AFFDL-TR-65-53

Reproduced From
Best Available Copy

SUBSYSTEM DESIGN CONSIDERATIONS FOR AN EXPERIMENTAL ATMOSPHERE REGENERATION SYSTEM FOR THE MANNED ORBITAL LABORATORY

EDWARD B. THOMPSON, JR.

AD-A954 969

INTERIM TECHNICAL REPORT

DTIC
ELECTE
OCT 1 8 1985
S A

JUNE 1965

Approved for public release; distribution unlimited

DTIC FILE COPY

AIR FORCE FLIGHT DYNAMICS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Distribution to the Defense Documentation Center is not authorized.

The distribution of this report is limited because it is an excepted report (AFSCR 80-20).

Copies of this report should not be returned to the Research and Technology Division unless return is required by security considerations, contractual obligations, or notice on a specific document.

30 - August 1960 - AF33(616)773-3-29

AD-A954 969

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFFDL-TR-65-53	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION AFWAL/FIE — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) Wright-Patterson AFB, OH 45433	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
	6146	19	

11. TITLE (Include Security Classification)
See Reverse

12. PERSONAL AUTHOR(S)
Edward B. Thompson Jr.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Interim	FROM _____ TO _____	June 1965	20

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

See Reverse

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code) 513-255-3311 — 22c. OFFICE SYMBOL AFWAL/FIE

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE

Block 11. Subsystem Design Considerations for an Experimental Atmosphere Regeneration System for the Manned Orbital Laboratory

Block 19.

ABSTRACT

[illegible] investigation undertaken by the Air Force Flight [illegible] 1 of the USAF Manned Orbital Laboratory (MOL) [illegible] investigation was conducted with the objective of [illegible] of an atmosphere regeneration system and sub- [illegible] in the MOL. Included in the discussion of the [illegible] can function as subsystems in an atmosphere [illegible] and mission constraints used were taken [illegible] programmed for the MOL. The experi- [illegible] configuration which resulted from this [illegible] absorbers, a catalytic reduction reactor [illegible] and a water electrolysis cell for oxygen [illegible] methods for each of these processes [illegible]. The resulting system configuration is [illegible] be used as a guide to determine an MOL [illegible] by referring to the subsystem comparison [illegible] will also be used by the Space Systems [illegible] considerations between the experiment and

Reproduced From
Best Available Copy

SUBSYSTEM DESIGN CONSIDERATIONS FOR AN EXPERIMENTAL ATMOSPHERE REGENERATION SYSTEM FOR THE MANNED ORBITAL LABORATORY

EDWARD B. THOMPSON, JR.

Accession For
NTIS GRA&I
A-1
UNANNOUNCED

FOREWORD

The Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, is sponsoring Secondary Experiment S-12, Experimental Atmosphere Regeneration System for the Manned Orbital Laboratory (MOL), in support of the Space Systems Division (SSD), Air Force Systems Command, MOL Experiments Program. The Laboratory's sponsorship of this experiment is authorized in the Memorandum of Understanding executed 29 September 1964 between the Laboratory and SSD. SSD has established requirements for documentation to be furnished during the experimental program. A primary item of documentation is an interim technical report describing the experiment sponsor's efforts to define the type of program required to furnish the experiment as a hardware item for on-orbit test in the MOL.

The literature survey, together with the results described in this report, was conducted as Pre-Phase 1 of the program to provide an experimental atmosphere regeneration system for the MOL. The program is being sponsored by the Air Force Flight Dynamics Laboratory under Project No. 6146, "Atmosphere and Thermal Control," Task No. 614619, "Atmosphere Regeneration System for the Manned Orbital Laboratory." The chief investigator is Mr. E. B. Thompson, Jr., with assistance from Mr. William B. Fox. This report covers the results of the Pre-Phase 1 investigation which was initiated in August 1964 and completed in November 1964. The manuscript was released by the author in March 1965 for publication as an RTD Technical Report.

This technical report has been reviewed and is approved.

Theron J. Baker

THERON J. BAKER
Assistant for Research and Technology
Vehicle Equipment Division
Air Force Flight Dynamics Laboratory

TABLE OF CONTENTS

	PAGE
INTRODUCTION	1
ATMOSPHERE COMPOSITION REQUIREMENTS FOR THE MOL	2
Atmosphere Composition	2
Temperature and Humidity	2
MISSION/VEHICLE DEPENDENT FACTORS	4
General Constraints	4
Leakage Constraint	4
ATMOSPHERE REGENERATION SYSTEM AND SUBSYSTEM CANDIDATES	6
Carbon Dioxide Management Subsystem	6
Condensation/Freeze-Out Process	6
Permeable Membranes	7
Molecular Sieves	7
Carbon Dioxide Reduction Subsystem	8
Sabatier CO_2 Reduction Mechanism	8
Bosch CO_2 Reduction Mechanism	10
Water Electrolysis Subsystem	10
Rotating Electrolysis Cell	10
Phosphorous Pentoxide Cell	11
Asbestos Matrix Cell	11
Ion-Exchange Cell	11
CONCLUSIONS AND RECOMMENDATIONS	12
BIBLIOGRAPHY	13

ILLUSTRATIONS

FIGURE		PAGE
1	Sabatier Atmosphere Regeneration System	9
2	Comparison of Sabatier Semiclosed Process and Bosch Process for Process Weight vs Mission Duration	9
3	Bosch Atmosphere Regeneration System	11

TABLES

NUMBER		
1	Atmosphere Composition Criteria for the MOL	2
2	Estimated Leakage Rate of Compartment Oxygen	5

INTRODUCTION

Beginning in the late 1960s earth orbital spacecraft having mission durations in the range of three to six weeks will serve as experimental stations in space.

