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CELSS Experiment Model and Design Concept of Gas Recycle System

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ABSTRACT

In order to prolong the duration of manned missions around the earth and to expand the human existing region from the earth to other planets such as a Lunar Base or a manned Mars flight mission, the CELSS becomes an essential factor of the future technology to be developed through utilization of Space Station.

The preliminary SE&I (System Engineering and Integration) efforts regarding CELSS have been carried out by the Japanese CELSS concept study group for clarifying the feasibility of hardware development for Space Station Experiments and for getting the time phased mission sets after Fy 1992. The results of these studies are breifly summarized and thereafter, the design and utilization methods of a Gas Recycle System for CELSS experiments are discussed.

1. PROPOSED EXPERIMENTS AND ITS MISSION ANALYSIS

According to NASA's call for international participation in the Space Station program, data sources for Space Station Utilization concepts in many fields have been collected at the Japanese Space Station Symposium held in October 1982. Among the papers presented at this Symposium, eleven experiment proposals as shown in Table 1 related to CELSS have been extracted as the data source for CELSS mission analysis. Using these data sources, extensive study for clarifying the development feasibility of hardware necessary to conduct the CELSS experiments with state of art equipment have been conducted.

Each proposed theme was divided into the research items closely connected with experiment hardware and the necessary time spans for developing hardware were investigated considering the technological maturity and effectiveness for experiments. Table 2 shows the strawman CELSS experiment concept and is described in next section.

2. CELSS EXPERIMENT CONCEPT

The CELSS is the technology for making a stable ecology among animals and plants without re-supply of materials and using a special controlled environment. Therefore the CELSS would be divided into two sections; the environmental control section and the cultivating and breeding section of plants and animals. In the environment control section, at least three major systems, shown Fig. 1, should be installed for sustaining the gas environment, for water recycle and for decomposing waste materials into a fertilizer solution.

In the cultivating and breeding section, the Algae and higher plant cultivation systems for converting carbon dioxide to oxygen and for producing food are to be installed. In addition aminal and fish breeding systems for obtaining animal protein should also be installed.

In order to develop CELSS technology, it is necessary to take a long time span as described in previous section because basic ground based experiments related to the CELSS are required before developing the flight experiment hardware, and also because the data of stabilities about the morphogenesis and physiology of the higher plants and algae in space environment have not been fully accumulated at the present time.

Based on the above considerations, the time phased mission sets for utilizing the space station were determined as a Japanese strawman CELSS mission model. (Reference 1) (Nitta, 1984)

According to this mission model, the first time mission is to be conducted during 1992 - 1995 for evaluating the higher plant and algae cultivation methods and for summing up the available data about the stability of

Table 1 Proposed Theme

No.	Theme	Description of Content
EL-01	Agricultural Laboratory in Space	Fungi production for cellulose decomposition, animal and fish breeding for food production, higher plant and algae plantation for food production and gas conversion, salt accumulation plant for sodium chloride extraction, hydrophyte planting for nitrogen fixation, methanogen fermentation for waste management and construct the closed ecology with bio species mentioned above.
EL-02	Space Agriculture Experiment	Vegetable planting for food production and gas conversion. Solar light supply system for photosynthetic reaction of vegetable.
EL-03	Study on Space Agriculture and Closed Ecological Life Support System	Gas recycle system for stabilizing gas environment, water recycle system for suppling the necessary water, wet oxidation system for waste management, higher plant and algae cultivator for food production and gas conversion, physico-chemical sodium extraction system, and low gravity generator for testing geotropism.
EL-04	Non-Gravity Plant Experiment System	Chetotaxis experiment in 0G. Organella growth experiment in 0G and geotropism experiment of higher plant.
EL-05	Project for establishments of Breeding and Management System of several Higher Animals under Space Environment	Reproduction, growth, enbryogenesis and genetics experiment in 0G using Mouse, Quail and Tilapia, and breeding technology development for future food production.
EL-06	Micro-Ecological System in Space Station	Gas recycle system, water recycle system and incineration waste management system are recommended.
EL-07	Microbial Fermentor in very low gravitational force	Space-use fermentor design for practical use of microbes in environment control.
EL-08	Field of Plant Research in Space Station	Cell culture, pathogen study and protein rich flour separation using 0G.
EL-09	Plant Experiment Subsystem	Plant cultivator, phytotron design.
EL-10	Biochemical Studies on elementary cycles in a Closed Ecosystem	Simple ecosystem and immobilized enzyme bio-reactor for supplementary food production.
EL-11	Space Station with an Artificial Gravity	Large scale ecological life support experiment station.

