



AEROSPACE INFORMATION REPORT

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LIFE-SUPPORT SYSTEMS FOR MANNED SPACECRAFT

PREFACE

This report was prepared to provide a summary of the first ten years, 1958 to 1968, of work performed on life-support systems for manned spacecraft. Members of the preparing committee and other life-support specialists reviewed all of the literature published on this subject before 1969, and agreed that the references cited herein present the best data available on each of the techniques or processes devised for life support. Tables are presented to indicate the type of data contained in each reference - i.e., descriptive, analytical, experimental and/or development data. In addition, discussions are presented on the past, present and future state-of-the-art of each subsystem. Thus, this report should be useful in training new personnel and avoiding the duplication of work performed in the past.

1. INTRODUCTION

Research and development of life-support systems for manned spacecraft began in the late 50's, after the U.S.S.R. and the U.S.A. demonstrated that rocket engines could be used to establish earth-orbital satellites. The U.S. Government began contract work on this subject during fiscal year 1958; hundreds of contracts were completed during the next ten years.

Life-support systems include a wide variety of equipment - in fact, sometimes everything that can be thought of as providing for the safety and well-being of the crew. In this report the definition is limited to the systems provided for:

- A. Pressure, Temperature and Humidity Control
- B. Oxygen Storage and Recovery
- C. Carbon Dioxide Removal
- D. Trace Contaminant Control
- E. Water Recovery
- F. Waste Management
- G. Food Supply and Synthesis

There have been many processes or techniques devised to accomplish these tasks. Most of them have been experimentally evaluated, but very few have ever reached the prototype stage of development. This report lists the best references on each subject, and cross-indexes them in table form to indicate that the reference contains a description and/or analysis of the process, or quantitative data, and/or the description of an experimental, flight prototype or flight qualified system. This format shows which systems have been seriously considered, and the ones that have been actually developed and qualified.

The discussions before each tabulation were prepared by several engineers or scientists that are recognized specialists on each subject. Their summary of the history and current status of each type of system should be valuable to new personnel entering this field. The comments on the future prospects should help experienced workers direct their efforts towards the most promising processes and type of equipment.

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2. THERMODYNAMIC CONTROL SYSTEMS

Pressure, temperature and relative humidity are the three properties of an internal atmosphere that are most important to the comfort of its occupants; composition is also a factor, but this subject is discussed later in this report. The techniques devised to supply and/or control these properties in manned spacecraft are listed on the next page.

- 2.1 Pressure: Gases dissolved in body fluids are liberated to some extent with relatively small decompressions; however, "bends" usually do not occur at altitudes less than 30,000 feet (250 torr). Since man requires an oxygen partial pressure greater than 90 torr, a pure oxygen atmosphere at 250 torr provides the required oxygen pressure and total pressure. This technique was successfully used in the Mercury, Gemini and Apollo spacecraft, while the Biosatellite contained oxygen diluted with nitrogen. Future manned spacecraft will most likely be provided with a two-gas atmosphere, which contains oxygen and a diluent such as nitrogen or helium to avoid any adverse effects of prolonged exposure to pure oxygen. A partial pressure sensor will then be required to control the supply of oxygen, while a total pressure sensor will then be used to control the supply of diluent.
- 2.2 Temperature: Heat generated by the crew and equipment must be rejected from the spacecraft at a controlled rate to maintain the atmosphere at the temperature required for crew comfort. To accomplish this task the spacecraft must contain a heat transport and disposal system. The internal atmosphere itself is the simplest technique for transporting heat from the crew and equipment to the disposal subsystem. This approach was used in the Mercury capsule to transport heat to an evaporative cooler. The Gemini and Apollo capsules utilize a circulating fluid to transport heat from the crew and equipment to a space radiator, and thereby eliminate the water loss associated with evaporative cooling. Future spacecraft may include a heat pump to reduce the size of space radiators.
- 2.3 Humidity: Condensation is the technique employed by the Mercury, Gemini and Apollo spacecraft to control relative humidity. This approach has proven to be reliable, but it requires a coolant at a temperature below the desired dew point. Consequently, future spacecraft may include the use of humidity sorbents that can be regenerated at higher temperatures. Another approach that appears to be promising is to maintain humidity control by absorbing water vapor in a matrix that contains an acid, which can then be used to generate oxygen and hydrogen by electrolysis.



