

Poly-Culture Food Production and Air Revitalization Mass and Energy Balances Measured in a Semi-Closed Lunar Greenhouse Prototype (LGH)

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Nomenclature

C	= temperature in degrees Celsius
cm	= centimeter
kcal	= kilocalorie
kg m^{-2} day^{-1}	= wet weight biomass production per area per unit time
kg day^{-1}	= kg per day
kg m^{-2}	= kilogram per square meter
kWh day^{-1}	= kilowatt hour per day
L day^{-1}	= liter per day
MJ day^{-1}	= megajoules per day
µMol m^{-2} s^{-1}	= micromole per square meter per second
mS cm^{-1}	= milliSiemens per cm
PPF	= photosynthetic photon flux
W	= Watt
ww	= wet weight

Abstract

Bioregenerative life-support (BLSS) studies were completed at the University of Arizona Controlled Environment Agriculture Center (UA-CEAC) with support by the Arizona NASA Ralph Steckler Phase II Space Grant. In cooperation with Sadler Machine Co. (USA) and international Italian collaborators, Thales Alenia Space Italia (TAS-I) and Aero-Sekur, SpA, and AGC Green-Tech Co. (Japan), a lightweight flexible cable culture hydroponic plant production system incorporated with an automated 23 m^3, sealed, collapsible plant growth chamber was used to demonstrate polyculture production of food crops and air revitalization in a semi-closed Lunar Greenhouse Prototype (LGH). Mass and energy balances were measured and the flows of input resources (i.e. water, carbon dioxide, dry fertilizer salts, labor, electricity and heat) and output production (i.e. food, water condensate, oxygen and heat) were quantified for the purpose of demonstrating life support capability utilizing biological processes under controlled environments for human space applications.

I. Introduction

To reduce consumables for future long term planetary exploratory missions, space research has considered bioregenerative life support systems (BLSS) capabilities. Higher plants used as a mean to recycle atmospheric carbon dioxide, and treat organic liquid wastes to provide oxygen, potable water and human nutrients in foods have been studied in integrated systems[6], with the goal to minimize Equivalent System Mass (ESM)[7], a measure of resources produced compared to system costs in terms of mass, volume, energy consumption and required crew time. Similar goals are in progress for the NASA Ralph Steckler Space Grant Lunar Greenhouse prototype (LGH) program at the University of Arizona Controlled Environment Agricultural Center (UA-CEAC)[8,9]. The LGH project consisted of the development and characterization of a multicrop, semi-closed planetary greenhouse prototype. The proposed system was composed of four cylindrical-shaped, independent plant production areas each with a volume of 22.9 m^3, and logistically linked by an interconnecting hallway. One module was equipped with a cable supported recirculating plant nutrient delivery system, six water-cooled high pressure sodium lamps for illumination[10], and a recirculating air handling and process control system (Figure 1). The atmosphere of the plant production environment was recycled as a semi-closed system (i.e. controlled and monitored leakage), processed to maintain atmospheric setpoint temperature and moisture content, and then returned by air distribution and diffusing plastic tubes located at the plant and cable culture system level. The capability of simultaneously growing various NASA targeted crops (i.e. lettuce, basil, sweet potatoes, strawberries) within a single, common environment (temperature, humidity, photoperiod, illumination intensity and carbon dioxide concentration) on both horizontal and vertical growing surface areas, allowed for exploiting the maximum available production volume during numerous tests of crop production during system test closures.

Understanding the dynamics and then providing semi-autonomous control strategies and systems will require models for accurately predicting mass and energy balances. In addition, determining the crew time needed to maintain such systems is important. The UA-CEAC has been collaborating with the Italian space company Thales Alenia Space Italia[11] and its Recyclab advanced life support research facility[12] to develop and validate a crop growth mass balance model for the LGH system.

An energy balance and mass balance analysis was performed for the purpose of quantifying the resource inputs (energy, mass, labor) and production outputs (food, water and oxygen) of the LGH for two carbon dioxide (CO_2) treatments. Multiple crops were grown simultaneously within the one LGH unit at consistently controlled environmental conditions. However, a series of plant growth experiments included two sequential and replicated treatments of atmosphere CO_2 concentrations of either 1000 or 2000 ppm. Additionally the Phase II LGH energy balance and mass balance results was compared to the Phase I results.

