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MELiSSA

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TECHNICAL NOTE 32.3

Including of a Higher Plants Chamber in the MELiSSA loop
Description of a HPC for MELiSSA loop steady state simulations

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CONTENT

Appendix 1: Requirements for plant growth (Eckart, 1994)

	Vegetative (Lettuce, Spinach)	Root (Onion, Radish, Carrot)	Fruit (Tomato, Pepper, Cucumber)	Sprout (Alfalfa, Bean, Radish)
Light (µmol m^2g^1) Photoperiod (hrs)	250 - 275 18 - 24	275 - 400 18	300 - 400 18	0 - Ambient Ambient
Temperature (°C)	22 - 28	15 - 25	20 - 28	20 - 28
Humidity (% Rh)	50 - 85	50 - 70	50 - 75	High - 90
Gas Composition (ppm)	CO_2 = 300-1500	TBD	CO_2 = 300-1500	Good aerobic germination
Biocompatibility	No vinyl plastics or copper	No aluminium	No vinyl or ammonia	Standard
Hoagland's Nutrient Solution	Half normal	Half normal	Half normal with 100% iron+calcium	Water
Air Flow (m/s)	0.1 - 1.0	0.1 - 1.0	0.1 - 1.0	Relative to oxygen humidity
Substrate, Nutrient Delivery	No substrate: aeroponics and hydroponics OK	No substrate	No special substrate	None / wetting
Plant Volume Root Zone	15x15x15cm 2.5cm deep	5x5x15cm 47cm^3 for bulb 25cm top for onion	30x30x30cm	10x10x5cm Food Pack
Contamination Control	Ethylene and gaseous ammonia control	TBD	Ethylene control	Standard
Access	No special access, except for varying plant spacing	Substrate containment during harvest	Pollination methos requires special access	Standard

T.N. 32.3: Including a HPC in the MELiSSA loop

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Introduction

MELiSSA has been conceived as a micro-organisms-based ecosystem intended as a tool for understanding the behaviour of artificial ecosystems and for the development of the technology for future biological life support systems. Based on an "aquatic ecosystem" MELiSSA consists of 4 microbial compartments (liquefying, photohetrotrophic, nitrifying and photosynthetic), and its driving element is the recovering of edible biomass from waste, carbon dioxide and minerals.

The purpose of this Technical Note is to obtain simplified mass-balanced stoichiometries for describing the growth of a pool of selected plants in a Higher Plants Chamber (HPC). These stoichiometries will allow a mass-balanced description of the HPC.

In a first section, a short survey of Higher Plants Compartment studies in Biological Life Support System (BLSS) projects is proposed.

The second part of this TN focuses on the definition of a Higher Plant Compartment (in term of plant composition) and the stoichiometric (mass balanced) representation of this HPC is made in order to link it to the MELiSSA loop for steady-state simulations.

A complete Biological Life Support System (BLSS) based on the MELiSSA loop, including a higher plant module is then proposed. The pseudo-steady state simulation of the mass fluxes between the different modules of the BLSS is performed, allowing the determination of the recycling efficiency of the system under various possible configurations with the respect of crew constraints.

The comparison of a MELiSSA and of a MELiSSA+HPC system was made. Because the Higher Plants Chamber produces a lot of non edible matter a process to oxidise the organic waste produced by the plants is added. An optimum for the recycling of the system MELiSSA+HPC including a physico-chemical process for the oxidation of organic matter is researched as a function the quantity of organic waste oxidised.

The influence on the system performances of another parameter was investigated: the parameter Y (e.g. the quantity of Rs. Rubrum produced by the phototroph compartment and effectively used in the crew's diet).

I - Higher plants and BLSS

A biological life support system, as the term is currently understood, is designed to create and maintain a living environment for human that is maximally appropriate to their needs. Of course this objective encompasses the traditional requirement for all life support systems (i.e. providing the major requirement for life -oxygen, water and food-), but is not limited to them.

The BLSS operates primarily through the utilisation of a biological substance cycle created by the combined metabolic activity of plants, animals, micro-organisms and humans themselves, who became an essential element of the system. Thus we consider the BLSS as a kind of functional analogue of natural ecosystem which is based on matter and energy linkages among individual functional components (subsystems) joined in a functionally integrated system (Melesko et al., 1991; Leiseifer et al., 1983)

I.1 - BLSS: current state of the art

First bioregeneratives testbed experiments conducted at the USAF School of Aviation Medicine, involved monkeys linked in gas exchange with algae compartment (*Chlorella*) up to 50h. These experiments were terminated because of the low productivity of algae culture, which results in carbon dioxide accumulation. Experiments conducted by Soviet researchers in 1960 with rats, dogs, lasting 6-8 days, and then with humans (lasting 1 day) were equally unsuccessful (Melesko et al., 1991).

Table 1: advantages and disadvantages of biological systems

Biological agent	Advantage in BLSS	Disadvantage in BLSS
Micro-organisms	Controlled processes Convert organic waste	Non edible biomass (except some species) Gas production (CO_2, methane, H_2,NOx) Nucleic acid content of edible biomass
Algae	Convert CO_2 to O_2 compatible to human needs Produce edible biomass Low inertia (generation time) Controlled processes Reduced volumes High harvest index	Insufficient to satisfy nutritional requirement High content in nucleic acids
Higher plants	Convert CO_2 to O_2 Provide food (pool of plants) Process water via transpiration	Production of non edible biomass High power and volume (surface) reclamation High inertia (life cycle>30days) culture phases (seeding.....)

Despite substantial amount of research in Japan, United States and Russia (USSR) were leaded on one-celled-algae system, most of the studies for a BLSS recovering water, food, and oxygen concern higher plants. As for USA and Russia, the countries which develop BLSS consider that higher plants systems are the best solution to produce a balanced food. Nevertheless, the food production from single cell (algae, some bacteria) used as complement for human (or animal food) is also considered as a promising approach (Averner,1984). The

relative advantages and disadvantages of the two options are presented in table 1. The best configuration seems a dual system higher plants/algae, of which relative importance depending on the constraints (available surfaces, volumes, food sources) and on the relative performance of plants and algae.

In table 2 can be found a survey of past and present closed bioregenerative research projects.

Table 2: Survey of past and present closed bioregenerative research projects (Melesko et al, 1991; Tamponnet, 1993)

System	Investigator/project	Characteristics
Small closed ecological systems	C. Folsome University of Hawaii (1967)	Sealed flask (100ml-5l) Multiculture aquatic solution Energy+information exchange
Large closed ecological systems	MELiSSA ESA (since 1989)	A 4 microbial compartments based ecosystem Recovery of human waste to produce food, oxygen and water The ecosystem is based on the terrestrial N-loop
Algae based systems (*Chlorella*)	US (1961)	Monkey/algae gas exchange Duration up to 50 hours
	USSR (1961) Bios 1 and 2	Rats and dogs up to 7 days First human/algae system (15-30 days)
Higher plants	US projects (since 1977) CELSS NASA-Ames Research Centre	Main goals: Food production Air revitalisation Water reclamation Contamination control Study of the productivity of CELSS higher plant crops under microgravity conditions (International Space Station)
	CELSS Breadboard Project NASA-Kennedy Space Centre	Testbed facility to develop and operate a sealed plant production chamber. Evaluation of biomass production, biomass conversion food processing and ressource recovery component in a scale up breadboard system.
	Regenerative Life Support Program NASA-Johnson Space Centre	Main goals: Food production Air revitalisation Water reclamation and treatment Contamination control Control, sensor and thermal control Systems integration Preparation of a lunar testbed. higher plants are involved mainly in air revitalisation
	Biosphere 2 Space Biosphere Venture (since 1984)	It is a program developed by a private company. The goal is to create an indefinitely operating bioregenerative system capable of full human life support. The current experiments have demonstrated the extreme difficulty to control and manage such a complex system (seven biomic areas) when using an holistic approach.
	Russia (USSR) Bios 3	2-3 peoples up to 6 months in a sealed area of 120 m^2 (300m^3).

	Institute of biophysics (1972-1984)	Higher plants produce 30-50% of the food and regenerate the habitat air and water.
	Bios 4 (under study)	Same of Bios 3 but smaller
	Japan Biosphere J CEEF	Understanding of material circulation and development of new advanced technologies for expanding the human habitation on Earth and in space. Determination of required plants cultivation area to satisfy human needs
	Canada Biological Air Regenerative System	Wall unit composed of a combination of different plants judiciously selected to provide high quality indoor air
	CNES - ESA BIORACK and EURECA (1993)	Biorack: incubator, freezer and cooler equipment EURECA: botany facility (greenhouse) - growth of higher plants and fungi from seed to seed (spore to spore)
	ESA . DASA-DORNIER Modular Cultivation System. (1996)	Experiment facility for biological investigations under microgravity. Humidification, deshumidification of atmosphere, temperature, light/dark cycle, illumination, gas composition control.

I.2 - Plants in space

I.2.1 - HPC objectives

As can be seen in table 1, only plants can provide most, if not all, of the major food needs of man. When introducing a higher plants compartment into a life support system, the plant may not only serve as a food provider but also be used for:

- atmosphere revitalisation
- water regeneration (liquid management)
- psychological comfort of the crew (Earth-like environment)

I.2.2 - Plant physiology in space

It is generally recognised by crop physiologists that the nutritive value of plants grown in controlled environments varies considerably but has nutritive values that are similar to that of plants grown in field environments. Thus requirements and performances data can be estimated based on terrestrial plants production (Eckart, 1994). A summary of these values is given in table 3.

Table 3: Plant requirements and performances mean values (Cited by Eckart, 1994)

Plant requirements		**Plant production**		**Needed higher plant area**	
Parameter	**Amount**	**Parameter**	**Amount**	**Consumable**	**Required area per person**
CO_2	40-300 g/m^2.day	O_2	30-220 g/m^2.day	Water	3-5 m^2
Water	5-10 kg/m^2.day	Transpiration water	5-10 kg/m^2.day	Oxygen	6-10 m^2
Minerals	10-100 mg/m^2	Edible biomass	20-40 g/m^2.day	Food	15-20 m^2
Lighting period	8-24h	Inedible biomass	4-20 g/m^2.day		
Lighting power	13-170 W/m^2				

The major goal of plant growth is to obtain maximum crop yield. It may also be possible to improve it by manipulation of the genotype of plants (genetical engineering), but the yield is still mainly dependent on the growth conditions. A list of the major environmental and biological parameters characterising plant growth is given below:

- Incident photosynthetic photon flux (PPF)
- Absorption of the incident PPF by photosynthetic tissue
- Photosynthetic efficiency (CO_2 fixed/photon absorbed)
- Respiratory carbon use efficiency (CUE), i.e. net carbon fixed in biomass per unit of carbon fixed in photosynthesis
- Harvest index (edible biomass/total biomass)
- Carbon dioxide assimilation rate [g CO_2/m^2.day]
- Transpiration rate [g H_2O/m^2.day]
- Leaf area index
- Dry mass production rate
- Respiration rate
- Vegetation duration
- Nutritional requirements
- Cultivation procedure
- Seed requirement
- Light requirements (photoperiod; intensity)
- Area requirement
- Temperature requirement

A review of physiological data and requirements for several higher plants is reported in appendix 1.

Researches are needed to utilise higher plants effectively in Space-farming systems. They are driven into 2 categories: research on physical and research on biological parameters. The early research focused on the physical parameters because control of these factors is required for successful conduct of most experiments giving biological parameters (NASA, 1982; Sallsbury, 1992). These physical and biological parameters are listed in table 4.

Table 4: Physical and biological parameters to take into account in the development of Space-farming systems (Cited by Eckart, 1994).

Physical parameters	Biological parameters
Water and nutrient delivery - growth media (see appendix 2) Liquid transport to and from roots in hydroponics and/or aeroponics systems Oxygen and carbon dioxide solubility and diffusion in liquid and solid media Air speed, humidity and CO_2 concentration Light intensity, quality and duration illumination Temperature	Seeding establishment and seed coast shedding Orientation of root, stem and leaves to maintain plant productivity Flower initiation, pollen transfer and fertilisation Accumulation of edible biomass Apical dominance Plant production and exchange rates

In extraterrestrial environment, the most important physical environmental factors which interfere with biological processes are:

- radiation
- gravitational forces (from 0 g in orbital station to 1/3 g on Mars).

- temperature and light exposition
- pressure

Experiments, conducted by USSR (MIR, Svet greenhouse), which observed the development of plant through a complete life cycle and the formation of viable seed in microgravity, indicated that viable seeds could be produced but that there was also a large number of abnormal seeds. In initial experiments (MIR in 1990), radishes and Chinese cabbage were grown in Svet. Although germination was lower and the flight plants grew considerably less, it was achieved for the first time to produce a radish root crop in microgravity (with only 31% fresh weight and 61% dry weight of the ground control plants).

In a mission on Salyut-6, the self pollinator Arabidopsis, which grows on artificial soil, bloomed in a plant grow chamber. This experiment demonstrated that it is principally possible to grow plants in weightlessness conditions from seed to seed. Nevertheless in most of the experiments leaded, it was not possible to bring plants to flowering (onions on Salyut in 1978 and wheat on MIR in 1991, for examples).

In order to investigate the effects of cosmic radiation on plants, lots of experiments were leaded on different plants (seeds and crops) from Sputnik-2 onboarding seeds and Chlorella. From the 2 millions of seeds onboard the US Long-Duration Exposure Facility (each received 3.5 to 7.25 Gy during the 6 years of orbiting) and from the seeds of lettuce, radish and garden cress stored onboard the MIR station, it seemed that there are no big differences between the growth of space-exposed seeds and Earth-based seeds. Anyway, on the contrary other results of both Americans and Russians showed that under space conditions the number of mutation increases. Further experiments and observations are under investigation to determine the effect of cosmic radiation on plants.

