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An Overview of Japanese CELSS Research Activities

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ABSTRACT

Many research activities regarding Controlled Ecological Life Support System (CELSS) have been conducted and continued all over the world since the 1960's and the concept of CELSS is now changing from Science Fiction to Scientific Reality. Development of CELSS technology is inevitable for future long duration stays of human beings in space, for lunar base construction and for manned mars flight programs. CELSS functions can be divided into two categories , Environment Control and Material Recycling.

Temperature, humidity, total atmospheric pressure and partial pressure of oxygen and carbon dioxide, necessary for all living things, are to be controlled by the environment control function. This function can be performed by technologies already developed and used as the Environment Control Life Support System (ECLSS) of Space Shuttle and Space Station. As for material recycling, matured technologies have not yet been established for fully satisfying the specific metabolic requirements of each living thing including human beings.

Therefore, research activities for establishing CELSS technology should be focused on material recycling technologies using biological systems such as plants and animals and physico-chemical systems, for example, a gas recycling system, a water purifying and recycling system and a waste management system.

Based on these considerations, Japanese research activities have been conducted and will be continued under the tentative guideline of CELSS research activities as shown in documents / 1 /, / 2 /.

The status of the over all activities are discussed in this paper.

INTRODUCTION

The appropriate quantities of oxygen, food and water should be continuously supplied to human beings in order to provide metabolic requirements and all waste materials such as carbon dioxide gas, induced contaminant gas, feces, and urine are to be taken away from their living space to sustain hygienic requirements.

Both the oxygen and food requirements for animals, including human beings, is well known, are originally produced from the photosynthetic reactions of plants and algae.

Suitable conditions for each plant and algae are automatically controlled by the functions of nature itself on the earth, i. e., the carbon dioxide concentration needed for plant growth is regulated by the reservoir function of sea-water, and the necessary quantities of water for all bio-species are supplied through the evaporation of sea-water, atmospheric circulation, rain and the water flow on and under ground. Temperature is automatically controlled by the energy balance between solar energy input and thermal radiation from the earth. Waste materials such as feces and urine of animals and the non-edible parts of plants are decomposed to inorganic components and minerals for fertilizer by the functions of microbes, protozoa and natural oxidation.

In an artificial space like the inside of pressurized modules, natural convections and regulations of materials such as carbon dioxide gas, water and so on can not be expected to occur and a large cultivating area and volume for plant and algae would be required to supply enough food and oxygen gas to human beings, if the plant and algae were cultivated under environmental conditions similar to the natural conditions on the earth.

Under the processes of development and evolution, almost all plants, as is well known, have accumulated a latent ability to adapt to different conditions from the present carbon dioxide concentration on the earth, and it is preferable to introduce a higher carbon dioxide concentration system for cultivating plants and algae efficiently in CELSS.

In order to maintain different gas conditions for autotrophs (plants & algae) and for heterotrophs (animals & human beings) the introduction of a Gas Recycling System is essential in CELSS.

As for recycling of waste and foods, applicability of the bio-systems to the narrow artificial space has various problems as follows ;
(1) How to reduce methane gas emitted from the waste management system.
(2) How to avoid the leakage of pathogenic bacteria from system.
(3) How to manage the organic sludge after the fermentation is over.

Therefore the physico-chemical system such as wet oxidation waste-manegement system is to be adopted, rather than the bio-system, as the main candidate for CELSS subsystem.

From these considerations. the system configuration of CELSS, as shown in Fig. 1., has been tentatively determined through the conceptual study described in Document / 3 /.

Almost all Japanese CELSS research activities have been conducted under the consideration of this system configuration in order to determine how to construct and control the total system including bio-systems and physico-chemical systems for establishing stable material recyclings.

Gas Recycling System

To supply an atmosphere of different gas concentrations to the plant cultivating facility, to the animal vivarium or the living quarters of human beings, all exhausted gases from plants, algae, animals and human beings are to be collected and sent into the gas recycling system. In the gas recycling system, each gas (oxygen, carbon dioxide and nitrogen) are to be separated, concentrated and stored in gas containers for mixing and resupply suitable gas concentrations, through gas manifolds, to the plant cultivating facility, to the animal vivarium or to the living quarters of human beings. Therefore, the gas recycling system has to have, at least, the following functions; carbon dioxide separation and concentration, oxygen gas separation and concentration and gas content regulation and re-supply / 4 /.