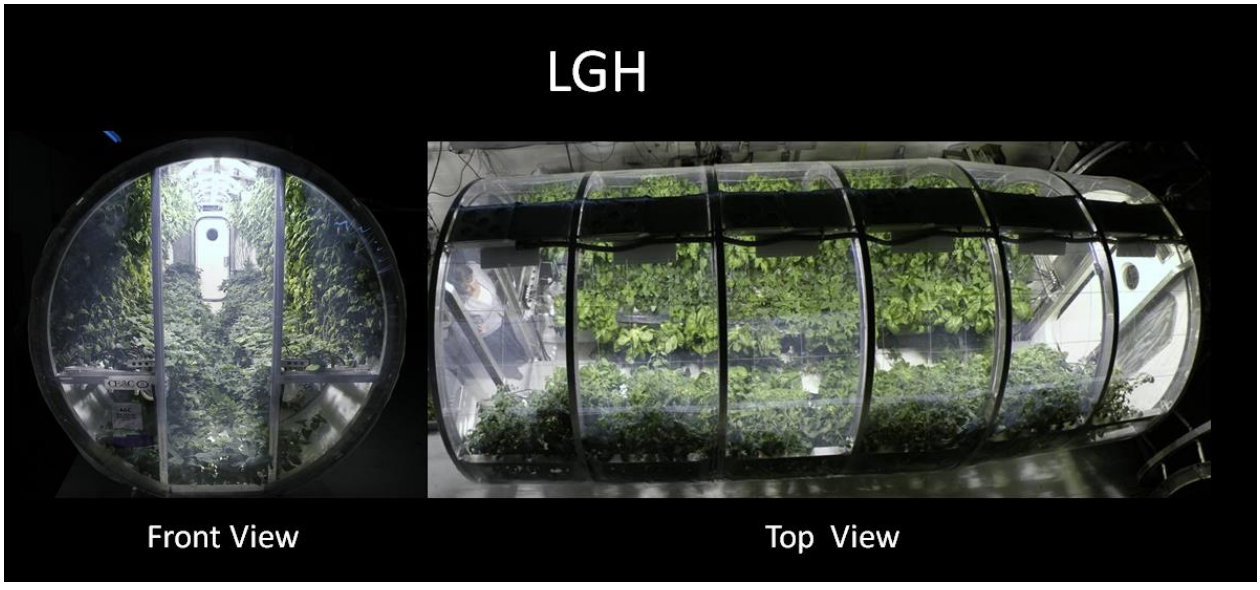

Figure 1. Front and top views of the Lunar Greenhouse Prototype (LGH).

II. Methods and Materials

A. LGH Environment Control Elements

The LGH (Figure 2) was comprised of an illuminated, inflated plastic bladder (A) that contained plants (B) suspended by a cable culture system[13] (C) that grow in envelopes containing hydroponic nutrient solution that was continuously cycled over their roots similar to the nutrient film technique (NFT). Moisture in the enclosed air (26.9 kg ~ total air mass) transpired from the plants was condensed by the two cooling heat exchangers (D) and collected for measurement within a graduated cylinder (E). The air blower (G) cycled the LGH atmosphere approximately once every 2.5 minutes while CO_2 (H) was provided to maintain set point of atmospheric carbon dioxide. Water removed from the hydroponic nutrient solution reservoir (K) by plant transpiration was replenished by a storage water tank (I) that was controlled by a float valve inside the hydroponic nutrient solution reservoir. The hydroponic nutrient solution was aerated by an air pump (J) such that air from the LGH was bubbled through the hydroponic nutrient solution reservoir and returned to the LGH in a closed, continuous cycle. Hydroponic nutrients consumed by the plants were replenished from concentrated hydroponic nutrient stock tanks (L) using peristaltic injection pumps. Nutrient concentration (EC) and acidity (pH) were measured at (M) by electrical conductivity and pH sensors, prior to returning to the nutrient solution reservoir. All data measured by the 13 sensors comprising the LGH sensor array and control system were connected to the Campbell Scientific Data Logger (F) for data monitoring, storage, and retrieval, and for automated environment control.

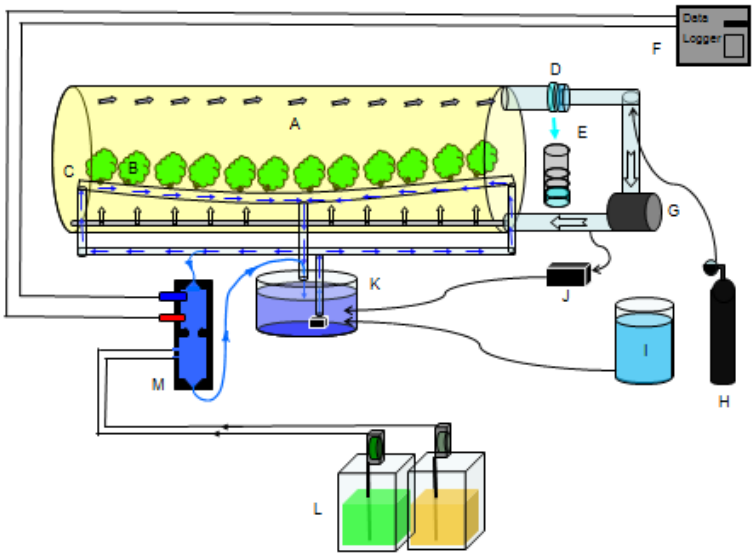

Figure 2. LGH environment control elements.