I.2.3- Plant growth and HPC

The main parameters to consider in a HPC design are the cultivable surface needed (see table 3), the volume required (from roots to canopy), the light (irradiance, photosynthetic efficiency, photoperiod), the atmosphere control (temperature, humidity, pressure, air composition) and the cultivation modes (seeding, vegetative multiplication, fecundating, fruiting, flowering, soil culture, hydroponics culture, aeroponic culture).

The environmental light conditions were investigated by Hernandez and de Llanza (1994) in their studies for the definition of a closed and controlled HPC. A comparison between the different culture conditions (hydroponics cultures, aeroponic cultures...) was reported by Eckart (1994) and is listed in appendix 2.

The environmental differences between a spacecraft and a planet lead Hernandez and de Llanza (1994) to propose different planning for HPC in spacecraft and HPC on a planet.

For HPC on a spacecraft:

- a few, small, easy to cultivate, and highly productive plants
- only hydroponics culture
- artificial lighting
- extremely atmospheric closure
- productivity adapted to 4 adult crew
- technical disposition adapted to the absence of gravity

For HPC on a planet:
- a broader collection of cultivable plants
- combination of hydroponics cultures and use of soil from the planet
- use of sunlight and greenhouse effect
- free architecture and geometry of HPC and CELSS in general
- modularity and diversity in the HPC configuration
- productivity for a 12 adult crew
- technical disposition adapted to the presence of gravity

I.2.4 - Plant selection for a HPC

In the sixties and seventies, many species were tested for the effect of gravity, radiation and air composition. Later, a wide set of experiments about nutrition, yields in different conditions and monitoring of atmosphere were developed in different facilities, following the different BLSS projects (table 1). Wheat (*Triticum aestivum L.*), soybean (*Soja max.*), potatoes (*Soluanum tuberosum L.*), and lettuce (*Lactua sativa*) are the species the most usually used for experimentation in BLSS.

Table 4: Plant selection for HPC

Group 1 - Nutritional interest	
Wheat	High caloric density Basis of many different types of food High edible portion of biomass (harvest index)
Rice	High caloric density 8% of nutritionally balanced protein, phosphorus, iron, thiamine and niacin
White potatoes	High caloric food Minimum processing High carbohydrate concentration and same protein concentration as rice Good source of vitamins
Sweet potatoes	Idem white potatoes Adapted to warm environment 30% more carbohydrate than white potatoes Leave and young shoots are edible Vigne-type growth of the stem can be a disadvantage
Soybeans	Major source of dietary proteins
Peanuts	Major source of proteins Contain a lot of oil Complex growing and harvesting procedures
Lettuce	Vitamins A and C
Sugar beets	Provide sugar Can be eaten raw. Tops are edibles

Group 2 - Psychological interest	
Taro	Tropical crop
Winged beans	Can be eaten (proteins source) Adapted to warm temperature
Broccoli	Contain vitamins A, B1, B2, B7 and C
Strawberries	Very high psychological value Contain vitamins B2, B7 and C
Onion	Low nutritional value
Peas	Proteins source Large quantities of minerals Require special culture system

In the three NASA centres (see table 2), wheat, soybean and lettuce are grown in hydroponics culture as well as in calcined clay substrate.

In the Breadboard Project, white potatoes, sweet potatoes, rice and peanuts are alsos tested.

In BIOS-3 , carrots, beet, radish, tomatoes, cucumbers, sedge-nut, potatoes, onions, dill, kohlrabi were grown.

The Japan CEEF higher plants chamber contains rice, soybean, komatsuna, tomatoes and potatoes.

Working for the NASA, a group of specialists selected some crop species that are of major interest as human food sources in BLSS. The selected plant species (table 4) were divided into 2 groups:

Group 1: Species that are commonly used food plants and can provide the major nutritional needs of man

Group 2: Species with lower nutritional values but high psychological value

I.2.5 - Some BLSS-HPC in details

Breadboard project

The NASA's Breadboard project was started in 1986 at the Kennedy Space centre. Its goal is the scaling-up from previous laboratory sized research studies in the production of food for human life support, water recycling, and atmospheric gas control in its Biomass Production Chamber (BPC: a cylindrical steel hyperbaric facility of 3.5 m diameter x 7.5 m high and an internal volume of 115 m^3). The structure offers a total plant area of 20 m^2. The air turnover is about 3 times a minute with a ventilation of 0.5 m^3/s. The initial crop tested was wheat, grown on nutrient film. In the following, studies of soybean, potatoes and multiple crop in continuous production are planned. Some results of tests conducted from 1988 to 1991 are given in table 5.

Table 5: Some results of Breadboard project (Wheeler et al., 1992). Irradiance level and yields

Crop	Date	Average PPF [µmol/m^2.s]	Photoperiod [h]	Daily PPF [µmol/m^2.s]	Length of study [day]
Wheat	5/88	666	24	57.7	68-86
	1/89	535	20	38.5	86
	5/89	691	20	49.7	85
Soybean	11/89	815	12	35.2	90
	5/90	477	12	20.6	97
	11/90	644	10	23.2	97
Lettuce	3/90	290	16	16.7	28
	9/90	280	16	16.1	28
	9/91	293	16	16.9	28

Table 5 (continued): Some results of Breadboard project (Wheeler et al., 1992). Irradiance level and yields

Crop	Date	Edible yield		Total biomass	
		[kg/m^2]	[g/m^2.day]	[kg/m^2]	[g/m^2.day]
Wheat	5/88	1.16	15	2.88	37.4
	1/89	0.67	8	2.36	27.4
	5/89	0.82	9.6	2.76	32.5
Soybean	11/89	0.54	6	1.66	18.5
	5/90	0.4	4.1	1.18	12.2
	11/90	0.49	5.0	1.3	13.4
Lettuce	3/90	0.16	5.7	0.17	6.0
	9/90	0.16	5.8	0.18	6.3
	9/91	0.2	7.2	0.22	7.9

Table 6: NASA Kennedy Space Centre BPC plant growth conditions.

Parameter	Lettuce	Potato	Soybean	Wheat
Growth rate	0.006 kg/m^2.day	0.033 kg/m^2.day	0.009 kg/m^2.day**	0.06 kg/m^2.day*
Planting	Every 4 days (fill a single chamber) Harvesting on a daily basis	Every 6 days (fill a single chamber) Harvesting on a daily basis	Every 4 days	Every 3 days
Edible part	Heads No processing required	Tuber Could be processed to flour	Beans Milling and processed food	Grain Milling, flour Pasta and bread processing
To waste processing	Roots and damaged leaves	Tops and roots	All except beans	All except grain
Spacing [number/m^2, initial/final]	54/24	12/8	40/16	1600/1200
Propagule	seed	explant or microtuber	seed 24 h soak	seed 24h soak
Thinning [days]	8-10	14	10-15	none
Time to harvest [days]	30	90	90	85
pH	5.8	5.5	6	5.8
Photoperiod [light/dark {days after planting}]	16/8	12/12 {0-45} 16/8 {46-end}	10/14	20/4
PFP [µmol/m^2.s]	300	800	0 {0-2} 800	800
Air temperature °C [light/dark {days after planting}]	23/23	20/16 {0-40} 16/16 {41-end}	26 {0-2} 26/20 {3-end}	24/20 {0-21} 18 {22-end}
Relative humidity [% {after planting}]	high {0-4} 70 {5-end}	high {0-3} 85 {4-10} 75 {11-end}	high {0-3.5} >85 {3.5-5} 70 {6-end}	high {0-4} 85 {5-10} 75 {11-end}
pCO_2 [ppm]	0.12	0.12	0.12	0.12

*Bugbee B.G. and Salisbury, F.B. (1989). "Current and potential productivity of wheet for a controlled environment LSS". Adv. Space. Res. 9 (8): 5-15 - Cited by Drysdale et al. (1994)

**Wheeler, R.M., Mackowiak, C.L. and Sager J.C. "Proximate composition of seed and biomass from soybean plants grown at different carbon dioxide concentration. NASA TM 103496 - Cited by Drysdale et al. (1994)

Some of the results obtained at the Kennedy Space Centre Biomass Production Chamber served as a basis for the description of a theoretical CELSS by Drysdale et al. (1994). They investigated a CELSS based on higher plants for its integration as a BLSS on lunar base. They concluded to the feasibility of a bioregenerative advanced life support system. The cost and availability of power and crew time will be critical factors. The Higher Plant Chamber of the CELSS proposed by Drysdale et al. (1994) is based on the cultivation of 4 plants grown in the Biomass Production Chamber at the Kennedy Space Centre. The plant growth conditions in BPC and the plants characteristics are given in table 6.

Table 7: CELSS baseline diet (for one person/day). Drysdale et al. (1994).

	Food	Wet mass [kg]	dry mass [kg]	Energy [kJ/kcal]
Locally produced	Potato	0.5	0.1	1600
	Soybean	0.05	0.05	840
	Wheat	0.51	0.51	9000
	Lettuce	0.1	0.01	84
	Carrots	0.06	0.01	100
	Subtotal	1.3	0.67	12000 / 2871
Supplied from Earth	Beef	0.09		910
	Bacon	0.01		150
	Orange	0.11		260
	Cheese	0.02		210
	Milk conc.	0.09		530
	Subtotal	0.32		2100 / 502
Total		**1.62**		**14000 / 3350**

Determining a baseline diet for the crew (table 7), Drysdale et al. (1994) estimated the required areas of crop to satisfy the crew needs (table 8). The salad use represented by lettuce was limited because of the low energy content, but was still included for aesthetic and psychological reasons.

Table 8: CELSS plant areas and equivalent mass. Drysdale et al. (1994).

Plants	**Area 1**	**Area 2**	**Area 3**	**Total**	**Equivalent mass**
Lettuce					3600 kg
Days	4	24		28	
area (m^2)	1	6		7	
photoperiod	16/8	16/8			
Air temp light/dark (°C)	23/23	23/23			
Relative Humidity	high	75			
Nutrient temp (°C)	23	23			
Potato					6400 kg
Days	8	84		90	
area (m^2)	1	4		5	
photoperiod	12/12	12/12			
Air temp light/dark (°C)	20/16	20/16			
Relative Humidity	high	75			
Nutrient temp (°C)	18	18			
Soybean					11200 kg
Days	4	86		90	
area (m^2)	1	20		21	
photoperiod	10/14	10/14			
Air temp light/dark (°C)	26/20	26/20			
Relative Humidity	high	75			
Nutrient temp (°C)	23	23			
Wheat					39000 kg
Days	3	17	65	85	
area (m^2)	1	6	26	33	
photoperiod	20/4	20/4	20/4		
Air temp light/dark (°C)	24/20	24/20	20/16		
Relative Humidity	high	75	75		
Nutrient temp (°C)	22	22	18		

BIOS-3

BIOS-3 projects were started by USSR in 1972. The building was a sealed laboratory where 2 to 3 persons can live, producing up to 80% of their food with a phytotron (controlled closed compartment for higher plant crop). Although plants were grown quite continuously in the phytotrons, there were only 3 full scale experiments with a crew sealed inside: one first experiment in 1972-1973, a second experiment in 1976-1977 and the last experiment in 1983-1984.

BIOS-3 was a 4-compartments sealed structure of 126 m^2 x 2.5 m high (315 m^3):

Two compartments are for hydroponics higher plant growth (20.5 m^2 each ; 17 m^2 for wheat and 3.5 m^2 for other vegetables: carrots, beets, radish, onion, tomatoes, potatoes..). The output of each phytotron is about 1m^3/day of oxygen. Environmental conditions are maintained to 70% relative humidity and at 22-24 °C. Inedible biomass is burnt in an incinerator.

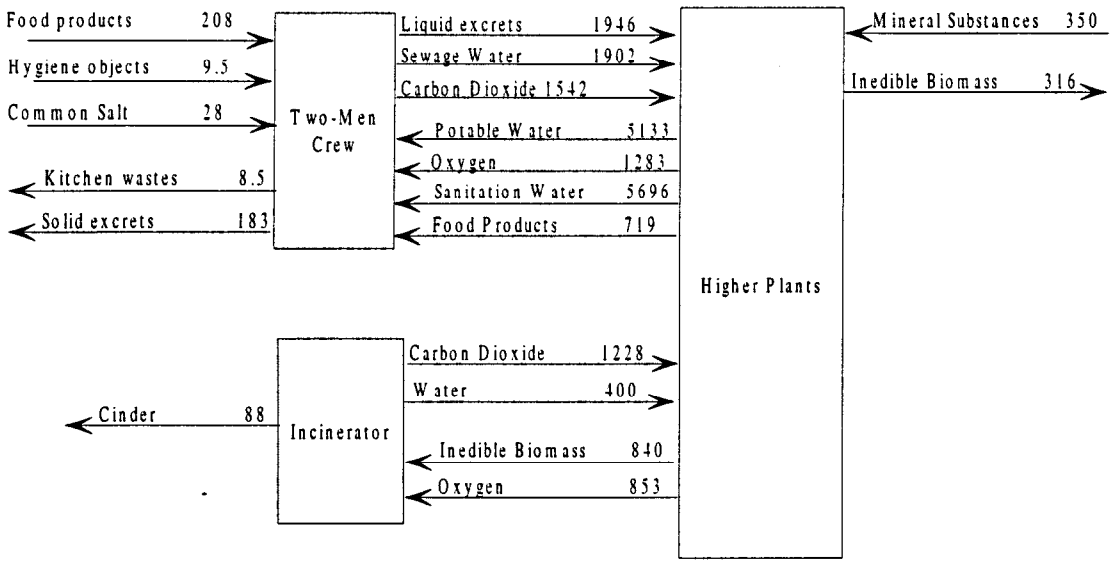


Figure 1: Mass exchange in BIOS-3 [Unit in g/day] (Salisbury[2], 1992)

One compartment contains 3 tanks for algae cultures of *Chlorella*. Each tank has an illuminated area of about $10m^2$ and produce 800 g/day of dry biomass. The fourth compartment is for the crew.