Table 2 Proposed Research Items

Exp. No.	Items contained	1991 ~1994	1995 ~1998	1999 ~	Reasons
EL-01	(1) Higher plant for food	V	V	V	Essentially required for CELSS
	(2) Microbial waste management			V	After the sludge problem is solved
	(3) Sodium accum. plant	V	V		Easy to conduct with phytotron
	(4) Hydrophyte for fertilizer			V	After the effectiveness is examined
	(5) Fish and Animal		V	V	Essential for animal protein
	(6) Fungus			V	After the effectiveness is examined
	(7) Integrated ecological test		V		Possible if physico-chemical systems introduced
EL-02	(1) Experiment module		V		Dedicated mission
	(2) Solar collector system	V	V		Required for higher plant
	(3) Vegetable for foods	V	V		Same as EL-01 (1)
EL-03	(1) Experiment module		V		Same as EL-02 (1)
	(2) Animal and Fish		V	V	Same as EL-01 (5)
	(3) Gas separation and reservoir		V	V	Essential for eco-stabilization
	(4) Higher plant for foods	V	V	V	Same as EL-01 (1)
	(5) Algae for gas exchange	V	V	V	Essential for gas conversion
	(6) Food preparation			V	After eco-system established
	(7) Wet oxidation waste manage.		V	V	Essential for eco-stabilities
	(8) Physico-chemical sodium extract.		V	V	Easily obtained with water recycle system
	(9) Nutrient chemical product.		V	V	Easily obtained with wet oxidation method
	(10) Low-G generator		V		Essential for testing gravity effect
EL-04	(1) Chetotaxis		V	V	After feasibility study is conducted
	(2) Organella		V	V	Same as above
	(3) Geotropism of plant	V	V		Essential for plantation
EL-05	(1) Fish and Animal production		V	V	Same as EL-01 (5)
EL-06	(1) Higher plant for foods	V	V	V	Same as EL-01 (1)
	(2) Algae for efficient gas exchange	V	V	V	Same as EL-03 (5)
	(3) Incineration waste management			V	After feasibility is studied
	(4) Physico-chemical sodium extract.		V		Same as EL-03 (8)
	(5) Nutrient chemical production		V		Same as EL-03 (9)
EL-07	(1) Fermentor			V	Same as EL-01 (2)
EL-08	(1) Cell culture			V	After feasibility is studied
	(2) Pathogen	V			Necessary to grow the bio-species
	(3) Protein rich flour separ.			V	After feasibility is studied
EL-09	(1) Plant cultivator	V	V		Essential for plantation
EL-10	(1) Bioreactor for food product.			V	After technology is established
EL-11	(1) Future experiment module			V	Future concept

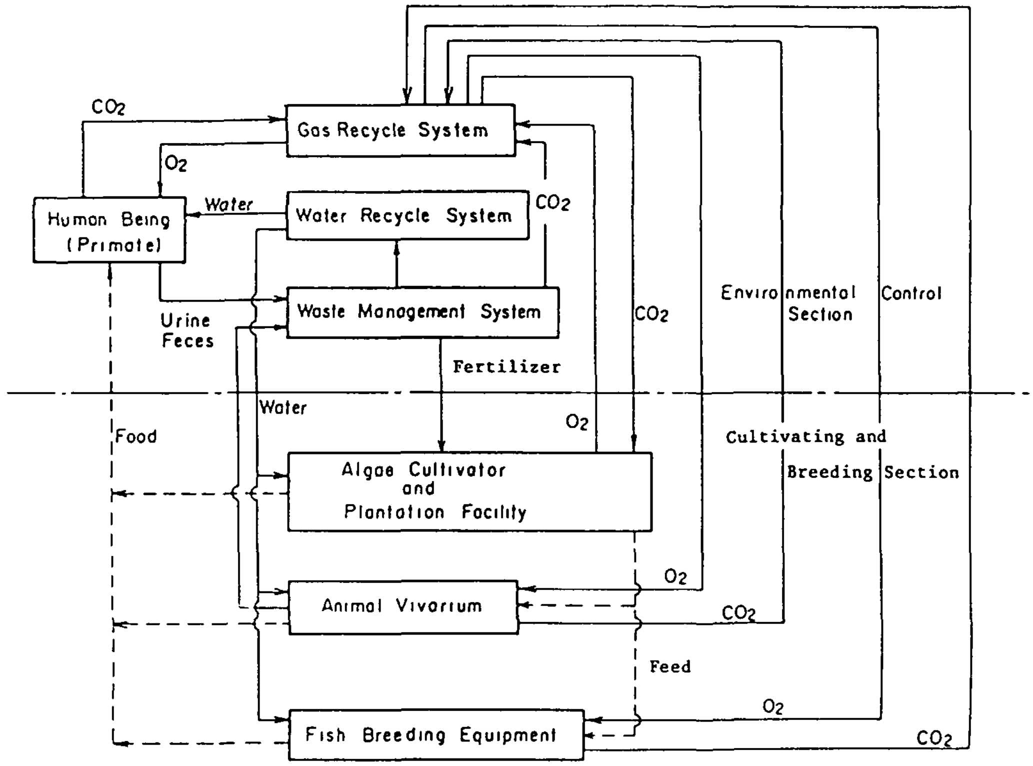

Fig. 1 CELSS Concept

photosynthesis and the possibility of propagation under the O-G environment in Manned Space Station.

The second time phased mission which constitutes the dedicated mission is to be conducted during 1995 - 1998 for checking the possibility of a micro closed-ecology system using animals and fish instead of human beings, and the testings and evaluation of the non-biological system performance such as the gas recycle system, the water recycle system and the wet oxidation waste management system. Artificial gravity effects on the biological system are also to be evaluated.

In the last time phased mission, the main food supply and gas conversion from carbon dioxide to oxygen for a one man crew support are to be tested using the photosynthetic reaction of the plant and algae and the necessary animal protein production systems are to be evaluated using small animals and fish.

The experiment architectures for each mission are shown in Fig. 2. Due to this mission model, the preliminary design of all hardware necessary to conduct each time phased experiments and the investigation of integration methods to the space station have been studied and reported as shown in references 2, 3.

3. FUNCTIONS OF GAS RECYCLE SYSTEM

The appropriate quantities of oxygen, food and water should be continuously supplied for human beings and animals, and carbon dioxide and waste materials such as urine and feces should be taken away.

Both the oxygen and food necessary to animals, including human beings, are originally generated from the photosynthetic reaction of plants and algae using carbon dioxide and solar light. The carbon dioxide concentration on the earth is stabilized by the function of atmospheric circulation and the gas reservior function of sea-water. This 0.03% CO_2 concentration is not always appropriate for plant growth and it seems preferable to use higher concentrations, 0.3% and so on, for obtaining maximum growth rate. Therefore, the Gas Recycle System to be used in CELSS experiments has to have the ability to supply different CO_2 concentrations to the cabin and animal vivarium and the phytotron or higher plant cultivator.