One particular vehicle, the USAF Manned Orbital Laboratory (MOL), will have a two-man crew and a variety of mission durations from several weeks to several months. As the mission time of the MOL increases, the point will be reached where the penalties for the use of expendable or open cycle atmospheric control systems will be prohibitive. The development of regenerative atmospheric control systems then becomes imperative in order to alleviate the weight and resupply penalties normally associated with expendable systems. In this report, atmospheric control is defined to mean the supply of oxygen and the removal of carbon dioxide and water vapor from the cabin atmosphere. It has been proved technically feasible to recover oxygen from carbon dioxide through atmosphere regeneration systems. Carbon dioxide reclamation systems will impose weight and power penalties on the vehicle and therefore, system design and integration are not simple. The recovery of breathable oxygen from expired carbon dioxide in practical engineering processes, then, requires experimental test proof of the present state of the art. An on-orbit experimental test program will be an essential milestone in the development of an efficient light-weight carbon dioxide reclamation and oxygen generation system for space vehicle use.

Many comparative studies on regenerative atmospheric control systems have been presented in the past (see Bibliography). This report (1) summarizes the candidate subsystems resulting from theoretical studies and experimental efforts expended on regenerating atmospheric control systems by industry and Government agencies; (2) evaluates two of the most feasible carbon dioxide reduction processes; and (3) recommends the most feasible system to serve as an on-orbit experimental system in the MOL.

ATMOSPHERE COMPOSITION REQUIREMENTS FOR MANNED ORBITAL LABORATORY

ATMOSPHERE COMPOSITION

The ideal environment for the crew of the MOL is one that will provide the atmosphere composition requirements necessary for comfort and well-being. Such an atmosphere should closely approximate that of earth-sea level characteristics although aboard the MOL the atmospheric composition and cabin pressure may vary over a much wider range than on earth. Table 1 was prepared as a guide to these requirements as they apply to the design of the atmosphere regeneration and control system.

TEMPERATURE AND HUMIDITY

Considerable research effort has gone into defining man's comfort zone and most of this work pertains to air at normal pressures in a gravitational field. A comfortable shirt-sleeve environment, however, should occur within the conventional limits shown in table 1 providing that the space vehicle inside surface temperature remains near the cabin air temperature. Man's thermal confort depends not only upon heat transfer by convection to the surrounding air, but by radiation to the walls of the cabin and by transpiration.

The effective temperature is an index of the degree of warmth experienced by the body, and is determined from the dry- and wet-bulb temperatures and air motion observations by reference to an Effective Temperature Chart (American Society of Heating and Ventilating Engineers Guide 1954.) At a relatve humidity of 50 percent, the wet-bulb temperature for the 68°F optimum effective temperature is 61°F. This is with an air velocity over the body of 20 feet per minute. Relative humidities over 70 percent are not desirable, and neither are those below 30 percent. The tolerances required in

TABLE 1

ATMOSPHERE COMPOSITION CRITERIA FOR THE MOL

PARAMETER	ONE GAS - OXYGEN ONLY	TWO GAS - OXYGEN PLUS DILUENT
Total Pressure	5.0 ± 0.5 psia	7.0 ± 0.3 psia
Oxygen Partial Pressure	4.7 ± 0.6 psia	3.0 ± 0.2 psia
Diluent Partial Pressure	----------	4.0 ± 0.3 psia
Carbon Dioxide Partial Pressure	0 - 2.6 mm Hg	0 - 4.0 mm Hg
Trace Contaminants	Below Human Tolerance	
Temperature	75 ± 5° F	75 ± 5° F
Relative Humidity	50 ± 10%	50 ± 10%
Leakage Rate (Necessary for the feasibility of a regenerating system)	0.25 to 0.5 lb/day dependent on total cabin pressure	

accurately maintaining the desired constituent quantities pose the common problem for all systems. However, there are advantages and disadvantages unique to each system. The One Gas-Oxygen "Only" system has the advantages of simplicity of sensor instrumentation and lower gas leakage rate from the vehicle because of lower total cabin pressure. But it has the disadvantage of imposing a greater fire and explosion hazard than a diluted atmosphere. The Two Gas-Oxygen Plus Diluent system is advantageous because it poses less of a fire hazard. It has the disadvantage, however, of requiring extra sensors, valves, and atmosphere monitoring equipment thereby making it a less reliable system.