TABULATION - THERMODYNAMIC CONTROL SYSTEMS

<u>Technique</u>	<u>Description or Analysis</u>	<u>Experimental Model/Data</u>	<u>Prototype System</u>	<u>Qualified System</u>
<u>Pressure</u>				
Oxygen	6			6, 12
Nitrogen	6	7	10	
Helium		11		
<u>Temperature</u>				
Heat Transport				
Gas	5			6
Liquid	5	7	10	12
Heat Pump				
Air Cycle	5			
Vapor Cycle	5, 9	7		
Thermoelectric	9			
Heat Disposal				
Chemosorption	5			
Vaporization	5			6
Radiation	3, 4, 5, 9	9		12
<u>Humidity</u>				
Condensation	1, 2, 3, 5, 8	7	10, 13	6, 12
Absorption	1, 5			
Chemosorption	1, 5			
Adsorption	2, 5			
Calcium Oxide	1			
Calcium Sulfate	1			
Barium Oxide	1			
Activated Alumina	1			
Silica Gel	1, 8			
Synthetic Zeolites	1			
Magnesium Perchlorate	1			

Note: Numbers listed here and in other Tabulations denote references listed in Appendix.

3. OXYGEN SUPPLY SYSTEMS

Gaseous oxygen stored at high pressure has been used for many years in high altitude aircraft. The same approach was used in the Project Mercury spacecraft. However, the Gemini and Apollo spacecraft were provided with oxygen stored at supercritical pressure to maximize storage density and thereby minimize the weight penalty of the storage containers. Chemical storage was considered for these spacecraft, but this technique appears best for applications that require a portable source of oxygen.

An average man engaged in sedentary activities consumes approximately 2 lb of oxygen per day - which is a relatively small weight penalty, even when the weight and volume of oxygen storage containers is considered. However, onboard generation of oxygen can be justified when the mission duration is longer than several months and/or the spacecraft is stored in orbit.

Most of the systems devised so far for onboard generation reduce carbon dioxide to water, which is then electrolyzed. This suggests an intermediate approach, namely, use stored water for onboard generation of oxygen via electrolysis. This approach is also attractive if the electrolysis cell can absorb moisture from the cabin atmosphere and thereby eliminate the need for radiator temperatures below the desired cabin dew point temperature; however, the power required to operate a dehumidifying electrolysis cell is higher than for a cell that utilizes liquid feed.

Direct dissociation of carbon dioxide to carbon and oxygen is the ultimate process; however, it has not been successfully demonstrated because carbon monoxide is formed as an intermediate product. Carbon monoxide can be catalytically decomposed to carbon and oxygen, but the catalyst is consumed and the carbon is difficult to handle. The electrochemical dissociation of carbon dioxide, using a solid electrolyte (an oxide), also generates carbon monoxide which must be catalytically decomposed. Electrochemical cells that use molten carbonates do not generate carbon monoxide, but carbon is deposited on the cathodes and the liquid carbonate is difficult to confine.

The Bosch process has been extensively studied because it produces carbon and water vapor from carbon dioxide and hydrogen in a single catalytic reactor. Unfortunately, no one has been able to develop a reliable, continuous method for removing carbon from the catalyst in a weightless state; the best systems developed so far use one or two reactors and cyclic operation. The Sabatier process is attractive because it produces methane instead of carbon, in a relatively small reactor. However, if carbon is vented overboard in the form of methane, too much hydrogen is lost. Eventually, someone will develop a reliable method for cracking methane to recover part of the hydrogen and thereby balance the hydrogen cycle.

The first oxygen regeneration system qualified for manned spacecraft will most likely use the Sabatier process with water electrolysis. A methane cracker will be used for longer duration missions, unless someone develops a reliable process that uses direct dissociation.

