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Test Phases and Major Findings

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SUMMARY

NASA' s (National Aeronautics and Space Administration's) Advanced Life Support Project life support systems are an enabling technology and are integral to the success of human space exploration. As NASA embarks on the Human Exploration and Development of Space (HEDS) Mission it becomes imperative, for considerations of both safety and cost, to minimize consumables and increase the autonomy of the life support system. Utilizing advanced life support technologies provides this autonomy and increases productivity of the mission by reducing mass, power, and volume necessary for human support, thus permitting larger payloads for science and exploration. Two basic classes of life support systems must be developed, those directed toward applications on a transportation/habitation vehicle and those directed toward applications on the planetary surfaces. In general, it can be viewed as those systems compatible with microgravity and those compatible with hypogravity environments. The goal of the Advanced Life Support Project is to provide life support self-sufficiency for human beings to carry out research and exploration productively in space and for benefits on Earth. To accomplish this goal, five major technical objectives have been identfied as follows:

1. Provide Advanced Life Support technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for missions of long duration

Supporting Objectives

- Fully closed (i.e., no additions of water or air from outside the chamber) air and water loops in a manner that minimizes expendables
- Develop and integrate resource recycling/processing from solid wastes and contaminant control systems that increase the level of self-sufficiency
- Optimize food loop closure, with concomitant air and water regeneration, based on the growth of crop plants

- Provide efficient, reliable active thermal control (heat acquisition, transport, and rejection)
- Develop fully regenerative integrated systems technologies that provide air, water, food, and resource recovery from waste. Note: The term "regenerative" used here refers to technologies which can perform the desired function without significant replacement of any component of the technology – with minimum use of expendables. (This is usually accomplished at the expense of energy input but is a favorable trade for long-duration space missions where high resupply rates are prohibitive.)

2. Develop and apply methods of systems analysis and engineering to guide investments in technology, resolve and integrate competing needs, and guide evolution of technologies

Supporting Objectives:

- Refine existing procedures for systems assessment to allow consideration of the whole spacecraft or mission – including medical and scientific needs – to obtain synergism with life support systems, resolve incompatibilities, and evaluate options
- Conduct ongoing cost/benefit trades to guide technology investments
- Conduct advanced mission studies to guide definition of technology requirements, long-term investments, and evolution
- Develop methods for concurrent engineering of technologies through subsystems to integrated systems
- Develop system models and maintain an archival database of lessons learned, operational results, and key design information

3. Resolve issues of microgravity and hypogravity performance through space flight research and evaluation

Supporting Objectives:

- Develop predictive models of fluid and fluid/gas behavior and interactions in both microgravity and hypogravity that can be used as a basis for design of new life support hardware
- Achieve equivalent productivity, control, and predictability of bioregenerative life support components in microgravity as on Earth and characterize performance of bioregenerative systems at lunar and Martian gravities
- Demonstrate microgravity and hypogravity performance of gravity-sensitive life support hardware components and subsystems (e.g., membrane behavior)

4. Ensure timely transfer of new life support technologies to missions
Supporting Objectives:
- Develop and maintain effective relationships between technology developer and mission user to establish needs or requirements for mission technology
- Conduct definitive (ground and in-space) testing and verification
- Conduct regular discussions between mission users and technology providers on technology development status and transfer protocols
- Disseminate scientific and technological information through journals, the Internet, electronic and video media, workshops, and special programs
- Work in partnership with intermediaries such as the entertainment industry, media, museums, etc. to bring the space experience to our nation's citizens
- Participate in preparation of instructional materials reflecting the discoveries and adventure inherent in space exploration through partnerships with educators, providing access to facilities and supporting classroom instruction
- Cooperate with other nations to design an international strategy for exploring the Moon and Mars

5. Transfer technologies to industrial and residential sectors for national benefit
Supporting Objectives:
- Identify and initiate dual-use development early in the technology development cycle
- Establish rapid response solicitation and funding mechanisms to maintain the national "market edge"
- Identify and provide incentives to NASA personnel that promote technology

To accomplish these objectives, the Advanced Life Support Project is conducting focused research and development to advance technology readiness of regenerative life support and thermal control components, validate regenerative life support technologies integration through long-term testing with humans, and identify terrestrial applications for life support technologies.