As for the separation and concentration of carbon dioxide gas, three types of the carbon dioxide absorption and desorption system have been developed and tested for application to the environment control system of the Japanese Experiment Module (JEM), to be attached to the Space Station.

Two systems using different kinds of the absorption and desorption agents, one agent is composed of micro porous beads coated with polyethylene-imine and another is composed of an ion exchange resin with an amine base, have been tested to evaluate the performance characteristics of each system developed independenty by Kawasaki Heavy Industries, Ltd. (KHI) / 5 / and Mitsubishi Heavy Industries, Ltd. (MHI). Sumitomo Heavy Industries has conducted their own experiments to compare the performance characteristics of two systems using the solid amine (ion exchange resin) and using a molecular sieve / 7 /. Mitsubishi Electric Corp. (MELCO) has proposed a new idea for the absorption and desorption of carbon dioxide using a super cooled molecular sieve and is now conducting a conceptual system design study using this new idea / 8 /.

On the other hand, Professor Nakabayashi of Tokyo Medical & Dental University, with the assistance of Fujikura Kasei Co. Ltd., has conducted research for obtaining an excellent, and more suitable, absorption and desorption agent by a copolymerization method between macro porous beads and various kinds of amines / 9 /. Table 1. shows the carbon dioxide absorption characteristics of various agents developed through his research activities.

As mentioned above, various intensive studies regarding the carbon dioxide separation and concentration have been conducted during the past two years by individual companies under the guideline of our CELSS research activities. The necessary technologies for a carbon dioxide separation and concentration system seem to be almost established and should be completed in the near future.

As for oxygen gas separation and concentration, the system design study and experimental test for developing an oxygen separation and concentration system using salcomine agent have been conducted by Kawasaki Heavy Industries under contract to the National Aerospace Laboratory, Fig. 2., / 10 /.

Fig. 3. shows the canister to be used for the carbon dioxide or oxygen concentration. This type of canister has distinctive features, for example, the heating and cooling, required for desorption and absorption, can be easily done because of the large surface area of gas contact. Additionally, there is an absorbent holder mechanism associated with the canister.

Based on these study results the integrated design studies for obtaining gas recycling system are under way in the National Aerospace Laboratory / 11 /.

Gas exchange functions between heterotrophic and autotrophic bio-species will be established under the support of this gas recycling system in CELSS.

Excess quantities of oxygen or carbon dioxide, due to the imbalance between the assimilation quotient and respiration quotient, may be generated in the total loop of gas recycling. Excess oxygen can be consumed easily and quickly by oxidizing the carbon in this loop. Otherwise, the generation of excess carbon dioxide gas becomes a serious problem for keeping a stable ecology because the excess quantity of carbon dioxide can not be quickly transfered to oxygen using the photosynthetic reaction of plants and algae.

Therefore, subsidiary oxygen recovery systems using physico-chemical methods such as Sabatier reaction and / or Bosch reaction are to be developed for emergency use. As for Sabatier and Bosch reactors, fundamental experiments about reaction mechanisms and system design studies are now conducted by MHI / 12 /, Fig. 4

Water Recycling System

According to the metabolic requirements of every bio-species, the appropriate quantity of high quality drinking water should be supplied to sustain the life of the bio-species. In addition to such metabolic requirements, hygiene requirements for human beings are also neccessary. Generally, the hygiene water quality requirements, such as COD or BOD etc. are not as strict as the metabolic requirements.

Therefore, the system should be composed of two main loops, the filtration recycling loop and the phase change purification loop. The filtration recycling loop is to be assembled using the permeate membranes such as ultra fine and reverse osmosis filter membranes. Permeabilities of membranes depend on the material characteristics of the membranes themselves.

Professor Ohya of Yokohama National University has conducted research to find the preferable membrane materials for the ultra and reverse osmosis filtrations of waste water, in order to assist the design of the filtration recycling loop.

Hitachi Ltd. and Sasakura Engineering Co. Ltd. have also worked on designing and testing the water recycling subsystems under contracts to the National Aerospace Laboratory / 13 /, / 14 /.