MISSION/VEHICLE DEPENDENT FACTORS

GENERAL CONSTRAINTS

This parametric preliminary design study is based on the MOL program managed by the Air Force Space Systems Division. The MOL requirements are used wherever possible in order to fix some of the many variables. The MOL is typical of any short to medium duration orbital vehicle which is capable of using a partially closed ecological system with O_2 recovery from CO_2. The MOL consists of two modules: the Gemini capsule for crew launch and reentry, and the laboratory itself for in-orbit testing and experimentation. The two modules are launched from the earth as a single unified spacecraft into an earth orbit. The crew transfers to the laboratory from the Gemini after orbit is attained. For purposes of this study, it is assumed that the crew stays in the laboratory for a period of time not less than 28 days nor more than 42 days during which the programmed experiments are conducted. The laboratory module is divided into two compartments: the main compartment in which the atmosphere is sustained by a primary stored gas system similar to the Mercury and Apollo systems, and the second compartment in which the atmosphere is rejuvenated continuously by the experimental regenerating system, the subject of this study. The two compartments are assumed to be isolated from one another from the standpoint of assessing the requirements and design features of the regenerating system for the recovery of oxygen from metabolic CO_2. The compartment leak rate is assumed to be in the range of 0.25 to 0.5 lb/day to make the recovery of O_2 from CO_2 practical. If the leak rate is too high, then there is a possibility that a trade-off may show that an all-expendable oxygen store is required. Selection of subsystems for the atmosphere regeneration system is influenced by several constraints. First, there are the usual constraints of weight, volume and power. Second, the system must be compatible with the MOL internal environment. Since this system does process the MOL internal atmosphere, it should not introduce undesirable effects that would burden the prime MOL atmosphere control system. Such unwanted effects might be dehumidification resulting in a low relative humidity for the MOL cabin air, or release of CH_4, H_2, CO_2 or other potentially hazardous gases to the MOL cabin. Third, the design of this experiment system must be representative of the system that will be utilized in future manned space flights. This constraint ensures the maximum applicability and transfer of data from this MOL experiment to the spacecraft of the future wherein this experiment system will be the prime part of the atmosphere control circuit. It is the intent, therefore, to design the experimental atmosphere regeneration system so that it will be applicable, in toto, for future spacecraft. This must be accomplished with the consideration that integration with other subsystems may be required some of which may not be present in the MOL (since MOL will differ from a future spacecraft in many respects) and others, while present, may not be available for use.

LEAKAGE CONSTRAINT

Leakage or the loss of cabin gases from the vehicle may affect the carbon dioxide regeneration system in the following ways:

1. The size of the regeneration system;

2. The use rate and type of makeup constituent required; and

3. The choice of a regeneration system.

If a mixed regeneration system using stored oxygen for a makeup is selected, leakage and mission duration will determine whether cryogenic oxygen storage is feasible. For these reasons, it is necessary to define the range of leakage rates expected for the MOL. Four of the principal sources of loss of cabin gases are: (1) leakage through seals; (2) use of air locks; (3) cabin decompression; and (4) extra-vehicular activity of crew members. Table 2 shows estimates of the magnitude of these sources. The results of the experimental work sponsored by the Air Force and NASA-Langley on space cabin sealing techniques were used as the bases for making these estimates.

TABLE 2

ESTIMATED LEAKAGE RATE OF OF COMPARTMENT OXYGEN

SOURCE	LOSS (lb / man - day)
Seals	0.10
Air Lock	0.03
Cabin Decompression	0.15
Backpack Operation	0.04
Total	0.32

The Air Force and NASA-Langley experiments show that leakage rates can be reduced to very low values by careful seal and vehicle design. The experiments by the Air Force showed that static seal leakage can be reduced to negligible rates (2.1×10^{-3} lb/day) and dynamic seal leakage can be reduced to less than 0.05 lb/day. An allowance of 0.1 lb/man-day is alloted for this source. The air lock on a long duration space vehicle will no doubt have a mechanical pump for conservation of cabin gases.

The air lock will probably be evacuated to about 10 percent of the cabin pressure. It is doubtful that there will be any recovery of the air lock gases much below this pressure level due to the increasing pump-down time and power requirement coupled with the decreasing recovery of gases. An air lock with 30 cubic feet of free volume reduced to 0.5 psia will contain approximately 0.09 lb of gas. For a long duration mission, the air lock will probably not be used more than once a day. This averages 0.03 lb/man-day in a three-man vehicle.

It is expected that partially open backpacks will be used for at least some extra-vehicular activities with the carbon dioxide absorbed in lithium hydroxide beds and oxygen supplied from a bottle. Assuming that two percent of the crew time will be spent in this mode of operation, a net loss of oxygen amounting to 0.04 lb/man-day for the vehicle can be shown.

Cabin decompression events cannot be easily determined, but the vehicle should be designed well enough to avoid more than one decompression per month. Assuming a loss of 150 cubic feet of oxygen at 5 psia for each man-month, results in an average loss rate of approximately 0.15 lb/man-day. These figures should be generous but uncertainty factors of 0.6 and 2.5 were used to obtain a range from 0.2 to 0.8 lb/man-day loss. This range is within the estimates made by several other Government agencies. The total estimated loss of vehicle oxygen from Table 2 is 0.32 lb/man-day. A realistic range of values to encompass this value is then 0.25 to 0.50 lb/man-day from the compartment in which the experimental atmosphere regeneration system will be housed.

