe / Kennedy Space Cen.
Gary Stutte / Kennedy Space Center
Yuri Syniak / IMBP
Ted Tibbitts / Univ. of Wisconsin
Yael Vodovotz / Johnson Space Center
Ray Wheeler / Kennedy Space Center
Neil Yorio / Kennedy Space Center
Scott Young / Kennedy Space Center

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**APPENDIX B. SUMMARY REPORT: ALS BIO-PLEX SALAD CROP
TIGER TEAM***

Submitted November 22, 2000

CHARTER

During March through May 2000, several scientists involved with biomass production and food systems research for Advanced Life Support (ALS) participated in a series of telephone conferences to discuss crop testing for initial phases of the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex). Participants included: Ray Wheeler, chair (NASA KSC), Dan Barta, co-chair (NASA JSC), Harry Janes (Rutgers Univ./ NJ NSCORT), Desmond Mortley (Tuskegee University / CFESH), Bruce Bugbee (Utah State University), Tony Hanford (Lockheed Martin/JSC), Greg Goins (Dynamac Corp./KSC), Neil Yorio (Dynamac Corp./KSC), and Yael Vodovotz (NASA JSC). Also participating in some telecons were Don Henninger (NASA JSC), Al Behrend (NASA JSC), and Charlie Barnes (NASA HQ). The group was asked to assess the role of “salad” crops for near-term Mars mission scenarios and justify why BIO-Plex would be useful for these investigations.

RATIONALE

Near-term space missions, such as the International Space Station (ISS) and early missions to Mars will be constrained in terms of available area (volume) and electrical power, and the life support role of plant (crop) production systems may be limited. Yet the impact of plants even on these early missions could be profound, especially with regard to enhancing diet diversity through fresh produce. Indeed, a “fresh food production unit” was identified within food provisions of all the recent concepts for Mars lander habitats and transit habitats (Design Reference Missions 1-4, Combo Lander #1 & #2, Dual Lander) (see also, MacElroy et al., 1992). In addition, a recent review of NASA Advanced Life Support by the National Research Council emphasized the need to better quantify the psychological value of fresh foods in closed life support systems (Recommendation 2-26; Advanced Technology for Human Support in Space, National Academy Press, Wash. DC 1997). Hence there is a need to study the effects of fresh food or salad crop production systems and their contribution to the diet and well being of crews living in confined habitats. Such studies could help assess the horticultural requirements for growing plants for near-term Mars transit scenarios, the processing needs for converting the plant biomass into useful foods, and any potential food safety issues associated with plants grown under these conditions.

The ALS BIO-Plex project currently under development at NASA’s Johnson Space Center will provide a valuable testbed to assess salad crop production systems and their impact on human crews living in a closed life support habitat.

RECOMMENDATIONS

Salad crop species identified for initial testing in the BIO-Plex project include some or all of the following:

- Tomato
- Lettuce
- Spinach
- Cabbage
- Radish
- Carrot
- Chard
- Green Onion

These eight crops were identified previously for space vehicle systems because of the nutritional value and low processing requirements (JSC Memo EC3-98-066) and have been common to several crop lists suggested for life support applications (e.g., Salisbury and Clark, 1995). Fresh herbs (e.g., dill, basil, chive, and spearmint) were also suggested for consideration to increase dietary variety and the potential to produce some seasonings for preliminary menus (see discussions in Drysdale and Hanford, 1999).

Several of these species have been studied extensively in controlled environments for ALS applications (e.g., lettuce and spinach), whereas others have been studied very little (e.g., cabbage, chard, onion, carrot, and herbs) (see Wheeler and Strayer, 1997). To advance the technology readiness levels, baseline testing should be initiated to define horticultural approaches and environmental responses. Testing should include screening of cultivars using horticultural approaches and lighting concepts envisioned for BIO-Plex. To meet BIO-Plex start-up dates, a team approach enlisting current grantees and field centers involved with ALS plant research should be considered, where each PI or center might conduct testing on one or two crops.