Integrated testing of life support technologies with humans allows for evaluations of their efficacy to provide sustenance to humans. Such tests allow for demonstration of technology-to-technology interface compatibility and end-to-end functionality and operability of life support hardware and software. Conducting integrated testing and verification of technologies on the ground greatly increases our confidence in successful in-space operations and greatly reduces risk to human crews.

Finally, integrated testing is an extremely useful tool to identify weaknesses in technologies and in turn allows better focusing of future research and technology development resources.

The Lunar-Mars Life Support Test Project's four tests (Phases I, II, IIa, and III) conducted in 1995-1997 were the beginning of the long-term testing with humans. All tests were conducted at the National Aeronautics and Space Administration's (NASA) Johnson Space Center (JSC), in the Crew and Thermal Systems Division's Variable Pressure Growth Chamber (VPGC) and its attached airlock (Figure 2.1-1). Future testing will include integration of all functional elements of a space-based life support system and will entail progressively longer testing durations.

Phase I

The goal of the Phase I test was to demonstrate the use of higher plants to provide the air revitalization requirements of a single test subject for 15 days. The primary objectives of the Phase I test performed in July and August 1995 were to: 1) demonstrate the ability of a wheat crop to continuously provide the CO_2 removal and O_2 supply functions for the air revitalization needs of a single human test subject for 15 days, 2) demonstrate three different methods of control of the O_2 and CO_2 concentrations for the human/plant system, 3) monitor populations of microorganisms important to human and plant health, and 4) determine ethylene and other significant trace gas contaminants generated during the test.

Plants were grown in the plant growth chamber, and the airlock was outfitted for human habitation. Air was transferred between the airlock and plant growth chamber through an interchamber ventilation system so that CO_2 produced by the test subject could be removed by the plants and O_2 produced by the plants could be used by the test subject (Figure 2.1-2). Three different methods of control were demonstrated. The first method optimized conditions for the plants so that they provided maximum photosynthetic output. The use of integrated physicochemical systems to complement the biological air revitalization was demonstrated. The second method demonstrated actively controlling the level of biological air revitalization by modulating the photosynthetic photon flux to control the rate of photosynthesis. The third method demonstrated passively controlling the level of biological air revitalization by limiting the amount of available CO_2 to control the rate of photosynthesis.

Comparison of plant performance before and after the human entry showed there was no effect of the human on the plants' photosynthetic rate. All three control methods were successfully demonstrated in the test. Microorganism populations in the human habitat increased over the course of the test but did not reach steady state. No microorganisms were identified which would be of concern to either human or plant health at the levels measured. Trace gas contaminants observed were those expected based on past spacecraft measurements. The test successfully demonstrated the use of higher plants for air revitalization for humans and the robustness of the plant systems as part of a human life support system. Also, the test demonstrated that plants can be integrated into regenerative life support systems and can be controlled to provide a specific desired performance.

Figure 2.1-1 *The Variable Pressure Growth Chamber shown positioned behind the Phase I support crew*