Water exchange of the ecosystem, as well as gas exchange are basically fully closed. The condensate water is recirculated and purified for drinking or boiled for other use. The sources of condensate water are water in air, phytotron moisture, the drying chamber (for inedible biomass) and the incinerator.

The 14 plant species provide 70% of the caloric requirement. An animal part was added to complete the diet, depending on the requirement of the crew.

An overall mass exchange balance is given in figure 1. The highest closure was achieved in the last experiment, with 91%. Nevertheless the mineral exchange accounted for only 1.5% of the closure. The problem of mineral recycling from plants-based BLSS was also demonstrated by Akitoshi et al. (1994).

CEEF

The Closed Environmental Experiment Facility (CEEF) is a Japanese project (Toki et al., 1994). Its goal is the study of material circulation in the nature for establishing fundamental conditions to be required for long term living in a closed system. CEEF comprises an habitat module, an animal feeding module and a crop module (HPC). Seven kind of plants were selected and cultivated in the plantation module by hydroponics (table 9). The objectives of the preliminary cultivation experiments were:

- the verification of the ability of the selected plants to growth from seed to harvest in hydroponics cultivation.
- the acquisition of data on the growth parameters of the plants.
- the determination of optimal growth conditions.

The results obtained from these first experiments are summarised in table 9.

Table 9: CEEF results

Plants	Ingested [g/day.man]	Run N°	Yields rate [g/m^2.day] Average value of open field cultivation	Design basis of the CEEF	Exp. results	Cultivation period [day] Expected	Measured
Rice	400	1	2.6	8	3.7	149	182
Soybean	150	1	1.1	14	5.81	114	126
Sesame	120	1	0.89	1.3	0.09	61	119
Komatsuna	400	1	60	118	67	31	
		2			119		15
		3			111		19
Tomato	100	1	38	17	68	92	16
Potato	150		23			93	
fog cultivation		1			5.9		77
sandponics		1			6.2		112
Soba	73	1	1	29	0.1	87	84
Total	1393						

Proteins	118
Lipid	97

Energy [kcal]	3000

I.3- Design and integration of HPC for a BLSS

A Higher Plants chamber is integrated to the different units of a Life Support System, in relation to its habilities of food provider, water producer and atmosphere regenerator. A scheme of such an integration is given in figure 2.

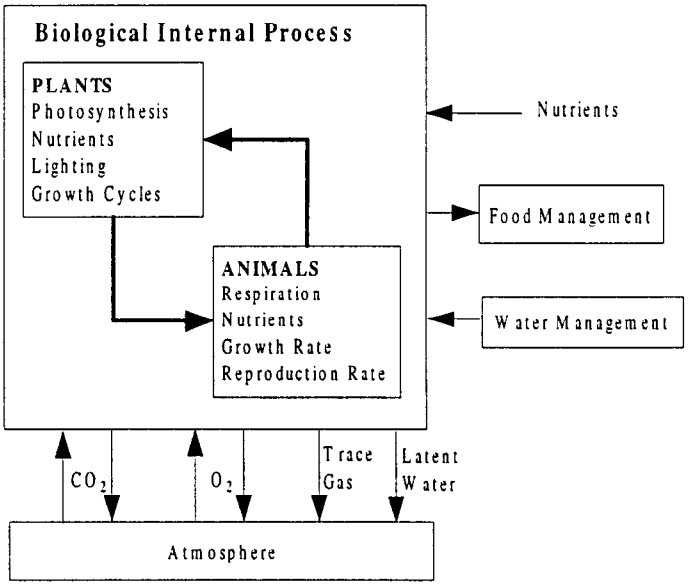


Figure 2: Interface between HPC and LSS

The development of the Higher Plant technology is under study since a few years. Most of them concern the type of lamps, the nutrition mode, the crop selection and the HPC structure, in relation to crops environmental and physical constraints (see section 1). Some reviews for the design and the technology of HPC are reported by Tamponnet (1993) and Hernandez and de Llanza (1994).

II - Higher plants: basis for the integration in a BLSS steady-state simulation

II.1 - HPC as a food source in the MELiSSA loop based BLSS

In the MELiSSA loop concept, food is provided by biomass production of *Spirulina*, and to a lower extent by biomass production of *Rhodospirillum rubrum*. Food from algae and microorganisms can only be a complement of the crew's diet. It can not be assumed that the food of the crew, in a spacecraft or in a extraterrestrial base, comes only from micro-organisms. There are three main reasons for that:

- the high content of nucleic acid in micro-organisms limit the quantity that can be consumed, even if it is proven that *Spirulina* is not toxic for man (de Chambure, 1992).
- a well balanced diet is composed of more than 2 food sources. The baseline diet reported in table 8, can be taken as an example of a balanced diet.
- in the previous simulations of the MELiSSA loop in steady-state conditions, the proteins need of the crew was satisfied by the consumption of *Spirulina* (and *Rhodospirillum rubrum*), but external food sources were necessary to supply the crew in carbohydrate and lipids. Finally, micro-organisms represent only 35-40% of the food (loop produced food), and then the carbon recycling efficiency of the loop was about 40%.

A Higher Plant Chamber must then be linked to the MELiSSA loop in order to offer a better balanced diet to the crew and to improve the recycling efficiency of the BLSS.

II.2 - Stoichiometries for the higher plants growth: mass balances

In the objective of a steady-state (mass-balanced) simulation of a BLSS based on a HPC-MELiSSA loop, a mass-balanced representation of the Higher Plant Chamber must be established. As previously done for the different compartments of the MELiSSA loop, a stoichiometric description of the growth of the plants involved was chosen.

II.2.1 - Vegetables composition

Vegetables are composed of 3 parts: an edible part, subdivided in a digestible part and in a dietary fibre part (assumed non digestible), and an inedible part (composed of non edible leaves, roots, stems ..).

Eight plants are considered in this first approach of a Higher Plants Chambers: wheat, tomato, potato, soybean, rice, spinach, onion and lettuce. Their complete composition is given in tables 10 to 14. The qualitative and quantitative compositions of the edible parts are calculated from the nutrition tables reported in appendix 3. It must be outlined that these mean compositions are representative of Earth soil cultivation. It is then assumed that the biomass produced is identical in space growth conditions.

Table 10: Plant composition (from harvest index, Wade, 1989)

	Mass % of fresh plant		Fresh Waste	Dry Waste
	Waste	Edible	% of fresh edible	% of dry edible
Tomato	55	45	122,22	955,00
Rice	55	45	122,22	119,77
Lettuce	15	85	17,65	85,51
Potato	17	83	20,48	49,96
Soybean	50	50	100,00	55,81
Spinach	30	70	42,86	157,55
Oinion	25	75	33,33	157,87
Wheat	60	40	150,00	152,50

Table 11: Plant edible part composition (from Soucy et al., 1990)

	Edible part composition [% wet mass]							Edible part composition - Normalised and without minerals [% wet mass]					
	Water	Proteins	Fat	Carbohyd.	Fibre	Minerals	Total	Water	Proteins	Fat	Carbohyd.	Fibre	Total
Tomato	94,20	0,95	0,21	3,45	1,83	0,61	101,25	93,60	0,94	0,21	3,43	1,82	100,00
Rice	13,10	7,22	2,20	73,41	2,87	1,20	100,00	13,26	7,31	2,23	74,30	2,90	100,00
Lettuce	95,00	1,25	0,22	1,10	1,52	0,72	99,81	95,87	1,26	0,22	1,11	1,53	100,00
Potato	77,80	2,04	0,11	15,40	2,51	1,02	98,88	79,50	2,08	0,11	15,74	2,56	100,00
Soybean	8,50	33,73	18,10	6,10	15,18	4,70	86,31	10,42	41,33	22,18	7,47	18,60	100,00
Spinach	91,60	2,52	0,30	0,61	1,84	1,51	98,38	94,56	2,60	0,31	0,63	1,90	100,00
Oinion	87,60	1,25	0,25	5,79	3,05	0,59	98,53	89,44	1,28	0,26	5,91	3,11	100,00
Wheat	13,20	11,73	2,00	60,97	10,30	1,80	100,00	13,44	11,95	2,04	62,09	10,49	100,00

	Edible part composition - Normalised and without minerals [% dry mass]				
	Proteins	Fat	Carbohyd.	Fibre	Total
Tomato	14,75	3,26	53,57	28,42	100,00
Rice	8,42	2,57	85,66	3,35	100,00
Lettuce	30,56	5,38	26,89	37,16	100,00
Potato	10,17	0,55	76,77	12,51	100,00
Soybean	46,14	24,76	8,34	20,76	100,00
Spinach	47,82	5,69	11,57	34,91	100,00
Oinion	12,09	2,42	56,00	29,50	100,00
Wheat	13,80	2,35	71,73	12,12	100,00

Table 12: Chemical composition of the digestible part (from Soucy et al., 1990)

	Proteins					Insatured lipids Lipide insat.			Satured lipids			Carbohydrates		
	C	H	O	N	S	C	H	O	C	H	O	C	H	O
Tomato	1	1,46731	0,46578	0,23469	0,00205	1	1,81116	0,11383	1	2	0,1231	1	1,8958	0,9924
Rice	1	1,53355	0,35016	0,25885	0,00626	1	1,86272	0,11663	1	2	0,1240	1	1,6680	0,8340
Lettuce	1	1,64190	0,19376	0,24682	0,00352	1	1,72585	0,11176	1	2	0,1236	1	1,7962	0,9919
Potato	1	1,50971	0,38347	0,25300	0,00425	1	1,74071	0,11164	1	2	0,1214	1	1,6686	0,8436
Soybean	1	1,53073	0,34292	0,25367	0,00667	1	1,83076	0,11495	1	2	0,1212	1	1,8822	0,9411
Spinach	1	1,62780	0,19299	0,24837	0,01169	1	1,70827	0,11226	1	2	0,1244	1	1,6154	0,9684
Oinion	1	1,64586	0,17818	0,34579	0,00448	1	1,76406	0,11111	1	2	0,1210	1	1,8551	0,9716
Wheat	1	1,50000	0,35900	0,24200	0,00700	1	1,87859	0,11774	1	2	0,1189	1	1,6762	0,8381

	Chemical composition of the digestible part				
	C	H	O	N	S
Tomato	1	1,7928	0,8004	0,0546	0,0005
Rice	1	1,6650	0,7546	0,0257	0,0006
Lettuce	1	1,7107	0,4464	0,1348	0,0019
Potato	1	1,6492	0,7750	0,0335	0,0006
Soybean	1	1,6878	0,2952	0,1321	0,0035
Spinach	1	1,6406	0,2835	0,1870	0,0088
Oinion	1	1,8113	0,7510	0,0742	0,0010
Wheat	1	1,6548	0,7215	0,0430	0,0012

Table 13: Chemical composition of the fibre (from Soucy et al., 1990)

	Chemical composition of the fibre		
	C	H	O
Tomato	1	1,6560	0,8280
Rice	1	1,6667	0,8333
Lettuce	1	1,6537	0,8268
Potato	1	1,6513	0,8257
Soybean	1	1,6000	0,8000
Spinach	1	1,6467	0,8233
Oinion	1	1,6560	0,8280
Wheat	1	1,6667	0,8333

Table 14: Composition of the non edible part of plants

	Fresh wastt composition		Chemical composition				
	Water	Dry waste	C	H	O	N	S
Tomato	50	50	1	1,43	0,62	0,017	0,007
Rice	15	85	1	1,43	0,62	0,017	0,007
Lettuce	80	20	1	1,43	0,62	0,017	0,007
Potato	50	50	1	1,43	0,62	0,017	0,007
Soybean	50	50	1	1,43	0,62	0,017	0,007
Spinach	80	20	1	1,43	0,62	0,017	0,007
Oinion	50	50	1	1,43	0,62	0,017	0,007
Wheat	12	88	1	1,43	0,62	0,017	0,007

The most sensitive point in the values given in tables 10-14 is the non edible (waste part) composition (table 14). The waste part indicated by Soucy et al. (1990) in the nutritional tables (appendix 3) corresponds to the waste part of the fruit or of the tuber and not of the non edible part of the complete cultivated plant. An average mass percentage of the edible part of a wet vegetable was given by Wade (1989) and is reported in table 10. This edible part corresponds to the harvest index. If harvest indexes are easily found, the qualitative composition of the wasted part of a plant is hard to found.

The water content of the non edible part was estimated from various sources. The CHONS composition was calculated assuming the average chemical composition of plants given by Javilliers (Soltner, 1988):

Average CHONS composition of the non edible part of the plants		
Element	Javilliers [%mass]	Used in table 14 [%mass]
C	40-50%	50%
H	6-7%	6%
O	42-44%	42%
N	1-3%	1%
S	0.05-1%	1%

The digestible part of edible biomass was calculated from the proteins, carbohydrate (sucrose, fructose, glucose, raffinose) and lipids (saturated and unsaturated). The fibre part is considered as composed of cellulose and pentosane.