Specific objectives to consider for salad crop testing in initial phases of BIO-Plex include:

- Determine development rates and quantify yield of salad crops under BIO-Plex conditions. Planted areas for each species should be based on meeting typical dietary intake of the crew and determined through discussions between food processing and plant production groups. Additional planted areas should be considered to assess and improve horticultural and environmental capabilities for future BIO-Plex tests. For example, tests might compare different lighting technologies, growing media, etc.
- Quantify proximate and elemental composition of salad crop biomass produced in BIO-Plex.
- Identify protocols and crew interactions associated with planting, harvesting, processing, and maintenance of salad crop production systems.
- Compare crop performance in BIO-Plex with previous laboratory (growth chamber) tests to assess the effects of planting scale. Laboratory tests are typically conducted on small scale and BIO-Plex will provide a higher fidelity test of crop performance in a larger, mission-related setting.

- Compare effects of a multi-species, cropping approach using a common nutrient solution and common foliar environment in BIO-Plex with previous laboratory (growth chamber) tests where systems are typically optimized for a single species.
- Assess effects/interactions of salad crop production systems with physico-chemical (PC) systems used for atmospheric control and water processing in BIO-Plex. This could include assessing impacts of any trace contaminants from PC systems on the plants, as well as quantifying contributions of salad crop systems to O₂ production, CO₂ removal, and production of transpired (clean) water.
- Determine reliability / safety issues related to salad crop production systems for Advanced Life Support.
- Identify potential food safety issues associated with human / plant interactions, system closure, and hardware integration.
- Quantify the sensory acceptability of supplemental, plant-produced foods in the diet.
- Examine the psychological benefits associated with growing plants and eating fresh foods in a contained, life support system.
- Meet the Science, Technology, and Operations Support Accommodations (STOSA) objectives for BIO-Plex.

VALUE OF BIO-PLEX

With the exception of several studies with lettuce and tomato, closed system tests with crops have been limited to “staple” crops, such as wheat, soybean, and potato (e.g. Wheeler et al., 1996). With the recent elevated interest in “salad” crops for near-term transit and/or surface missions, there is a need to test these species in atmospherically closed systems with human crews. The initial phases of BIO-Plex will provide a valuable opportunity for assessing horticultural requirements of salad crops using a diverse crew (that might not include a horticulturist), as well as the impact of these crops on the food processing, air, water, and waste treatment subsystems. In addition, BIO-Plex tests including salad crops could provide valuable information regarding the effects of fresh foods, plant aromas, and bright light (from plant production systems) on the well-being of crews living in confined life support habitats for long durations.

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** Initial findings of the group were first released in a statement on May 5, 2000. This revision of that statement includes discussion comments raised at the Life Support and Biosphere Science meeting in Baltimore, MD (Aug. 6-9, 2000), inputs from the ALS Technology Selection Team (TST) document dated Aug. 28, 2000, and comments from an ALS Research and Technology telecon held on Nov. 2, 2000.*

**APPENDIX C. BIOMASS PRODUCTION SUMMARY, BIOASTRONAUTICS
WORKSHOP PROCEEDINGS**

Galveston, Texas, January 2001

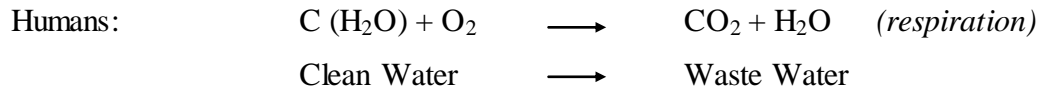
Raymond M. Wheeler, Kennedy Space Center, FL

Bruce Bugbee, Utah State University, Logan, UT

INTRODUCTION

The concept of using plants for life support systems has been discussed and studied for nearly 40 years. The underlying principle involves the process of photosynthesis, where carbon dioxide (CO₂) is removed from the air and fixed into organic compounds. Simultaneously, oxygen (O₂) is released as a byproduct, thus providing two fundamental life support needs, i.e., a supply of O₂ and CO₂ removal from the air. By selecting plant species that generate edible biomass (crops), a source of food is then added. On a stoichiometric basis, this process of “biomass production” is exactly the opposite of human respiration, where food and O₂ are consumed creating CO₂ as a waste product (Figure 1).