In other words, the Gas Recycle System should have the following functions,

(1) to separate carbon dioxide and oxygen within the atmosphere provided from the cabin, the animal vivarium and/or the phytotron individually,

(2) to compress the separated gases such that carbon dioxide, oxygen and nitrogen can be stored in high pressure bottles,

(3) to release and supply the appropriate gases to the cabin, the animal vivarium and the phytotron individually through gas regulator manifolds.

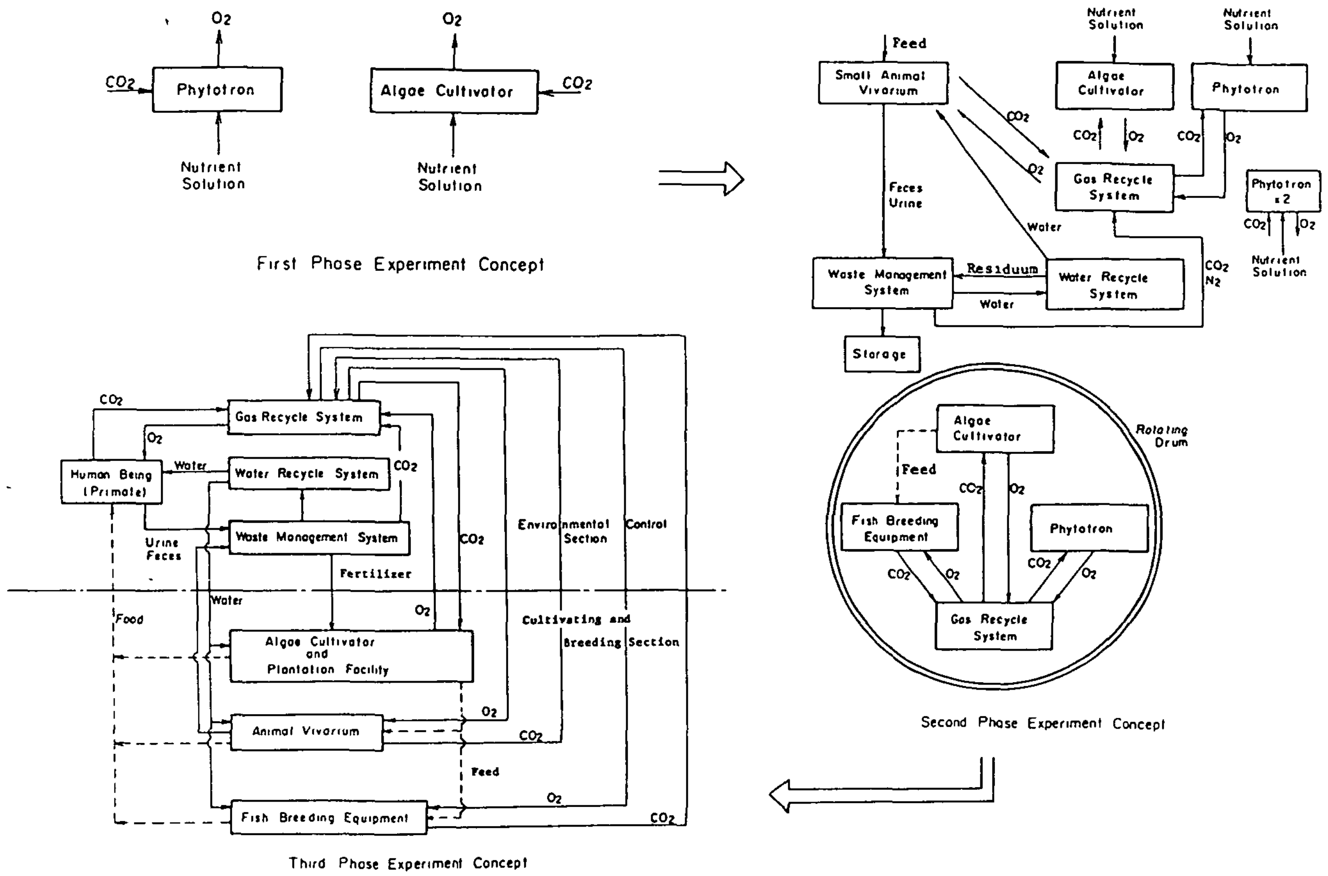

Fig. 2 Experiment Architectures of Each Mission

4. REQUIREMENTS FOR GAS RECYCLE SYSTEM

The various methods for separating each gas have been proposed and studied. (Reference 4-16)

Carbon dioxide gas separation, has typically used three methods, the molecular sieve, the hydrogen polarized cell and chemical absorption and desorption methods. Each has been discussed for application to CELSS experiments.

The molecular sieve method seems to be most reliable and has been used in Skylab, however dehumidification and the precise temperature and pressure control required for constructing the system using this method, would become more complicated. The hydrogen polarized cell method requires hydrogen to concentrate carbon dioxide, again the separation of hydrogen gas from the resultant gas and reduction of hydrogen gas are required.

The chemical absorption and desorption method seems to become more important since solid amine has been developed because of its regenerable and simple characteristics instead of LiOH, and the various applications are now being considered for use in the environmental control system in Space Station.

Therefore, based on this matter, this chemical method using the solid amine looks to be more preferable for adoption to the CELSS experiment hardwares.

As for the oxygen gas separation, three typical methods has been developed and used for various applications. One is again the molecular sieve method which has the same defect as mentioned above.

The second is the chemical absorption and desorption method using complex salt. This method has already been applied to testing the atmospheric control of the submarine and to the oxygen supply system for B-1 bomber, and this method is again preferable for being adopted to the CELSS experiment hardwares because of its simple characteristics.