ATMOSPHERE REGENERATION SYSTEM AND SUBSYSTEM CANDIDATES

The primary reason for the decision to sponsor an experiment involving the regeneration of a breathable atmosphere for the MOL was that an atmosphere regeneration system had never actually been tested for satisfactory operation and performance reliability under long term weightless conditions. It is true, of course, that extensive analytical and laboratory investigative programs, both Government sponsored and industry funded have been conducted over the past several years. These programs were initiated because it was generally believed that regenerating atmosphere control systems for space vehicles would eventually be needed, although when they would be needed was not certain. The need for the regenerating or self-sustaining atmosphere control systems which reclaim oxygen from carbon dioxide by chemical, mechanical, electronic or photosynthetic methods is based on the fact that the regenerating system eventually assumes a weight advantage over the stored oxygen/diluent gas system as the mission time of the space vehicle increases. The stored oxygen system is typified by the NASA Mercury atmosphere control system, the Mercury vehicle requiring an atmosphere control system with high reliability and simplicity of operation. Reliability and simplicity of operation overrode any possibility of selecting a regenerating system of greater complexity and higher power requirement because of the vehicle's extremely short mission duration.

The range of mission durations considered for the MOL is several weeks to several months. This consideration prompted the Air Force Flight Dynamics Laboratory to conduct a survey of the probable mechanisms through which an atmosphere regeneration system would function. The present state of the art in the exploratory development status of chemical, mechanical, electronic, and photosynthetic methods for recovering oxygen from carbon dioxide was reviewed. It was determined that chemical/mechanical based systems were presently in the engineering development status and, consequently, this type of atmosphere regeneration system was best suited to serve as an experiment on the MOL. The chemical/mechanical atmosphere regeneration system on which the most research has been accomplished and resultant experience accrued, consists of the following three major subsystem modules:

1. Carbon dioxide management subsystem
2. Carbon dioxide reduction subsystem
3. Water electrolysis subsystem

In addition to the major subsystems there is a considerable quantity of plumbing and accessory equipment. A review and comparison of the well-known functions which can serve in each of the above major subsystems follows.

CARBON DIOXIDE MANAGEMENT SUBSYSTEM

The following is a description of the most pertinent techniques under development to remove carbon dioxide from cabin atmospheres. Advantages and disadvantages of each are discussed and summarized.

Condensation/Freeze-Out Process

In vehicles where cryogenic heat sinks are available, a freeze-out method of CO_2 or water vapor removal might be considered for utilization. However, since this experimental system is applicable to vehicles where cryogenic oxygen will be stored as makeup oxygen for loss through leakage only (metabolic O_2 is removed from CO_2), a large overproduction of gaseous oxygen would result from handling the CO_2 freeze-out load. This overproduction is attributed to the low heat of vaporization of liquid oxygen (92 btu/lb) and the large quantity of vehicle atmosphere that must be cooled in freezing out the CO_2 with respect to the amounts of gaseous oxygen normally produced. As an alternative, a space radiator could be used to provide the low temperature heat sink. However, since the heat rejection rate is a function of the fourth power absolute temperature difference between the radiator and

the spatial heat sink, a prohibitively large radiator size would be required for use as a low temperature heat sink.

Of even more importance, the design complexity and vehicle integration effort required to implement this approach is certainly not warranted in the case of an experimental system aboard the MOL.

Permeable Membranes

Permeable membranes can accomplish the separation of exhaled CO_2 from the MOL cabin atmosphere on a continuous basis. The separated CO_2 may then be discarded to space or fed to a carbon dioxide catalytic reduction reactor for eventual recovery of oxygen. For development of a practical system to effect the separation of gaseous elements, membrane materials should have the following characteristics:

1. High absolute permeability, to minimize the area required;

2. High selective permeability toward the desired gas to reduce the energy required for separation; and

3. Chemical and physical stability.

Since known membrane materials are not perfectly selectable toward the desired gas to be separated, a multistage, recycle system must be employed to obtain gases of high purity. Furthermore, development of this concept is at present in the laboratory experimental stage and before the necessary data for a flight prototype design can be made available, considerable developmental effort is required.

Molecular Sieves

Molecular sieves for use as CO_2 adsorbers in space vehicles have been under development for some time. A molecular sieve is a zeolite crystal grown under controlled conditions. The material is porous and contains very large internal surface areas in the form of hollow spherical chambers. Gases are selectively removed from the gas stream by sorting out, so to speak, the gas molecules of a certain size range and holding them by adhesion to the internal surfaces. The sorting is accomplished by controlling the diameter of the capillary size of the chamber access holes in the molecular sieve. Several molecular sieves of varying pore size are manufactured which are able to separate CO_2 molecules from the combination of gases expected to be found within a space cabin. These adsorbents, packed within a canister, offer excellent properties for space applications. Although their ability to adsorb CO_2 is far below that of some chemical absorbents such as KO_2 or lithium hydroxide, sieves can be regenerated for repeated usage. In this way, the relatively high initial weight is traded off against long mission duration. The canister size or amount of molecular sieve material is dependent only upon crew size and relative rates of adsorption and regeneration.

One apparent disadvantage in using sieves is the need to dry the air prior to its introduction to the canister. This is necessary since the sieves have an even greater affinity for water than for CO_2. Therefore, should the air contain excessive moisture, the sieves will become saturated and not only experience a reduction in CO_2 adsorptive capability, but also will be rendered more difficult to regenerate.

