ATMOSPHERIC-CONTROL SYSTEMS FOR EXTENDED-DURATION

MANNED SPACE FLIGHT

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INTRODUCTION

The subject of this paper is atmospheric control for manned spacecraft for missions of longer than 60 days duration. Atmospheric-control systems may be defined as the hardware systems necessary to provide a habitable environment for man, including the following: carbon dioxide removal, water vapor removal, oxygen and nitrogen provision, contaminant control, and temperature control. This discussion is confined to the first three of these factors; namely, carbon dioxide removal, water vapor removal, and oxygen-nitrogen provision.

Man, existing in any near-leak-free vessel, such as a spacecraft, must be provided with certain environmental controls, in order that the atmosphere will provide both comfort and support for his needs. Man in a living habitat may be pictured crudely as analogous to a hydrocarbon-fueled engine; he consumes oxygen by the oxidation of hydrocarbons, giving off both carbon dioxide and water vapor from this oxidation, as well as heat energy and contaminants. He operates best within a fairly narrow range of variables within this environment, but has a surprising capability of coping, especially for short periods, with variables of his environment. For example, man is most comfortable at a given temperature and relative humidity, the exact degree of comfort being dependent upon such things as: wall temperature, air temperature, water-vapor partial pressure, gas composition, air circulation rate, clothing, and work load. He can cope with either increased or decreased cooling from this environment and has adaptive mechanisms that will allow continued functioning, for short time periods, depending on the extent of these changes.

In a similar fashion, man can tolerate both increases and decreases in other variables; oxygen partial pressure, carbon dioxide partial pressure, and water-vapor partial pressure. The greater the departure from normal in these parameters, however, the shorter is man's capability of coping with them without degradation in his abilities. In the design of environmental controls for manned spacecraft, therefore, prudence demands systems which minimize departures from these norms, while providing this control in a reliable and efficient manner.

The purpose of the present study is to indicate changes that must be made in atmospheric-control systems, because of the mission goal, as a result of changes in power penalty, and because of the considerations which must be made for reliability.

The simplest of all space missions is the earth-orbital mission, because of the relative ease of rendezvous and resupply, and the relatively short abort times. The next most simple mission is the lunar base, wherein large, fixed installations utilizing nuclear power supplies and taking advantage of the 1/6 gravity of the moon's surface may eventually become feasible. Most difficult of the missions are the planetary explorations, wherein abort and resupply are difficult. For the first of these planetary missions, all materials and supplies that will be required must be provided in the initial vehicle, and unrepairable system failures cannot be tolerated, because the presently envisioned booster systems would be unable to provide an abort capability that is significantly shorter than the length of time that the mission may have already accomplished.

In addition to mission orientation, the configurations of atmospheric control systems are dependent upon power penalty. Regenerative systems utilize considerably greater quantities of electrical and heat energy than do the nonregenerative systems. Therefore, the equivalent penalty which must be assessed against these control systems for the power that they use will have an effect on the relative desirability of these systems. To site an example, reduction of carbon dioxide to oxygen and carbon requires a given theoretical minimum amount of energy. This energy, plus any losses or inefficiencies must be supplied to all processes that are expected to fill this function. In addition, certain techniques are more inefficient than others and thus require a greater penalty. Certain of these energies are more costly, in terms of weight of power supply, than others; heat energy, for example, can be provided at a lesser penalty than can electrical energy.

These power penalties are illustrated in figure 1. Shown are the estimated weights of two types of oxygen provision systems. Without going into details at this point concerning their operational methods, it is assumed that process A consists of a regenerative carbon dioxide removal system and cryogenic oxygen stores. System B utilizes a technique to reduce carbon dioxide to water and methane, and the water is subsequently electrolyzed to oxygen and hydrogen, which is reused in the carbon dioxide reduction. System A requires about 100 watts of electrical energy, per man, and about 30 pounds (13.6 kg) plus 2.5 pounds (1.13 kg) per day of supplies to continue its function. System B requires about 400 watts of electrical energy, and 100 pounds (45.36 kg) per man plus 0.5 pound (0.23 kg) per man per day of supplies. Given two power provision systems to provide this electrical energy requirement, one requiring about 200 pounds (90.7 kg) of equipment to provide a kilowatt of energy and the other, of 500 pounds/kilowatt (229 kg/kW), the effects of power penalty can be readily demonstrated. If the decision to utilize one or the other of these two systems rested solely on the basis of system weight plus weight of equivalent power required, the regenerative carbon dioxide removal and stored oxygen would be preferred over the oxygen reclamation system, at a power penalty of 500 pounds/kilowatt (229 kg/kW); for a penalty of 200 pounds/kilowatt (90.7 kg/kW), the opposite would be true.

After the first successful lunar landings, lunar explorations will be undertaken for longer and longer times. Eventually, a permanent logistically resupplied lunar colony will be established. The life-support systems for such colonies will differ markedly from those presently envisioned for earth orbit, in that longer-term usage will be expected, with a periodic resupply of expendables, and additional reliability will be necessary. In the design of these systems, advantage can be taken of the 1/6 g that is present on the lunar surface, so that many of the systems which now require zero-g operation can be simplified.

Reliability, or failure-free operation is not as easily quantified as are the variables of power penalty. Nevertheless, this consideration can result in modification of system selection, simply on the basis of the degree of knowledge and experience with the candidate systems, as well as consideration of the relative complexities of the system.

The following three sections of this paper will deal with: (1) the control of humidity; (2) the removal and dumping of carbon dioxide and the provision of oxygen and nitrogen from stores; and (3) the removal and concentration of carbon dioxide and the reduction of this carbon dioxide and some additional water to breathable oxygen, with consequent reduction in the quantity of oxygen that must be supplied. The most attractive candidate techniques for fulfilling these functions will be discussed, and an attempt will be made to show the relative merits and disadvantages of these systems. In many cases, these techniques are undergoing fairly rapid changes because of the current research efforts. Certain of these efforts may uncover techniques that will ultimately prove to be better than the best shown here. One of the functions of the Langley Research Center is to encourage new research, develop new techniques that have merit over presently known methods, and reduce even further the weight and power requirements of presently known systems, while increasing their efficiency and reliability.

HUMIDITY CONTROL

If the engine analogy used in the beginning is again considered, man is an oxygen consuming system. In order to acquire this oxygen, he respires about 16 volumes of air for each volume of oxygen that he takes up from this air. All the air passing through the lungs becomes saturated with water vapor. In addition, water is evaporated from the surface of the body. Therefore, about 2 pounds (0.91 kg) or more of water are lost to the atmosphere per man per day, assuming about 50 percent initial saturation. If this water vapor is not removed from the atmosphere, and a comfortable environment maintained, the moisture level will increase to saturation, and will begin to condense on the coolest surfaces available. A high humidity environment is undesirable from consideration of comfort, as well as for other reasons, and uncontrolled condensation is to be avoided. Therefore, humidity-control systems (in conjunction with temperature and air moving equipment) that sustain a desired comfort level are a necessity. Further, the water condensed from the air is a valueable waste product suitable for reclamation to drinking water.