B. LGH Mass Balance

The LGH was instrumented with mass or volume transducers to determine the consumption (or production) of resources during the operation of the system. As the plants increased biomass, the load cell mass measurement system beneath the LGH structure provided real-time data mass increase. Simultaneously, the resources consumed were determined by their decreased mass (i.e. CO_2, fresh water, nutrient stock). This combination, of data, plus the leakage rate from the LGH allowed for continuous monitoring and calculation of mass balances.

1. Carbon balance

Automated control of the LGH atmospheric carbon dioxide concentration was maintained by injection of pure gas from pressurized CO_2 cylinder tanks. Carbon comprising the LGH system mass was calculated from measured LGH mass gained over a given closure time period, and the total dry mass of the coincident LGH plant harvests. The LGH carbon balance during the closure periods was characterized by the equation:

$$CO_{2\,Injection} = C_{Biomass} + "O_2" + CO_{2\,Leaks} \quad (1)$$

where,

$C_{Biomass}$ = dry mass of the LGH plant harvests during the LGH closure periods;
"O_2" = equivalent amount of carbon dioxide converted to oxygen (assume 1:1) in the photosynthetic equation;
$CO_{2\ Leaks}$ = CO_2 lost due to the infiltration-exfiltration, or the leakage of the LGH atmosphere; and,
$CO_{2\ Injection}$ = automated injection of CO_2 required to maintain set point concentration of the LGH atmosphere.

a. LGH nitrous oxide leak test

The carbon dioxide leakage rate was calculated by use of nitrous oxide (N_2O) leak rate testing procedure with measurements of the LGH atmosphere during the real-time operation and plant growth experiments. LGH air leak rates were calculated by measuring the decrease of atmospheric N_2O concentration as a tracer gas[14]. After injecting to achieve concentrations of 1500 ppm, N_2O concentrations were recorded (5 minute samples) until they reached 0 ppm. The two-point decay trace gas equation[15] was then used to calculate LGH air leak rates.

The LGH Nitrous oxide leak test equation was:

$$Q = \frac{V}{T}\ln\left(\frac{C_{initial}}{C_{final}}\right)$$

where,

Q = air leak rate of LGH;
V = volume of the LGH;
T = duration of the leak test;
C_{inital} = initial N_2O concentration; and,
C_{final} = final N_2O concentration.

2. Water balance

The LGH water balance during the closure periods was characterized by the equation:

$$W_{Replinishment} = W_{Biomass} + W_{Vapor\ Leak} + W_{Condensate} \quad (2)$$

where,

$W_{Biomass}$ = mass of the water comprising the plants in the LGH;
$W_{Vapor\ Leak}$ = net water loss due to water vapor leakage from the LGH atmosphere;
$W_{condensate}$ = water condensate from atmosphere of the LGH; and,
$W_{replenishment}$ = water added to the LGH hydroponic nutrient solution reservoir to replenish the water the LGH plants removed through transpiration.

3. Plant fertilizer salts consumption

Two concentrated stock solutions (i.e. using Peters 16-4-17, 40 g per liter, and potassium hydroxide (KOH), 12 g per liter) were automatically added to maintain the desired EC and pH, by replenishing the fertilizer formulation and the KOH within the LGH hydroponic nutrient solution reservoir. Fertilizer salts consumption was indirectly determined by measurement with load cells of the mass of the nutrient stock tanks, and then multiplied by their respective concentrations.

C. LGH Energy Balance

An analysis of the LGH energy inputs and outputs was conducted for a 30-day period. The electrical, thermal and radiation energy transfer flows were quantified over a representative plant growth period in the LGH control volume (CV). See (Figure 3) for the LGH energy transfer flows and hardware elements.

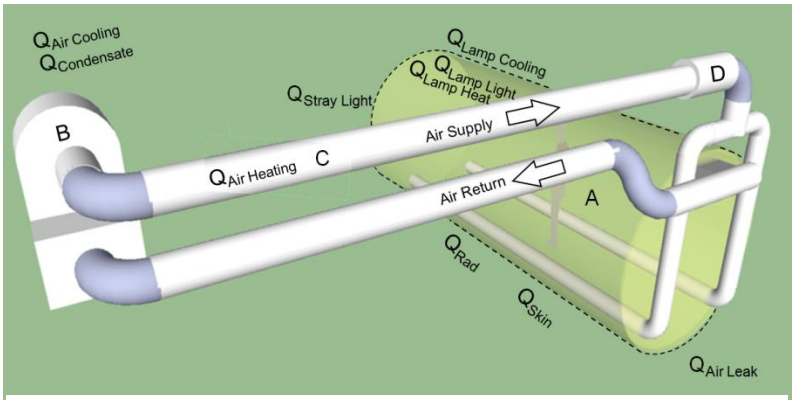

Figure 3. LGH energy transfer flows and hardware elements.