Drying of the air prior to entering the molecular sieve may be effected by either silica gel or 13X molecular sieve. Silica gel is a good desiccant with a lower heat of adsorption but its capacity is lower and the resulting gas dew point is higher than that possible with 13X molecular sieve.

The 5A molecular sieve is usually considered as the adsorbent medium to separate CO_2 from the atmosphere. This is based upon the high degree of confidence given to 5A molecular sieve for this purpose through experimentation and development programs that have been completed.

CARBON DIOXIDE REDUCTION SUBSYSTEM

There are two catalytic CO_2 reduction mechanisms that can be used to convert carbon dioxide to water, namely, the Sabatier and the Bosch.

Sabatier CO_2 Reduction Mechanism

Semiclosed Process

The Sabatier CO_2 reduction mechanism, shown diagramatically in Figure 1, uses hydrogen as the reducing agent in the CO_2 reduction reactor. The reaction produces methane as shown in the following equation:

$$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O$$

The water can then be electrolyzed to provide oxygen. The reaction takes place at the relatively low temperature range of 300° to 600°F depending on the catalyst selected to promote the reaction. The reactions at the lower temperatures of 300° to 400°F are effected by ruthenium or ruthenium bearing catalysts and proceeds to better than 99 percent conversion in a one-step reactor without recycling. The methane can then be discarded or used for another purpose such as vehicle attitude control. Without further processing of the methane it is necessary to add approximately 0.4 lb of water per man-day to the electrolysis cell, since hydrogen is continually being lost in the disposal of the methane. Even accounting for water makeup stores, however, the Sabatier process still shows a weight penalty reduction over the stored oxygen expendable system of at least 1.3 lb/man-day per pound of oxygen required.

The Sabatier reaction is an exothermic process which requires active cooling of the reactor to prevent it from exceeding the low favorable reaction temperatures. The reactor shell temperature should be maintained as close to the reaction temperature as possible.

When the Sabatier mechanism is operated as a semiclosed process (that is, the methane is discarded) it provides the following advantages over the Bosch CO_2 reduction mechanism:

a. Low temperature exothermic system requiring little or no reaction initiation power;

b. No carbon deposition or removal problems;

c. A simple one-step system requiring no recirculating or recycling component;

d. A simpler, lighter weight reactor due to the lower temperatures involved; and

e. Little or no necessity for continual catalyst replacement since the metallic catalyst characteristics are stable at Sabatier reaction temperature.

These advantages indicate the semiclosed Sabatier reaction process to be favorable over the Bosch CO_2 reduction mechanism, discussed later.

Closed Process

The alternative to the semiclosed process consists of the catalytic or thermal decomposition of methane to carbon and hydrogen. The most common method for accomplishing this is shown in the following equation:

$$CH_4 \xrightarrow[\text{CAT}]{\text{HEAT}} C + 2H_2$$

Another possibility for accomplishing this is the reaction of methane and CO_2 to form carbon and water. The reaction shown above, however, requires approximately 50 watts of heat per man to raise the methane gas temperature from 400° to 2000°F at which temperature the reaction is complete. This additional power required to close the Sabatier process reduces the total power requirement to the extent that there is virtually little power weight penalty difference between the Sabatier and the Bosch mechanisms. The fixed weight penalty is in the same catagory, since the high temperature methane cracking reactor will require ceramic construction materials and high temperature insulation thereby offsetting the advantage of the lighter weight Sabatier reactor. Figure 2 demonstrates that the