Chemical absorbers, such as lithium chloride, and other water sorbers become so costly in terms of weight in a short period of time that they have never been used in a manned spacecraft. All systems to date have been of the regenerative type, that is, the type that performs its function without loss of capacity with time. The only way that humidity control has been approached is to cool the air to some temperature below its dew point, condense a part of this moisture, and separate this moisture from the cooled airstream. Mercury, Gemini, and Apollo all use heat exchanges and regenerative-type separators. These systems have disadvantages, however, such as large pressure drops, requiring large and power consuming fans, and a number of improvements have been proposed, including centrifugal separators, for use in the lunar module of Apollo. Presently, two concepts appear to be very attractive for future use: a technique utilizing a cooled sintered metal plate; and a technique using hydrophobic screens to separate the droplets from the airstream, and hydrophilic surfaces to remove the separated water, free of air bubbles, to holding tanks. It should be emphasized at this point that the maintenance of air-free water from the humidity control system is most desirable, since any bubbles which are allowed to enter the condensed water stream may collect in the holding tank, under zero g, and cause a failure of the system or subsequent systems.

The first of these humidity-control systems, shown in figure 2, was developed at the Langley Research Center and consists of a number of sintered metal plates which are exposed to the airstream. The plates are cooled to below the dew point of the airstream by circulating cold water. The moisture, condensed from the airstream by this cooling, is drawn through the sintered metal plate by maintaining the pressure within the circulating fluid loop at a pressure lower than the airstream pressure. The condensed water is thus added to the volume of cooled circulating water and may be removed continuously, or periodically, for storage or further treatment. Care must be taken with this unit to prevent the differential pressure across the face of the plate from becoming so great as to break the capillary forces which tend to keep the pores of the metal plate filled with water. If the pore size of the plate is made small, these pressure differentials can be surprisingly high; in this case, a differential pressure of about 7 psi (4.8×10^4 newton/meter^2) is required before air is forced through the plate. Sintered metal plates can be fabricated in a number of configurations, and the concept possesses the desirable characteristics of simplicity, lack of moving parts, and a capability of operating under conditions of zero g, as well as any orientation under conditions of one or more g's.

The second of these promising techniques is that in which hydrophobic and hydrophilic surfaces are used to separate entrained water droplets downstream from the heat exchanger. Figure 3 shows, in cross section, how such a device operates. The airstream, moving through the separator and carrying the entrained water droplets, passes through a fine-mesh conical screen which is coated with a hydrophobic material such as Teflon. The surface tension of the water and the contact angle of the air-water Teflon interface results in the prevention of the passage of the water droplets, and because of the angle of the hydrophobic cone, these droplets are forced to migrate into the sump. In this region, these water droplets collect, and encounter a fine-meshed hydrophilic screen, constructed of material such as stainless steel. This screen and the tubing downstream from it will remain filled with water, and will retain its resistance to air passage with a differential pressure of about 0.3 psi (2.07×10^3 newton/meter^2) between the air at the surface and the water within the screen. As water from the hydrophobic cone comes into contact with the screen, it passes through with only a small resistance (again because of the surface tension of the water, and the contact angle of the air-water stainless steel interface) and is eventually routed to a holding tank for reprocessing.

The major advantages of a humidity-control device of this type is its low pressure drop, and consequently low fan power, and the lack of moving parts. Tests at the Langley Research Center and research under contract to the Lockheed Missile and Space Company have confirmed the operational advantages of this separator and long-term testing of the unit is planned in manned test chambers. Some of the significant operational parameters of this system are shown in figure 4.

CARBON DIOXIDE REMOVAL AND OXYGEN-NITROGEN SUPPLY

The removal of carbon dioxide, as given off by man in spacecraft environments, requires a removal capacity of about 2.24 pounds (1.02 kg) of CO_2 per man per day, with a flow rate through the removal system of some 3 cubic feet (0.085 meter^3) per minute to maintain a concentration of 1/2 percent of carbon dioxide in the cabin atmosphere, assuming near 100 percent removal of carbon dioxide per pass. If the removal efficiency per pass is less than 100 percent, the airflow rate must be increased proportionally, in order to maintain this partial pressure of carbon dioxide.

There are many techniques for removing carbon dioxide from spacecraft atmospheres. Carbon dioxide removal can be accomplished by chemical means (lithium hydroxide), or be regenerative means of several varieties: water sensitive sorbers (molecular sieves), water insensitive sorbers (modified resins, among others) and other means, such as the carbonation cell. The first of these techniques, lithium hydroxide, has been demonstrated to be successful on the Mercury and Gemini flights and is scheduled for use in the Apollo mission. Its chief drawback, when used for long missions, is its weight and volume, since it is expended rather than regenerated. Molecular sieves also possess an affinity for carbon dioxide and, furthermore, its affinity is not so strong as the chemical bond formed with lithium hydroxide so that the application of moderate amounts of heat energy, or reduction in the carbon dioxide partial pressure, or both, will cause this adsorbed carbon dioxide to be desorbed. Therefore, the molecular sieves (or other regenerable sorber) can be made reusable by removing the previously collected carbon dioxide.

Since molecular sieves possess a preferential affinity for water over carbon dioxide, it is necessary to protect the carbon dioxide sorption beds by predrying the airstream containing the carbon dioxide with another sorber such as a different molecular sieve, a silica gel, or some other sorber which removes water, rather than carbon dioxide. This predrying system must also be made regenerable, and thus by the application of heat energy, or a reduction in water vapor partial pressure, as by exposure to space vacuum or both, the water is removed from the sorber and its predrying function capability restored. For continuous operation, it is necessary to have one set of beds adsorbing water and carbon dioxide while the other is desorbing. A minimum of four beds are necessary for predrying and for carbon dioxide removal. As indicated, water can be removed from the predrying beds by exposure to space vacuum; however, this process results in the loss of this moisture and unless a low penalty source of water is available, such as a fuel cell, the penalty for this water loss is excessive. Almost all studies with this concept, for longer-duration missions wherein fuel cells for electrical power are not an economical choice from a weight standpoint, utilize a heat-regenerated desiccant bed, and a vacuum regenerated carbon dioxide sorber. Heat regeneration allows the return of the moisture which the bed has adsorbed in protecting the molecular sieve beds.

Before a discussion is given of the numerous ways in which these molecular sieve, desiccant sorbers can be operated, some brief mention will be made of two additional concepts that are capable of removing carbon dioxide. These concepts have their most promising application in the carbon dioxide concentration mode; that is, in the removal and collection of metabolic carbon dioxide, in order that subsequent reduction of this carbon dioxide can be performed and the stores of oxygen supplies reduced. One of these concepts is a modified resin which shows a capability for sorbing carbon dioxide in the presence of water vapor. In fact, water of hydration within the resins is essential for their proper operation.

These resins have shown a capacity for the adsorption of carbon dioxide which is slightly greater than the adsorption capacity of molecular sieves, and have the capability of being completely regenerated at temperatures of about 212° F (100° C). The total quantity of heat energy which is necessary to regenerate these resins is about the same as that necessary for molecular sieves. The carbon dioxide which is desorbed from these resins has a high water content, however, and if these resins are to provide carbon dioxide for oxygen reclamation systems, care must be taken in the integration of these two processes to accommodate the wet carbon dioxide.