Plants can also be used to purify water, for example, where wastewater (gray water and urine) is added to the plant root-zone. Through the process of transpiration, plants take up and filter the water, which evaporates from their leaves creating humidity (water vapor), which can then be condensed and recycled to humans (Figure 1). The organic components in the wastewater are then degraded to CO₂ by microorganisms in the root-zone or by the plants themselves. The plants can also recycle valuable nutrients from the wastewater stream (e.g., nitrogen from the urine).



light

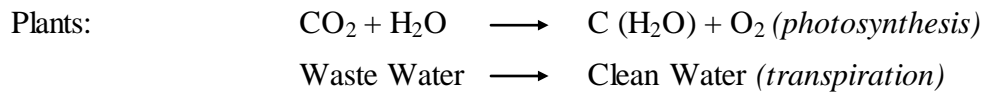


Figure 1. Simplified equations showing the opposite (balancing) effects of plant photosynthesis and human respiration. The key input to drive photosynthesis is light energy, while the evaporative potential (vapor pressure deficit) surrounding the plant leaves strongly controls transpiration rates.

Biomass production research sponsored by NASA in the 1980s and early 1990s focused largely on controlled environment production tests of several candidate crops, especially crops rich in carbohydrate and protein, e.g., “staple” crops. The studies typically involved the use of recirculating hydroponic culture systems, electric lighting systems, and careful management of the ambient environment to optimize growth and yields. Similar horticultural and physiological studies have continued through the 1990s under NASA’s Advanced Life Support (ALS) Program. Testing in recent years has also included integration studies, where plants were linked with waste treatment /resource recovery processes, studies of plant growth and management in atmospherically closed systems, and definition studies for growing plants in a spaceflight environment, such as development of gravity-independent watering systems.

SUMMARY OF PRESENTATIONS

Detailed overviews of biomass research from the past year can be found in abstracts in these proceedings. This research might be classified into five general categories:

1) Horticulture:

- a) Studies to refine cultural procedures for candidate staple crops (i.e., rice, sweetpotato, peanut, and bean).
- b) Studies to define growing procedures for candidate salad crops (i.e., tomato, radish, lettuce, spinach, chard, and carrot) for near-term missions, where fresh vegetables could provide dietary supplements for the crew. In particular, tests focused on germination and plant establishment procedures, plant spacing, and cropping duration.

2) Environmental physiology:

- a) Studies to determine sub-optimal, optimal, and super-optimal concentrations of CO₂, light intensity, photoperiod, and temperature for candidate crops.
- b) Studies of crop growth at the reduced atmospheric pressures that might be used for future missions.
- c) Comparisons of different electric light sources (e.g., high-pressure sodium, microwave sulfur lamps, and LEDs) to determine their effects on plant growth and the overall electrical efficiency of the lighting system.
- d) Measurements of production rates and effects of volatile organic compounds (e.g., ethylene) on plants.
- e) Studies of water and nutrient delivery concepts, including the effects of different ratios of NH₄: NO₃ in hydroponic systems, and the use of nutrient-loaded zeolite growing media that would only require addition of water to sustain crop growth.

3) Crop selection / genetic improvement:

- a) Continued studies with sweet potatoes that have been genetically altered for increased storage protein.
- b) Studies to introduce green fluorescent protein to indicate environmental stresses in canola and *Arabidopsis*.
- c) Studies of ADP glucosepyrophosphorylase, a key carbohydrate metabolism enzyme in tomato.
- d) Continued breeding and selection of short stature (dwarf) varieties of wheat, rice, and tomato for more efficient use of volume in plant growing systems.

4) Crop modeling and systems analysis:

- a) Studies on the effects of environmental perturbations and failures on crop growth.
- b) Use of neural net approaches to control and optimize growing environments.
- c) Software for simulating and compensating for the effects of environmental perturbations to crop production systems.
- d) Continued development of crop growth models for predicting yields under optimal and sub-optimal environments. For example, could plants tolerate a 14-d long “night” cycle in a lunar production system that used solar light.