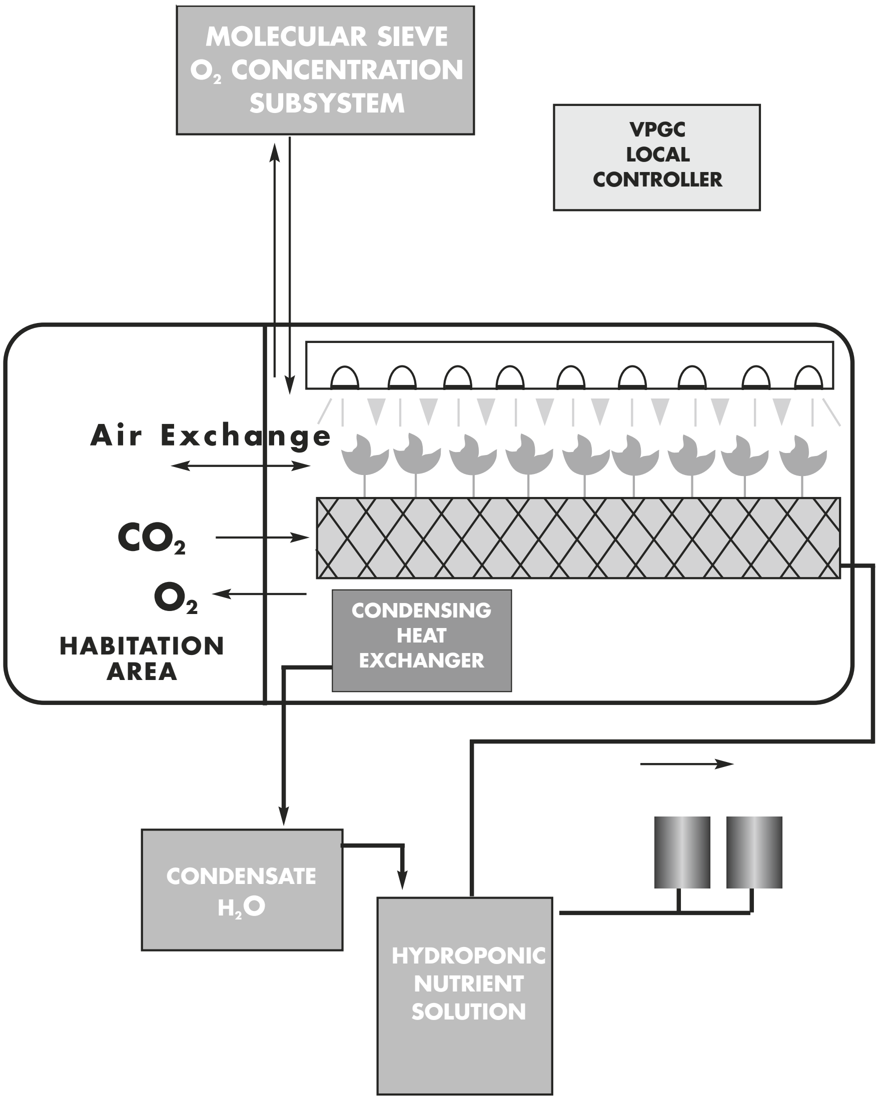


Figure 2.1-2 *The Phase I, 15-day test functional schematic*

Phase II

The Phase II test was a 30-day, 4-person test completed on July 12, 1996. The purpose of the test was to verify performance of integrated physicochemical life support system technologies for air revitalization, water recovery, and thermal control. Testing began with a human metabolic simulator and culminated in a continuous 30-day human test. The specific objectives were as follows:

Primary Objective:

- Develop and test an integrated human life support system capable of sustaining a crew of four for 30 days in a closed chamber

Secondary Objectives:

- Provide a regenerative air revitalization subsystem capable of removing carbon dioxide from the internal atmosphere of a sealed chamber, recovering oxygen from the carbon dioxide, and controlling trace gas contaminants for a crew of four for 30 days
- Provide a regenerative water recovery subsystem capable of recovering potable water from hygiene water (shower, hand wash, laundry), urine, and humidity condensate for a crew of four for 30 days
- Evaluate an active thermal control subsystem capable of acquiring heat from the chamber interior, transporting the heat to the exterior, and simulate the capability of rejecting the heat in a lunar day environment (107°C surface temperature)

Tertiary Objective:

- Evaluate a computer monitoring and control system for operation of the air, water, and thermal subsystems

Cooperative Research Objectives:

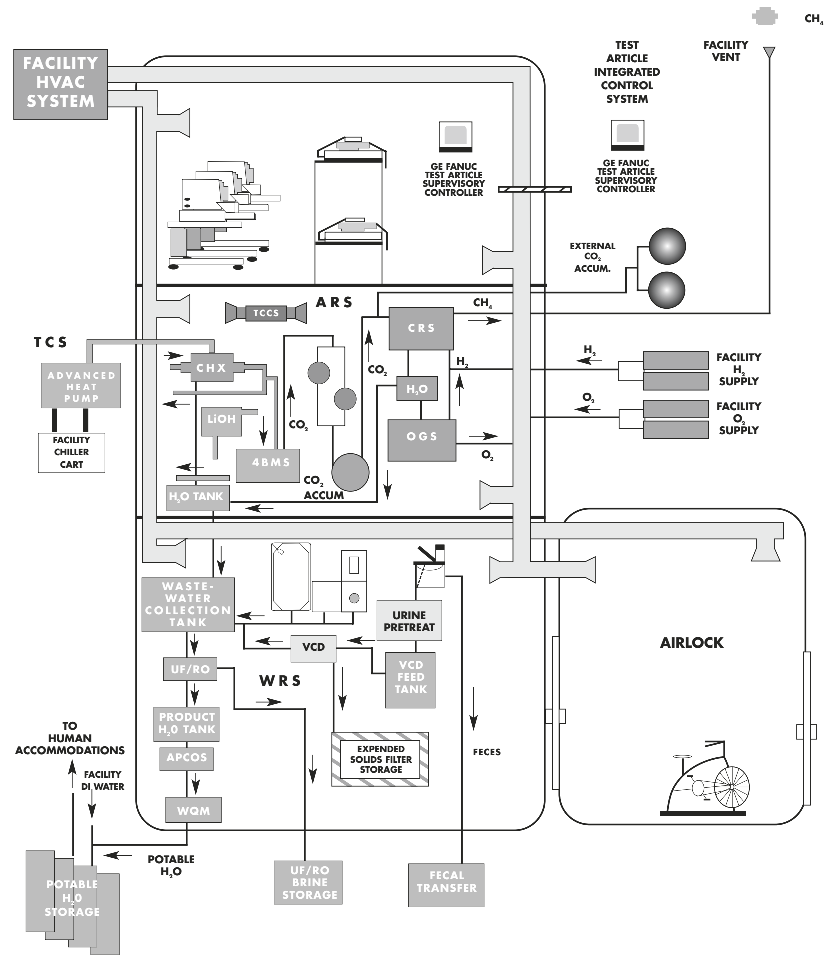
- Psychology: Evaluate test subject productivity as a function of time in the test chamber using a computer survey system
- Microbiology: Evaluate changes in the human microbiological population as a function of time in the test chamber
- Human Factors: Evaluate the perceived effects of sound on the human test subjects as a function of time and type of sound

The test was carried out in the Life Support System Integrated Test Facility (LSSIF) (Figure 2.1-3). The LSSIF is a modification of an existing vacuum chamber with a diameter of 6.1 meters and a height of 8.4 meters separated into three

Figure 2.1-3 *The LSSIF standing over the shoulders of the Phase III crew*

working levels. The LSSIF is outfitted with an emergency monitoring system (e.g., fire detection-suppression-warning, low oxygen monitoring-warning, etc.) and was outfitted with an air revitalization system, water recovery system, habitation areas, and all other associated hardware and subsystems (Figure 2.1-4).

The air revitalization system maintained an acceptable chamber atmosphere during the entire 30-day test with normal CO_2 levels between 0.30 and 0.55%. The CO_2 removal system (4-bed molecular sieve) was operated for 700 hours and removed 112 kg of CO_2. The Sabatier CO_2 reduction system performed satisfactorily, operating 600 hours reducing the CO_2 to water and methane. The O_2 generation system (electrolysis unit) operated for 700 hours and processed 100 kg of water (69% from the Sabatier unit and 31% from the water recovery system) to produce 86 kg of O_2. Oxygen levels were maintained between 20.3 and 21.4% during the 30-day test. Trace gas contaminants were controlled by passing air through an activated charcoal canister which maintained air quality within acceptable limits for U.S. space vehicles.