As for the filtration recycling loop, a Bread Board Model, as shown in Fig. 5., has already been developed and evaluated. As for the phase change purification loop, a Bread Board Model of a VCD (Vapor Compression Distillation Unit), as shown in Fig. 6., has also been developed and the experimental tests for finding optimum driving points are now under way in the National Aerospace Laboratory and the Sasakura Engineering Co. Ltd. Another type of phase change purification method, which uses hydrophobic porous membranes to evaporate the water, called the thermopervaporation method, has been studied experimentally by Hitachi, Ltd / 15 /.

Waste Management System

The wet oxidation method for decomposing waste and non-edible parts of plants and animals is one of the most preferable candidates for the CELSS waste management system.

However, low - grade carboxylic acids, such as acetic acid, remain, in the residual liquid after the oxidation process is terminated.

In order to avoid the generation of carboxylic acid, catalysts such as ruthenium are essential to be introduced in the reactor. The problem is how to get stable catalysts for long - term operation. Dr. Takahashi, Niigata University, in corporation with the National Aerospace Laboratory, has conducted research for elucidating the oxidation mechanism and for obtaining more stable catalysts, / 16 /, /17 /. In addition to this study, Dr. Watanabe, National Institute for Environmental Studies, has proposed another method for eliminating carboxylic acid using photosynthetic bacteria, / 18 /.

Plant and Algae Physiology and Cultivation Technologies

To realize the economic cultivation of plants and algae in space, it is necessary to deteimine the latent physiological abilities of plants and algae, and to develop a more economical nutrient solution supply system. Dr. Inada and Mr. Takanashi, National Institute of Agro-Resources, and Dr. Takatsuji and Dr. Kaneko, Hitachi, Ltd. are now studying periodical lighting effects on the photosynthesis of plants such as rice, mug, bean, komatsuna, lettuce and pimento to obtain data concerning gas exchange, growth rate, and harvest index, using their own phytotron as shown in Fig. 7., / 19 /, / 20 /, / 21 /.

Dr. Ohmasa, National Institute for Environmental Studies, and Professor Nishi, Science University of Tokyo, are now studying the information system of pathogenical diagnosis and an instrument system for determining the quantities of exhausted oxygen and assimilated carbon dioxide., / 23 /, / 24 /.

As for algae, Dr. Matsumoto and Professor Ohya, Yokohama National University, Dr. Nagamune and Dr. Endo, The Institute of Physical and Chemical Research, and Mr. Oguchi and his colleagues at the National Aerospace Laboratory are now studying a gas exchange module composed of porous membranes, to be used for algae cultivation, automatic cultivation methods and the total integration method for developing an algae cultivator for space-use. / 25 /, / 26 /, / 27 /.

Animal and Fish Physiology and Breeding Technologies

Animal and Fish Breeding becomes essential for supplying animal protein to human beings in space. Animals and fish have the same hetetrophic characteristics as human beings and thus consume oxygen and exhaust carbon dioxide. The waste of animals and fish generate ammonia and harmful gases such as indole, skatole etc. Therefore, the gas exchange characteristics of each animal and fish are to be accurately determined to balance the oxygen and carbon dioxide gas exchange between the autotrophic and the heterotrophic bio-species and the harmful gases are to be removed and reduced.

Dr. Muramatsu, National Institute of Animal Industries, and Professor Nishi, Science University of Tokyo are studying the instrumentation system for acquiring the metabolic gas exchange data /23/, /28/. Mr. Sudo of KHI is now studying how to eliminate the ammonia gas from the vivarium. Dr. Tamura and Dr. Suzuki, National Food Research Institute, are now investigating the nutrient values of each plant to the animals and the human beings for determining what kinds of plants are desireable in space /29/.

In addition, Mr. Oguchi, National Aerospace Laboratory, is now developing and testing a closed type of aquarium for demonstrating semi-closed ecology experiments, with the colaboration of Mitsubishi Rayon Co, Ltd., as shown in Fig. 8.

Gravitational Effects on Plant and Animal

Success of long run plant cultivation experiments conducted by the Soviet Union has been frequently reported. Unfortunately, detailed data about the effects of micro-gravity on the physiology of plants are scarcely presented.