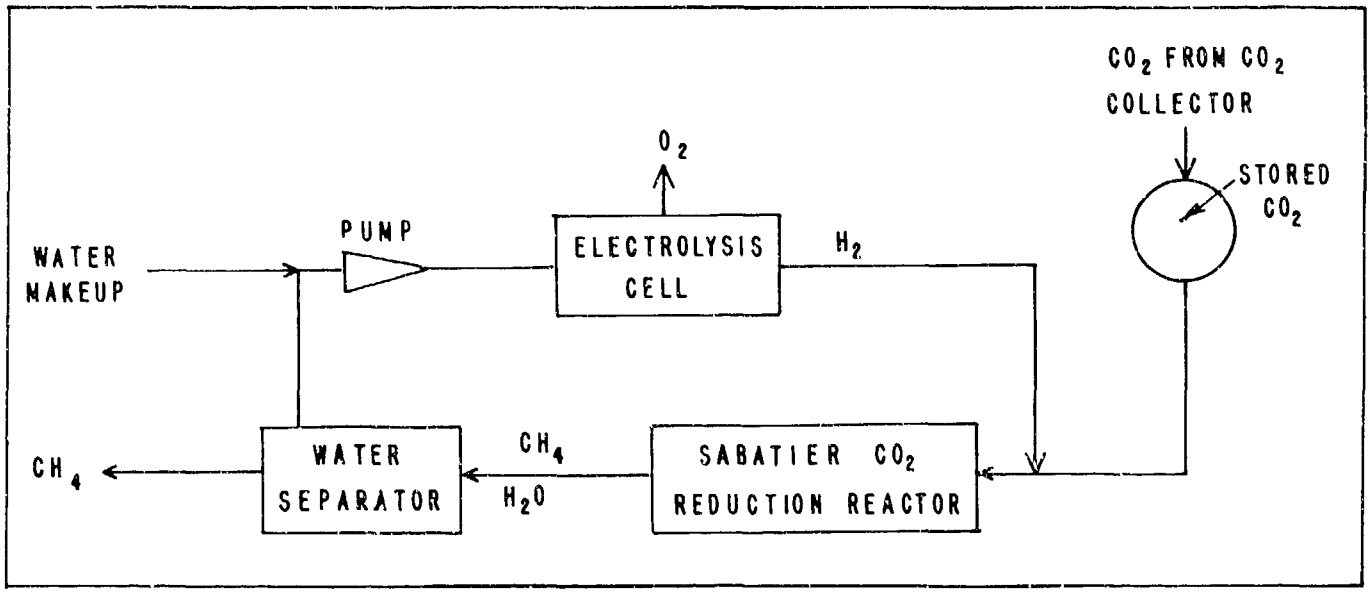

Figure 1. Sabatier Atmosphere Regeneration System

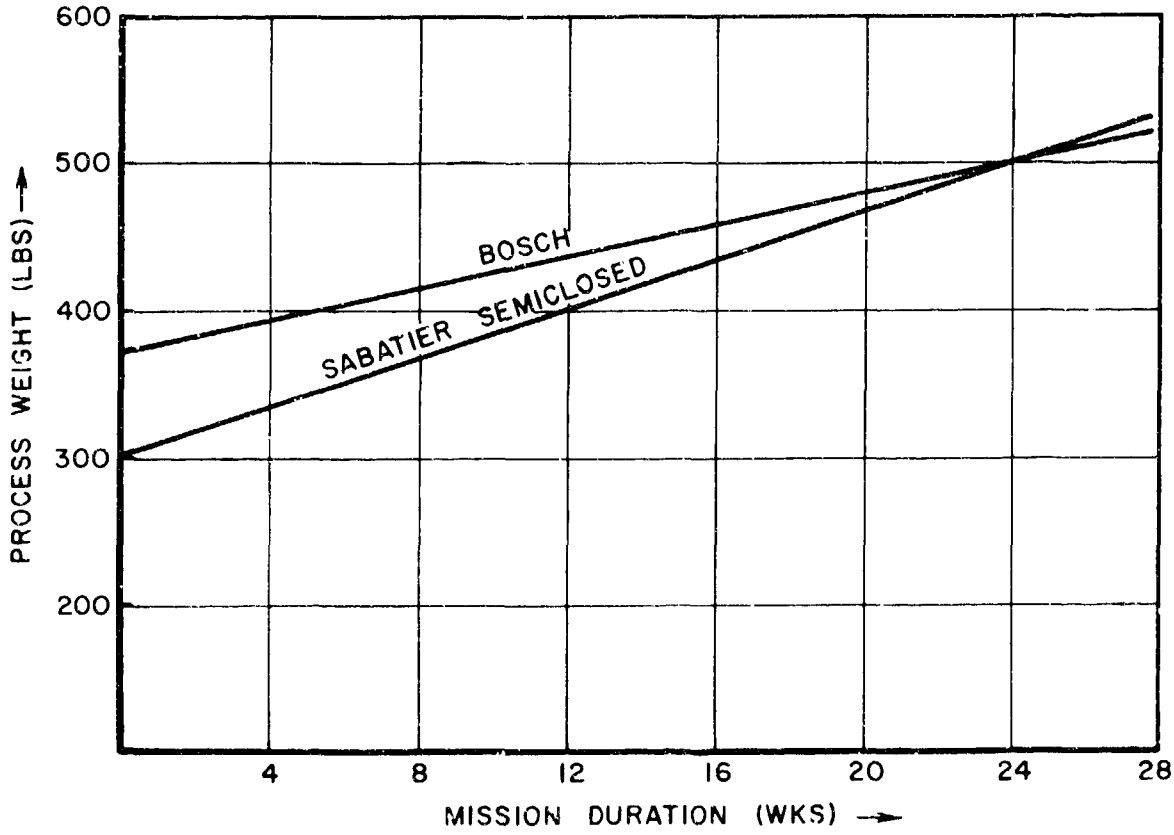

Figure 2. Comparison of Sabatier Semiclosed Process and Bosch Process for Process Weight vs Mission Duration

semiclosed Sabatier process has a distinct weight advantage over the Bosch process for the mission durations normally considered for the MOL. In addition, it is considered that the Sabatier process is more reliable because of the fewer number of dynamic components involved.