The third type of sorption system is the carbonation cell. This system consists of three cells; the first two producing increasingly concentrated carbon dioxide which is absorbed from a cabin airstream by the first cell, together with some oxygen. The third cell provides the separation of the carbon dioxide from the oxygen. This process operates on an electrolysis principle, the electrolyte in the first two cells being a potassium carbonate solution, and the electrolyte in the third cell being an aqueous sulfuric acid solution. This process, like the resins, has its application in the providing of carbon dioxide for further reduction, as a part of an oxygen reclamation system.

The use of molecular sieves, in combination with predrying beds, has had the most intensive study and testing of all of the regenerative carbon dioxide removal methods. The concept is capable of being used in three separate and distinct ways: all-vacuum desorbed, wherein both the water and carbon dioxide are removed from the cabin airstream, and desorbed to space vacuum; carbon dioxide vent, water conservation method, wherein the adsorbed carbon dioxide is vented to space vacuum, but the water which was adsorbed is conserved and returned to the cabin; and an all-conservation method wherein the adsorbed water and carbon dioxide are retained, the water being returned to the cabin and the carbon dioxide collected for reduction as part of an oxygen reclamation process. These operating methods are shown on the next figure (fig. 5), as "vent H_2O and CO_2," "vent CO_2, conserve water," and "conserve H_2O and CO_2." It should be noted that these three methods are in order of increasing mission duration. The venting of both carbon dioxide and water has its best application on vehicles which use a fuel cell, and the water can therefore be lost without penalty. This desorption technique requires the least power. The intermediate case, the venting of carbon dioxide and conservation of water, has its application on spacecraft which do not use fuel cells, but at the same time are not of sufficient mission duration to warrant the reclamation of oxygen. In this case, the conservation of water adds to the complexity and power requirements of the system. The case of the conservation of both water and carbon dioxide results in the most complex and power consuming of these operating concepts, in that the water vapor is returned to the cabin, and the carbon dioxide is collected and stored, usually with the aid of a pump, for subsequent reduction.

On the vertical scale of this figure are shown different operating modes for both adsorption and desorption; the isothermal and nonisothermal mode for adsorption, and the pressure change, temperature change, and both pressure and temperature change, for the desorption mode. The adsorption of water and carbon dioxide by these materials results in the liberation of heat energy; the heat of adsorption. The capacity of these sorbers decreases with increasing temperature. The sorbers may be operated in the constant temperature mode (isothermal) by removing the heat of adsorption, or may be allowed to "free-run," with the heat of adsorption raising the temperature of the bed, thus decreasing its capacity, and raising the temperature of the airstream leaving the bed. In the desorption mode, two methods for removing the water or carbon dioxide may be used, or a combination of both: increased temperature, thus supplying the heat of desorption and decreasing the capacity of the sorber or decreased partial pressure of the sorbate, carbon dioxide or water vapor. The latter can be accomplished by purging the bed with sorbate-free gas, or reducing the total pressure within the bed by means of a pump or exposure to space vacuum.

Currently, at least five different approaches are bing studied. The first of these is the all-vacuum desorption case, as envisioned for the Manned Orbital Laboratory (MOL) and Apollo applications. The MOL system concept adsorbs water and carbon dioxide in a nonisothermal mode, and desorbs these gases by vacuum only. The Apollo applications program concept uses active cooling of the water sorber to increase the capacity of this bed, and active heating of the bed, on desorption, to aid in its regeneration. as well as the application of space vacuum.

The second approach is the best known of the molecular sieve concepts, wherein water and carbon dioxide are sorbed, nonisothermally, and the water is desorbed by the application of heat to the process air entering the bed to be regenerated while the carbon dioxide is vented to space vacuum.

The third approach is one in which active cooling and heating of both the water and carbon dioxide sorbers are used, plus a pump for the collection and storage of the carbon dioxide. This system is in use at the Langley Research Center as the carbon dioxide concentration unit in the Integrated Life Support System (ILSS).

The fourth approach is currently under study by contract from Langley. This study involves the isothermal sorption and heat-assisted desorption of both water and carbon dioxide for molecular sieves, silica gel, and other materials. The study is being carried out using heat exchanger surfaces, coated with the sorber materials, and very high heat-transfer rates are being studied from the standpoint of increasing the adsorption capacity and decreasing the desorption time.

The fifth operating method is the adiabatic, or "heatless" desorption, wherein the heat of adsorption is conserved within the bed, and the loading of the bed is confined to the linear portion of the capacity-loading curve. The heat of adsorption is therefore available to supply the energy requirement for desorption. This operating method depends not on changes in bed temperature, but on increased volume flow rate of sorbate-free air through the beds to regenerate them. Both of these last two methods show some advantages over the more conventional approaches, and may apply both to the conservation as well as the venting of carbon dioxide.

In addition to the removal of carbon dioxide, it is necessary to provide oxygen for man's consumption, as well as oxygen and nitrogen to make up for vehicle leakage, and other losses such as air-lock cycling. Cryogenically supplied oxygen and nitrogen appear to hold the most promise for the mission duration wherein oxygen is not reclaimed. Depending on power penalty and the time for which the cryogenic stores are to be used, the electrolysis of water may be used to supply part, or all of the oxygen supply. The differences in these two techniques may be seen in an estimate of the weight, power, and storage penalties: where cryogenic oxygen can be stored on a one-man basis at a weight penalty of about 2 pounds (0.91 kg) plus about 2.4 pounds (1.09 kg) per day, whereas water storage and electrolysis may be accomplished for about 30 pounds (13.6 kg), 260 watts, and about 2.3 pounds (0.94 kg) per day for storage and container. Depending on the power penalty, these two are about equal for longer term missions. If some water can be derived from the water reclamation cycle, at no storage penalty, this will increase the attractiveness of the electrolysis method. For very long-term storage, and with little continuous usage to account for the boil-off losses, the storage and electrolysis of water are probably advantageous.

OXYGEN RECLAMATION SYSTEMS

As mission length increases, the use of systems to reduce or eliminate the storage of oxygen, either cryogenically or as water, becomes feasible. These concepts, as shown in the next figure (fig. 6), involve the collection of carbon dioxide, its reduction to water and methane (Sabatier), water and carbon (Bosch), oxygen and carbon monoxide (Solid Electrolyte), or oxygen and carbon (Molten Carbonate). In the case of the first two, the water produced must be electrolyzed to oxygen and hydrogen, and the hydrogen reused in the process. The minimum theoretical electrical power necessary to reduce carbon dioxide and water to the required quantity of oxygen, carbon, and hydrogen, in order to balance the oxygen cycle is about 125 watts per man on a continuous basis. The relative efficiencies of these processes are calculated on the basis of the actual amount of power required to accomplish the overall task, including the collection of carbon dioxide if necessary, and the electrolysis of water as required.