The third one is the zirconia oxygen pumping method in which zirconia is used as a solid electrolyte for oxygen separation, this method also has simple characteristics and is preferable for being adopted to the CELSS experiment hardwares.

The gas recycle system capability to be designed has been assumed for supporting the respiration of a one man crew where the oxygen consumption per man-day is about 925 g/day and the carbon dioxide exhaust per man-day is about 1,130 g/day, corresponding to 30 lit./hr. of oxygen and 25 lit./hr. of carbon dioxide.

Therefore, the Gas Recycle System to be used in the CELSS experiments has to have the ability to supply these quantities of each gas.

5. DESIGN CONCEPT OF GAS RECYCLE SYSTEM

Fig. 3 shows the gas recycle sytstem functional *diagram*. Inlet gas is a mixture of O_2 (Oxygen), N_2 (Nitrogen), CO_2 (Carbon dioxide) and various trace contaminants.

At the filter, trace contaminants are removed.

CO_2 is separated and concentrated by a regenerable CO_2 absorber, and then, compressed and stored into the CO_2 gas bottle.

O_2 is also separated and concentrated by a regenerable O_2 concentrator, and, compressed and stored into the O_2 gas bottle.

Thus, inlet gas is separated and concentrated into CO_2, O_2 and N_2 gases.

Then, these gases are mixed properly and supplied to various utilities.

6. GAS ABSORPTION AND DESORPTION

In the gas recycle system, there are CO_2 and O_2 concentration processes. These are accomplished by two gas absorption and desorption processes, one is CO_2 absorption and desorption process using Solid Amine, and the other is O_2 absorption and desorption processes using Salcomine.

6.1 CO_2 Absorption and Desorption Process

CO_2 absorption and desorption is generally acomplished by using various kinds of amines, the chemical reaction could be described as shown below.

The solution of Ethanol Amine, such as Mono Ethanol Amine (MEA) and/or Diethanol Amine (DEA) absorbs CO_2 at the normal temperature and desorbs CO_2 at the high temperature, as indicated by the following reaction equation.

$$RR'NH + H_2O + CO_2 \underset{\text{(high temp.)}}{\overset{\text{(normal temp.)}}{\rightleftarrows}} RR'NH_2CO_3$$

where $R = HOCH_2CH_2$, $R' = H$, for MEA
$R = R' = HOCH_2CH_2$, for DEA

This reaction has been directly applied to the CO_2 scrubbing unit in submarines. However, in space craft under the microgravity environment, such chemical agents seem not to be appropriate because of the difficulties of the gas and liquid separation.

Therefore, the solidification method of the amine has been studied and developed. Solid Amine consists of micro porous beads whose surface are coated with an amine. The substrate of beads is composed of a polymeric acrylic ester. (Reference 17,18)

Fig. 4 shows the CO_2 separating and concentrating system diagram. In this system, Solid Amine absorbes CO_2 at the normal temperature, and outlet gas from the solid amine canister is CO_2 lean gas.

Part of the CO_2 lean outlet gas flow returns to the cabin atmosphere, and the residual part of the flow is led to the next process.

When one canister becomes saturated with CO_2, the inlet flow is switched to the other canister and CO_2 absorption is continued in the new canister. The CO_2 saturated Solid Amine canister is heated and desorbs the CO_2. This CO_2 gas is led to the CO_2 compressor to be compressed and stored.

These Solid Amine canisters are used as absorbing, desorbing and precooling, respectively, and by the combination of canister cooling and heating, continuous CO_2 separation and concentration can be accomplished.

6.2 O_2 Absorption and Desorption

The O_2 absorption and desorption process is carried out using Salcomine. Salcomine (Bis(3-ethoxy salicyl aldehyde) ethylene *diamine cobalt(II) - Fig. 5)* absorbes O_2 at normal temperature and desorbes O_2 at the high temperature. (Reference 1)

Fig. 6 shows the O_2 separating and concentrating system diagram.