In the early stage of CELSS experiments, micro gravity facilities, such as the Space Station module, would be useful for verifying the CELSS concept, because artificial gravity facilities such as a lunar base or space colony will not be developed until around 2010 to 2050. Therefore, gravitational effects on the physiology and morphology of plants and animals should be studied onboard Shuttle or Space Station.

Professor Ito, Nagoya University, Dr. Yamashita, Institute of Space and Astronautical Science, and Professor Yatazawa, Nagoya Institute of Technology, are now conducting research on the gravitational effects on plant growth using the Biaxial Clinostat as shown in Fig. 9., /30/.
Their studies are now being concentrated to:

(a) polarization of the axial organs (stem, root),
(b) differentiation and development of tissues and organs,
(c) morphogenesis of an evidently specific form of organs,
(d) interference of gravity with cell division and cell development.

Dr. Ishikawa, Kyorin University, has studied the gravitational effect on the geotropic phenomena by measuring the electric potential of cell membranes in the elongating part of bean roots. Dr. Mizutani and his colleagues, Mitsubishi-Kasei Institute of Life Science, are conducting basic research about the gravitational effects on development and morphogenesis of various bio-species's organs. /31/, /32/.

Bio-reactor in CELSS

Food production using plant photosynthesis is not always efficient and economical because the reaction rate in organs is restricted by various factors and because every bio-species have inherent unstable characteristics. In order to overcome such inconveniences, it seems better to adopt the bio-reactor for producing foods from carbon dioxide in atmosphere instead of the utilization of plant. Professor Ohshima, Tokyo Institute of Technology, has been investigating how to construct the bio-reactor for fixing carbon dioxide and producing food using various enzymes, /33/.

Future Study Plan

As already mentioned, almost all Japanese CELSS research activities have been conducted along the guidelines produced from concept study of CELSS /1/.
However, this guide line is tentative because detailed information about the technical problems could not be obtained at the initiation of this concept study. Therefore, this guide line should be revised based upon the results of research activities now being conducted. This revision study is to be started in the very near future, perhaps at the end of this year, and continuing for two years. In parallel with this study the research activities for solving each technical problem, in order to develop the equipment and facilities needed for conducting the closed recycling test, should be performed and continued. After this study, ground based closed experiments for evaluating the control strategy of CELSS are to be conducted during two or three years. Tentative study plans are shown in Fig. 10. The progress of these plans would be affected by the amount of government investment.

Conclusion

The over all images of Japanese CELSS activities now being conducted and the sketch of next research plans have been briefly reviewed and discussed. The important thing to do now is to get adequate research funds and to expand the research community.

Multilateral and / or Bilateral International Corporations seem to be very useful for accelerating research investment and for expanding the community.

Therefore, the initiation of mutual communications for promoting international corporation seems to be very important and preferable.

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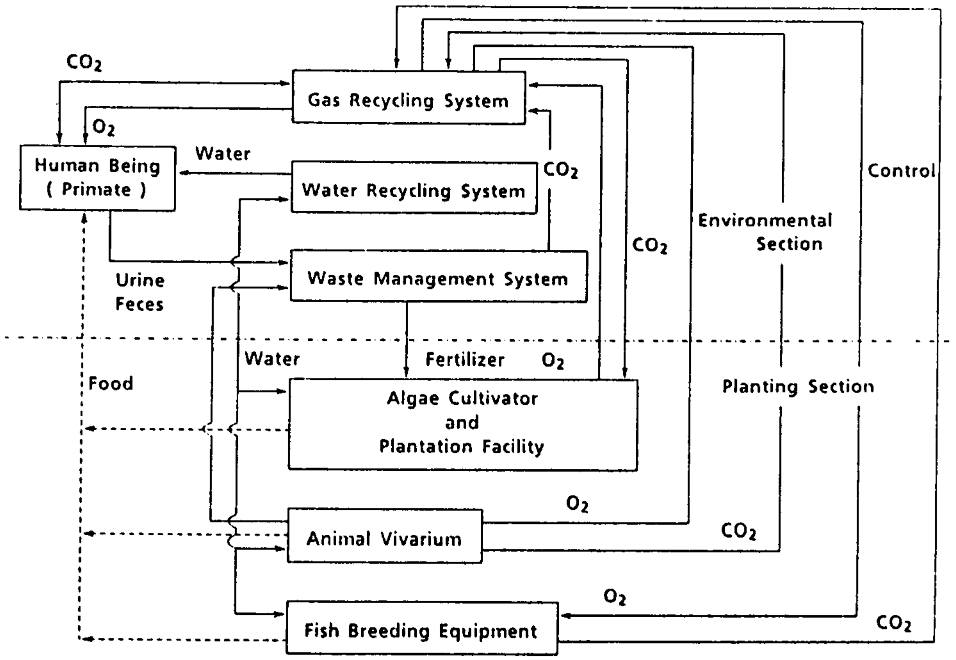