In the later two cases shown in figure 6, a small amount of water electrolysis must be performed separately from the basic reduction of carbon dioxide. (The Sabatier and Bosch processes produce water from hydrogen and carbon dioxide, all of which must be electrolyzed, along with some additional water, to achieve balance in the oxygen cycle.) In the case of the solid electrolyte the carbon monoxide must undergo a disproportionation reaction and the resulting carbon dioxide recycled to the solid electrolyte unit. Of these processes, the molten carbonate process is unique in that it is capable of sorbing carbon dioxide directly from the cabin airstream, rather than requiring a nearly pure feed stream of carbon dioxide from a concentration system.

These processes vary considerably in their efficiency, complexity, and ease of reduction to practical flight hardware. As might be suspected, the methane dump Sabatier, the simplest reaction requiring the lowest temperature, is the easiest to construct in a reliable operational unit, but possesses, at the same time, the greatest penalties for losses. Figure 7 shows this concept as a part of an overall oxygen reclamation process. Since methane is vented in this process, some hydrogen must be stored in order to allow continued operation with a balanced oxygen cycle. In addition to the loss of methane, some water vapor is lost, adding to the inefficiencies of the unit. By the incorporation of a methane cracking subsystem, as shown in figure 8, many of these drawbacks can be eliminated. Unfortunately, the problem of methane cracking is very difficult and this addition adds greatly to the base weight and the problem of the system.

The Bosch reaction shown in figure 9 is accomplished at a somewhat higher temperature than the Sabatier (1250° F (680° C) as compared with 300-500° F (150-260° C) for the Sabatier). It is, however, a closed system and losses are minimized. The losses in this system come about principally because of the inclusion of nitrogen in the carbon dioxide feed stream, so that purging the system is required in order to maintain a constant pressure. The purge gases consist of those which exist in equilibrium in the reaction cycle, unreacted hydrogen and carbon dioxide, carbon monoxide, water vapor, and other hydrocarbons. Both the Sabatier and the Bosch reactors are fed from a carbon dioxide concentration unit, and both require water electrolysis to complete the process of oxygen reclamation.

Figure 10 shows the solid electrolyte process, which is currently under investigation by several research laboratories. It differs considerably from the Bosch and Sabatier processes in that, although it requires a nearly pure carbon dioxide feed stream, the products which result from this high-temperature electrolysis process are oxygen and carbon monoxide. This carbon monoxide is made to undergo a disproportionation reaction which, in the presence of a catalyst, results in the deposition of carbon, and the formation of carbon dioxide, which is recirculated back to the solid electrolyte. There is evidence that this process is capable of reducing water concurrently with carbon dioxide, and there is also reason to believe that the reduction of carbon dioxide is enhanced by the presence of water vapor. Thus, by separating proper amounts of hydrogen from this process, and feeding a stream of carbon dioxide and water vapor to the process, it may be possible to achieve a balance in the oxygen cycle, without resort to a separate water electrolysis.

The molten carbonate process, shown on the last figure (fig. 11), is being investigated by the Hamilton-Standard Division of United Aircraft Corporation, under a research and development contract from Langley Research Center. This process shows promise of reducing weight, power requirement, and complexity of the overall oxygen reclamation process. This process, as mentioned previously, is unique in that it is capable of sorbing carbon dioxide directly from a cabin airstream and, in a one-step process, of reducing this carbon dioxide to carbon, which is deposited on the cathode, and oxygen, which is liberated at the anode and leaves the system along with the cabin airstream. The oxygen and nitrogen in this airstream are unaffected and do not enter into the process in any way. There is evidence to show that large amounts of water vapor may be detrimental to the process, and it is planned to minimize the quantities of water vapor entering the molten carbonate system by reversibly adsorbing and desorbing this water by the use of silica gel or other predrying beds in much the same manner that molecular sieves are protected by predrying beds.

The molten carbonate process takes place at relatively high temperatures, some 1100° F (600° C) and the process operates by the electrolysis of a molten mixture of lithium carbonate and lithium chloride. Some problems are still to be overcome in the application of this process; however, there is no reason to believe that these will not be solved. Laboratory demonstrators are now operating for relatively long-time periods, and the inherent high electrical efficiency of this process is reflected in these demonstrators. Current efforts are centering around the design of a 1/6 g prototype system, and subsequent efforts will include the construction of this system, and the design and construction of a zero-g system. In the application of this technique to oxygen reclamation in spacecraft, it will be necessary to provide for a balance in the oxygen cycle, by electrolysis of some water, which according to present indications must be accomplished separately from this process.

These system processes that have been discussed represent what is believed to be the most attractive candidate processes for oxygen reclamation in spacecraft. They are all capable, with some water input (0.33 pound per man per day) of achieving a balance in the oxygen cycle. Certainly some additional oxygen must be stored, along with nitrogen to make up for leaks and possible air-lock cycling. However, again dependent upon a number of considerations, such as power penalty, reliability considerations, and the like, they are capable of being utilized to reduce greatly the amounts of stores that are necessary for atmospheric provision and the support of man. The use of oxygen reclamation systems for long-term orbital spacecraft and lunar colonies will show logistic advantages by minimizing the resupply of oxygen.

Some mention should be made concerning bioregenerative systems for manned spacecraft. Several candidate systems that are believed to be capable of removing carbon dioxide and supplying oxygen have been proposed. If this were the only capability of these bioregenerative systems, they would not be competitive with the electro-chemical systems on the basis of weight and power requirements. They are potentially capable, however, of also providing all, or part of the nutritional requirements of man, and of utilizing all, or part of the waste products of man. When these factors are taken into consideration, it is apparent that for very long missions, or for permanently established planetary or lunar colonies, these bioregenerative systems will ultimately be the processes of choice. A much longer development time will be required for these processes, however, than is necessary for the physical-chemical and electro-chemical processes that have been discussed here.

CONCLUSIONS

Several general problems can be noted from examination of the physical-chemical and electro-chemical systems for application to long-term manned spacecraft. These problems can be separated into two types, the first of which is operational problems, or those which can be overcome by experience and further knowledge of the process, and more knowledge of materials and the way they react to the environment in which they are applied.

Carbon deposition, as required for the successful operation of the Bosch process, the methane-cracking Sabatier process, and the disproportionation reaction of the solid electrolyte, appears to be a common difficulty. The trouble-free continuous deposition and removal of this carbon in a zero-g configuration has not been successfully demonstrated for long-time periods; however, there is no reason to believe that this cannot be done. What is necessary is further attention to the problem, further knowledge of the details of the process, and perhaps the utilization of new materials.

In the past, the separation in a zero-g system of mixtures of gases and liquids has presented much difficulty. This difficulty appears to be successfully overcome, at least for small quantities of nearly pure water in air at moderate temperatures. Further attention and effort will undoubtedly result in success for other liquids and gases at higher temperatures. These kinds of problems present no insurmountable difficulties; time and effort will provide an acceptable solution.