KEY

APCOS = aqueous phase catalytic oxidation subsystem
ARS = air revitalization subsystem
4BMS = four-bed molecular sieve
CHX = condensing heat exchanger
CRS = carbon dioxide reduction subsystem
DI = deionized
GE FANUC = programmable logic controller used for the LMLSTP
HVAC = heating ventilation, and air conditioning
OGS = oxygen generation subsystem
TCCS = trace contaminant control subsystem
TCS = thermal control subsystem
UF/RO = ultrafiltration/reverse osmosis
VCD = vapor compression distillation
WQM = water quality monitor
WRS = water recovery subsystem

__Figure 2.1-4__ The Phase II, 30-day test functional schematic

The water recovery system treated all wastewater originating from the shower, hand wash units, galley sink, laundry, and urinal as well as humidity condensate water. Pretest verifications of the water recovery system were carried out, including hardware functional tests, two donor-mode tests where volunteers provided the life support loads to the hardware but were not restricted to the chamber, and a viral challenge test of the water recovery system to ensure the proper functioning of the system prior to the 30-day test. The Vapor Compression Distillation (VCD) urine processor operated nominally for the first 27 days of the test when a motor controller failed. However, enough urine had been processed to complete the 30-day test. The VCD processed 182 kg of urine and flush water, recovering 179 kg of processed water (98% recovery rate). The Ultrafiltration/Reverse Osmosis (UF/RO) system operated nominally and processed 3089 kg of waste water, recovering 2957 kg of water (95% recovery rate). The postprocessing subsystem operated in the modified state as described in a later section and produced potable water for consumption by the crew during the 30-day test. (The tests described herein are the first times NASA has ever recycled water for potable use.)

The thermal control system included a high-temperature life heat pump which was to be evaluated as a technique for rejecting heat on the Earth's moon. This component of the thermal control system developed a leak just prior to the 30-day test and could not be repaired in time to start the test. Consequently, cooling was provided by a facility cooling cart and facility-chilled water during the 30-day test.

The controls system consisted of three main components: 1) the regenerative systems control and data acquisition component for controlling the air revitalization and water recovery system; 2) the facility emergency matrix component which managed all devices critical to ensuring human safety within the test facility such as fire detection and suppressions systems; and 3) the basic facility systems control and monitoring component which supervised the external test chamber equipment such as the chamber heating, ventilation, and air conditioning system. The controls system operated nominally during the test with relatively minor modifications during the test in terms of hardware replacement and software changes.

Phase IIa

The Phase IIa test was a 60-day, 4-person test completed on March 14, 1997, with life support subsystems functionally similar to those on the International Space Station (ISS). The purpose of the test was to verify integrated performance of baselined ISS life support technologies for air revitalization and water recovery and to provide additional integrated test data to the Advanced Life Support