Fig. 1. System Configulation of CELSS

Table 1. CO_2 saturated adsorption amount of CO_2 adsorbent containing various amine compounds

Amine compound	Mw	Solvent	CO_2 adsorbed
Diethy lenetriamine	103	Water / Ethanol	1.68 (Wt %)
Polyethyoeneimine	600	〃	2.28
〃	10000	〃	2.70
〃	70000	〃	3.35
Polyallylamined	10000	Ethanol	2.23
〃	60000	〃	2.55
Diethylenetriamine	103	None	6.42
Polyethyleneimine	300	〃	6.85
〃	600	〃	7.08
〃	10000	〃	7.05

Macroporus polymer beads : DVB / GMA = 50 / 50Wt%

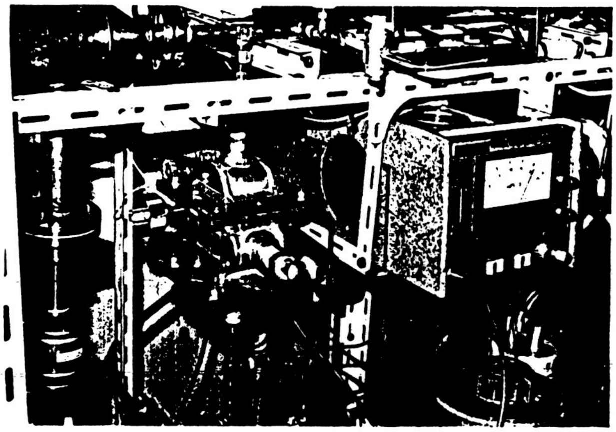

Fig. 2. Oxygen Separation and Concentration System (NAL , KHI)

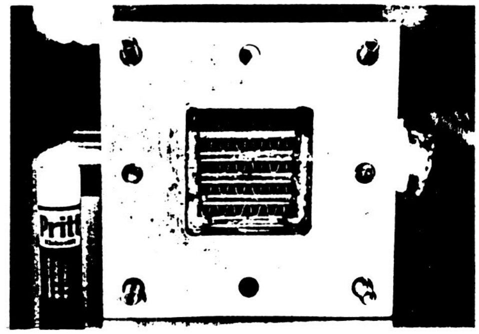

Fig. 3. Canister Used for Gas Separation and Concentration (NAL)

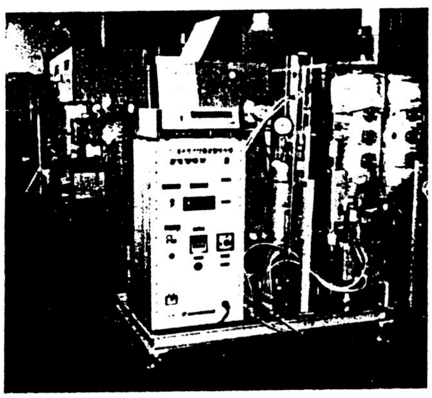

Fig. 4. Bosch and Sabatier Reactors (MHI)

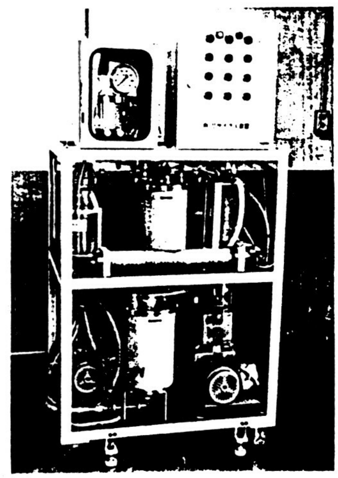

Fig. 5. Water Recycling System Using Filtration Membranes (NAL , HITACHI)