Aside from operational problems, the second problem area to be overcome is one of long-term reliable operation. Here again, knowledge of the exact nature of the failures and provisions to prevent their recurrence will aid in reducing failures. Systems can be made to operate, with a high degree of freedom from failure for a specified time, but the more complex the system and the longer the mission duration, the more difficult the task becomes. Research is in progress to deal with both of these problems: for longer missions more complex systems will replace the more simple systems, and the resultant requirement for failure-free operation becomes many times more difficult. The only escape from this dilemma is the allowance of maintenance and repair by the crew members, in addition to the strenuous effort being applied to the final flight hardware. Provision for this repair and maintenance must be incorporated into the design of these systems and spares must be provided. The crew members must be familiar with the operation and maintenance of these systems, and they must be skilled in the diagnosis and repair of this hardware, as problems occur.

SUMMARY

In this paper has been discussed, in order of increasing complexity and mission duration, candidate processes and techniques for atmospheric control of manned spacecraft. The processes and techniques have been briefly described, and some estimates have been given as to their weight, power requirement, and required supplies. Factors that affect the use and attractiveness of such systems have been discussed, and the influence of such factors as power penalty, mission objective, and so forth, have been shown. The intent of this paper is not so much to acquaint the readers with the detailed working of these processes or to provide enough knowledge to allow selection of these systems on the basis of the variables stated, but rather to give an overall view of candidate processes for atmospheric control systems and to show the important factors which influence selection, power penalty, mission goal, and mission duration.

BIBLIOGRAPHY

1. Martin, R. B.: "Carbon Dioxide Control for Manned Spacecraft", NASA TM X-57524, Presented at the 37th Annual Scientific Meeting of the Aerospace Medical Association, Las Vegas, Nevada, April 18-21, 1966.

2. Popma, D. C.: "Oxygen Reclamation for Manned Spacecraft", NASA TM X-57535, Presented at the 37th Annual Scientific Meeting of the Aerospace Medical Association, Las Vegas, Nevada, April 18-21, 1966.

3. Bioastronautics Data Book, NASA SP-3005; Scientific and Technical Information Division, NASA Washington, D.C., 1964.

4. Babinsky, A. D.; DeRespiris, D. L.; and Derezinski, S. J.: "Carbon Dioxide Concentration System", NASA CR-72086, Prepared for NASA by TRW Equipment Laboratories, Cleveland, Ohio, July 30, 1966.

5. General Dynamics, Convair Division, "Life Support System for Space Flights of Extended Time Periods", NASA CR-614, Prepared for NASA by General Dynamics, San Diego, California, November 1966.

6. Hamilton Standard, Division of United Aircraft, "Research and Development Program for a Combined Carbon Dioxide Removal and Reduction System", NASA CR-66085, Prepared for NASA by Hamilton Standard, Windsor Locks, Connecticut, November 1965.

7. Ames Research Center, "The Closed Life-Support System", NASA SP-134, Ames Research Center, Moffett Field, California, April 14-16, 1966.

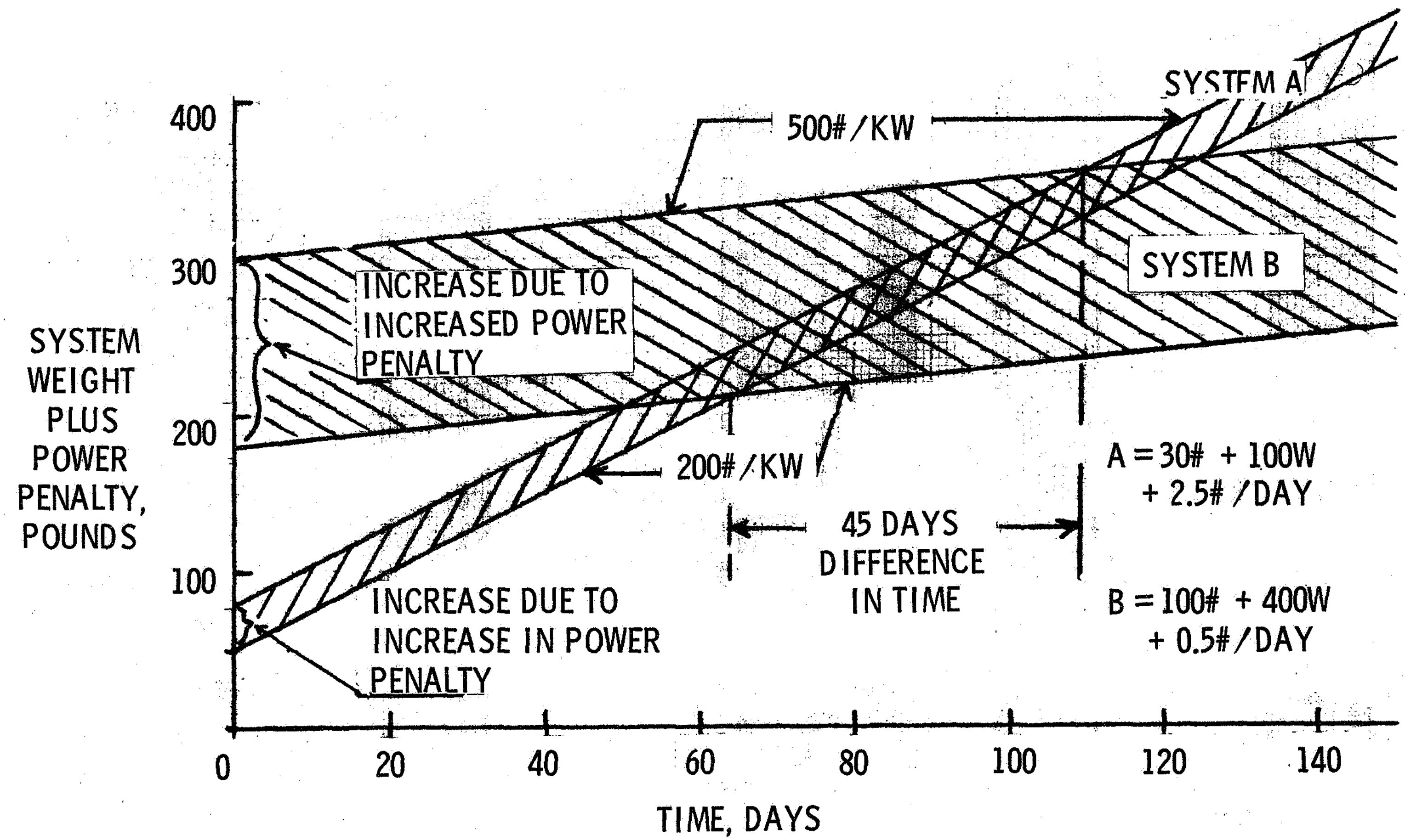

Figure 1.- Atmospheric control at different power penalties.