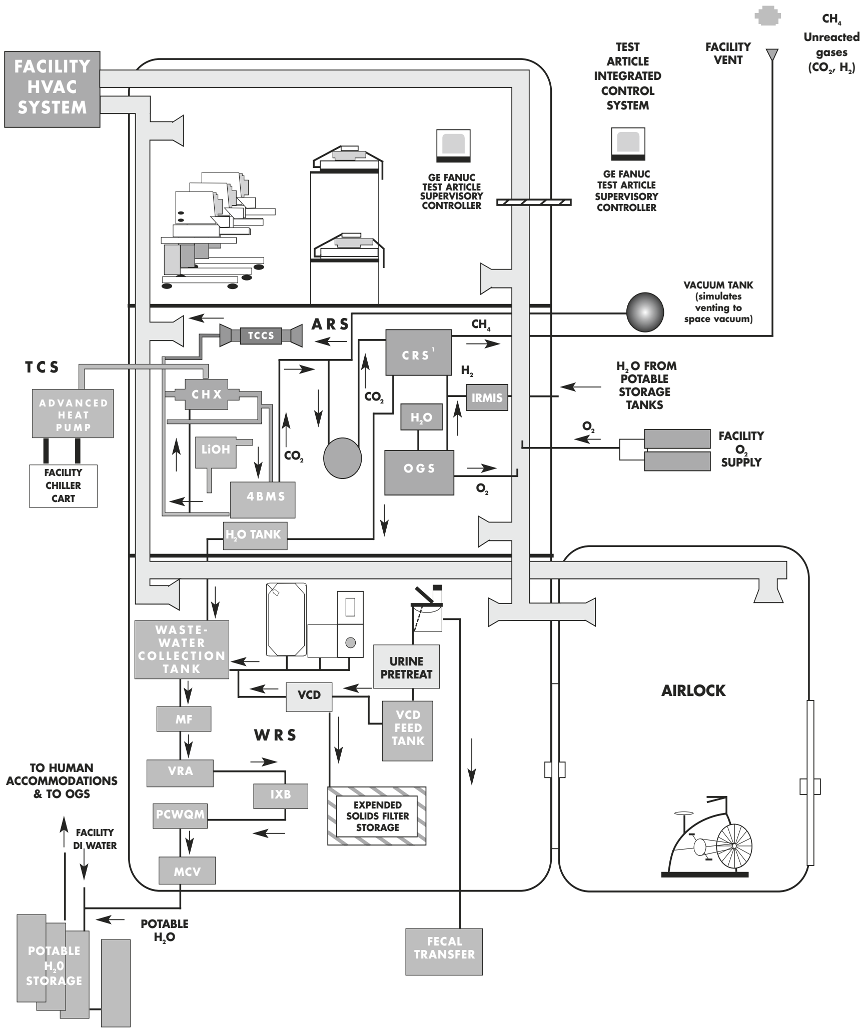
Project. ISS-like hardware representing significant advances in state-of-the-art life support capabilities emulated the flight hardware and provided integrated data to the ISS Program.

The test was carried out in the LSSIF (Figure 2.1-3). The Phase IIa LSSIF was outfitted with an emergency monitoring system, air revitalization system, water recovery system, habitation areas, and all other associated hardware and subsystems (Figure 2.1-5).

The air revitalization system maintained an acceptable chamber atmosphere during the entire 60-day test with normal CO_2 levels between 0.22 and 0.60%, while O_2 concentrations were maintained between 20.05 and 21.85%. Two air revitalization system configurations were evaluated during the test. The first 30 days of the test consisted of CO_2 removal as in Phase II with the CO_2 vented (to a vacuum tank simulating space vacuum), oxygen generation with an electrolysis unit, and operation of a catalytic oxidation trace gas contaminant control unit. The second 30 days of the test consisted of CO_2 removal as in Phase II with the CO_2 fed to a carbon dioxide reduction unit, oxygen generation with an electrolysis unit, and operation of a catalytic oxidation trace gas contaminant control unit. The first segment was representative of initial ISS operations, and the second segment was representative of enhanced ISS Earth orbital operations. Additionally, the air revitalization system was controlled in a cyclic manner simulating orbital day/night cycles of the 90-minute orbit of the ISS (53 minutes of day and 37 minutes of night).

With the exception of formaldehyde, all trace gas contaminants were kept within acceptable spacecraft maximum allowable concentrations (SMAC). The formaldehyde level was approximately 0.16 ppm throughout the test. The 7-day SMAC is 0.04 ppm, and the threshold limit value for industrial workers is 0.30 ppm. The sources of formaldehyde were later identified to be the acoustic tile used throughout the chamber walls and ceilings, while the carpeting was a secondary source.

The water recovery system treated all waste water originating from the shower, hand wash units, galley sink, and urinal as well as humidity condensate water. The VCD urine processor operated nominally but required servicing of both the vacuum pump and fluids pump. The Multifiltration (MF) unibed was changed on day 45 after processing 2858 L (755 gal) of waste water. The 0.5-micron filter was changed five times during the 60-day test. The ion exchange bed in the Volatile Removal Assembly (VRA) was changed on day 28. The two Microbial Check Valves (MCV) were changed on day 50 after iodine levels in the recovered water declined.