The LGH cylindrical control volume as indicated by the dotted line around (A) contained the atmosphere that was cycled through the supply and return to the cooling (B) and heating heat exchangers (C) by inline blower (D) at a rate of 0.38 $m^3\ s^{-1}$ (equivalent to one LGH volume (22.9 m^3) per minute). The LGH heat inputs and outputs were labeled relative to the location of their respective energy transfer approximately occurred, such that $Q_{Air\ Heating}$ was the heat imparted to the LGH atmosphere by the heating heat exchanger (C) located inside the

supply air duct, $Q_{Lamp\ Light}$ was radiant energy, from the six high pressure sodium (HPS) lamps, that converted to heat inside the LGH CV, $Q_{Lamp\ Heat}$ was heat transferred to the LGH due to the HPS lamps high operating temperature, and $Q_{Air\ Leak}$ was the net heat gained by the LGH due to air infiltration (~0.003 $m^3\ s^{-1}$) from its surroundings. $Q_{Air\ Cooling}$ was the heat transferred from the LGH to the cooling heat exchanger (B) for the purpose of cooling the LGH air and removing ($Q_{Condensate}$) plant transpired water vapor from the LGH atmosphere. $Q_{Lamp\ Cooling}$ was heat removed from the water-cooled HPS lamps by coolant water circulation through each of the six lamps. $Q_{Stray\ Light}$ was HPS light lost through the transparent end of the LGH CV (Figure 1). Q_{Skin} was the heat conducted through the 'F-Clean' ETFE plastic film skin (AGC Green-Tech Co., Japan) of the LGH inflated structure and Q_{Rad} was infra-red radiation lost as a function of the LGH CV surface temperature. The LGH energy transfer elements and energy balance was characterized by the equation:

$$Q_{Air\ Heating} + Q_{Lamp\ Light} + Q_{Lamp\ Heat} + Q_{Air\ Leak} = \\ = Q_{Air\ Cooling} + Q_{Condensate} + Q_{Lamp\ Cooling} + Q_{Stray\ Light} + Q_{Skin} + Q_{Rad} \quad (3)$$

D. Crop Schedule and Production

The LGH growing area (walls, cable-supported envelopes and floor) comprised the plant growing interior plant growing surfaces of the cylindrical structure. Positioned to capture all of the light energy from the electrical powered lamps, the horizontal envelopes, with the vine crop covering the floor, intercept all the downward light; while the vertically positioned vine crop is trellised along the sidewalls to intercept all the horizontally distributed light energy (Figure 4).

The LGH growing area was assumed to be comprised of more than simply the horizontal projected area. Although it does include the horizontal area of the cable-supported plant growing system at the 0.5 m height above the walkway floor of the LGH, it also includes the growing area described by the floor and wall areas beneath the cable-supported plant growing system, as well as, the distance of the vertical walls above the cable-supported growing system that extends to the peak of the LGH where the HPS lamps are mounted, directly above the walkway of the LGH. See Figure 4 and the locations indicated as wall, cables and floor.

Figure 4. LGH Crop Locations.

Green Oakleaf Lettuce and Red Oakleaf Lettuce (Lactuca sativa), Sweet Potato (Ipomoea batatas, cv. Louisiana Beauregard), Red Basil (Ocimum basilicum), and Strawberry (Fragaria spp. Sarian F1 day neutral variety) plants were grown simultaneously within the LGH. The lettuce, basil and strawberry crops were germinated in rockwool substrate (2 x 2 x15 cm, w x d x h) and transplanted (20 cm plant-to-plant spacing) into the cable-supported envelopes (15 cm depth, 5.5 m, row length) as seedlings. Row-to-row spacing was 30 cm for each of the 4 rows located on each side of the center walkway. Rooted cuttings of sweet potato grown in a sand bed (separate from the LGH) were transplanted into the envelopes at 20 cm plant-to-plant spacing.

All crops were grown in one or more of the eight hydroponic NFT envelopes suspended by cables[13] spanning the length of the LGH, with six, water-cooled HPS lamps providing PPF of 400 µMol $m^{-2}\ s^{-1}$ as measured at the elevation of the cables for 17 hour photoperiods. Harvested wet and dry weights of both edible and non-edible biomass were recorded. Dry biomass was obtained after 7 days in oven at 60 C.

The lettuces, basil and strawberry were grown within elevated horizontal location the LGH (i.e. cables, Figure 4). The sweet potato was grown both on the lower region beneath elevated horizontal location, and on the walls (i.e. floor and wall, Figure 4).