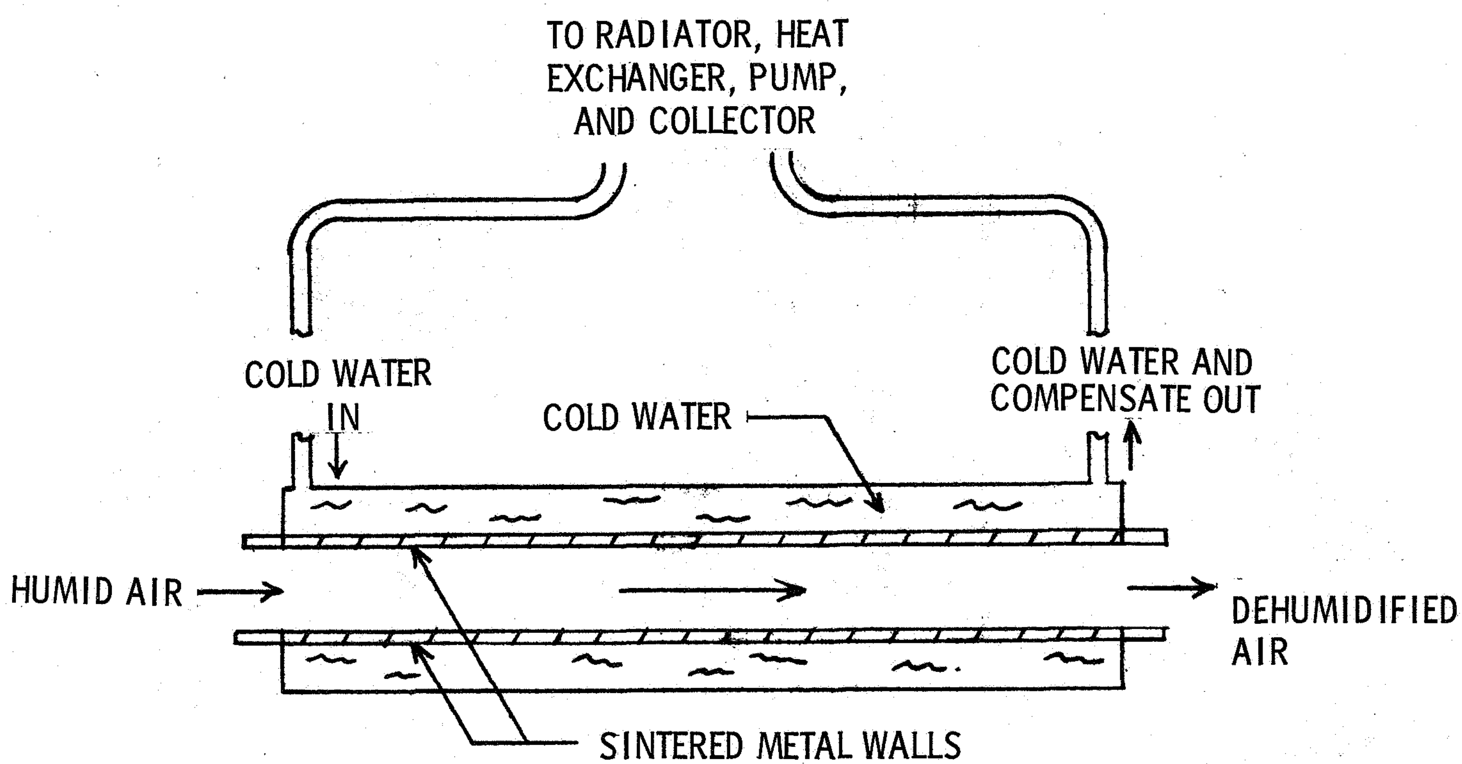

Figure 2.- Humidity control by the use of porous metal heat exchanger.

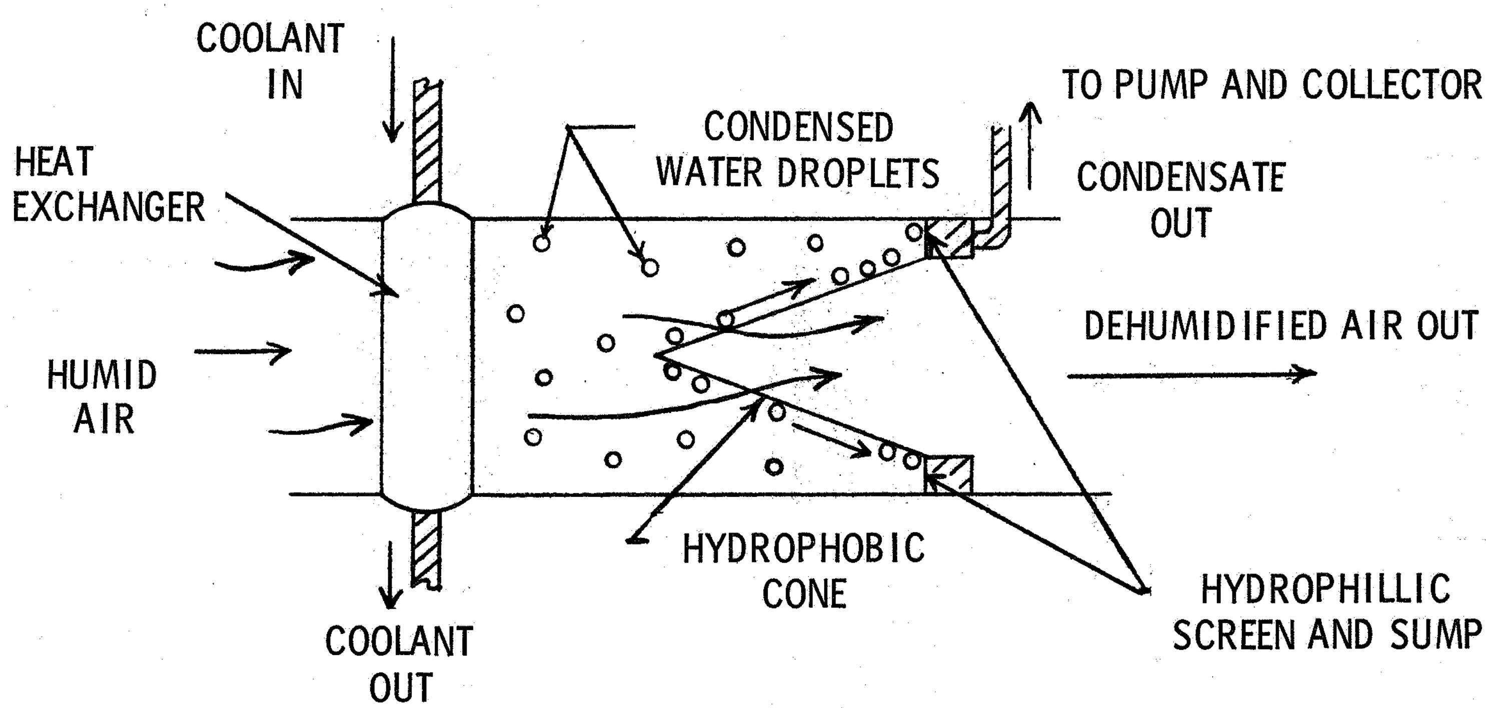

Figure 3.- Humidity control and water separation by use of hydrophobic and hydrophillic materials.