In this system, O_2 is absorbed into the Salcomine and N_2 gas comes out of the

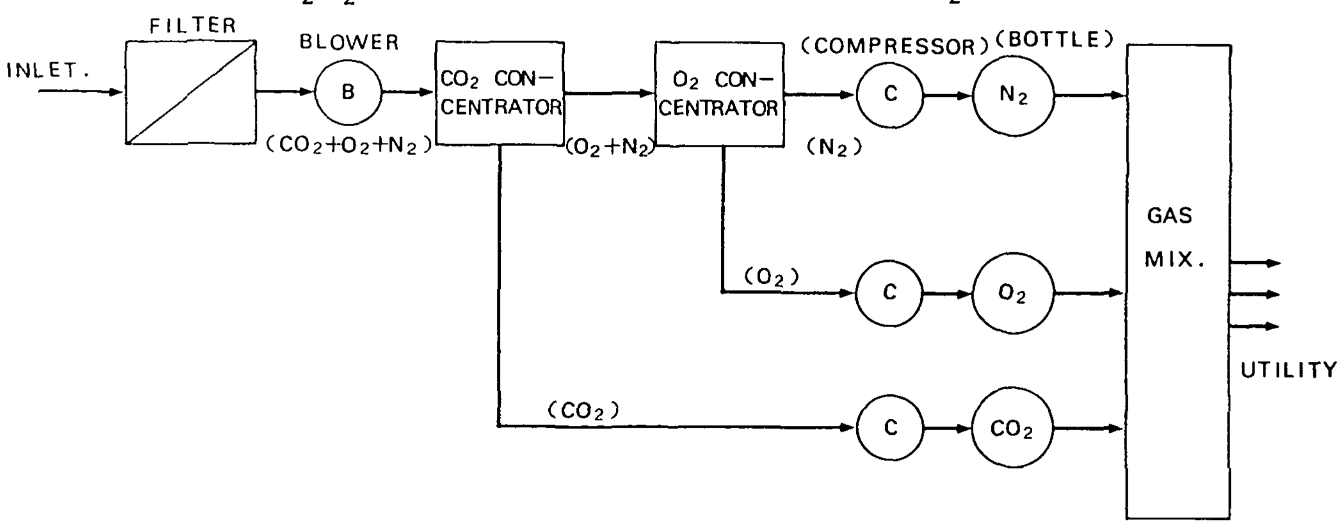

Fig 3 GAS RECYCLE SYSTEM FUNCTIONAL DIAGRAM

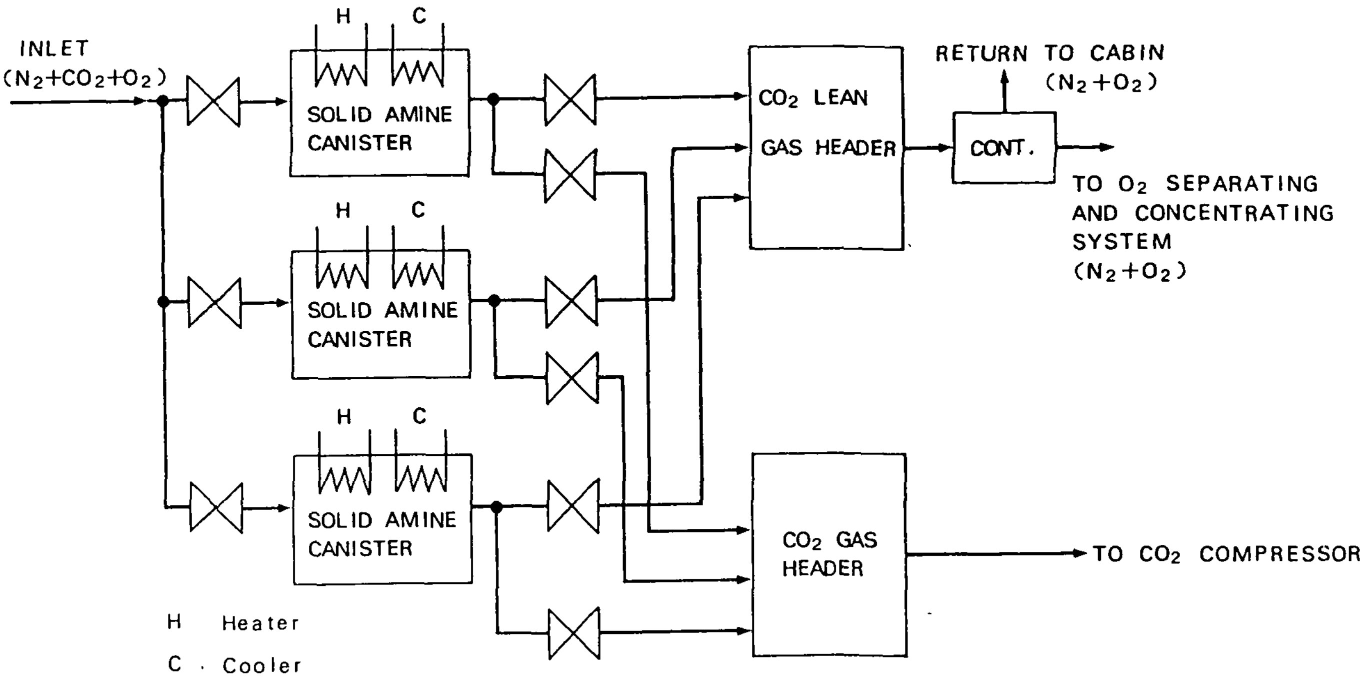

Fig 4 CO_2 SEPARATING AND CONCENTRATING SYSTEM DIAGRAM

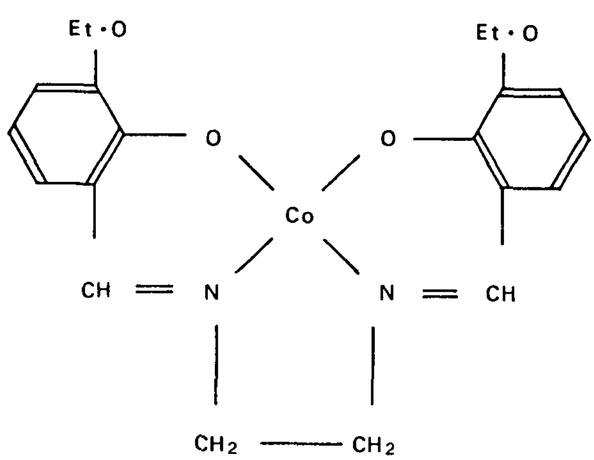

Fig 5 SALCOMINE

canister outlet. This outlet N_2 gas is led to the compressor to be compressed and stored.

When the Salcomine canister becomes saturated the absorption cycle is terminated and the desorption cycle is started, in this desorption cycle this canister is heated and desorbs O_2 gas. This O_2 gas is led to the gas compressor to be compressed and stored. Continuous O_2 absorption and desorption is carried out by means of cooling and heating three canisters alternately.

7. CONSIDERATION FOR DESIGN

Various CELSS experiment equipment will be considered in the design of the Gas Recycle System.

Phytotron (Plant cultivator) and RAHF (Research Animal Holding Facility) so called, the animal vivarium are considered.

Fig. 7 shows an example of Gas Recycle System application to the Phytotron and RAHF. In the RAHF, O_2 is consumed and CO_2 is exhaled by the metabolism of animals. In Phytotron, CO_2 is consumed and O_2 is exhaled according to the photosynthetic reaction of plants.