5) Definition studies for spaceflight tests:

- a) Tests of rooting systems to optimize delivery of water and oxygen to root surfaces and comparisons of different watering techniques for microgravity. A current technique uses porous tubes to deliver water to plant roots, which is then taken up by the plants through capillary action.
- b) Extrapolation of the data from the physiological studies to determine the effects of reduced pressure, elevated CO₂ concentrations, and the build-up of ethylene in spaceflight for near-term space missions.

Participating universities and institutions in biomass research for the past year included:

Utah State University	Kennedy Space Center
Rutgers University	Johnson Space Center
Tuskegee University	Stevens Institute
University of Arizona	Dynamac Corp.
Texas A & M University	Jet Propulsion Lab
University of North Carolina, Greensboro	

IMPLICATIONS FOR FUTURE RESEARCH

1) Near-Term:

Develop crop handbook for BIO-Plex

Many handbooks are available to provide guidelines for growing crops in field settings. But plants in controlled environments (growth chambers) never see sunlight or touch the soil. Thus, unique guidelines are needed to grow crops under the controlled conditions of BIO-Plex (Bioregenerative Life Support Systems Complex) and related ALS systems. An ALS crop handbook should be developed to provide recommendations on horticultural approaches for crop establishment, planting densities, harvest procedures, and environmental set-points (i.e., photoperiod, temperature, CO₂, and light intensity) for each of the candidate crops. Specific chapters of this handbook could be written by investigators that have direct experience with individual crops and could include descriptions of the underlying physiology related to the different environmental recommendations. In many cases multiple authors will be needed to contribute to the recommendations for each crop.

Increased collaboration / interaction with food & waste processing groups

Plant biomass produced from controlled environments can have different biochemical characteristics than biomass from field settings. In some cases, the nutritional value and food processing characteristics can be better in controlled environment grown plants. On the other hand, anti-nutritional factors, such as nitrate, and oxalic and phytic acid, can be higher in controlled environment grown plants. Clearly more research and collaboration are needed, particularly for determining what changes in the environment are important for improving the quality of harvested food. Changes in the environment might also be used to make inedible biomass easier to degrade. For example, environments might be managed to reduce lignin content or the inorganic mineral content of inedible biomass. Reduced lignin could facilitate biological processing of inedible plant materials, while reduced mineral content could minimize slagging effects during combustion treatments. Combined approaches using biological pretreatment (stirred-tank bioreactors) to remove minerals prior to combustion need continued study, particularly with regard to their potential for recycling nutrients directly back to plant growing systems.

Cultivar selections for high yield, dwarf growth, and short life cycles

Smaller, quicker growing plants are needed for Advanced Life Support applications, where time, energy, and volume will be limiting factors. Dwarf cultivars exist for many crop plants, but they must be identified through careful comparison of multiple genetic lines in an optimal environment. Yields usually decrease with super dwarf plants, but increased planting density can often overcome any yield reduction. Selection and study of dwarf cultivars are especially important for spaceflight testing, where growing volumes are limited.

Salad crop testing and yield optimization

The first opportunities to grow plants for life support applications will likely involve small-scale systems to grow vegetables or salad crops as dietary supplements. Tomato, lettuce, spinach,

onion, carrot, radish, chard, and cabbage have been identified for initial testing, yet we know relatively little about controlled environment physiology and culture for some of these crops. For example, carrot production in hydroponics has not been rigorously tested, and carrot, onion, chard, and cabbage are not typically grown in controlled environments. Each crop will likely provide unique challenges, as will optimizing approaches for growing multiple species in common environments.

- *Refine capability to grow plants in microgravity and the spaceflight environment*
- Biologists have successfully grown some plants through entire life cycles in space (e.g., *Arabidopsis*, *Brassica*, and wheat). Thus microgravity does not appear to pose any fundamental impediments to plant growth. But many details must be refined before we can grow a wide range of plants reliably in space. In addition to microgravity, the effects of other factors typical of the spaceflight environment, such as super-elevated CO₂, elevated ethylene, low to moderate irradiance, and poor aeration of root zones, need continued study. In many cases, these ancillary factors may present bigger challenges than micro- or hypogravity.