SYSTEM WEIGHT, 1-1/2 POUNDS/MAN

POWER REQUIREMENT, 8 WATTS/MAN

PRESSURE DROP, 2" H_2O AT 75 CFM

REMOVAL CAPACITY 1.08 POUNDS/HR

CAPACITY 12 MEN

Figure 4.- Humidity control separation by use of hydrophobic and hydrophillic materials.

<table>
<tr><th colspan="2"></th><th colspan="6">INCREASING MISSION DURATION →</th></tr>
<tr><th colspan="2"></th><th colspan="2">VENT H_2O AND CO_2</th><th>VENT CO_2</th><th colspan="2">CONSERVE H_2O</th><th>CONSERVE H_2O AND CO_2</th></tr>
<tr><th colspan="2"></th><th>MOL</th><th>AAP</th><th>CONVENTIONAL</th><th>G.E.</th><th>ESSO</th><th>ILSS</th></tr>
<tr><td rowspan="2">ADSORPTION</td><td>ISOTHERMAL</td><td></td><td>H_2O</td><td></td><td>H_2O AND CO_2</td><td></td><td>H_2O AND CO_2</td></tr>
<tr><td>NON-ISOTHERMAL</td><td>H_2O AND CO_2</td><td>CO_2</td><td>H_2O AND CO_2</td><td></td><td>H_2O AND CO_2</td><td></td></tr>
<tr><td rowspan="3">DESORPTION</td><td>TEMPERATURE CHANGE</td><td></td><td></td><td>H_2O</td><td rowspan="2">H_2O AND CO_2</td><td></td><td>H_2O</td></tr>
<tr><td>BOTH</td><td></td><td>H_2O</td><td></td><td rowspan="2">H_2O AND CO_2</td><td>CO_2</td></tr>
<tr><td>PRESSURE CHANGE</td><td>H_2O AND CO_2</td><td>CO_2</td><td>CO_2</td><td></td><td></td></tr>
</table>

Figure 5.- Regenerable CO_2 removal.

		Resupply to make up losses	Requires CO_2 concentration	Requires water electrolysis	Requires phase separation	Requires carbon deposition	High temperature operation	Efficiency (125 watts/man theoretical)
SABATIER	CH_4 VENT	0.4#	YES	YES	YES	NO	400^0 F	30%
	CH_4 CRACK	—	YES PURE	YES	YES	YES,	2000^0 F	25%
BOSCH		—	YES PURE	YES	YES	YES, $CO_2+2H_2O \rightarrow C+2H_2O$	1250^0 F	21%
SOLID ELECTROLYTE		—	YES	NO	NO	YES, $2CO \rightarrow C+CO_2$	1800^0 F	19%
MOLTEN CARBONATE		—	NO	YES, 15%	YES HIGH TEMP.	YES, ON CATHODE	1100^0 F	32%

Figure 6.- Oxygen reclamation techniques.

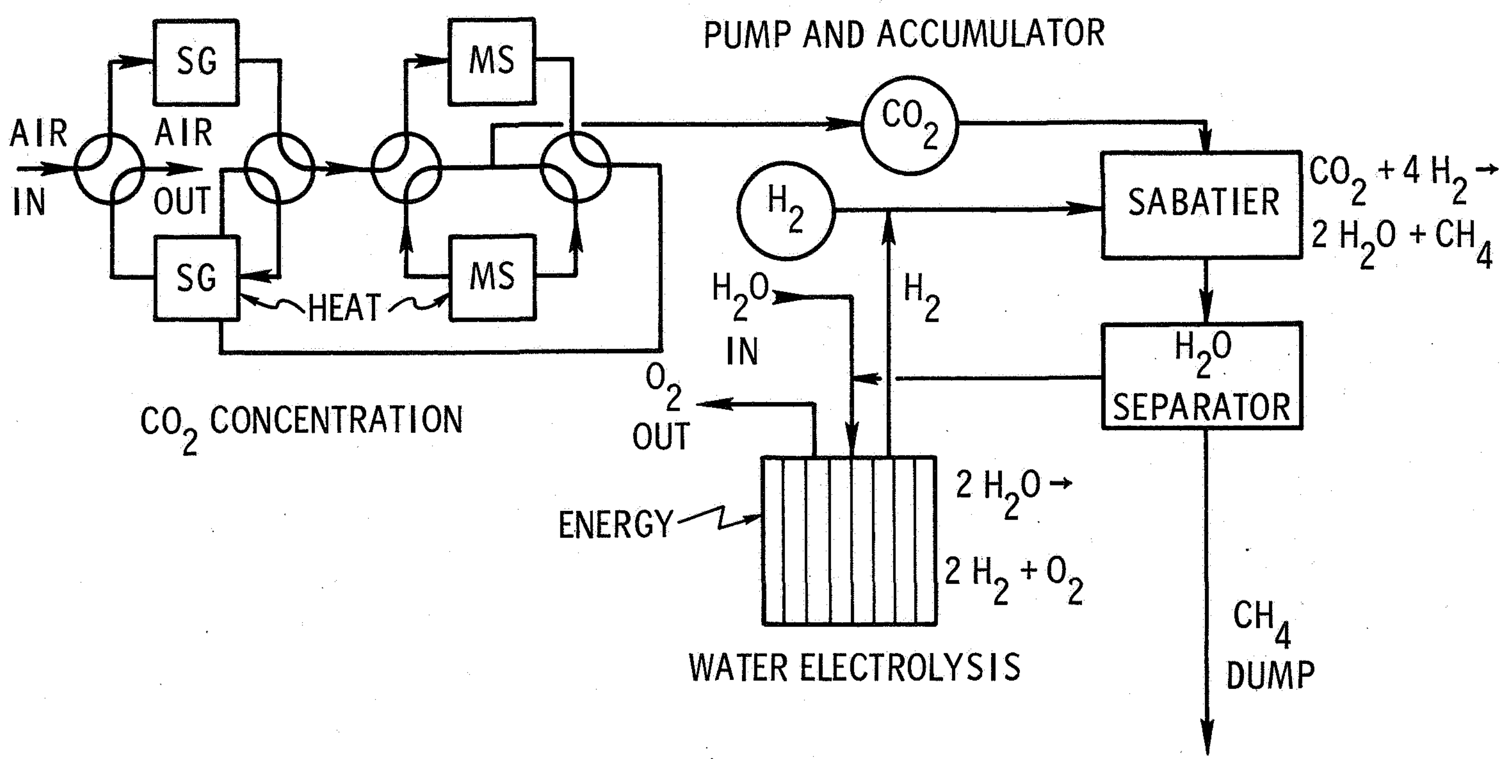

Figure 7.- Sabatier oxygen reclamation.