For stabilizing the O_2 and CO_2 gas concentrations inside the RAHF, O_2 is supplied from Gas Recycle System, and the CO_2 is pulled-out through the ventilator, this vented gas is mixed with the gas from the phytotron and the resultant gas is circulated through the Gas Recycle System and CO_2 is separated and stored for re-use.

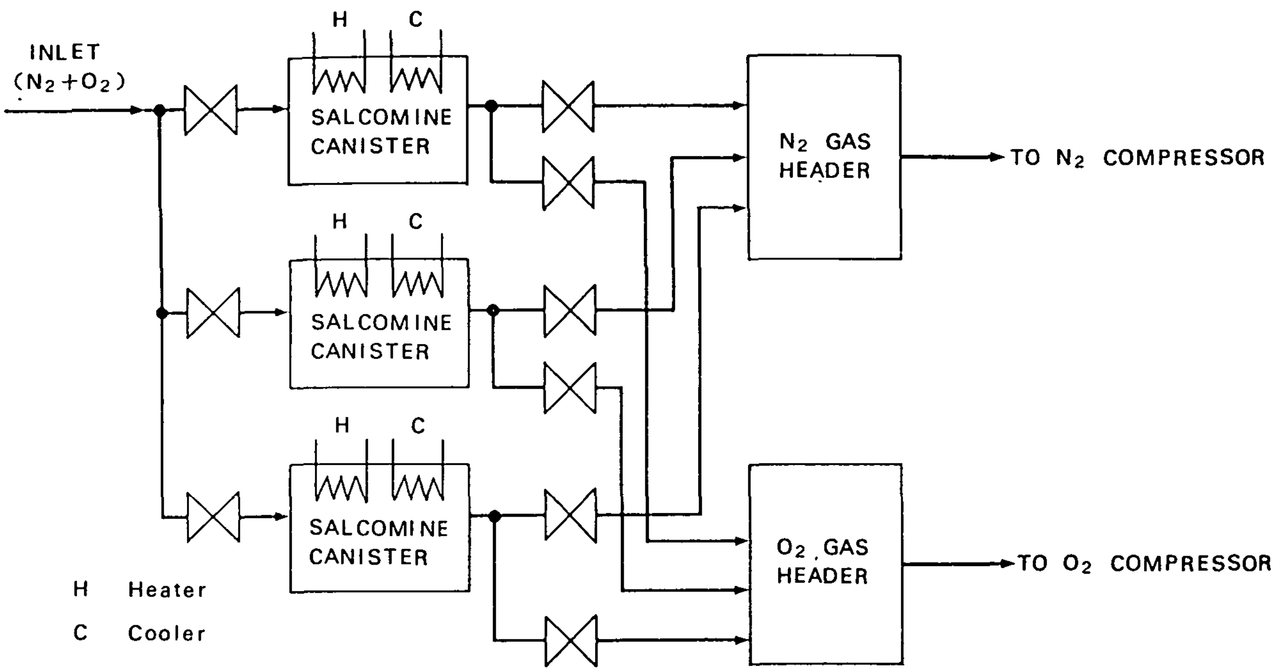

Fig 6 O_2 SEPARATING AND CONCENTRATING SYSTEM DIAGRAM

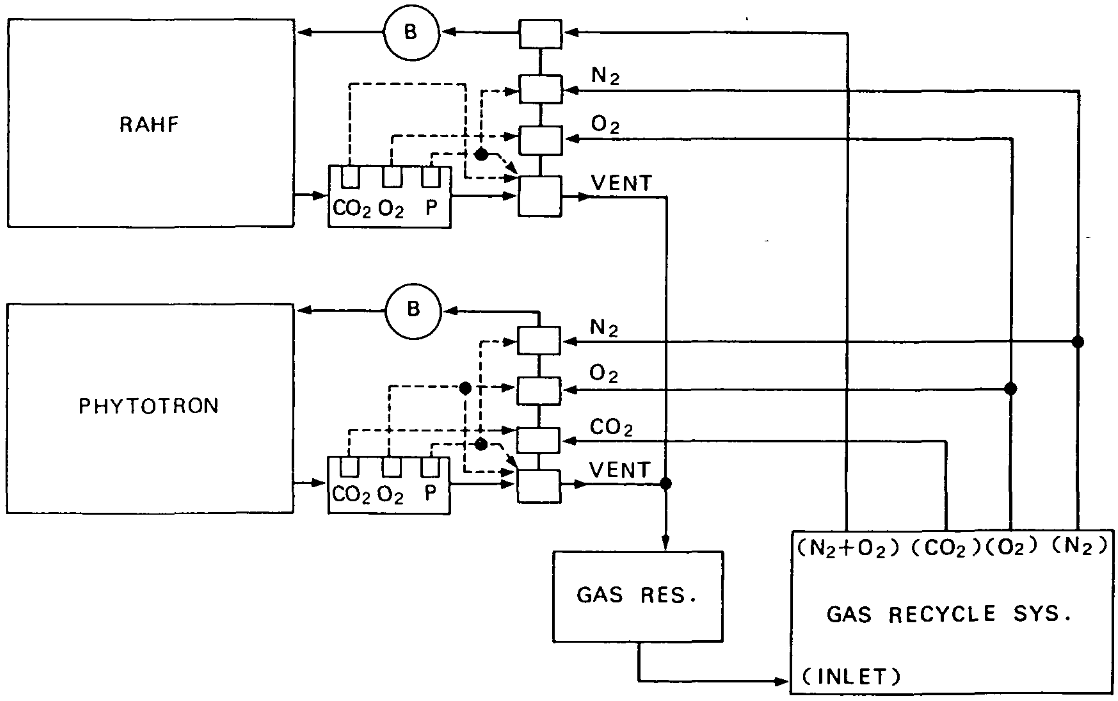

Fig 7 GAS RECYCLE SYSTEM APPLIED TO RAHF AND PHYTOTRON

According to the measurements of the pO_2 (partial pressure of O_2) and pCO_2 (partial pressure of CO_2) inside the RAHF the O_2 supply and gas venting is controlled.