II.2.2 - Stoichiometry of a plant growth

The stoichiometries of each plant are obtained by a "black box approach". The general form of the stoichiometric equation is set to:

$$CO_2 + NH_3 + HNO_3 + H_2SO_4 + H_2O \Downarrow O_2 + [CHONS]_{digestible} + [CHONS]_{fibre}$$

and

$$CO_2 + NH_3 + HNO_3 + H_2SO_4 + H_2O \Downarrow O_2 + [CHONS]_{waste}$$

or the global form:

$$CO_2 + NH_3 + HNO_3 + H_2SO_4 + H_2O \Downarrow O_2 + [CHONS]_{digestible} + [CHONS]_{fibre} + [CHONS]_{waste}$$

Table 15: Stoichiometric coefficients for the representation of the growth of the plants

	Digestible part						Fibre				CO2	H2O	NH3	HNO3	O2	H2SO4
	Coeff	C	H	O	N	S	Coeff	C	H	O						
Tomato	1	1	1,7928	0,8004	0,0546	0,0005	0,4040	1	1,6560	0,8280	-1,4040	-1,1799	-0,0232	-0,0313	1,4744	-0,0005
Rice	1	1	1,6650	0,7546	0,0257	0,0006	0,0335	1	1,6667	0,8333	-1,0335	-0,8360	-0,0109	-0,0147	1,0836	-0,0006
Lettuce	1	1	1,7107	0,4464	0,1348	0,0019	0,5016	1	1,6537	0,8268	-1,5016	-1,1435	-0,0019	-0,0774	1,7627	-0,0019
Potato	1	1	1,6492	0,7750	0,0335	0,0006	0,1413	1	1,6513	0,8257	-1,1413	-0,9097	-0,0142	-0,0192	1,1803	-0,0006
Soybean	1	1	1,6878	0,2952	0,1321	0,0035	0,2022	1	1,6000	0,8000	-1,2022	-0,8799	-0,0562	-0,0758	1,5344	-0,0035
Spinach	1	1	1,6406	0,2835	0,1870	0,0088	0,4215	1	1,6467	0,8233	-1,4215	-0,9855	-0,0796	-0,1074	1,7777	-0,0088
Onion	1	1	1,8113	0,7510	0,0742	0,0010	0,4183	1	1,6560	0,8280	-1,4183	-1,1823	-0,0316	-0,0426	1,5266	-0,0010
Wheat	1	1	1,6548	0,7215	0,0430	0,0012	0,1320	1	1,6667	0,8333	-1,1320	-0,8963	-0,0183	-0,0247	1,2039	-0,0012

	Waste						CO2	H2O	NH3	HNO3	O2	H2SO4
	Coeff	C	H	O	N	S						
Tomato	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Rice	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Lettuce	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Potato	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Soybean	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Spinach	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Onion	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070
Wheat	1	1	1,43	0,62	0,017	0,007	-1	-0,6923	-0,0072	-0,0098	1,0648	-0,0070

The CHONS compositions are given in tables 10-14 for the different plants, as well as the yields fibre/edible, waste/edible, and the water content of edible and non edible part of the plant. Nevertheless, another yield need to be known in order to solve the system represented by the previous stoichiometric equations.

The yield NH_3/HNO_3 was used to solve the system. Vilain (1987) proposed a mass ratio of 5 to avoid acidification problems. From the nutrient solution reported by Eckart (1994) a mass ratio of $N\text{-}NO_3/N\text{-}NH_3$ equal to 10.8 can be calculated. For the HOAGLAND nutritive solution, often used to feed plants, a mass ratio of $N\text{-}NO_3/N\text{-}NH_3$ equal to 18 was calculated. In the nutrients solutions used by Atkitoshi et al. (1994), the mass ratio $N\text{-}NO_3/N\text{-}NH_3$ was equal to:

4.84 to 2.72 for rice
1.92 for soybean
9.41 for lettuce
11.33 for strawberry

For simplicity, the mean value of 5 proposed by Vilain (1987) was used to solve the stoichiometric system. But this assumption will probably have to be modified in the further studies of the HPC.

The stoichiometric coefficients for the two stoichiometries representing the plant growth are reported in table 15.

II.3 - Definition of a menu

The definition of a diet menu is of crucial importance for the choice of the Higher Plants Chamber design. The quantity and the type of plants used impose constraints to the HPC design (see section 1), such as the cultures area, the photoperiod or the nutrient composition.

From the pool of 8 plants listed above, and with the biomass produced by *Spirulina* and *Rhodospirillum rubrum*, a large set of combinations can be used. It is then necessary to fix several constraints to establish a diet menu for the crew (i.e. the quantitative composition of the Higher Plants Chamber).

The following constraints appears the most judicious:

- to fix a minimal and a maximal ratio of a particular plant in the diet
- to maximise the quantity of the micro-organism biomass in the diet
- to minimise the crop area, the volume and the mass
- to minimise the non edible plant production
- to minimise the external food sources

To determine the required surface A for the growth of a plant , Eckart (1994) proposed the following formula:

$$A = \frac{\text{Production required } [g / day] \text{ x Life cycle days } [day]}{\text{Absolute seed yields } [g / m^2]}$$

The values reported in table 16 are used in our calculation of the required surface. The determination of the volumes V for the biological reactors (*Spirulina* and *Rhodobacter*) are calculated by:

$$V = \frac{\text{Production yield [g / m}^3\text{.d]}}{\text{Required production [g / d]}}$$

Table 16: Parameters for the estimation of crop area and bioreactor volume

	Crop Yield [edible g/m^2.day]	Référence
Tomato	18	From CEEF results (table 9)
Rice	4	From CEEF results (table 9)
Lettuce	6	Drysdale et al. (table 6)
Potato	33	Drysdale et al. (table 6)
Soybean	15	Average value (from table 5)
Spinach	21	Estimated*
Onion	22.5	Estimated*
Wheat	33	Average value (from table 5)

	Biomass Yield [g dry /m^3.day]	Référence
Spirulina	1440	Calculated with PHOTOSIM for radial illuminated reactor (300 W/m^2)**
Rhodobacter	2880	Estimated to 2 times Spirulina for radial illuminated reactor

*Estimated: calculated from a mean plant yield (total biomass) of 30g/m^2.day and from the harvest indices
**Cornet J.F. TN 19.3

Note: For an irradiance level of 300 W/m2 , the Spirulina platensis composition can not be calculated with the relation given in TN 17.3 and available in the range of 10 to 180 W/m2. The composition of spirulina used in simulation was (Lu, 1996:
Proteins: 40%
Carbohydrates: 10%
Lipids: 10%
Nucleic acids: 4%
Exopolysaccharride: 36%

It can be noticed than for a lunar base the estimated mean area required to provided food to one man is 15-20 m^2/man for Blüm and Kreutzberg (1992), 40-50 m^2/man for Meleshsko et al., (1991) or 150 m^2/man for Toki et al. (1994). In fact the area depends on the number, the type of plants used and their crop yield, which depend themself on the culture conditions. For wheat, the crop yield values can be found in the range of 8 to 60 g edible/m^2/day. For potatoes, it must noticed that experiments conducted by Toki et al. (1994) have demonstrated a lower growth yield in sandponic than in open field (table 9).

Tables 17a, 17b, and 17c summarize a menu obtained using the Excel© (Microsoft©™) solver for different configurations. It must be noted that with this solver, all the constraints listed above cannot be used simultaneously. The constraints used are indicated in each table.

Table 17a can be considered as a representation of the MELiSSA loop alone.

Table 17b represents a menu for a diet which is not submitted to the constraints of a maximum and a minimum for each plant in the diet.

Table 17c is representative of a better balanced diet. The constraints values for minimum and maximum of percentage of plants in this third menu are chosen in accordance with the different menus used for the other BLSS projects (see section 1). The crop area estimated for the menu proposed in table 17c is 67 m^2/man and can be compared to the area of 73 m^2/man calculated by Drysdale et al.(1994) for the diet menu they have proposed (see table 7). The relative surface required for each plant is reported in table 18. It can be noted that tomato and lettuce, representing only 1.3 % of the plants consumed, required 17 % of the surface.

The calculated crop area does not appear excessive compared to the usually estimated areas for HPC in space. Moreover, the crop composition offers an important food variety for the diet.

Table 18: Surface required by plants for the menu of table 17c.

Plants	% of dry matter of total edible plants	% of required surface
Tomato	0.8	3
Rice	16.1	19.9
Lettuce	0.5	8.4
Potato	29.5	18.7
Soybean	1.6	0.5
Spinach	1.6	6
Onion	1.6	2.9
Wheat	48.2	7.2
Total	430 g/day.man.	66.7 m^2/man

Table 17a: Diet composition based on biomassonly (MELiSSA loop). The diet is obtain assuming several constraints, and calculated with the Microsoft -Excel- Solver.
The biomass composition of Spirulina, as its growth yield are calculated for an irradiance of 300W/m2

CONSTRAINTS

Minimize the plants waste
Dry edible biomass between Maximun and Minimun
Below the maximun of Nucleic Acids
Satisfy metabolic needs
Irradiance set to 300W/m2

Diet	% Mini	% Maxi	% Nucl Acids Maxi
Fat (External source)	0,00	100,00	5,00
Proteins (External source)	0,00	0,00	
Carbohyd. (External Source)	0,00	100,00	
Spirulines	0,00	100,00	
Rhobobacter	0,00	100,00	
Tomato	0,00	0,00	
Rice	0,00	0,00	
Lettuce	0,00	0,00	
Potato	0,00	0,00	
Soybean	0,00	0,00	
Spinach	0,00	0,00	
Onion	0,00	0,00	
Wheat	0,00	0,00	

Metabolic needs	g/day,man
Proteins	134,25
Lipids	94,56
Carbohydrates	403

RESULTS

Dimension estimation (1 man)

Crop area	Bioreactor Vol.
m2	liter
0,00	225,55

Diet Composition (1 man.day)

Total edible food	Biomass in Diet	Nucleic Acids	Plants	External
g dry	% of dry food	% of dry food	% of dry food	% of dry food
645,23	52,02	2,08	0,00	47,98

Detailled Diet composition (1 man.day)

	Waste g dry mass produced	Edible g Wet mass produced	Edible g Dry mass produced	Edible % of total Edible	HPC Composition % mass
Fat (External source)	0,00	61,00	61,00	9,45	
Proteins (External source)	0,00	0,00	0,00	0,00	
Carbohyd. (External Source)	0,00	248,61	248,61	38,53	
Spirulines	0,00	1118,75	335,63	52,02	
Rhobobacter	0,00	0,00	0,00	0,00	
Tomato	0,00	0,00	0,00	0,00	0,00
Rice	0,00	0,00	0,00	0,00	0,00
Lettuce	0,00	0,00	0,00	0,00	0,00
Potato	0,00	0,00	0,00	0,00	99,99
Soybean	0,00	0,00	0,00	0,00	0,00
Spinach	0,00	0,00	0,00	0,00	0,00
Onion	0,00	0,00	0,00	0,00	0,00
Wheat	0,00	0,00	0,00	0,00	0,00
Total	0,00	1428,36	645,23	100,00	100,00

Energetics-Metabolics

	Total	Proteins	Lipids	Carbohyd+Exopoly
kcal	3000,04	537,00	851,04	1612,00
% of total	100,00	17,90	28,37	53,73

Table 17b: Diet composition based on biomass andplants (MELiSSA +HPC). The diet is obtain assuming several constraints, and calculated with the Microsoft -Excel- Solver.
The biomass composition of Spirulina, as its growth yield are calculated for an irradiance of 300W/m2
There is no limitation for plants quantity in the composition of the diet

CONSTRAINTS

Minimize the plants waste
Dry edible biomass between Maximun and Minimun
Below the maximun of Nucleic Acids
Satisfy metabolic needs
Irradiance set to 300W/m2

Diet	% Mini	% Maxi	% Nucl Acids Maxi
Fat (External source)	0,00	100,00	5,00
Proteins (External source)	0,00	0,00	
Carbohyd. (External Source)	0,00	0,00	
Spirulines	0,00	100,00	
Rhobobacter	0,00	100,00	
Tomato	0,00	100,00	
Rice	0,00	100,00	
Lettuce	0,00	100,00	
Potato	0,00	100,00	
Soybean	0,00	100,00	
Spinach	0,00	100,00	
Onion	0,00	100,00	
Wheat	0,00	100,00	

Metabolic needs	g/day,man
Proteins	134,25
Lipids	94,56
Carbohydrates	403

RESULTS

Dimension estimation (1 man)

Crop area	Bioreactor Vol.
m2	liter
56,48	160,28

Diet Composition (1 man.day)

Total edible food	Biomass in Diet	Nucleic Acids	Plants	External
g dry	% of dry food	% of dry food	% of dry food	% of dry food
689,15	34,61	1,38	55,44	9,96

Detailled Diet composition (1 man.day)