KEY

ARS = air revitalization subsystem
4BMS = four-bed molecular sieve
CHX = condensing heat exchanger
CRS = carbon dioxide reduction subsystem
DI = deionized
GE FANUC = programmable logic controller used for the LMLSTP
HVAC = heating ventilation, and air conditioning
IRMIS = iodine removal and mineral injection system
IXB = ion-exchange bed
MCV = microbial check valve
MF = multifiltration unit
OGS = oxygen generation subsystem
PCWQM = process control water quality monitor
TCCS = trace contaminant control subsystem
TCS = thermal control subsystem
VCD = vapor compression distillation
VRA = volatile removal assembly
WRS = water recovery subsystem
[1]Operated during second half of test

Figure 2.1-5 *The Phase IIa, 60-day test functional schematic*

Phase III

The final test was the Phase III test, which incorporated the use of biological systems in concert with physicochemical (P/C) life support system technologies to continuously recycle air, water, and part of the solid waste stream generated by a 4-person crew for 91 days.

The Phase III test was conducted using two environmental test chambers at JSC. The Life Support Systems Integrated Test Facility (LSSIF) (Figure 2.1-3) housed the crew as well as most of the life support systems. This chamber was integrated with the Variable Pressure Growth Chamber (VPGC) (Figure 2.1-1) in which wheat was grown to provide supplemental food and air revitalization for the crew during the test. The human portion of the test began on September 19, 1997, and ended on December 19, 1997, for a duration of 91 days. The wheat crop was initially planted on July 23, 1997, and the final harvest was on January 9, 1998.

The Phase III test was the first test conducted by NASA to integrate human test subjects with combined biological and P/C life support systems (Figure 2.1-6). This integration was accomplished in four distinct ways. First, the CO_2 generated by the crew in the LSSIF was separated from the atmosphere, concentrated, and used by wheat in the VPGC as the major source of CO_2 for photosynthesis. In tandem with this process, 95% of the O_2 produced by the wheat plants was separated, concentrated, and used by the crew for respiration. On average, the plants consumed CO_2 and generated O_2 equal to that required by one crew person over the course of the test. The remaining three person-equivalent's worth of CO_2 removal and reduction and O_2 production was accomplished with P/C systems.

The second biological and P/C integration involved the Water Recovery System (WRS). The WRS processed 110.6 L (29.2 gal) of wastewater each day, equivalent to the daily requirement for a crew of four. Bioreactors (aerobic digesters) were used as the primary treatment step for the combined wastewater stream generated by the crew's showering, hand washing, clothes washing, and urination as well as humidity condensate from the chamber. These bioreactors depended on microbial species to oxidize organic carbonaceous and nitrogenous materials in the wastewater. The bioreactors were integrated with P/C subsystems, which removed inorganic salts and performed final polishing of the water before being reused by the crew. The initial eight-day supply of water cycled though the chamber and the crew 10 times. No additional water was required during the test.

The third biological and P/C integration method pertained to the Solid Waste Incineration System (SWIS) and the wheat plants. The crew's fecal material was incinerated in a fluidized bed incinerator. Oxygen required for the combustion of the fecal material was provided from the O_2 produced by the wheat plants. The CO_2 produced as a result of the incineration reaction was used as a second source of CO_2 for wheat photosynthesis. The test utilized a hierarchical control system for handling the competition for resources. This competition is inevitable when biological systems, which operate continuously, are used to provide the life support function for a crew. Wheat was harvested periodically throughout the test and after drying, threshing, and milling, the wheat flour was provided to the crew to bake bread in the LSSIF. The wheat provided less than 5% of the crew's caloric intake during the course of the test.

The final biological and P/C integration method was the incorporation of a small chamber to grow lettuce within the LSSIF. This chamber was able to provide four heads of lettuce for the crew approximately every 11 days.