Bosch CO_2 Reduction Mechanism

This process is shown diagramatically in Figure 3. It is an iron catalyst reaction occurring at moderately high temperatures of 1100° to 1400°F. The reaction, usually termed the Bosch or carbonization reaction, is described by the following equation:

$$CO_2 + 2H_2 \rightarrow C + 2H_2O$$

This reaction produces carbon instead of methane, and also water which must be continually removed to drive the reaction to the right. Further examination shows that several side reactions take place simultaneously, such as:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

A quantitative and qualitative analysis of the exit gases produced by this reaction shows that it takes place at a rate high enough to make it necessary to recycle the products through the reactor in order to obtain maximum water yield. Some investigators have concluded that the Bosch process is unfavorable for this reason. Other investigators, however, believe the process to be promising. The efficiency of the Bosch mechanism is dependent upon the design of the reactor and the ability to conserve heat in the recirculating loop. The exit gases leaving the reactor must be cooled in order to condense the water and then are recirculated through the reactor making it necessary to reheat them. In a simple recirculating loop the Bosch mechanism has a power requirement of approximately 300 watts per man for heating and recirculating which is relatively high compared to the Sabatier mechanism. Theoretically, there is no hydrogen lost in the Bosch process and therefore there is no need for hydrogen makeup as in the case of the Sabatier process. It is usually erroneously concluded, therefore, that the weight of the Bosch atmosphere regeneration system is less than the Sabatier atmosphere regeneration system. However, the high power requirement of the Bosch reactor, together with the weight of the carbon removal components and the recirculating equipment, offsets this so-called weight advantage.

The reliability of the Bosch mechanism is less than that of the Sabatier mechanism simply because of the large number of dynamic components involved. In addition, the iron catalyst used in the Bosch reactor is continually depleted because of the formation of iron carbide at the high reaction temperatures. The catalyst must therefore be continually replaced and the free carbon and iron carbide removed from the system loop which increases the maintenance and servicing time of the vehicle crew. There are, however, carbon removal devices being developed that look promising but they have not been fully proved. In summary, the Bosch process has the following advantages.

1. It is almost a closed cycle system requiring small amounts of makeup water to balance the hydrogen supply.

2. Several full scale laboratory models have been operated.

3. Little development effort is required to produce a system that can be tested in a weightless environment.

WATER ELECTROLYSIS SUBSYSTEM

Rotating Electrolysis Cell

This type of cell has potentially a number of advantages over static cells in that it is capable of a low power/weight ratio at high electrolysis rates. However, for a one-man system, the power weight ratio is prohibitively high. The current development status of the cell is below that of the ion-exchange membrane type cell because of problems associated with its rotating machinery. The main advantage of this cell is its use of materials currently available in commercial units which may be operated at high current densities without degradation of performance.

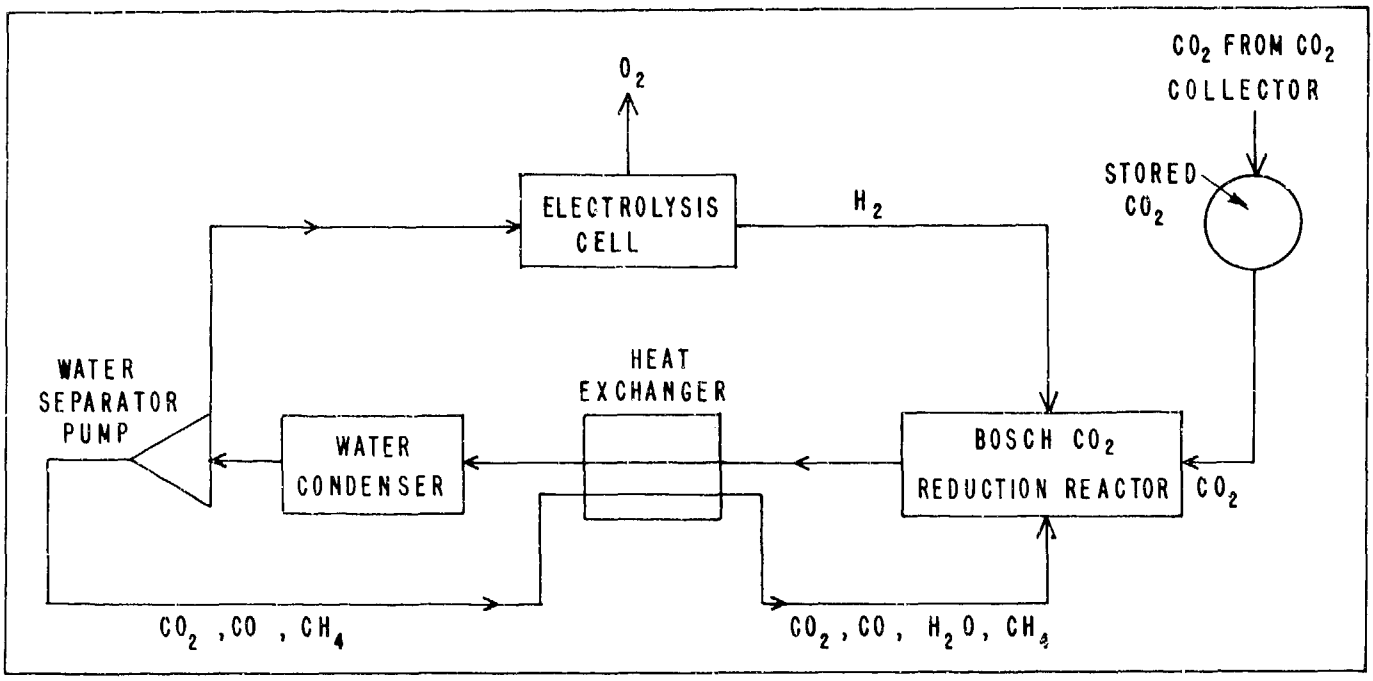

Figure 3. Bosch Atmosphere Regeneration System

Phosphorous Pentoxide Cell

This cell uses P_2O_5 paste to dehumidify an incoming air stream, is sensitive to humidity change, and its internal resistance is high. The P_2O_5 may possibly expel phosphoric acid vapor into the air stream. The development status of this cell is one of laboratory research.