	Waste	Edible	Edible	Edible	HPC Composition
	g dry mass produced	g Wet mass produced	g Dry mass produced	% of total Edible	% mass
Fat (External source)	0,00	66,62	66,62	9,96	
Proteins (External source)	0,00	0,00	0,00	0,00	
Carbohyd. (External Source)	0,00	0,00	0,00	0,00	
Spirulines	0,00	794,99	238,50	34,61	
Rhobobacter	0,00	0,00	0,00	0,00	
Tomato	0,00	0,00	0,00	0,00	0,00
Rice	0,00	0,00	0,00	0,00	0,00
Lettuce	0,00	0,00	0,00	0,00	0,00
Potato	190,86	1863,74	382,04	55,44	100,00
Soybean	0,00	0,00	0,00	0,00	0,00
Spinach	0,00	0,00	0,00	0,00	0,00
Onion	0,00	0,00	0,00	0,00	0,00
Wheat	0,00	0,00	0,00	0,00	0,00
Total	190,86	2727,34	689,15	100,00	100,00

Energetics-Metabolics

	Total	Proteins	Lipids	Carbohyd+Exopoly
kcal	3000,04	537,00	851,04	1612,00
% of total	100,00	17,90	28,37	53,73

Table 17c: Diet composition based on biomass andplants (MELiSSA +HPC). The diet is obtain assuming several constraints, and calculated with the Microsoft -Excel- Solver.
The biomass composition of Spirulina, as its growth yield are calculated for an irradiance of 300W/m2
There is a limitation for plants quantity in the composition of the diet

CONSTRAINTS

Minimize the plants waste
Dry edible biomass between Maximun and Minimun
Below the maximun of Nucleic Acids
Satisfy metabolic needs
Irradiance set to 300W/m2

Diet	% Mini	% Maxi	% Nucl Acids Maxi
Fat (External source)	0,00	100,00	5,00
Proteins (External source)	0,00	0,00	
Carbohyd. (External Source)	0,00	0,00	
Spirulines	0,00	100,00	
Rhobobacter	0,00	100,00	
Tomato	0,50	1,50	
Rice	10,00	20,00	
Lettuce	0,30	1,00	
Potato	10,00	20,00	
Soybean	1,00	4,00	
Spinach	1,00	5,00	
Onion	1,00	5,00	
Wheat	30,00	50,00	

Metabolic needs	g/day,man
Proteins	134,25
Lipids	94,56
Carbohydrates	403

RESULTS

Dimension estimation (1 man)

Crop area	Bioreactor Vol.
m2	liter
66,73	131,86

Diet Composition (1 man.day)

Total edible food	Biomass in Diet	Nucleic Acids	Plants	External
g dry	% of dry food	% of dry food	% of dry food	% of dry food
690,57	28,41	1,14	62,16	9,43

Detailled Diet composition (1 man.day)

	Waste	Edible	Edible	Edible	HPC Composition
	g dry mass produced	g Wet mass produced	g Dry mass produced	% of total Edible	% mass
Fat (External source)	0,00	65,10	65,10	9,43	
Proteins (External source)	0,00	0,00	0,00	0,00	
Carbohyd. (External Source)	0,00	0,00	0,00	0,00	
Spirulines	0,00	654,02	196,21	28,41	
Rhobobacter	0,00	0,00	0,00	0,00	
Tomato	32,97	53,96	3,45	0,50	0,80
Rice	82,71	79,61	69,06	10,00	16,09
Lettuce	1,77	50,19	2,07	0,30	0,48
Potato	63,34	618,54	126,79	18,36	29,54
Soybean	3,85	7,71	6,91	1,00	1,61
Spinach	10,88	126,94	6,91	1,00	1,61
Onion	10,90	65,41	6,91	1,00	1,61
Wheat	315,93	239,34	207,17	30,00	48,26
Total	**522,37**	**1960,83**	**690,57**	**100,00**	**100,00**

Energetics-Metabolics

	Total	Proteins	Lipids	Carbohyd+Exopoly
kcal	3000,04	537,00	851,04	1612,00
% of total	100,00	17,90	28,37	53,73

III - Simulation of the MELiSSA loop as a BLSS element in steady state conditions

Since 1994 (TN 17.1, 17.3), no global simulations of the MELiSSA loop in steady-state were performed. The purpose of this section is to present the flowsheet and the mass balanced description of MELiSSA compartments, integrated in a Biological Life Support System with a Higher Plant Chamber, and the results of steady state simulations of this BLSS for different configurations.

Some update of the previous description of the loop was made, including the stoichiometries describing the photoheterotroph compartment (TN 23.3) and the stoichiometries representing nitrification (TN 32.1). A new flowsheet for a Biological Life Support System based on the MELiSSA loop with a Higher Plants Chamber was built (figure 2).

III.1- Habitability constraints for the BLSS

As its definition suggests it, a Biological Life Support System must create and maintain an environment appropriate for human life, including physical needs and to a lesser extend the psychological requirements. Habitability is a general term which denotes a given level of environmental acceptability. The requirement which represents the basic level of habitability can be subdivided into 3 categories:

- Human environment
- Crew consumable
- Crew waste products

III.1.1 - Environmental aspects

The term environmental aspect summarises the human need for respirable and confortable atmosphere, for protection from all kinds of radiation and possibly the provision of artificial gravity. Only the requirement of a respirable and confortable atmosphere is considered here and for MELiSSA loop simulations.

Standards for atmosphere are reported in table 19. The values set for the crew environment in MELiSSA simulations are in the range of standard limits.

It must be noted that the air ventilation chosen (390 kg/h), is the value defined for the Space Station Logistic module (D'auria and Malosti, 1991), and was used in the previous simulations of MELiSSA. The high ventilation is the result of the microgravity constraints for gas convection. Drysdale et al. (1994) reported a crew air exchange of 2.5 L/s (i.e. about 40 kg/h) for each crew member, in their CELSS design for a lunar base. They concluded to parallel air loops between the crew and the plant modules, rather than in line loop. Yet, a flow rate for atmosphere was not found for a lunar base.

The crew modules ventilation could be an important parameter for the design of a BLSS as it imposed the ratio of crew atmosphere used in the air loop of bioreactor and plants chamber.

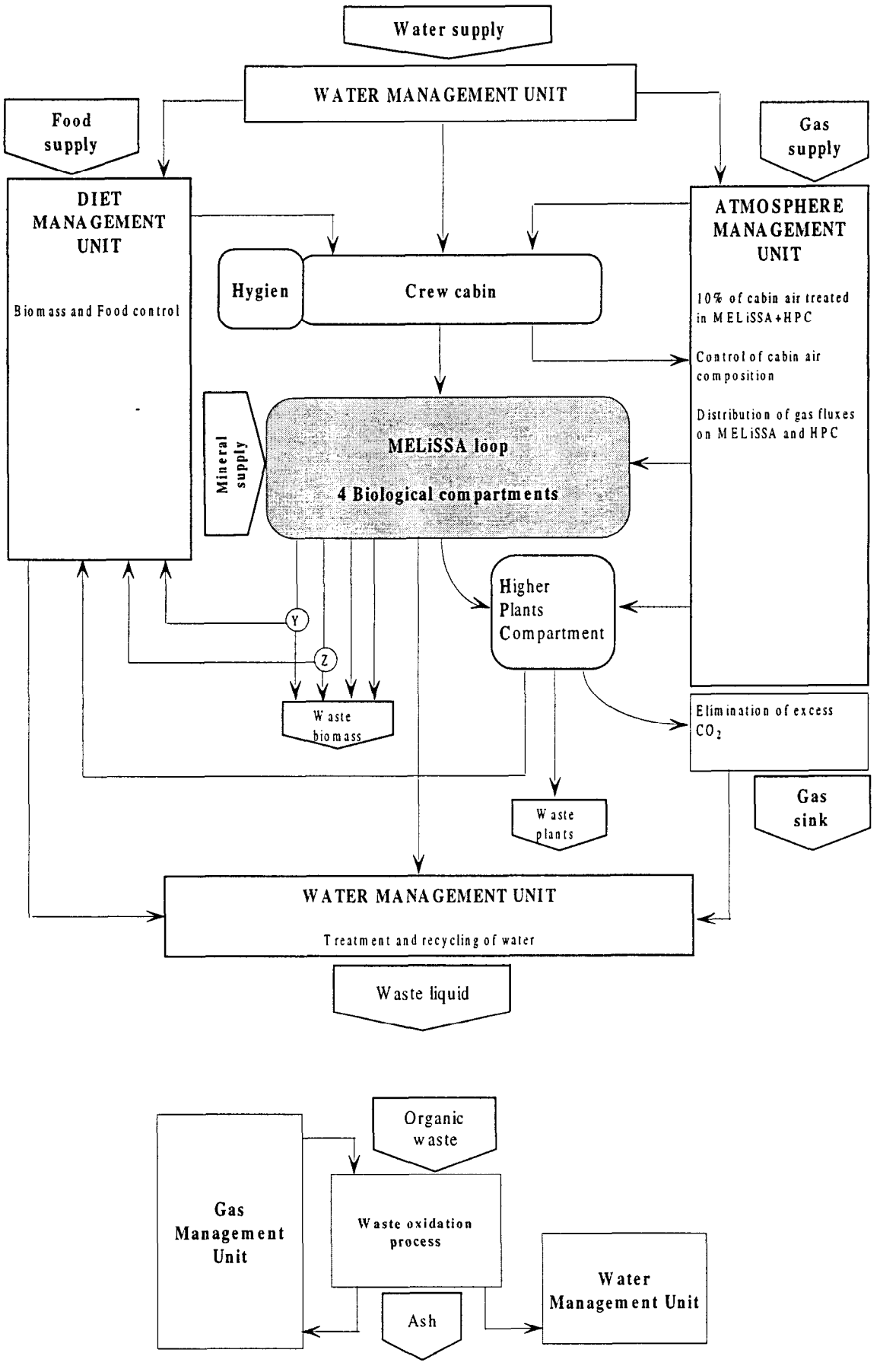


Figure 2: Interface diagram for the MELiSSA loop with the LSS functions

Table 19: Atmosphere standard and setting values for the MELiSSA simulations

	CELSS environment (Drysdale et al., 1994)	MELiSSA setting values	Atmospheric Standards
p_{CO2}	0.12 kPa	-	< 0.4kPa (4000 ppm)
p_{O2}	normoxic	20% (20 kPa)	19.5 - 23.1 kPa
Temperature	16-26 °C	-	18-17 °C
Relative Humidity	75%	55%	24-82%
Spacecraft ventilation (microgravity constraint)	-	390 kg/h	0.08-0.2 m/s
Lunar base ventilation	40 kg/h (e.g 2.5 L/s)	-	-

III.1.2- Nutritional aspects

Diet is the basis for the energy supply of the human organism (catabolism) and for the biosynthesis of several body substances (anabolism). Human nutrition consists of organic substances taken in as vegetables, fruits and meat. The major nutrients are carbohydrates, lipids and proteins. We based the crew diet for the MELiSSA loop simulations on the human requirement for these major nutrients.

Two parameters were considered to define the diet composition for the crew:

- the basal metabolic needs. A mean Energy Expenditure Rate (EER) of 3000 Kcal/day.man. was calculated considering human activity in space, including EVA (Life Support and Habitability Manual. ESA -PSS-03-406).
- the ratio of the 3 majors nutrients in food. A mean value was calculated from data of Soyuz and Skylab (Life Support and Habitability Manual. ESA -PSS-03-406).

The definition of the diet used for the crew in MELiSSA simulations is reported in table 20. It can be noted that this diet was used for the calculation of the plant menu (tables 17).

Table 20: Diet composition

	Mass percentage	EER percentage
Proteins	21.25	17.50
Lipids	14.97	28.37
Carbohydrates	63.79	53.73
Total	632 g/day.man	3000 Kcal/day.man

III.2- MELiSSA loop: interfaces with the BLSS units

Basically , Life Support Systems can be divided into five main areas (Eckart, 1994):

- Atmosphere management
- Water management
- Food production and storage
- Waste management
- Crew safety (fire detection, radiation shielding...)

In previous simulations, we demonstrated the ability of the MELiSSA loop to supply the totality of the proteins requirement of the crew with the biomass produced (without the consideration of food variety and nucleic acid limitation in food). But the loop alone can not be simultaneously a good atmosphere regenerator and a N-artificial ecosystem (TN 14.1 and TN 17.3).

A Higher Plant Chamber was then added, working in parallel with the photosynthetic compartment, and providing a more balanced and a more varied food to the crew.

The atmosphere management stays quite unchanged (see TN 17.3). Hydrogen or methane are produced by the liquefying compartment. They are supposed to be oxidised. This step need to be discussed and improved. The setting value for the atmosphere management and control are reported in table 19. Only 10% of the air flow from the crew cabin is sent to the MELiSSA + HPC loop. The recycle ratio of the cabin air has to be defined and will be linked to the scaling up of the MELiSSA bioreactors and of the HPC (as an example, the gas flow rate on the nitrifying column is actually of 1.8 m^3/h.)

The water management is completed by the addition of an hygiene unit to the crew compartment (including toilette, personal hygiene and wash water). The water flow rate values for the representation of this unit are reported in table 21.

The diet management is based upon the setting values of table 20. It controls the food content in biomass and it defines the quantity of plants required to minimise the food supply by external source.

The human waste management is taken into account by the 2 first MELiSSA compartments (liquefying and photoheterotrophs compartments). It must be noted that the photoautotroph bioreactor considered in the previous MELiSSA design is suppressed. The organic wastes produced by the MELiSSA loop (wasted biomass) and by the plants (non edible part of the plants) are treated by a waste oxidative process (producing CO_2 and consuming O_2). This could be a wet oxidation, a supercritical waste oxidation, a combustion or incineration process (Eckart, 1994). A system bioreactor/incinerator was chosen by Drysdale et al. (1994) for their CELSS module concept, but in order to decrease the quantity of organic waste, the MELiSSA objective will be the use the liquefying compartment.