TABULATION - OXYGEN SUPPLY SYSTEMS

<u>Techniques</u>	<u>Description or Analysis</u>	<u>Experimental Model/Data</u>	<u>Prototype System</u>	<u>Qualified System</u>
<u>Separation</u>				
Electrochemical				
Rare Earth Oxides	30	22, 38, 51, 52		
Potassium Hydroxide		56		
<u>Gaseous Storage</u>	1, 19, 28			4, 20
<u>Liquid Storage</u>				
Bladder	19, 28			
Thermal Pressurization	19, 28			
Dielectrophoresis	34, 39			
Capillary	39		27	
<u>Supercritical Storage</u>	19		20	
Bladder	28			
Thermal Pressurization	28			
<u>Chemical Storage</u>				
Chlorate Candles	1, 3, 19, 28	33		
Hydrogen Peroxide	1, 19, 28			
Potassium Superoxide	1, 3, 19	5, 16, 23, 25, 47	49	
Sodium Superoxide	1, 19	23		
<u>Electrolysis of Water</u>				
Water	12, 19, 28, 66, 67	21, 24, 53, 37 63, 64, 65, 69	50, 68	
Hydroxides(Li, Na)	12	41, 42		
Phosphoric Acid	10, 36	35, 58, 61	59	
Sulfuric Acid		54		
<u>Recovery from CO₂</u>				
Dissociation				
CO ₂ to C+O ₂	2, 30, 36	71, 72		
2CO ₂ to 2CO+O ₂	6, 9, 13, 30, 31			
2CO to 2C +O ₂	8, 36			
Reduction to Water				
CO ₂ + H ₂ to CO + H ₂ O	6, 30			
CO ₂ +2H ₂ to C + 2H ₂ O	2, 6, 12, 15, 19, 30	7, 17, 18, 21, 29 37, 61, 71, 72, 73	55	
CO ₂ +4H ₂ to CH ₄ +2H ₂ O	2, 6, 11, 15, 19, 30	8, 26, 42, 44, 45 46, 48, 57, 62, 70	55	
CO +3H ₂ to CH ₄ + H ₂ O		43		
<u>Electrolysis</u>				
Carbonates	13, 14, 19, 30, 32	8, 22, 60		
<u>Photosynthesis</u>	11, 12, 15, 31, 36	40		

4. CARBON DIOXIDE REMOVAL

The atmosphere control system provided in manned spacecraft removes carbon dioxide to maintain the CO₂ partial pressure at an acceptable level. The table presented on the next page indicates that many processes have been devised to accomplish this function.

The Project Mercury, Gemini and Apollo spacecraft all used lithium hydroxide to remove carbon dioxide by chemisorption. This process is extremely reliable because it requires only the flow of gas through a packed bed of lithium hydroxide granules. Unfortunately, it is impractical to regenerate the granules in flight; therefore, weight penalty is a linear function of mission duration. A non-expendable or regenerable process is warranted when the mission duration exceeds approximately one month.

Freezeout has been considered for vehicles that contain cryogenic fluids such as liquid oxygen. However, this approach actually is complicated or inefficient, because water vapor must be removed before carbon dioxide can be solidified.

Semi-permeable membranes can be used to remove carbon dioxide by concentration. However, existing materials do not have the selectivity required to satisfactorily do this in one stage; many stages with separate compressors are required to avoid excessive loss of oxygen.

The electrochemical techniques use a matrix instead of a membrane, and electric current to selectively remove carbon dioxide from a gas stream. Laboratory models have demonstrated that this technique can be reliable and have a long useful life. Its eventual application depends upon its effective weight penalty in comparison to other techniques.

Synthetic zeolites have been used in many prototype systems because they can be regenerated by evacuation. Since these materials have a higher affinity for water vapor than carbon dioxide, and it is impractical to vent overboard water vapor with carbon dioxide, synthetic zeolites require a predrier. When carbon dioxide must be collected for an oxygen regeneration system, in-bed heat exchangers are required to thermally desorb the synthetic zeolites.

Adsorption materials and immobilized amines, which are not moisture sensitive, have been investigated to determine if their lower capacity for carbon dioxide can be offset by simplification and increased thermal efficacy. One of these techniques, an electrochemical cell, or direct dissociation will probably be the eventual process used on extended missions in the late 70's.