Asbestos Matrix Cell

This cell is an asbestos wick membrane saturated with KOH between porous plate electrodes. High current densities are possible, but temperature control is a problem. If the asbestos dries out, there is danger of H_2 and O_2 mixing. Development status as an electrolysis cell is limited; actually, only fuel cell configurations have been operated to date.

Ion-Exchange Membrane Cell

The ion-exchange membrane type electrolysis cell has been investigated intensively and considerable development work has been completed with this type of cell. The cell is, in effect, a fuel cell operating in reverse and utilizing catalyst coated ion-exchange membranes as the active elements. The memranes have an advantage of positively separating the hydrogen and oxygen gas produced during zero gravity operation. The operation and reliability of this cell has been proved in a NASA sponsored contract.

CONCLUSIONS AND RECOMMENDATIONS

The following principal conclusions and recommendations were derived from this study.

a. The Sabatier CO_2 reduction mechanism has the greatest potential as the primary module of an experimental regenerative atmospheric system for the MOL. The Sabatier mechanism is an all gas/vapor reaction process and lends itself readily to qualitative and quantitative analysis of reaction products which is an absolute necessity since the CO_2 reduction module serves as an experiment. There is therefore no need to disassemble the reactor to remove solid reaction products for measurement such as is the case with Bosch CO_2 reduction reactor. Accordingly, the maintainability of the experiment under actual orbital test is greatly simplied for the astronaut.

b. When the Sabatier mechanism is operated as a semiclosed system it has a weight and simplicity advantage for medium duration missions and moderate leakage rates. The selection of a semiclosed Sabatier system or a closed system will depend on reliability and logistics considerations, exact leakage rates, and whether the by-products can be useful in another vehicle subsystem.

c. Carbon dioxide concentration and recovery subsystems require further development and testing. A system utilizing molecular sieves is the only one that has proved reasonably successful. Its operation in a weightless environment should be proved.

d. Water recovery systems should be developed with higher recovery efficiencies than those tested in order to provide water for oxygen leakage makeup.

e. Electrolysis of water contributes the largest single power penalty to a selected atmosphere regeneration system. Further developmental work should be directed toward proving the operation of varying electrolysis cell configurations under weightless conditions.

f. General trade-off comparison studies are only valid within a narrow range based on the particular assumptions made for the study. It will always be necessary to make a penalty comparison study for each vehicle and mission based on the design and operational constraints imposed by the particular mission and vehicle system.

BIBLIOGRAPHY

"Adsorption of Carbon Dioxide by Artificial Zeolites." Flight Accessories Laboratory Technical Memorandum TM-62-81. Flight Accessories Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. 20 November 1962.

Babinsky, A. D. "Reduction of CO_2 Using a Fluidized Catalyst Bed." Thompson-Ramo-Wooldridge Report TRW-ER 5159. 15 December 1962.

Burris, W. L., and Mason, J. L. "Advanced Environmental Systems." Proceedings of IAS-NASA National Meeting on Manned Space Flight. St. Louis, Missouri. 30 April-2 May 1962.

Christensen, G. Low Temperature Adsorption of Carbon Dioxide. ASD TDR 62-560. Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. September 1962.

Clifford, J., Gates, J., McCallum, J., and Faust, C. Research on the Electrolysis of Water Under Weightless Conditions. MRL TDR 62-44. Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. May 1962.

Dale, S H., and Tamplin, R. A. "The Sabatier Reaction for Inorganic Recovery of Oxygen in Manned Space Capsules." Proceedings of Closed Circuit Respiratory Systems Symposium. WADD TR 60-574. Wright Air Development Division, Wright-Patterson Air Force Base, Ohio. August 1960

Foster, J. F., and McNulty, J. S. "Hydrogen Reduction of Carbon Dioxide to Elementary Carbon." Proceedings of Closed Circuit Respiratory Systems Symposium. WADD TR 60-574. Wright Air Development Division, Wright-Patterson Air Force Base, Ohio. August 1960.

Remus, G. A. Catalytic Reduction of Carbon Dioxide to Methane and Water. AFFDL-TR-65-12. Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. January 1965.

Rousseau, J., Burris, W. L., Coe, C. S., and Hummel, L. E. Atmospheric Control Systems for Space Vehicles. ASD-TR-62-527. Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. July 1962.

Rydelek, R. F. Investigation of Integrated Carbon Dioxide Hydrogeneration Systems. ASD-TDR-62-581. Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. October 1962.

Smylie, J. W. Evaluation and Application of Chemically Regenerative Atmospheric Control Systems. SSD-TDR-64-95. Space Systems Division, Los Angeles, California. June 1964.

Thompson, E. B., Jr. Investigation of Catalytic Reactions for CO_2 Reduction. Part I, Evaluation of a Nickel-Kiesilguhr Catalyst. October 1964. Part II, Evaluation of Base Metal Catalysts. March 1965. FDL-TDR-64-22. Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.