Table 21: water flow rate for hygiene facilities

	Water involved [kg/day.man]	Solids involved [mass percentage]
Personal Hygiene	5.5	0.13
Wash Water	12.5	0.44
Latent Water		
Hygiene	0.462	
Washing	0.06	
Toilette Water	0.5	
Total	18.986	62.15 g/d.p.

The interface diagram between the MELiSSA loop, the Higher Plants Chamber and the different functions of the Life Support System is reported in figure 2.

III.3- Description of MELiSSA compartments with the objective of a mass balance simulation

This section reviews the stoichiometries of each MELiSSA compartment, used to represent their mass-balanced behaviour. Some updates were made concerning the nitrifying compartment and the photoheterotrophic compartment according to the results presented respectively in TN 32.1 and 23.3.

Crew - Digestion of food	Keys for resolution
$[CHONSP]_{food} + O_2$ $\Downarrow$ $[CHONSP]_{faeces} + CO_2 + H_2O + H_2SO_4 + H_3PO_4 + NH_3 + VFA + Urea$	% Faeces proteins fixed % Faeces lipids fixed % Faeces carbohydrates calculated with non digestible fibres % VFA and composition fixed O_2 consumption fixed % NH3 fixed
Crew - Hygiene [table 21] 18.986 kg water /day.man + 62.15 g solids/day.man $\Downarrow$ 0.468 kg latent water /day.man + 18.518 kg waste waster /day.man + 62.15 g solids/day.man	

Liquefying compartment	Keys for resolution
Proteins acidogenesis Proteins + H2O $\Rightarrow$ Amino acids Amino Acids + $H_2O \Rightarrow CO_2 + H_2 + VFA$	% faecal proteins degraded % Amino acid composition of proteins known End product (VFA) of each amino acid known
Carbohydrate acidogenesis CHO + 0.1667 H2O $\Rightarrow$ 0.5 Acetate	% of carbohydrates degraded Fibres assimilated to carbohydrates
Lipids acidogenesis CHO + 0.875 H2O $\Rightarrow$ 0.5 Acetate + 1.375 H_2	% of lipids degraded
VFA acetogenesis - 1 equation for each VFA $[CHO]_{VFA} + H_2O \Rightarrow CO_2 + Acetate + H_2$	Only for C5 and C6 VFA
Methanogenesis - from CO_2 $CO_2 + 4\,H_2 \Rightarrow CH_4 + 2\,H_2O$	No methanogenesis
Methanogenesis - acetoclastic $Acetate + H_2 \Rightarrow CH_4 + CO_2$	No methanogenesis

Photoheterotroph compartment	Keys for resolution
$Acetate + 0.3876\,NH_3 + 0.0282\,H_3PO_4 + 0.0062\,H_2SO_4$ $\Downarrow$ $1.8505\,CH_{1.5951}O_{0.3699}N_{0.2094}S_{0.0034}P_{0.0152} + 0.1495\,CO_2 + 1.1540\,H_2O$	% Acetate assimilated
$Propionate + 0.6782\,NH_3 + 0.0493\,H_3PO_4 + 0.0102\,H_2SO_4 + 0.2383\,CO_2$ $\Downarrow$ $3.2383\,CH_{1.5951}O_{0.3699}N_{0.2094}S_{0.0034}P_{0.0152} + 2.5195\,H_2O$	% Propionate assimilated
$Butyrate + 0.9689\,NH_3 + 0.0704\,H_3PO_4 + 0.0156\,H_2SO_4 + 0.6261\,CO_2$ $\Downarrow$ $4.6261\,CH_{1.5951}O_{0.3699}N_{0.2094}S_{0.0034}P_{0.0152} + 1.8850\,H_2O$	% Butyrate assimilated

Nitrifying compartment	Keys for resolution
$13.0108\ NH_3 + 0.0136\ H_3PO_4 + 0.0041\ H_2SO_4 + CO_2 + 24.5215\ O_2$ ⇓ $CH_{1.6097}O_{0.3777}N_{0.2107}S_{0.0046}P_{0.0136} + 12.3357\ H_2O + 12.8001\ HNO_3$	% Ammonia oxidised

Photosynthetic compartment (Spiruline)	Keys for resolution
$HNO_3 + H_3PO_4 + H_2SO_4 + CO_2$ ⇓ $[\ CHONSP]_{Biomass} + H_2O + O_2$	Irradiance (W/m^2) Composition (Proteins, Carbohydrates, Lipids, Nucleic Acids, Exopolysacharide) function of irradiance % Nitrate assimilated

For the liquefying compartment, the equations are different of those proposed by Dries et al. (TN 34.1), but will be probably updated accordingly to the results obtained at Gent.

Each MELiSSA compartment is represented by one or more stoichiometric equations. Some of them depends on the composition of the substrate (crew and liquefying bioreactor). The quality of the biomass produced by the photosynthetic compartment depends on the irradiance on the photobioreactor (TN 17.3).

An ideal gas-liquid equilibrium is supposed in each bioreactor (TN 17.1, 23.1).

III.4- Description of HPC for the MELiSSA loop design

The Higher Plants Chamber is composed of a set of 8 plants described in section 2.2.1. The crop composition (ratio of each plant) is deduced from the results obtained for the diet menu reported in table 17c. This crop composition was determined in order to minimise the inedible part of the plants and the external food supply, with the use of *Spirulina* as the major proteic source (see the constraints reported in table 17c). The crop composition is reported in table 22.

The stoichiometries for the edible and the inedible part of the plants are reported in table 15 (see section 2.2). The key parameter used to define the HPC working conditions in steady state simulations is the production yield. This parameter was calculated via the diet management in order to minimise the external food supply, taking into account the variation in quality and quantity of the biomass (*Spirulina* and *Rhodobacter*) provided by the MELiSSA loop.

Table 22: Composition of the HPC in MELiSSA simulations.

	Crop composition % of dry edible plants	Evapotranspiration [$kg/m^2.day$]	
Tomato	0.8	5	Mean Value
Rice	16.1	5	Mean Value
Lettuce	0.5	1.2	Hernandez and de Llanza (1994)
Potato	29.5	5	Mean Value
Soybean	1.6	5	Mean Value
Spinach	1.6	5	Mean Value
Onion	1.6	5	Mean Value
Wheat	48.3	2.9	Hernandez and de Llanza (1994)

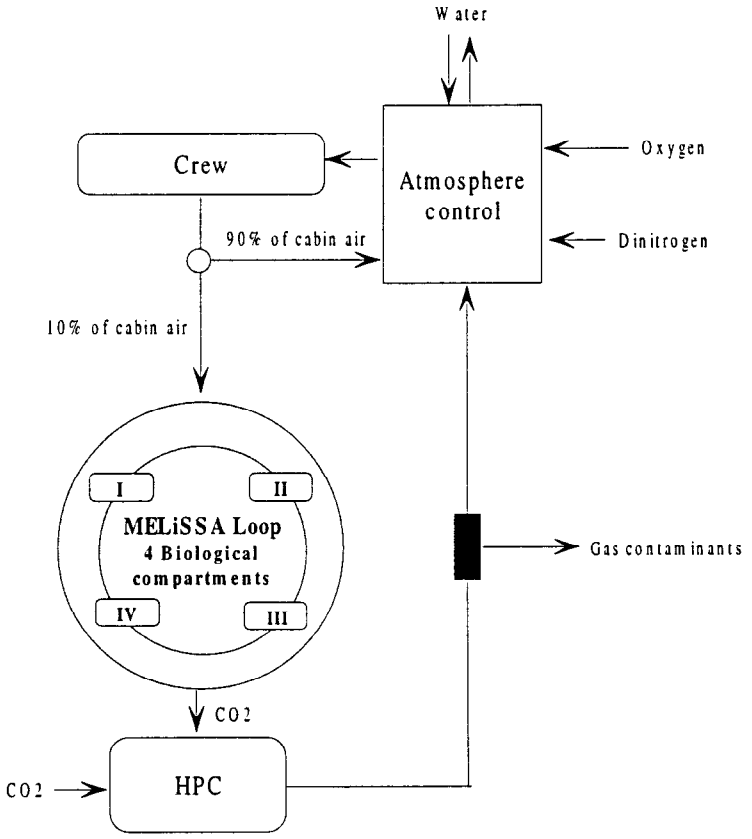
III.5 - Results of simulations

III.5.1 - Analysis of the flowsheet

The flowsheet involves liquid, gas and solid/biomass/food fluxes.

Gas management

All gas fluxes from bioreactors and HPC are dried and the condensate is used in water management. Only 10% of the gas flow rate of the crew air loop is recycled in the MELiSSA and HPC gas loop (e.g. 90% of the crew atmosphere is in a closed loop). A general scheme of gas flow is given below. There is in fact no real control of the gas flow rate in the bioreactors (in line gas flow). This will be one of the ways to precise in order to prepare dynamic simulation and pre scaling-up of the system. Final gas separators are placed at the end of the MELiSSA-HPC loop in order to eliminate gas trace (H_2, CH_4, CO_2). Inputs or outputs of gases (N_2, CO_2, O_2, Argon) are included in order to satisfy the atmosphere constraints (table 19).



Water management

Water is provided to the crew for drink, hygiene and food preparation. Water is recovered by condensation. At the present time, the control of water fluxes to maintain the bioreactors volumes and the plants nutrients concentration is not included in the steady state simulation. It is an important point to investigate if we want to determine the concentrations of the products in the input and the output liquid fluxes in the different compartments. The

water content of final liquid outputs from the photosynthetic compartment and from the HPC is considered completely recovered.

Minerals are supplied to the MELiSSA loop to compensate the loss in biomass and in non edible plants. The minerals in the ash (from organic waste oxidation) are supposed to be recovered in order to limit losses.

Diet management

The diet is defined in table 20. It controls the productions yields in the photosynthetic reactor (*Spirulina*) and in the HPC (quantity of plant produced; the ratio of each plants is defined as explained in section 3.4). An external food source supplies the crew in components (lipids, carbohydrates, proteins) not recovered from the loop. The objective of the diet management is to minimise these entries. The quantity of biomass in the diet can be limited if necessary.

In the MELiSSA loop alone, as in the previous description of the loop (TN 17.1), biomass dividers for Rhodobacter (Y) and *Spirulina* (Z) are added. It was demonstrated in the previous simulation that by allowing more or less biomass waste (i.e. by increasing or reducing Y and Z setting values) the behaviour of the loop varied from an atmosphere regenerator to a closed N-cycle.

List of main constraints applied to the system

- 10% of the cabin air loop recycled to the MELiSSA loop
- Output gas from bioreactor and HPC is dried
- Key parameters on bioreactors are fixed
- Biomass food is dried.
- All organic wastes are collected
- Habitability constraints (diet and atmosphere are fixed)
- HPC composition is fixed
- Ideal gas-liquid equilibrium is assumed in bioreactors
- Perspiration of the crew and evapotranspiration of plants are considered
- Condensate water is recycled
- Finals liquid fluxes are treated to recover all water

List of manipulated parameters (dll)

- Ratio of the produced *Spirulina* wasted (Z)
- Ratio of the produced Rhodobacter wasted (Y)
- Irradiance on the photosynthetic (Spirulina) compartment (Fo)
- Limitation of the biomass quantity in the diet
- Quantity of organic waste oxidised
- Presence or not of the Higher plants chamber in the MELiSSA design

III.5.2 - Simulation of the MELiSSA loop alone

A simulation of the MELiSSA loop alone (without the HPC) was performed, with the flow design presented in figure 2 and the updated stoichiometric equations. The irradiance on

the photosynthetic compartment was set to 300 W/m^2. The organic waste are not treated (not oxidised) and are then lost for the loop. Both Y and Z are set to 100% (all the edible biomass produced is consumed). In the previous simulations, this represents a loop behaviour where atmosphere regeneration is minimal and N-recycling is maximal. The results of the simulation give the same behaviours for the MELiSSA loop as the previous ones (TN 14.1;14.2;17.3).

It is more interesting to compare the recycling efficiencies of the system with and without HPC, the other parameters being unchanged. The recycling efficiencies and the estimated total mass flow rates of resupply for the loop with and without HPC are reported in table 23 and figure 3.