Collect existing data on psychological value of plants

Evidence continues to mount for plants having positive psychological effects on humans living in closed environments (see Flagler and Poincelot, 1994). But much of this evidence is anecdotal, e.g., reports from cosmonauts on the MIR space station and the use of hydroponic systems for Antarctic habitats (see Sadler, 1995). Some additional evidence from closed life support experiments is available, for example from Russian studies and Biosphere II, and efforts are needed to assimilate and assess these observations in an unbiased, scientific manner.

2) Long-Term:

Improved efficiency of lighting systems

Significant improvements in electrical efficiency are needed in lighting systems. Possible improvements include changes in radiation quality (to maximize photosynthesis while satisfying photomorphological needs), development of efficient, low-mass light delivery systems, use of solid-state (electronic) ballasts, and improvements on reflector designs and efficiencies.

Genetic modification

Efficient food production systems on Earth were developed by manipulating both environmental and genetic factors to improve crop yields. We cannot be efficient in space without manipulating both genetics and the environment. Both classical plant breeding and molecular approaches will be important to matching genetic characteristics with environmental constraints. For example, it appears that we can select plants for tolerance to high ethylene levels that will probably occur in space. We should also be able to modify short-day crop plants (e.g. potatoes, soybeans, rice) so that they can be grown in continuous light and to develop plants that grow well under efficient, narrow-spectrum light sources.

Nonoptimal environmental responses – failure analysis

It probably will not be cost effective to provide the exact environmental conditions needed to maximize yields of each individual species. System efficiency will most likely be optimized by providing near optimal conditions for all the crops that share a common environment. The effects of nonoptimal conditions have not yet been fully characterized. Furthermore, failures of environmental control systems will occur and we need to understand the tolerance of plants to these failures. In some cases it will be more cost effective to replant rather than to keep growing a crop that has been stressed by failure of the environmental control systems.

Long-term reliability testing

Most crop life cycles are relatively short (2 to 3 months), but the hardware and control systems that support crop production can fail. Microbial growth can degrade solution flow rates and electronic components, and pathogen outbreaks can occur. Our best long-term reliability data come from the biomass production chamber at Kennedy Space Center where multiple crops were grown back to back in a large, atmospherically closed chamber for over 400 days. But more testing is needed to assess the long-term reliabilities of these systems and make informed decisions on their life support applications.

Study psychological value of plants

After the existing data have been collected and analyzed (see short term goals above), NASA should carefully consider controlled studies to assess the effects of plants and plant growing systems on humans living in confined habitats. This could include the effects of bright light and visual stimuli from plant systems, aromas associated with plants, as well as the contribution of fresh food to the human diet.

Quantify long-term water purification capability of plants

Crop plants have been successfully grown using wastewater from humans, but the long-term ability of plants to filter water without reducing the yield, quality, or reliability of the systems has not yet been established. Water is the largest mass consideration in any regenerative life support system and more thorough understanding of the capacity of plant systems to process and purify water is needed.

3) Mission Opportunities and Considerations for Plant Research

A primary objective for near-term research with plants for NASA will be the BIO-Plex project, which is a large-scale, integrated test-bed being developed at Johnson Space Center for the ALS Program. In addition, several spaceflight experiments with plant growing systems for Shuttle and the International Space Station (ISS) are in development (Figure 2). Although no official project has yet been initiated, development of a "Vegetable Production Unit" (VPU) should be considered for ISS to gather data and experience with operating plant production systems in space (Kliss and MacElroy, 1990). A possible timeline for developing and deploying a VPU is shown in Figure 2. In addition, suggested timelines for development of a VPU for Mars transit vehicles and an inflatable greenhouse for planetary surface missions are recommended (Figure 2). Research for meeting these objectives should begin soon to provide sufficient time to gather critical data and gain operational experience.

	2000	2005	2010	2015	2020	2025
BIO-Plex ¹ Research and Development	████████████████████					
BIO-Plex Integration Tests		X X X X				
Vegetable Production Unit (VPU) Research and Development	████████████████████					
Vegetable Production Unit Subsystem Flight Tests ²	WONDER	X (?) Root Zone O ₂				
Vegetable Production Unit Placement on ISS		X (?)				
Humans to Moon or Mars Transit Vehicle VPU R & D		 Surface Deployable Greenhouse R & D		
Related Plant Testing Fundamental Biology Program ²	X X X PESTO PASTA RASTA	Others?				