The deviation of the total pressure (P) is compensated by the N_2 gas supply or gas discharging from the RAHF.

To the Phytotron, CO_2 is supplied from Gas Recycle System and the gas containing O_2 is also taken out by mean of the gas ventilator and this gas is again mixed with the gas from the RAHF and sent to the Gas Recycle System.

CO_2 supply is necessary to compensate the pCO_2 decrease caused by the photosynthetic reaction of plants.

The total pressure and the partial pressures are also controlled similar to the case of RAHF.

8. PRELIMINARY RESULTS OF DESIGN

The Gas Recycle System mentioned here comes from the design concept of carbon dioxide reduction system in the cabin for supporting human respiration. It may be possible to be able to improve the system for reducing power consumption. However the more detailed studies on the phytotron, the RAHF and so on will become necessary for this improvement.

8.1 Requirements

The design goal of this Gas Recycle System capability has been temporally given as shown in section 4. Namely this Gas Recycle System should manage 925 g/day of Oxygen and 1,130 g/day of carbon dioxide corresponding to 30 lit./hr. of O_2 and 25 lit./hr. of CO_2.

The operational pressure of the gas bottles is about 10 kgt/cm^2G.

For saving the gas compression energy, the lower pressure is better, but for making the compact design of system the appropriate high pressure such as 10 kgt/cm^2G is required.

Table 3 shows these requirements.

8.2 Gas Recycle System Block Diagram

Fig. 8 shows the Gas Recycle System Block diagram.

Inlet gas of 3,600 lit./hr. is drawn by the blower. At the filter containing activated chacoal and Hophalite (Carbonmonoxide (CO) oxiding catalyzer), the contaminants such as CO, odor and particles are removed.

At the CO_2 concentrater of Solid Amine (Solid Amine Canister) about 40 lit./hr. of CO_2 is obtained, and compressed to the pressure of 10 kgt/cm^2G and stored into the CO_2 gas bottles.

3,360 lit./hr. of the outlet gas (CO_2 lean) returns to the cabine atmosphere. The residual flow of 200 lit/hr. is led to the next process, Salcomine O_2 concentration.

At the Salcomine O_2 concentrator (Salcomine Canister), about 40 lit./hr. of O_2 is obtained and is compressed to the pressure of 10 kgt/cm^2G and stored into the O_2 gas bottles.

The residual flow, 160 lit./hr. of N_2 gas is compressed to the 10 kgt/cm^2G and stored into the N_2 gas bottles.

8.3 Gas Recycle System Configuration

Table 4 shows the list of principal components of the Gas Recycle System.

Table 3 GAS RECYCLE SYSTEM REQUIREMENTS

No.	Item	Unit	Value	Remarks
1.	Flow Rate			
	Oxygen	l/h	30	for one man
	Carbon dioxide	l/h	25	Life Support
2.	Purity			
	Oxygen	%	above 90	
	Carbon dioxide	%	about 90	
	Nitrogen	%	about 90	
3.	Operating Pressure	kgt/cm^2G	10	