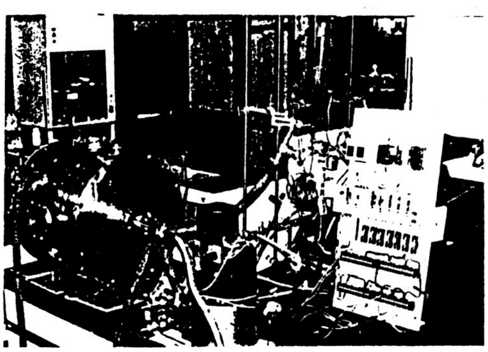

Fig. 6. VCD (Vapor Compression Distillation) (NAL, SASAKURA)

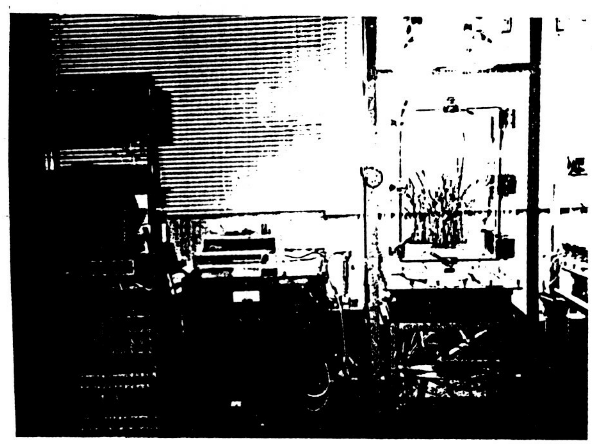

Fig. 7. Test Phytotron (National Inst. of Agro-Resources)

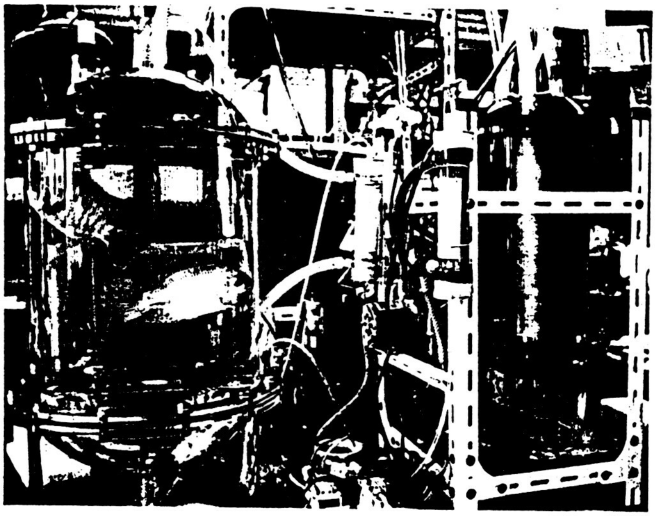

Fig. 8. Semi-Closed Ecology Experiment (NAL)

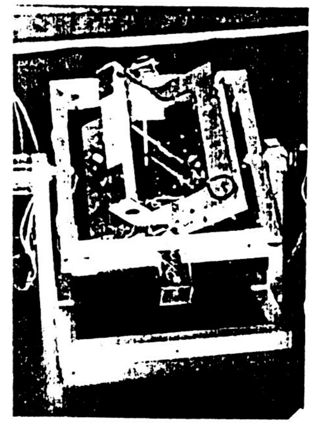

Fig. 9. Biaxial Clinostat (ISAS)

Items / FY	1987	88	89	90	91	92	93	94	95	96	97
Revision Studies for Future RFP	1st Revision				2nd Revision				RFP		
IOC Hardware Studies (Phytotron, Algae Cultivator)	Technology Development Study for Hardware		Phase A/B Studies		Phase C/D Studies		Integration & Lunch		Experiments in Orbit		
Technology Studies for Closed Test	Technology Development Studies for Each Hardware to be Used in GB CELSS										
Ground-Based CELSS Experiments							Ground Based Experiment Test				

Fig. 10. Future Study Plan