Seven LGH closure intervals were completed such that replicates of both 1000 and 2000 ppm carbon dioxide treatments of the LGH atmosphere were obtained. Closure interval dates, duration and carbon dioxide treatments were:

A: (12-Dec-12 to 21-Dec-12), 9 days, 1000 ppm;
B: (30-Dec-12 to 7-Jan-13), 8 days, 2500 ppm;
C: (1-Mar-13 to 29-Mar-13), 28 days, 1000 ppm;
D: (2-Apr-13 to 29-Apr-13), 27 days, 2000 ppm;
E: (30-Apr-13 to 27-May-13), 27 days, 1000 ppm;
F: (21-Jul-13 to 16-Aug-13), 26 days, 2000 ppm;
G: (21-Aug-13 to 31-Aug-13), 10 days, 2000 ppm.

All harvest, plant care and system maintenance were completed only once for each seven day period. No other entry into the LGH was completed unless for an emergency situation. This provided a continuous closed and securely sealed LGH system to minimize air exchange.

E. LGH Environmental Conditions

LGH closure interval C environment				
	Photoperiod	(+ -)	Darkperiod	(+ -)
CO_2 concentration (ppm)	900	89.2	1081	68.6
Max CO_2 concentration (ppm)	2171		2043	
Air temperature (C)	26.3	1.4	21.7	2.3
Max air temperature (C)	30.3		30.00	
EC (mS cm^{-1})	2.9	0.4	2.9	
Max EC (mS cm^{-1})	11.2		11.6	
pH	6.6	0.2	6.6	0.3
Max pH	7.5		10	
Dissolved O_2 (ppm)	6.9	1.3	6.9	1.4
Max dissolved O_2 (ppm)	13.5		10.8	
Nutrient temperature (C)	23.8	1.0	23.2	
Max nutrient temperature (C)	26.2		25.9	

Table 1. LGH Environmental Conditions for Test Interval 'C', March 3 - 31.

The fundamental environmental conditions were monitored and recorded (Table 1), where CO_2 concentration was the concentration of carbon dioxide in the LGH atmosphere, temperature was that of the air or nutrient solution in degrees Celsius, EC was the electrical conductivity of the nutrient solution in millisiemens per cm, and dissolved O2 was the dissolved oxygen in the nutrient solution. Carbon dioxide was supplied from 22.5 kg high-pressure cylinders of compressed pure CO_2 gas. Municipal tap water was used for the replenishment water. Two concentrated stock nutrient solutions (i.e. Peters 16-4-17 and potassium hydroxide) were injected automatically to replenish fertilizer and maintain EC and pH of the recirculating nutrient solution. Photoperiod was 17 hours per day.

III. Results and Discussion

A. LGH Plant Production

The LGH was filled with a similar (but varying) number of test plants with varying physiological maturity of lettuce, sweet potato, basil and strawberry during the test intervals because of the different growth rates and time to harvest of each crop. Thus, comparison of results among the tests was completed by normalizing the results using the total biomass within the LGH for each time period. Continuous, real-time monitoring of the total mass of the plants within the LGH was completed by electronic load cells located beneath the LGH structure. See Tables 2 and 3, noting varying data responses, but also the relatively consistent results when normalized by the total mass within the LGH.

B. LGH Carbon Balance and Biomass Production Rate

Table 2 includes the biomass production rate (ww), CO_2 consumption, carbon balance and normalized biomass production rate (ww) for seven separate test Intervals (ranging from 8 to 30 days) with either 1000, 2000, or 2500

ppm of constant atmospheric CO_2 Treatment for the combination of crops listed above. Short term production varied from 9.3 to 34.5 kg for 10 and 8 days of growth, respectively. Long term production varied from 19.7 to 81.7 kg for 26 and 27 days of growth, respectively. For each biomass production time period, the estimated dry matter (C_{bio}) was assumed to be 5% of the wet weight (ww), and ranged from 0.5 to 4.1 kg (DW). The determination of the carbon balance (Eq. 1) comparison of output resources from the LGH determined from the sum of the values for

Interval	CO_2 Treatment		Biomass Production	C_{Bio}	CO_2 Leakage	$C_{Bio} + O_2$	CO_2 Inject	Carbon Balance	Daily $CO_{2\,Bio}$ per Biomass Gain	Biomass Production	
	ppm	d	kg	kg	kg	kg	kg	% Difference	kg kg^{-1} d^{-1}	kg d^{-1}	kg d^{-1} m^{-2}
A	1000	9	9.3	0.5	1.9	1.1	4.5	33	0.013	1.0	0.03
B	2500	8	34.5	1.7	3.9	4.0	7.0	-14	0.015	4.3	0.12
C	1000	28	29.9	1.5	5.3	3.5	6.0	-47	0.004	1.1	0.03
D	2000	30	54.2	2.7	14.7	6.3	33.6	37	0.004	1.8	0.05
E	1000	27	81.7	4.1	4.2	9.5	11.2	-22	0.004	3.0	0.09
F	1000	26	19.7	1.0	2.8	2.3	9.0	43	0.004	0.8	0.02
G	2000	10	23.1	1.2	2.5	2.9	5.5	0.2	0.012	2.3	0.07