The Phase III test was very successful in integrating biological and P/C life support system technologies for long-duration life support. The use of a biologically-based WRS demonstrated the operation of a system that recovered essentially 100% of the influent wastewater for reuse. In addition, the first step in recovering useful materials from the crew's fecal material was demonstrated in an integrated system. These capabilities are critical for all of NASA's future, long-duration human exploration missions.

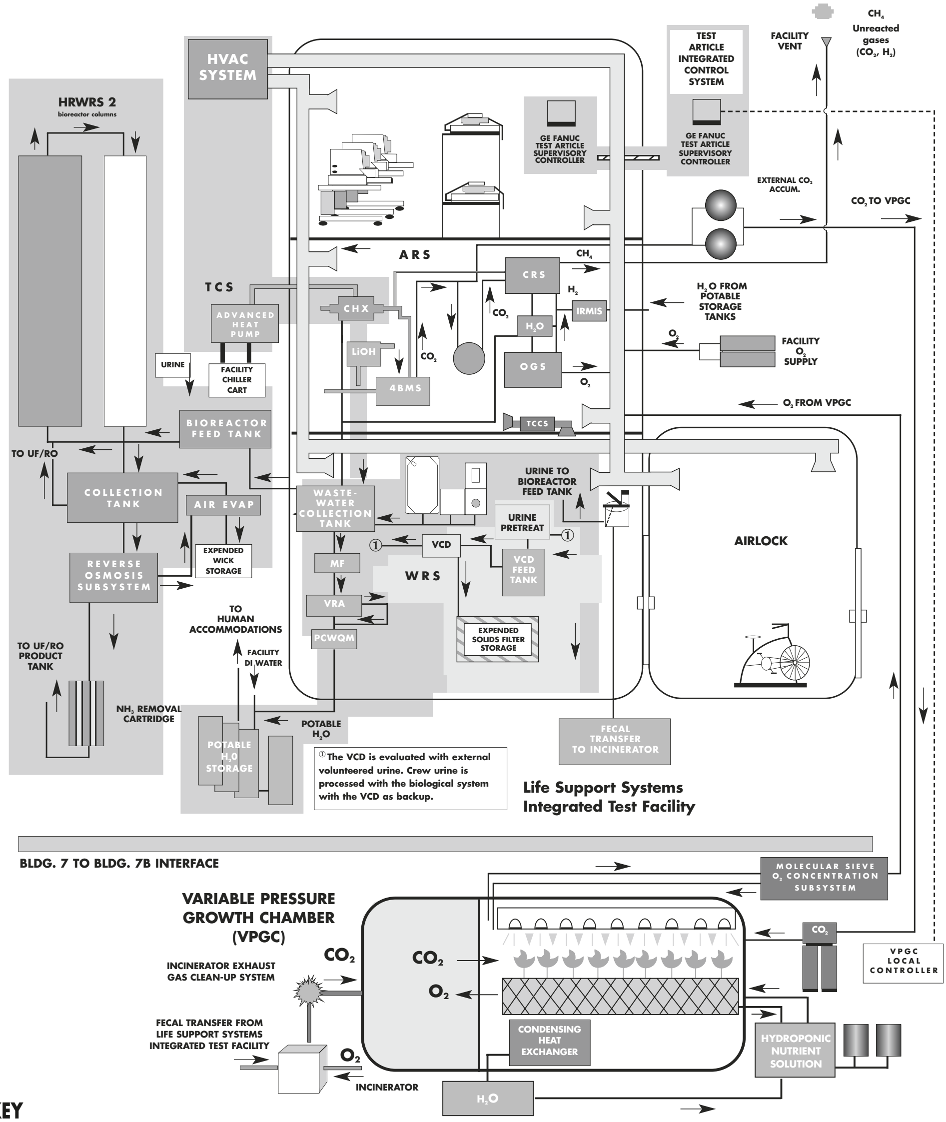


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Figure 2.1-6 *The Phase III, 91-day test functional schematic*