¹ BIO-Plex = Bioregenerative Life Support Systems Complex be developed for NASA’s Advanced Life Support Program

² WONDER, PESTO, PASTA, RASTA indicate existing plant research projects scheduled for spaceflight-testing.

³ Schedule suggestions and mission concepts also provided by Dr. Dan Barta of NASA JSC.

Figure 2. Mission considerations for implementing plant systems in space. Other than BIO-Plex¹ “Research and Development” and “Integration” tests and several named flight experiments, table timelines and missions represent unofficial goals that might be considered for biomass production research³.

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**APPENDIX D. FOOD AND CROP SYSTEMS WORKSHOP REPORT,
16 FEBRUARY 2005**

Attendees: D. Strayer, M. Roberts, M. Hummerick, V. Kern, S. Edney, J. Prenger, H. Kim, O. Monje, A. Mills, T. Murdoch, B. Wells, N. Yorio, L. Levine, J. Sager, J. Richards, R. Wheeler, G. Stutte, D. Gruendel, D. Cox, J. Garland

The Food and Crop Systems Workshop was held on 16 February 2005 in the Space Life Science Lab at Kennedy Space Center (KSC). The objectives of the workshop were to: (1) status ongoing Technology Development Project (TDP) tasks being performed through the Life Sciences Support Contract (LSSC), (2) review long-term objectives and milestones for Food and Crop Systems, (3) provide recommendations for near- to mid-term crop research priorities for Food and Crop Systems, and (4) identify fiscal year (FY) 2006 Food and Crop Systems research areas. This report summarizes the findings and discussion of that workshop.

1. Status of ongoing FY05 TDP activities

a. Environmental Baseline Studies

Baseline testing of the lettuce, radish, and onion are ongoing. The PPF (150, 300 and 150 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and CO_2 (400, 1200, and 4000 ppm) tests have been completed for 2 of the 3 candidate temperatures (25°C and 28°C). The 22°C treatments have been initiated. All testing should be completed by February 2006. These tests are approximately three months behind the original target date due to restarts required from CEC environmental failures and from the 2004 hurricane season. The delays have been minimized by reducing the time between harvest/planting of each series. Results were presented at ICES and ASHS meetings.

Baseline testing of tomato and pepper has been started. These tests are delayed by approximately 1 month due to nutrient issue in CEC1 that had to be restarted. The progress of the experiment was further delayed due to chamber failures during the hurricane season. It is anticipated that a single CO_2 /PPF series at 25°C will be completed by the end of FY05.

b. Mixed Cropping Studies

Mixed cropping studies with lettuce, radish, and onion have been completed for 25°C and 28°C at all CO_2 concentrations. Testing at 22°C will be completed by June 2006. No negative effects of intercropping have been identified. Results of these experiments the 2004 were presented at PGRSA meetings in Charleston, SC.

Mixed cropping studies with tomato and pepper have been started. Issues with nutrient competition between pepper and tomato during the transition to flowering have been identified. These issues required that replanting of the tests occur. The issue was identified at increased demand for Ca and Mg. Modifications to the NDS replenishment solutions were made and those tests are ongoing.

c. Strawberry Cultivar Evaluation

An evaluation of the strawberry production system was conducted between October and December 2004. This test was extended for 1 month longer than originally planned in order to support visits from HQ personnel and media events in the SLS.

Target strawberry cultivars were collected from Canada, United Kingdom, Maryland, and California and placed into tissue culture. A method for rooting and hardening the TC plantlets prior to transplanting to hydroponics was developed. A power outage during the 2004 Hurricane season resulted in the loss of several plantlets, which necessitated reestablishing the plant material prior to the start of the test. Once the plants were reestablished in tissue culture, the cultivar evaluation was initiated in January 2005. The cultivars being tested are Tristar, Tribute, Everest, Cavandish, Evie-3, and Whitney.