Table 2. LGH seven tests of short or long duration with either 1000, 2000 (or 2500) ppm of atmospheric CO_2 for the combination of crops including sweet potato, lettuce, basil and strawberry. Where Biomass production (ww) was the mass of the biomass produced by the LGH over the given closure intervals, C_{Bio} was the carbon comprising the plants of the LGH, CO_2 Leakage was the CO_2 lost through gas leaks in the LGH, O_2 was the equivalent mass of carbon dioxide required for oxygen produced, CO_2 Inject was the carbon dioxide consumed by the LGH over the closure intervals, Carbon Balance % Difference was the percent difference between the measured input and output of carbon, Daily CO_{2Bio} / Biomass Gain was the daily carbon dioxide (kg) consumed per kg of biomass produced in the LGH, over the given closure interval, and Wet Weight Biomass production rate per unit area.

$C_{Biomass}$, "O_2" and $CO_{2\ Leaks}$, or, as the direct input measurement of resource, $CO_{2\ Injection}$, indicated relatively large percent differences that ranged from 0.2 to 47%. The normalized biomass production rate (based on maturity of crops within the LGH) allowed comparison among all tests and determined a range from 0.004 – 0.015 kg_{DW} per day per total kg production, and that 0.004 kg_{DW} per day per total kg production was a typical value. This parameter indicated that dry matter production rate was about the same for either 1000 or 2000 ppm CO_2. However, total wet weight biomass production ranged from 0.8 – 3.0 kg d^{-1} for 1000 ppm and 1.8 – 4.3 kg d^{-1} for 2000+ ppm.

C. LGH Water Balance

Table 3 includes the average daily water consumption (as replenishment) and production (as condensate), water

Interval	CO_2 Treatment		Average Daily LGH Water Consumption and Production (kg d^{-1})								Balance	Daily Condensate per Biomass Gain
	ppm	d	Replenishment	(+-)	Condensate	(+-)	Biomass	(+-)	Vapor Leak	(+-)	% Difference	kg kg^{-1} d^{-1}
A	1000	9	38.6	15.4	30.6	3.1	2.6	2.1	0.6	0.2	12.2	1.3
B	2500	8	15.6	6.3	11.6	5.6	1.5	1.0	0.4	0.2	13.9	1.0
C	1000	28	21.6	4.7	19.2	4.2	2.5	0.9	0.6	0.1	3.0	0.3
D	2000	27	28.8	6.8	26.3	4.2	3.3	0.6	0.4	0.1	4.4	0.3
E	1000	27	19.6	2.8	17.0	2.1	2.5	0.7	0.7	0.1	3.0	0.3
F	1000	26	31.8	5.8	30.0	2.2	1.9	1.2	0.7	0.1	2.2	0.6

Table 3. LGH seven tests of short or long duration with either 1000, 2000 (or 2500) ppm of atmospheric CO_2 for the combination of crops including sweet potato, lettuce, basil and strawberry. Where Replenishment was the total amount of tap water added, Condensate was the total amount of water condensed by the cooling system, Biomass was the water measured within the harvested plants, Vapor Leak was the total amount of water vapor lost from the LGH, Balance % Difference was the percent difference between the measured input (Replenishment) and output (sum of Condensate, Biomass and Vapor Leak) of water, and Daily Condensate / Biomass Gain was the daily water condensate (kg) consumed per kg of biomass produced in the LGH, over the given closure interval.

balance, and normalized daily condensate rate for seven separate test Intervals (ranging from 8 to 28 days) with

either 1000, 2000, or 2500 ppm of constant atmospheric CO_2 Treatment for the combination of crops listed above. Short term water consumption varied from 15.6 to 38.6 kg for 8 and 9 days of growth, respectively. Long term consumption varied from 19.6 to 31.8 kg for 27 and 26 days of growth, respectively. Short term production varied from 11.6 to 30.6 kg for 8 and 9 days of growth, respectively. Long term production varied from 17.0 to 30.0 kg for 27 and 26 days of growth, respectively. The determination of the water balance Eq. (2) comparison of output resources from the LGH determined from the sum of the values for Condensate, Biomass and Vapor Leak, or, as the direct input measurement of resource, Replenishment, indicated relatively small percent differences that ranged from 2.2 to 13.9%. The normalized biomass production rate (based on maturity of crops within the LGH) allowed comparison among all tests and determined a range from 0.3 – 1.3 kg per day per total kg production.