Table 23: Simulation of the MELiSSA with and without HPC

Parameters with and without HPC				
Biomass total	Y (Ṙh)	Z (Sp)	O.M. Oxidised	Sp Light (W/M^2)
Free	100%	100%	0%	300

	N-Recycling	S-Recycling	Water Recycling	CO2 Recycling	O2 Recycling	P-Recycling
Without HPC	99	100<	> 101	44	46	100<
With HPC	91	80	> 100	100	172	100<

	% of Biomass in Diet	% Sp in biomass	% of Supplied Diet	% of Plants in diet	Total Entry (g/p.d.)
Without HPC	48.47	64.53	51.53	0	935
With HPC	21.86	45.33	8.63	65.51	1300

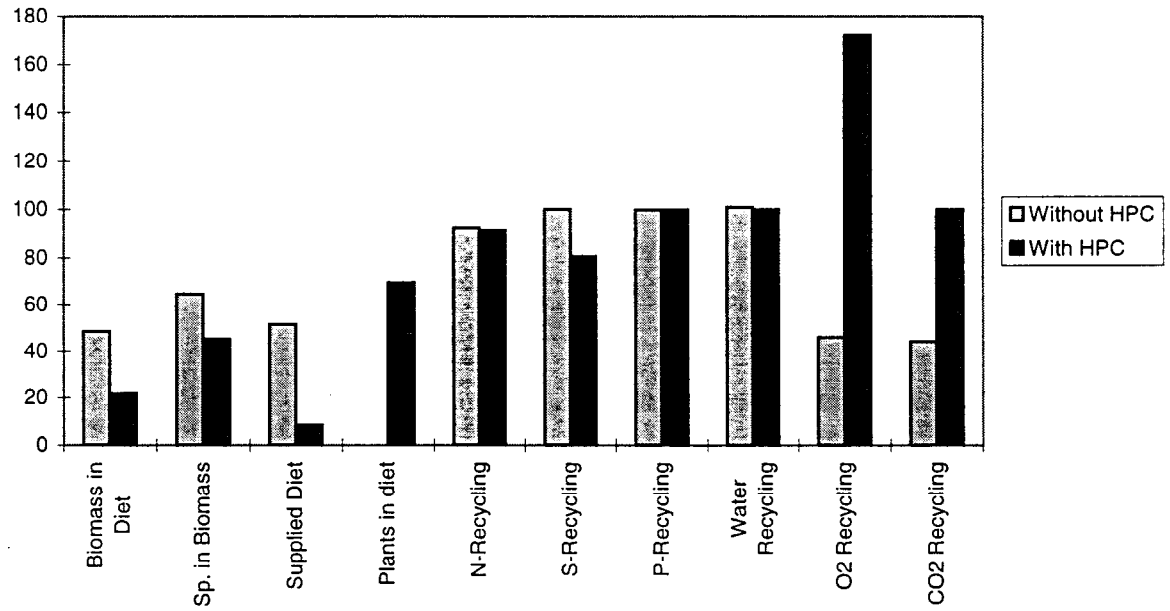


Figure 3: Comparison of the recycling efficiencies for MELiSSA with and without a Higher Plants Compartment

Note: In simulations without HPC, the quantity of oxygen consumed by the crew was reduced to 90% of the calculated value (using the relation between O_2 consumed and the metabolic rate [TN 17.1]). This has been necessary because of the resolution of the stoichiometry for the crew lead to a very low production of faeces (below 15 g/d.p.) and a high Respiratory Quotient (RQ over 0.92), which seems not realistic. That can be

confirmed by the results on rats feeded with *Spirulina* (Test Report YCV/932.DDC/if) which indicate a lower respiratory metabolism for a diet of 40% *Spirulina.*

First it can be noticed that for mineral (N, S and P) and water recycling the loop performances are similar. If with HPC the N and S recycling efficiencies are lower, it is due to the non edible part of plant which contains N and S and is not recycled.

With the plants, the system is able to regenerate the atmosphere. In fact it produce oxygen (172% of the system needs). But carbon dioxide must be imported to the HPC for the growth of the plant. This represents most of the mass of resupply to this loop, while in the loop without HPC the resupply is composed of oxygen and food.

The lack of carbon dioxide in the HPC justifies of the addition of a physico-chemical treatment of the organic waste to produce CO_2 and then increase the recycling efficiency of the loop.

The term "total entry" means all products (CO_2, O_2, food, water...) provided to the loop. Without HPC, oxygen represents the main part of the mass to supply to the loop. With HPC, CO2 is the main part of the mass to supply to the loop.

III.5.3 - Simulation of the MELiSSA loop with HPC

The only way to reduce the resupply in carbon dioxide for the plants is to oxidise the organic waste produced by the system in order to produce the carbon dioxide required for the plant growth. Three ways can be considered. The first consists in a physico-chemical process (wet oxidation, SCWO, combustion/incineration), the second consists in taking the advantage of the possible ability of the liquefying compartment to degrade the plants, the third will be the addition of another "biological" compartment composed of animals able to eat the plants waste.

Simulation of the system based on MEliSSA loop including a Higher Plant Chamber and a physico-chemical treatment of plants were performed.

First the effect of the quantity of organic matter processed in the physico-chemical treatment (assimilated to an incinerator in a first approach) and the variations of Y (ratio of *Rhodospirillum rubrum* produced used in the diet) was investigated.

Recycling of the non edible and the non consumed biomass and plants

The percentage of the organic matter (mainly represented by the non edible part of the plant) processed in the physico-chemical treatment was changed from 100% to 0%. The recycling efficiencies of the system were reported in table 24 and figures 4a and 4b.

The optimal quantity of organic waste recycled is about 80%. This oxidation uses the excess of oxygen (mainly produced by the plants) to produce the CO_2 required for the plant growth. For this value of 80% the mass of resupply is minimal.

The value of 100% for the CO_2 recycling must be carefully considered because an entry of CO_2 on the loop is considered. These 100% mean that all the CO_2 produced and introduced in the loop is assimilated in the biomass and the plants.

Table 24: Recycling efficiencies of the MELiSSA+HPC loop for various quantities of wasted organic matter oxidised (Rh=*Rhodospirillum rubrum*; Sp=*Spirulina*).

		Parameters		
HPC	Biomass total	Y (Rh)	Z (Sp)	Sp Light (W/m^2)
Yes	Free	100	100	300

Organic matter oxidised (%)	Biomass in Diet %	Sp in biomass %	Supplied Diet %	Plants in diet %	Total Entry * (g/day.man)
100	21.86	45.33	8.63	69.51	321
90	21.86	45.33	8.63	69.51	241
80	21.86	45.33	8.63	69.51	237
70	21.86	45.33	8.63	69.51	315
55	21.86	45.33	8.63	69.51	523
35	21.86	45.33	8.63	69.51	809
15	21.86	45.33	8.63	69.51	1085
0	21.86	45.33	8.63	69.51	1300

Organic matter oxidised (%)	N-Recycling %	S-Recycling %	P-Recycling %	Water Recycling %	O2 Recycling %	CO2 Removal %
100	100	100	100	> 100	89	94
90	99	98	100	> 100	94	98
80	98	96	100	> 100	98	100
70	97	94	100	> 100	104	100
55	96	91	100	100 <	114	100
35	94	87	100	100 <	129	100
15	92	83	100	100<	153	100
0	91	80	100	100 <	172	100

* Total entry represents the sum of all compound that must be supply to the loop, including oxygen, carbon dioxide, water and food.

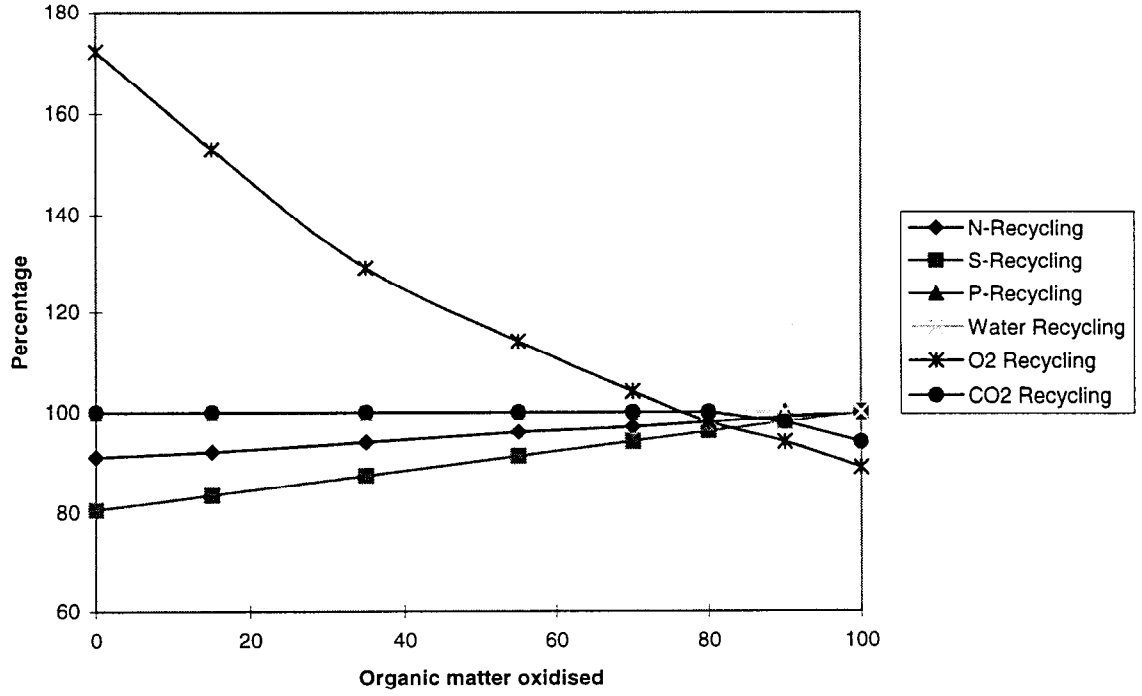


Figure 4a: Recycling efficiency of the system MELiSSA+HPC for different quantities of non edible organic matter (wastes) oxidised.

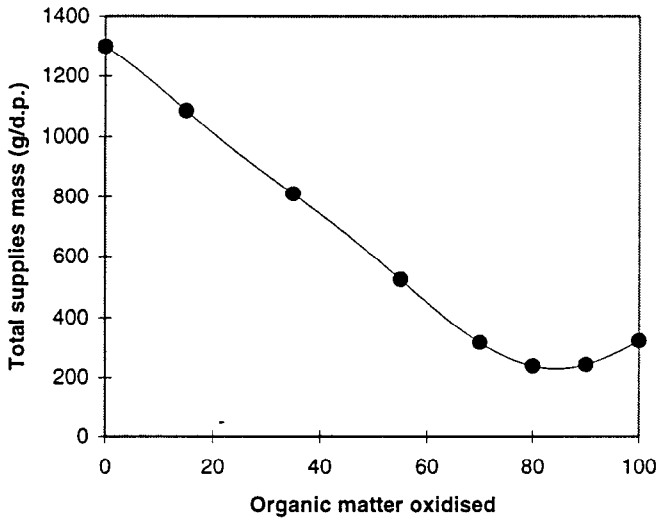


Figure 4b: Mass supplied to the system MELiSSA+HPC for different quantities of non edible organic matter (wastes) oxidised.

Influence of the quantity of *Rhodospirillum rubrum* in the diet

The influence of the quantity of *Rhodospirillum rubrum* in the diet (parameter Y) was studied, considering the oxidation of 80% of the organic waste.

The results of the simulations are reported in table 25 and figures 5a and 5b.

The decrease of the oxygen recycling is both the result of an increase of the biomass content in the diet and of an increase of the quantity of organic matter to oxidise.

If all the recycling efficiencies stay in the range of 90-100%, the mass of resupply is inceased when Y is varied from 0% to 100%. This is the result of the increase of the oxygen resupply and to a lower extent to the food resupply.

Table 25: Recycling efficiencies of the MELiSSA+HPC loop for various values of Y.

Parameters				
HPC	Biomass total	Z	O.M. Oxidised	Sp Light (W/m^2)
Yes	Free	100	80	300
Yes	Free	100	80	300
Yes	Free	100	80	300
Yes	Free	100	80	300

Y % of Rs used in diet	Biomass in Diet %	% Sp in biomass	Supplied Diet %	Plants in diet %	Total Entry* (g/day.man.)
100	21.86	45.33	8.88	69.51	237
80	23.33	55.9	8.79	67.99	231
60	24.55	65.09	8.96	66.49	256
40	25.86	73.09	9.12	65.02	275
20	27.15	80.11	9.27	63.58	291
0	28.41	100	9.43	62.16	298

Y % of Rs used in diet	N-Recycling %	S-Recycling %	P-Recycling %	Water Recycling %	O_2 Recycling %	CO_2 Removal %
100	98	96	100<	>100	98	100
80	96	97	100<	>100	98	100
60	95	98	99	>100	96	100
40	94	99	99	>100	96	100
20	94	99	99	>100	95	100
0	93	100<	99<	>100	95	100

* Total entry represents the sum of all compound that must be supply to the loop, including oxygen, carbon dioxide, water and food.

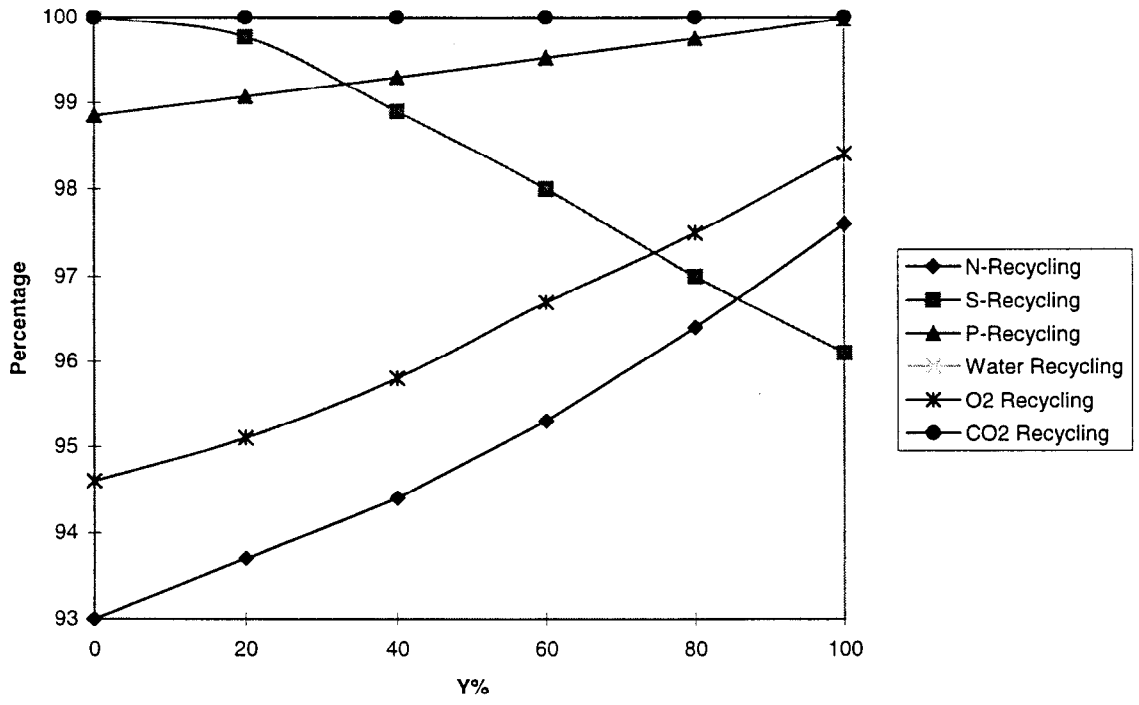


Figure 5a: Recycling efficiency of the system MELiSSA+HPC for different values of Y (percentage of *Rs. rubrum* used in the diet).