2. Status on FY 2005 Augmentation Studies

a. Food Quality Studies

A lack of rigorous evaluation of the food quality characteristics of candidate crops was identified as a missing component of food and crop system testing, and a request to augmenting the existing TDP with this task was approved. A food quality assessment plan was developed in conjunction with Michele Perchonok at JSC. Freshly harvested tomatoes and peppers are being shipped for sensory analysis and overall acceptability using standardized testing protocols. Dried tissue is being sent out for total proximate analysis. In-house and collaborative capabilities for determining antioxidant potential are being investigated. A job description for an MS level chemist to support this activity at 0.5 WYE was prepared and a chemist has been identified to support this activity. An external collaboration with Dr. Navindra P. Seeram (Asst. Director, UCLA Center for Human Nutrition) to conduct total anti-oxidant analysis on strawberry, tomato, and peppers has been established. Samples from ongoing experiments are being taken and preserved pending development and testing of final analytical protocols.

b. Low Pressure Testing

Determining the effects of low pressure testing on growth of salad crops was also identified as critical environmental parameter requiring additional resources. A visit to the University of Guelph was made in December to evaluate the feasibility of using the Low Pressure Chambers (LPC) in the Controlled Environment Systems Research Facilities (CESRF) for these evaluations. It was determined that these facilities were ideal for these types of tests and an agreement to rent those chambers for approximately 3 months was made and a test plan for performing the evaluations was also made. The test plan was approved and the experiments were initiated in March, 2005. A series of replicated experiments determining the effects of 1/3, 2/3 and 1 atm pressure should be completed by June 2005.

3. Long-Term Research Objectives and Milestones

Ray Wheeler (ALS Crop Element Lead) provided a short briefing of ongoing activities to define the role of biomass production within NASA's Exploration Vision. A significant ongoing effort

is development of capability roadmaps to meet the primary vision objectives for Spirals 1 through 5. The target capabilities being discussed for each spiral include the following.

- Spiral 1 (CEV mission to Moon): Capability to fly a Robotic Lunar Mission Payload for Crop Production System (CPS) component testing by 2012.
- Spiral 2 (Extended Duration Lunar Mission): Capability to fly a Robotic Mars Mission Payload for CPS component testing by 2016.
- Spiral 3 (Long Duration Lunar Surface): Capability to produce fresh food on the Lunar Surface with prototype CPS by 2020.
- Spiral 4 (Mars Vicinity): Capability to produce fresh food in transit on an operation transit CPS by 2025.
- Spiral 5 (Initial Mars Surface): Capability to produce fresh food on the surface in an operational surface CPS by 2030 and provide a bioregenerative Integrated Crop Production System (ICPS) on the surface by 2035.

These are target milestones that are currently under active discussion and review and will likely change as the scope and constraints of the Exploration mission become more defined.

4. Near- to Mid-Term Research Priorities

There was a broad- ranging discussion of the research priorities needed to meet the spiral objectives outlined above. The discussion identified three primary research areas: (1) Transit Crop Production (g-independent); (2) Planetary Surface Crop Production (g-dependent) and (3) Bioregenerative Life Support. The primary research areas in each are discussed below.

Transit Crop Production: Lighting system capabilities for electric light sources (KSC NRA & NRC support) and solar light capabilities (no activity at KSC), develop water/nutrient capabilities (NRA support at KSC), mission appropriate cultivar selections (ongoing at KSC), and GM crop development (no activity at KSC). Environment testing for light, temperature CO₂ (ongoing at KSC), low pressure testing (KSC at UG), VOCs (KCS with NRA), radiation (no activity at KSC), and microgravity effects (flight opportunity limited) needs to be continued. Food safety and microbial safety assessments are required. Sustained Production and operations capability is needed and long-term stability of mixed cropping systems is required. This will require component testing and ESM analysis.

Planetary Surface Crop Production: Lighting system capabilities for electric light sources (KSC NRA & NRC support) and solar light capabilities (no activity at KSC), develop water/nutrient capabilities (NRA support at KSC), mission appropriate cultivar selections (ongoing at KSC) and GM crop development (no activity at KSC). Environment testing for light, temperature CO₂ (ongoing at KSC), low pressure testing (KSC @ University of Guelph), VOCs (KCS with NRA), radiation (no activity at KSC), and partial-g effects (flight opportunity limited) needs to be continued. Food safety and microbial safety assessments are required. Sustained production and operations capability are needed and long-term stability of mixed cropping systems is required.