The difference between the measured LGH water consumption and water production ranged from 2.2 – 13.9%, with an overall average of 6.5 %.

D. LGH Energy Balance

The distribution of the significant thermal, electrical, and latent heat loads were measured and provided in Table 4. Only the distribution of the thermal and irradiance output for the HPS lamps were not measured, but were found in the literature[10]. The energy balance of the LGH CV measurements of inputs and outputs differed by 10.9 %, indicating that more energy was measured entering than exiting. This could be partly due to the pyranometer measurements being limited to 400 - 1100 nm wavelengths thus not measuring energy outside this waveband. The heating and thus cooling load was most significant from the HPS Lamps, accounting for 52% of the input heat (37.7 + 49.0 kWh), while re-heating of the conditioned air after dehumidification was 66.0 kWh, or 40% of the total. The water cooled lamp was able to remove 30% (42.8 kWh) of the total heat load. Sensible cooling (67.9 kWh) and latent energy removal (34.3) from the conditioned air accounted for 46% and 23% of the total energy load, respectively.

Inputs	kWh
$Q_{Air\ Heating}$	66.0 ± 2.1
[1] $Q_{Lamp\ Light}$	37.7
[1] $Q_{Lamp\ Heat}$	49.0
$Q_{Air\ Leak}$	13.6 ± 2.7
Total	166.3 ± 4.8

Outputs	kWh
[1] $Q_{Lamp\ Cooling}$	42.8
$Q_{Stay\ Light}$	2.5 ± NA
$Q_{Air\ Cooling}$	67.9 ± 1.3
$Q_{Condensate}$	34.3 ± 17.3
Q_{Skin}	0.6 ± 0.1
Q_{rad}	0.003 ± 0.001
	148.1 ± 18.6

Table 4. LGH Average Daily Energy Inputs and Outputs.

Finally note that the standard deviation of $Q_{Stray\ Light}$ was reported as not available in Table 4. This measurement was only completed once, as it required large numbers of measurements of the 3.9 m^2 transparent end of the LGH to be summed to attain an estimate of energy loss.

E. LGH Labor

Many of the operations required for the continuous production of multiple types of crops will be automated. These already include control of environment, irrigation, fertilization, and others, which should only require regular inspection for repairs and maintenance. However, the manual labor required for direct care of the crop would require extensive robotization, and without a final design and subsequent procedures of operations a true understanding of labor demands cannot be known. Thus some of the typical manual tasks for production of plants within the LGH design have been monitored, and range from seeding through final harvest and removal from the LGH. These include (1) daily inspections of systems, and (2) weekly: (a) seeding, to establish new transplants, and

Labor tasks for crop production in LGH (one person)		h d^{-1}	h wk^{-1}
Daily	Inspect systems	0.17	1.2
Weekly	Seed and transplant		1.2
	Harvest		2.3
	Prune		0.3
Total			5.0

Table 5. Labor tasks for production of LGH crops.

transplant, adding new seedlings to replace those harvested, (b) pruning, to remove unwanted leaves and other growths, and (c) harvest, to remove selected plants providing space for new seedlings to be transplanted.

The values in Table 5 were specifically for the combination of types and quantity of crops as described for the LGH. From the numerous tasks required to maintain and operate the LGH this subset was created and categorized into the general topics. These topics were assumed to require manual crew time as automation of the task, or remote support accomplishing the task, was impractical.

Seeding, transplanting, harvesting and pruning occurred once a week. Inspection of systems occurred daily, and included a check list of critical elements to life support system such as food production, fertilizer stocks, water leakage on the floor, and plant status in contrast to recent environment conditions (i.e. air temperature, humidity, plant nutrients). Total labor required was 5 hours per week for one person.

F. LGH Fertilizer Salts

Table 6 includes the total mass of dry fertilizer, and total mass of dry fertilizer per kilogram of biomass produced per day, for the test intervals. The overall average was 36 g kg^{-1} d^{-1} of dry fertilizer per kilogram of biomass produced per day. This included salts for both nutrient and pH control of the hydroponic solutions.

Interval	LGH dry fertilizer salts CO_2 Treatment ppm	g d^{-1}	g kg^{-1} d^{-1}
A	1000	57	55
B	2500	116	27
C	1000	45	42
D	2000	67	37
E	1000	45	15
F	1000	32	42
G	2000	36	34
Average			36
Standard Deviation			13

Table 6. Total mass of dry fertilizer per day, and total mass of dry fertilizer per kilogram of biomass produced per day, for the test intervals.