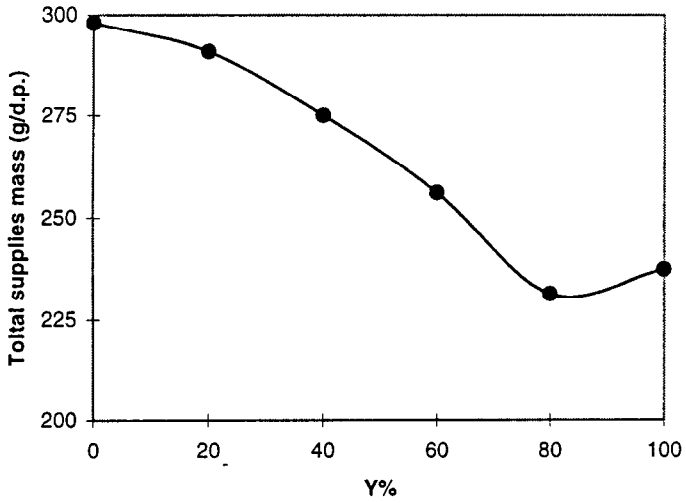


Figure 5b: Mass supplied to the system MELiSSA+HPC for different values of Y (percentage of *Rs. rubrum* used in the diet).

Conclusion

After an overview of the current state of art of Higher Plants Chamber into Biological Life Support Systems, the bases for the integration of an higher Plants Chamber in the global steady-state simulation design of a MELiSSA loop based BLSS were established. This include:

- a first choice of a varied pool of plants for the Higher Plant Chamber
- a mass-balanced representation of the growth of plants (i.e. stoichiometries)
- the determination of a diet menu based on plants and on the biomass (*Spirulina* and *Rs. Rubrum*) produced by the MELiSSA loop, taking into account the daily metabolic requirement of a man.

Once the Higher Plants Chamber was defined, it was integrated into a MELiSSA loop based BLSS. The flow-sheet analysis indicated the existence of 5 manipulated parameters.

The comparison of the performance of the BLSS with and without HPC was simulated. The presence of HPC increases the recycling performances of the BLSS, and offers a more varied food to the crew. Nevertheless, there is an important quantity of non edible plants produced by the HPC. With HPC, the system produces more oxygen (172%) than the requirements, and a CO_2 gas supply is needed for the plants. Finally, the mass of supply (food, O_2, CO_2,...) is high in the 2 configurations (935 g/day.man without HPC and 1300 g/day.man with HPC).

To reduce the entries, an oxidiser was added. Its objective is to produce CO_2 from the non edible organic waste (mainly plants), using the excess of oxygen produced by the loop. A minimun of mass entries is obtained when 80% of the organic matter wasted by the loop is oxidised, and all recycling efficiencies are over 95%.

The influence of the quantity of *Rs. Rubrum* used in the diet was investigated. With the oxidation of organic matter, this parameter has a relative low influence on the global efficiency of the loop.

The recycling (oxidation) of an important part of the non edible plant and biomass is of crucial importance for the recycling efficiency of the loop. At the present time a process using the excess of oxygen to produce CO_2 was added, but the most interesting feature would be the use of the liquefying compartment to produce CO_2 from organic waste.

Another option can be to define the HPC in an objective of atmosphere regenerator instead of a food producer, and then reducing the waste produced. But for this option more food will be supply from external.

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Factors	Hydroponics	Aeroponics	Soil
Nutrient System (General description)	Liquid solution (bathes plant roots)	Mist (thin film on plant roots)	Soil solution (thin film on media particles and roots)
Amount required per plant	High volume of solution	Low volume of solution	Moderate portion stored in rood media
Weight per plant	High	Low	High
Respiration oxygen needs	Requires aeration system	Misting results in aeration	Present as result of porous root media
Nutrient concentration	High (e.g. nitrogen 310-620 ppm)	High (e.g. nitrogen 310-620 ppm)	Low (e.g. nitrogen 101-150 ppm)
Nutrient sources	Restricted to nutrient solution	Restricted to nutrient solution	Replenished from root media
Supply and maintenance of nutrients	Needs frequent maintenance and adjustments. Amenable to adjustments.	Needs almost daily replenishment. Amenable to adjustments	Adequate amounts of nutrients can be stored on media matrix. Not readily adjusted - additionally nutrients can be added.
pH	Susceptible to variation of remaining nutrient ratios	Susceptible to variation of remaining nutrient ratios	Buffered by ion exchange capacity of media

WEIZEN | **WHEAT** | **BLÉ**
GANZES KORN | WHOLE GRAIN | GRAINS ENTIERS

TRITICUM VULGARE VILL.

		PROTEIN	FAT	CARBOHYDRATES	TOTAL
ENERGY VALUE (AVERAGE) PER 100 G EDIBLE PORTION	KJOULE	223	78	1020	1322
	(KCAL)	53	19	244	316
AMOUNT OF DIGESTIBLE CONSTITUENTS PER 100 G	GRAM	9.26	1.80	60.97	
ENERGY VALUE (AVERAGE) OF THE DIGESTIBLE FRACTION PER 100 G EDIBLE PORTION	KJOULE	176	70	1020	1267
	(KCAL)	42	17	244	303

WASTE PERCENTAGE AVERAGE 0.00

CONSTITUENTS	DIM	AV		VARIATION	AVR	NUTR. DENS.	MOLPERC.
WATER	GRAM	13.20		12.80 - 13.50	13.20	GRAM/MJ	10.42
PROTEIN	GRAM	11.73	1	10.20 - 13.21	11.73	GRAM/MJ	9.26
FAT	GRAM	2.00		1.90 - 2.10	2.00	GRAM/MJ	1.58
AVAILABLE CARBOHYDR.	GRAM	60.97	2	- - -	60.97	GRAM/MJ	48.13
TOTAL DIETARY FIBRE	GRAM	10.30	3	- - -	10.30	GRAM/MJ	8.13
MINERALS	GRAM	1.80		1.38 - 2.50	1.80	GRAM/MJ	1.42
SODIUM	MILLI	7.80		6.60 - 9.00	7.80	MILLI/MJ	6.16
POTASSIUM	MILLI	502.00		432.00 - 571.00	502.00	MILLI/MJ	396.26
MAGNESIUM	MILLI	147.00		119.00 - 175.00	147.00	MILLI/MJ	116.04
CALCIUM	MILLI	43.70		39.40 - 48.00	43.70	MILLI/MJ	34.50
MANGANESE	MILLI	3.40		2.40 - 4.30	3.40	MILLI/MJ	2.68
IRON	MILLI	3.30		3.10 - 3.50	3.30	MILLI/MJ	2.60
COBALT	MICRO	2.00		0.50 - 9.00	2.00	MICRO/MJ	1.58
COPPER	MILLI	0.63		0.48 - 0.78	0.63	MILLI/MJ	0.50
ZINC	MILLI	4.10		2.20 - 10.00	4.10	MILLI/MJ	3.24
NICKEL	MICRO	34.00		16.00 - 89.00	34.00	MICRO/MJ	26.84
CHROMIUM	MICRO	3.00		2.00 - 175.00	3.00	MICRO/MJ	2.37
MOLYBDENUM	MILLI	-		0.02 - 0.08			
VANADIUM	MICRO	-		2.00 - 230.00			
PHOSPHORUS	MILLI	344.42		341.00 - 406.00	344.42	MILLI/MJ	271.87
CHLORIDE	MILLI	55.00		- - -	55.00	MILLI/MJ	43.41
FLUORIDE	MICRO	90.00		10.00 - 400.00	90.00	MICRO/MJ	71.04
IODIDE	MICRO	0.60		- - -	0.60	MICRO/MJ	0.47
BORON	MILLI	-		0.20 - 0.73			
SELENIUM	MICRO	-	4	0.70 - 130.00			
SILICON	MILLI	8.00		5.00 - 19.00	8.00	MILLI/MJ	6.31

1 VARIATION: LOW VALUE: MW SOFT WHEAT VARIETIES (1)
HIGH VALUE: MW OF HARD WHEAT VARIETIES

2 ESTIMATED BY THE DIFFERENCE METHOD (2)
100 - (WATER + PROTEIN + FAT + MINERALS + TOTAL DIETARY FIBRE)

3 METHOD OF MEUSER, SUCKOW AND KULIKOWSKI ("BERLINER METHODE") (3)

4 GREAT REGIONAL DIFFERENCES: USA 5 - 100 UG/100 G
MIDDLE AMERICA: 100 - 3000 UG/100 G (4)
SCANDINAVIAN COUNTRIES: 0,3 - 1,0 UG/100 G

Appendix 3: an example of the food composition table (Soucy et al. 1990)

CONSTITUENTS	DIM	AV	VARIATION			AVR	NUTR. DENS.		MOLPERC
ARGININE	GRAM	0.38	-	-	-	0.38	GRAM/MJ	0.27	2.4
ASPARTIC ACID	GRAM	0.71	-	-	-	0.71	GRAM/MJ	0.51	6.0
CYSTINE	GRAM	0.10	-	-	-	0.10	GRAM/MJ	0.07	0.5
GLUTAMIC ACID	GRAM	2.29	-	-	-	2.29	GRAM/MJ	1.65	17.5
GLYCINE	GRAM	0.43	-	-	-	0.43	GRAM/MJ	0.31	6.4
HISTIDINE	GRAM	0.22	-	-	-	0.22	GRAM/MJ	0.16	1.6
ISOLEUCINE	GRAM	0.58	-	-	-	0.58	GRAM/MJ	0.42	5.0
LEUCINE	GRAM	1.36	-	-	-	1.36	GRAM/MJ	0.98	11.6
LYSINE	GRAM	0.26	-	-	-	0.26	GRAM/MJ	0.19	2.0
METHIONINE	GRAM	0.20	-	-	-	0.20	GRAM/MJ	0.14	1.5
PHENYLALANINE	GRAM	0.44	-	-	-	0.44	GRAM/MJ	0.32	3.0
PROLINE	GRAM	1.55	-	-	-	1.55	GRAM/MJ	1.12	15.1
SERINE	GRAM	0.42	-	-	-	0.42	GRAM/MJ	0.30	4.5
THREONINE	GRAM	0.44	-	-	-	0.44	GRAM/MJ	0.32	4.1
TRYPTOPHAN	GRAM	0.11	-	-	-	0.11	GRAM/MJ	0.08	0.6
TYROSINE	GRAM	0.25	-	-	-	0.25	GRAM/MJ	0.18	1.5
VALINE	GRAM	0.58	-	-	-	0.58	GRAM/MJ	0.42	5.6
SUCROSE	GRAM	1.68	0.93	-	3.90	1.68	GRAM/MJ	1.21	
RAFFINOSE	GRAM	0.23	0.10	-	0.39	0.23	GRAM/MJ	0.17	
STACHYOSE	GRAM	0.10	0.05	-	0.21	0.10	GRAM/MJ	0.07	
CELLULOSE	GRAM	3.50	1.20	-	5.20	3.50	GRAM/MJ	2.53	
MYRISTIC ACID	MILLI	5.00	0.00	-	10.00	5.00	MILLI/MJ	3.61	
PALMITIC ACID	MILLI	340.00	310.00	-	350.00	340.00	MILLI/MJ	245.58	
STEARIC ACID	MILLI	90.00	70.00	-	110.00	90.00	MILLI/MJ	65.01	
ARACHIDIC ACID	MILLI	70.00	0.00	-	200.00	70.00	MILLI/MJ	50.56	
BEHENIC ACID	MILLI	-	0.00	-	110.00				
LIGNOCERIC ACID	MILLI	-	0.00	-	30.00				
PALMITOLEIC ACID	MILLI	25.00	10.00	-	30.00	25.00	MILLI/MJ	18.06	
OLEIC ACID	GRAM	0.99	-	-	-	0.99	GRAM/MJ	0.72	
LINOLEIC ACID	GRAM	1.01	-	-	-	1.01	GRAM/MJ	0.73	
LINOLENIC ACID	MILLI	70.00	-	-	-	70.00	MILLI/MJ	50.56	
DIETARY FIBRE,WAT.SOL.	GRAM	1.01	0.93	-	1.09	1.01	GRAM/MJ	0.73	
DIETARY FIBRE,WAT.INS.	GRAM	6.27	5.78	-	6.99	6.27	GRAM/MJ	4.53	