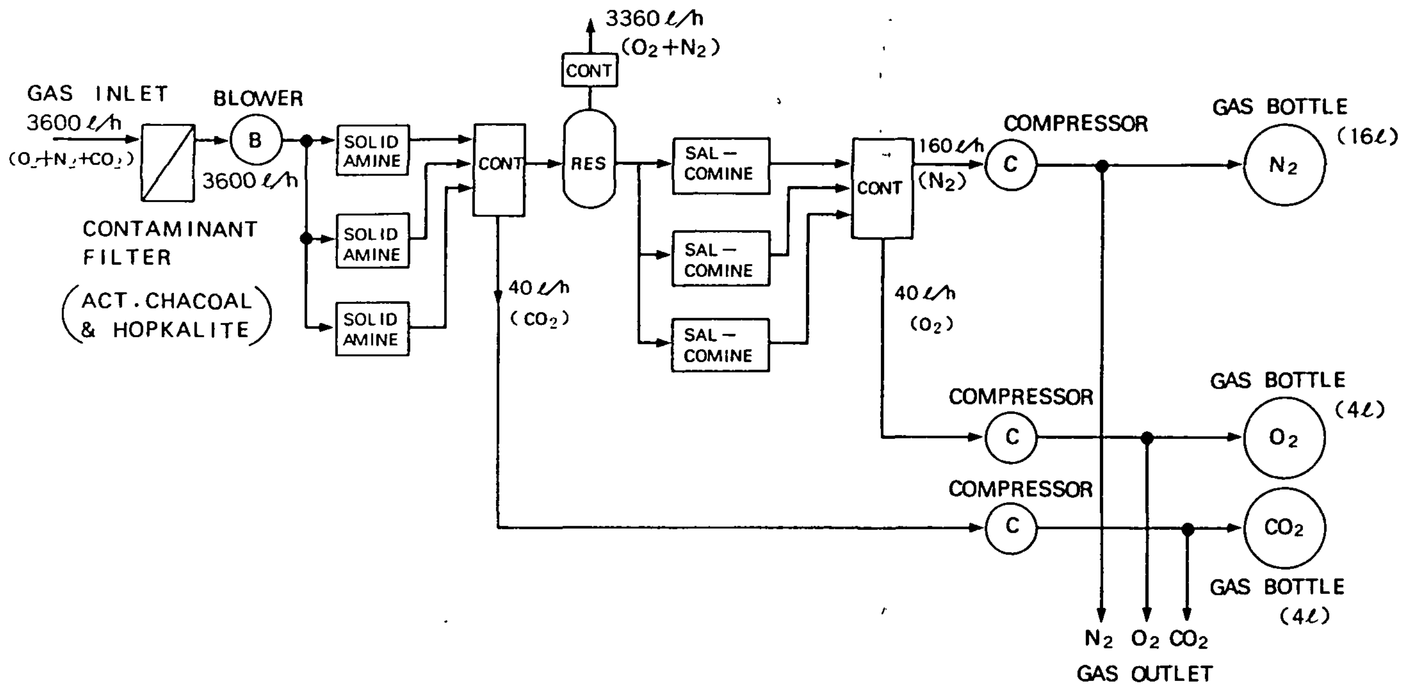

Fig 8 GAS RECYCLE SYSTEM BLOCK DIAGRAM

Table 4 GAS RECYCLE SYSTEM COMPONENTS LIST

No.	Name	Quan.	Particulars	Man (kg) @	Total	Power(kw) @	Total	Remarks
1.	Reservor	1	30 lit.	3	3	-	-	
2.	Filter	1	Act. Chacoal Hopkalite etc.	2	2	-	-	
3.	Blower	1	3,600 lit./h	6	6	0.1	0.1	
4.	Sol.Amin Unit	3	3,600 lit./h	4	15	0.5	0.5	
5.	Reservor	1	10 lit.	2	2	-	-	
6.	Salcomine Unit	3	20 lit./h	3	9	0.5	0.5	
7.	Compressor	1	160 Nlit./hx10k	6	6	0.1	0.1	N_2
8.	Do.	1	40 Nlit./hx10k	4	4	0.05	0.05	O_2
9.	Do.	1	40 Nlit./hx10k	4	4	0.05	0.05	CO_2
10.	Gas Bottle	1	16 lit.x10k	3	3	-	-	N_2
11.	Do.	1	4 lit.x10k	1	1	-	-	O_2
12.	Do.	1	4 lit.x10k	1	1	-	-	CO_2
13.	Controler	1	-	16	16	0.1	0.1	
14.	Valve Pipe	-	-	-	50	-	-	
15.	Cable etc.	-	-	-	30	-	-	
16.	Frame	-	-	-	50	-	-	
	TOTAL				202		1.40	

The total mass of this system and the electric power consumption are estimated about 202 kg and about 1.40 kw respectively.

Fig. 9 shows the configuration of the Gas Recycle System. The components of the Gas Recycle System will be assembled within the space of the Single Rack of the SPACE LAB.

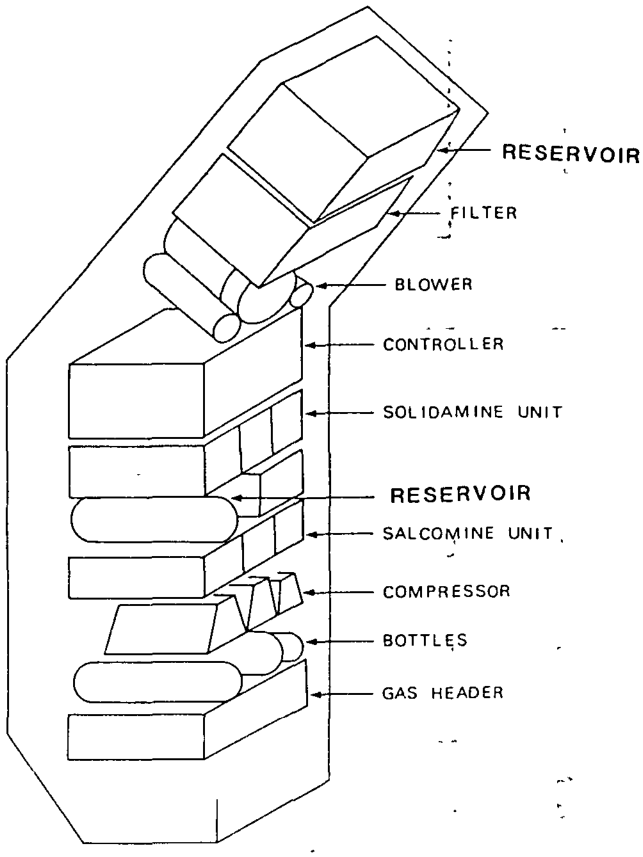

Fig 9 GAS RECYCLE SYSTEM CONFIGURATION

9. Conclusion

Through the concept studies for CELSS experiments in Space Station, the following results had been obtained.

(1) The guideline of the CELSS technology research and development has been elucidated through the time phase mission sets as the strawman model,

(2) The development feasibility of the various hardware necessary to conduct the CELSS experiments in each time phased mission and the preliminary interface requirements for each mission sets has been clarified through the concept design studies.
In spite of these fruitful results, many problems to be solved for developing hardware have been found through these studies.
As for the Gas Recycle System, the next two problems seem to be very important for establishing the stability of the system.

(3) The degradation mechanism of O_2 absorber agent such as complex salt should be tested and analyzed through bench tests and if the degradation characteristics are not sufficient a more stable agent should be developed.

(4) For establishing complete gas recycle in the CELSS, the balance between the respiration quotient of hetetotroph and the assimulation quotient of autotroph should be established within a definite period of time, the possibility for keeping this balance with the gas recycle system should be tested and checked through ground based experiments, if impossible, the additional equipment for keeping the balance should be introduced as a subsystem in the CELSS hardware.

These studies had been conducted under the support of many researchers belonging to the CELSS research group.

The Authors greatly appreciate their support.

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APPENDIX

Tables

Figures