G. LGH Phase II vs. Phase I Results

Table 7 provides for comparison of the general system results from Phase I and Phase II. Despite our improvements in the environmental control and monitoring of the LGH, the system responses were similar in Phase II (2012-13) to that of Phase I (2010-11). There were little changes in the plant responses which create the system responses, even with the inclusion of a new crop, sweet potato as an attempt to more efficiently fill the complete volume of the LGH with biomass. The average daily biomass production was 60 g m^{-2} which was 21.9 kg $m^{-2}yr^{-1}$. The average daily water produced from condensation was 22 kg d^{-1} (22 liters per day). CO2 enrichment required 220 g d^{-1} to maintain a minimum of 1000 ppm atmosphere. Using the daily energy measurement of 166 kWh from Table 4, then the amount of energy required to produce biomass (includes both edible and non-edible) within the LGH system was 8.4 g kWh^{-1}. This includes both electrical and thermal energy.

Daily Average	Phase II	Phase I	
Biomass increase	0.06 ± 0.04	0.06 ± 0.01	kg m^{-2} d^{-1}
Water production	22.4 ± 7.7	21.4 ± 1.9	kg d^{-1}
Water consumption	26.4 ± 8.6	25.7 ± 1.10	kg d^{-1}
CO_2 consumption	0.23 ± 0.16	0.22	kg d^{-1}

Table 7. Comparison of LGH system from Phase I and Phase II for biomass production, water production and CO_2 consumption.

H. LGH Resource Production and Consumption

Table 8 includes the resource production (condensate water, biomass and oxygen) and resource consumption (replenishment water, CO_2 and fertilizer) contrasted on the production surface area and volume bases of the LGH system. The data is from LGH closure interval 'A' (9 days, 1000 ppm) and includes, condensate which was the daily condensate water produced by dehumidification, biomass which was the wet weight biomass produced, Oxygen which was the oxygen produce by photosynthesis, replenishment water which was the tap water added into

hydroponic nutrient solution, CO_2 which was the carbon dioxide consumed by photosynthesis, and fertilizer salts which were the dry hydroponic nutrients consumed.

Surface area for production was defined as either the horizontal cross-sectional plane (2.1 m x 5.5 m) located at the cables position at the center of the cylindrical LGH, or as the sum of interior walls, cables and floor of the LGH (Figure 4; Table 8, column1). The latter was approximately 10 times the size as the former.

	[1.] Growing Area kg m^{-2}	[2.] Growing Area kg m^{-2}	Growing Volume kg m^{-3}
Condensate	0.63	6.18	1.39
Biomass (wet)	0.05	0.53	0.12
O_2	0.001	0.01	0.003
Replenishment water	0.79	7.79	1.75
CO_2	0.003	0.03	0.01
Fertilizer salts	0.001	0.01	0.003

Table 8. Production and consumption of resources per unit growing area(s) and per unit volume. [1.]Defined growing area as the sum of interior walls, cable and floor areas. [2.]Defined growing area as a horizontal cross-sectional plane through the middle of the LGH.

IV. Conclusion

The UA-CEAC-SMC Lunar Greenhouse prototype (LGH) supported by NASA Ralph Steckler Phase II Space Grant successfully provided operational data for the demonstration of the resource production and resource consumption during the operation of its BLSS-type, semi-closed, polyculture system. The relative proportion of outputs (water, oxygen, and biomass) to inputs (water, plant nutrients, CO_2, electrical power, and labor) were documented for the production system.

Appendix – Acronyms Used

AGC = Asahi Glass Co., Ltd.
A-S = Aero-Sekur, SpA
ASI = Agenzia Spaziale Italiana (Italian Space Agency)
ASABE = American Society of Agricultural and Biological Engineers
BLSS = Bioregenerative Life Support System
CAB = Controllo Ambientale Biorigenerativo (Bioregenerative Environmental Control)
CEA = Controlled Environment Agriculture
CELSS = Controlled Ecological Life Support System
CO_2 = Carbon Dioxide
CV = Control Volume
EC = Electrical Conductivity
ESA = European Space Agency
ESM = Equivalent System Mass
HPS = High Pressure Sodium
ICES = International Controlled Environment Systems
ISS = International Space Station
LGH = Lunar Greenhouse
LSS = Life Support System
MEC = Modified Energy Cascade computer model
NASA = National Aeronautics and Space Administration
NDS = Nutrient Delivery System
NFT = Nutrient Film Technique
NSF = National Science Foundation
PAR = Photosynthetically Active Radiation
PPF = Photosynthetic Photon Flux
RENDSys = Remote Expert horticultural Decision-Support System network
RH = Relative Humidity
SMC = Sadler Machine Company
SPFGC = South Pole Food Growth Chamber

TAS-I = Thales Alenia Space – Italy
UA-CEAC = University of Arizona-Controlled Environment Agriculture Center
USA = United States of America

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