TABULATION - CARBON DIOXIDE REMOVAL

<u>Techniques</u>	<u>Description or Analysis</u>	<u>Experimental Model/Data</u>	<u>Prototype System</u>	<u>Qualified System</u>
<u>Freezeout</u>	1, 22, 24, 30, 50			
<u>Permeation</u>	14	26, 36		
<u>Absorption</u>	5, 60	37		
<u>Adsorption</u>				
Synthetic Zeolites	5, 8, 14, 22, 24	7, 11, 12, 17, 18 20, 21, 24, 25 27, 54, 63	10, 13, 17 28, 39, 53 55	
Ion Exchange Resins		27, 37, 45, 51		
Activated Carbon		45, 59		
Coprecipitated Gels		45		
<u>Chemosorption</u>				
Limes, Soda	1	27, 42		
Baralyme	1	17, 42		
Hydroxides, Lithium	1, 3, 8, 14, 22	32, 56, 57		15
Potassium		27, 29, 37, 46		
Oxides, Metallic	24	42, 61		
Silver	5, 8, 14	21, 34, 48		
Magnesium	23	52		
Ozonides		33		
Superoxides	1, 2, 22, 58	4, 9, 16, 19, 62	38, 41, 42	
Carbonates	5, 8	6, 27		
Phosphates		27, 37		
Amines	1, 5	6, 27, 29, 37, 46	31	
<u>Electrochemical</u>				
Electrodialysis	22	51		
Carbonation		35, 40, 44, 49		
Depolarization		64		
<u>Biochemical</u>	24	37, 47		

5. TRACE CONTAMINANT CONTROL

The major background in this area has been developed as a result of industrial and submarine requirements for atmospheric contamination removal. Primary problems are (1) to define the expected cabin contamination load and allowable limits, and (2) to effectively apply the industrial, submarine and current spacecraft background to the spacecabin contaminant removal problem. To date, contaminant measurements in simulators and operational vehicles have provided only limited data on contaminant types and generation rates. Definition of the contaminant load for any closed environment remains a problem which still requires an adequate solution. Similarly, the allowable contaminant concentrations for continuous long-duration exposure under spaceflight conditions are not well established, due to the large number of possible contaminants and the large scope of the experimental effort required to define allowable levels.

Given the contaminant types, generation rates and allowable cabin concentrations, one can begin to define the equipment and materials required for contaminant removal. It is important to recognize that various processes already in the life support and environmental control system (e.g., CO₂ removal and H₂O condensation) play a part in removing a variety of contaminants from the atmosphere. These effects should be accounted for in defining the net load on the trace contaminant removal system.

The removal techniques listed in the table represent the primary ones considered for atmosphere purification. This table also provides the key to the bibliography of major efforts in this field. Currently, more experimentation is underway to characterize such important processes as catalyst deactivation and production of undesirable contaminants by contaminant "removal" devices, using multiple rather than single contaminants. A major emphasis is also being placed on the reduction of weight and power required to operate contaminant removal devices. Part of this emphasis is consideration of radio-isotopes and improved insulation techniques to reduce the weight penalty for heating catalytic oxidizers. Also, research is being conducted to search for improved sorbent materials and more active catalysts.

Regenerative systems to reduce the quantities of sorbents which must be carried are the subject of current research which should allow future engineering development of such equipment. Less costly and faster biological techniques for the identification of potentially toxic contaminants are under investigation together with similarly improved techniques for materials offgassing testing. A comprehensive computer-based analytical approach for optimizing such systems is another important future goal in this complex design area.

The work in this field is being done to provide safe, reliable and lightweight contaminant removal systems for advanced manned space vehicles, and the potential spin-offs from this work, to meet undersea vehicle and air pollution requirements, are being pursued.

TABULATION - TRACE CONTAMINANT CONTROL

<u>Techniques</u>	<u>Description or Analysis</u>	<u>Experimental Model/Data</u>	<u>Prototype System</u>	<u>Qualified System</u>
<u>Adsorption</u>				
Activated Carbon	1, 3, 22	8, 19	13, 17, 18, 23	4
Synthetic Zeolites	3	2, 19		
Silica Gel		8		
Lithium Hydroxide		8		
<u>Freezeout</u>	15	9		
<u>Absorption</u>		12		
<u>Oxidation</u>				
Ozone	1			
Catalytic				
Hopcalite	3, 6	7, 8, 11	17, 23	
Metals		5, 8, 11, 20, 21	10, 13, 18	
GAT-A-LYST			10, 17	
Oxides		8, 11		
Permanganates		8, 11		
<u>Filtration</u>	3, 6	5	17	4
<u>Electrostatic Precip</u>	14			
Chemosorption			23	