Identification of areas for greater automation and inclusion of robotics will be required. This will require long component testing and ESM analysis of total systems during each phase of design and testing.

Bioregenerative Life Support: Long-term integrated testing for sustained crop production, wastewater processing, air regeneration, food processing, and solid waste processing is required. A facility for performing this task is not currently available, and a strategy for implementing these integrated tests is required.

5. FY06 Candidate Crop Research Priorities

It was clear that the ongoing ground research needed to be continued and some research activities being supported by outside funds (e.g. NRC, NRA's) should become primary research areas with the Crop Task. The following areas are recommended as high priority areas for FY06.

Environmental Testing: Environmental testing to determine the baseline crop response surface of lettuce, onion, and radish to air temperature, light intensity, and CO₂ concentration should be completed. Environmental testing to determine the baseline crop response surface of tomato and pepper to air temperature, light intensity, and CO₂ concentration should be continued. Environmental testing of strawberry should be initiated.

Lighting systems. Ongoing research on lighting systems needs to be continued. The lighting system work being performed at KSC is funded outside the TDP process through the NRC and NRA. The existing funding for these projects expires at end of FY05. Lighting is a critical research need that should be continued within the crop element with a clear exploration objective. Areas of research include role of green light, light quality effects on stomatal conductance, and psychosocial effects of light quality.

Atmospheric contaminants: Ongoing research being supported through NRA's and CDDF to identify bioactivity of atmospheric contaminants on crop performance should be continued. The existing funding for these projects expires at the end of FY05. Closed systems are inherent to long duration space missions and the biological constraints need to be defined. Identification of the biological threshold of probable system contaminants on crop performance is required in order to establish system design standards.

Low pressure testing: Low pressure studies to determine effects on crop growth are being performed in chambers at the University of Guelph. Assuming that the initial low pressure testing is successful, additional testing to identify the critical components of reduced pressure (e.g., atmospheric composition, VPD, etc.) should be conducted. It is recommended that existing chamber rental arrangement be continued (assuming successful outcome of current FY05 tests).

Cultivar Evaluation: The strawberry cultivar testing should be completed and selected cultivar will be transitioned into the environmental testing.

A "Tiger team" workshop should be held to re-visit the existing candidate crop list and make recommendations for additions or deletions as appropriate. It is recommended that the workshop be relatively small yet have representations from both the NASA programmatic and PI

communities. Additional crops for cultivar testing will be made following the completion of this workshop.

Mixed Crop Testing. Multiple crops testing with a shared nutrient solution and atmosphere should be continued to identify nutrient management and/or biological incompatibility issues that would affect their use on a long-duration mission.

Food Quality: Food quality and crew acceptability are important elements for salad crops that will provide psychosocial and sensory roles for the crew. It is recommended that sensory analysis be performed in conjunction with JSC during cultivar evaluations and environmental testing. The capabilities for analyzing the antioxidant capabilities of the produce should be developed and analysis routinely incorporated into the test plan for crops.

Sustained Crop Production: Long-term component testing and sustained crop testing should be started. An assessment of the infrastructure needs (e.g., chamber size, laboratory space, personnel) to conduct sustained component testing for a transit production system and a planetary component system should be initiated, and appropriate testing started as soon as feasible.

Prepared 24 March 2005 by Gary Stutte, Dynamac Corp., Kennedy Space Center, FL.

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14. ABSTRACT This Technical Memorandum summarizes/reviews several NASA roadmaps and strategies on the use of plants and bioregenerative life support for space exploration. Bioregenerative life support with plants has been one the most enduring themes of research throughout NASA's existence but has recently been curtailed to direct funding toward more pressing needs in NASA's Constellation Program. But as mission distances and durations increase (e.g., lunar and Mars surface outposts), plants and bioregenerative technologies will likely play a key role in sustaining the human crews. Even prior to this, small plant production systems, often called a "salad machine" or "vegetable production unit," could provide a continuous supply of fresh foods to supplement the crew's diet and improve the quality of life in the confined environments of space, and some testing of this concept is already underway on the International Space Station (ISS).					
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