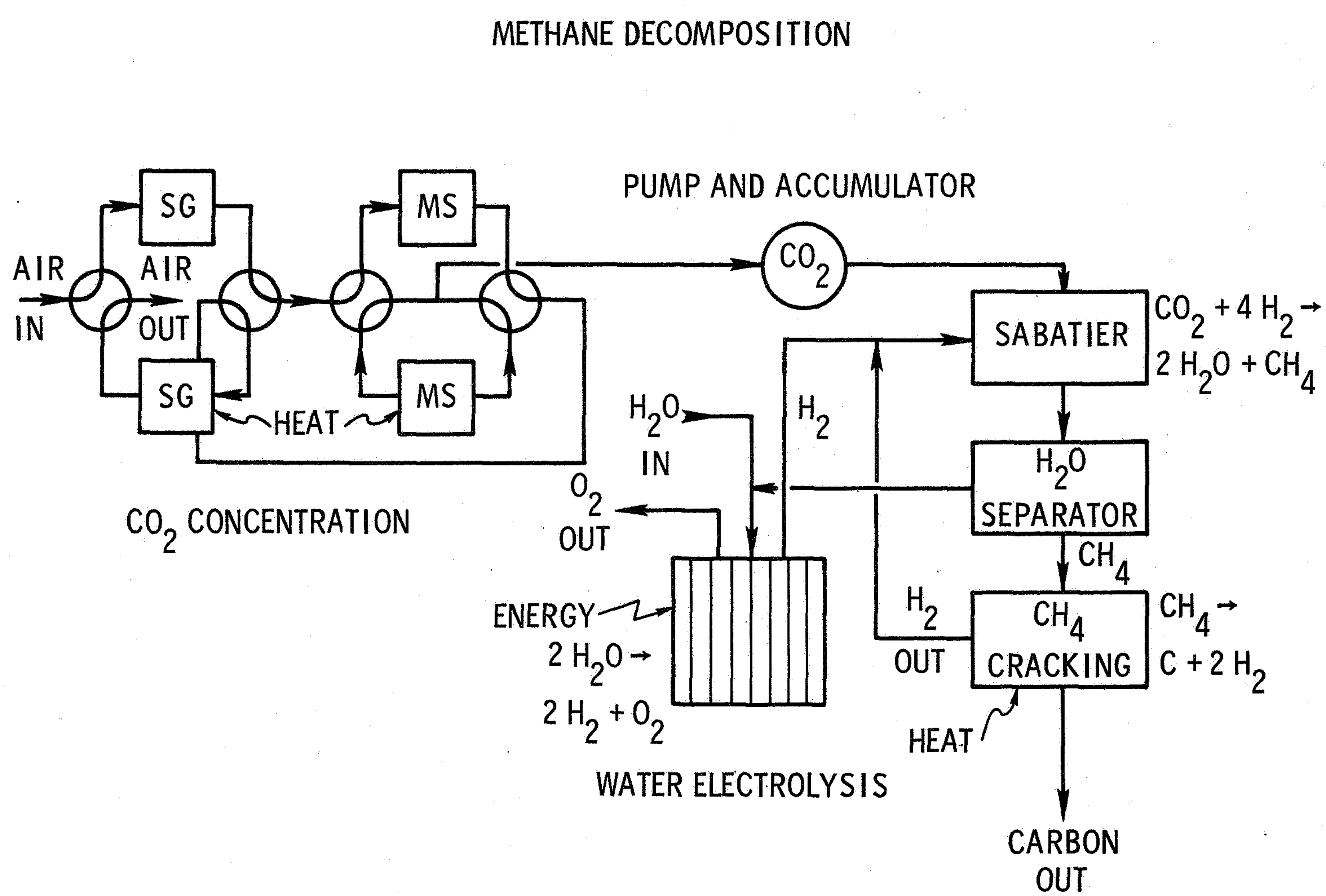

Figure 8.- Sabatier oxygen reclamation.

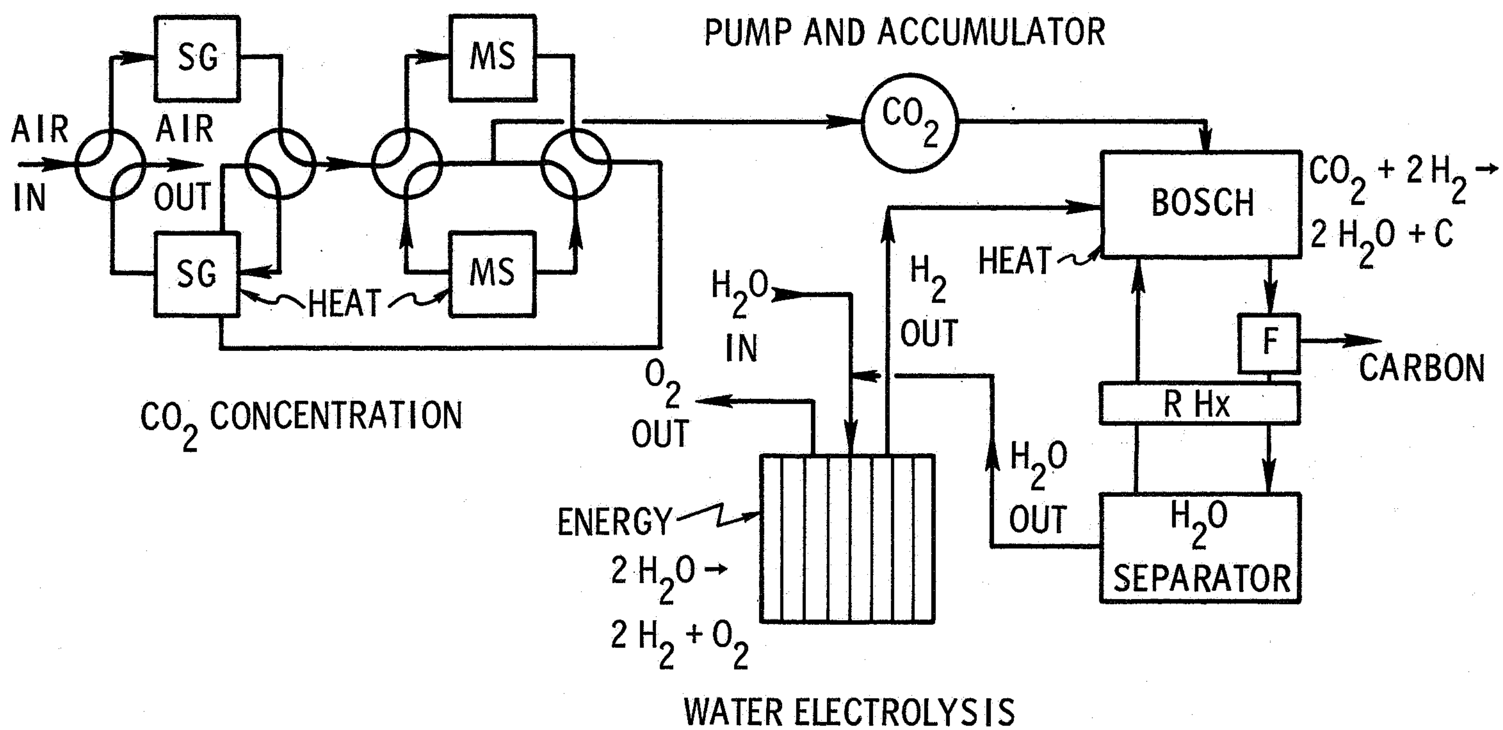

Figure 9.- Bosch oxygen reclamation.

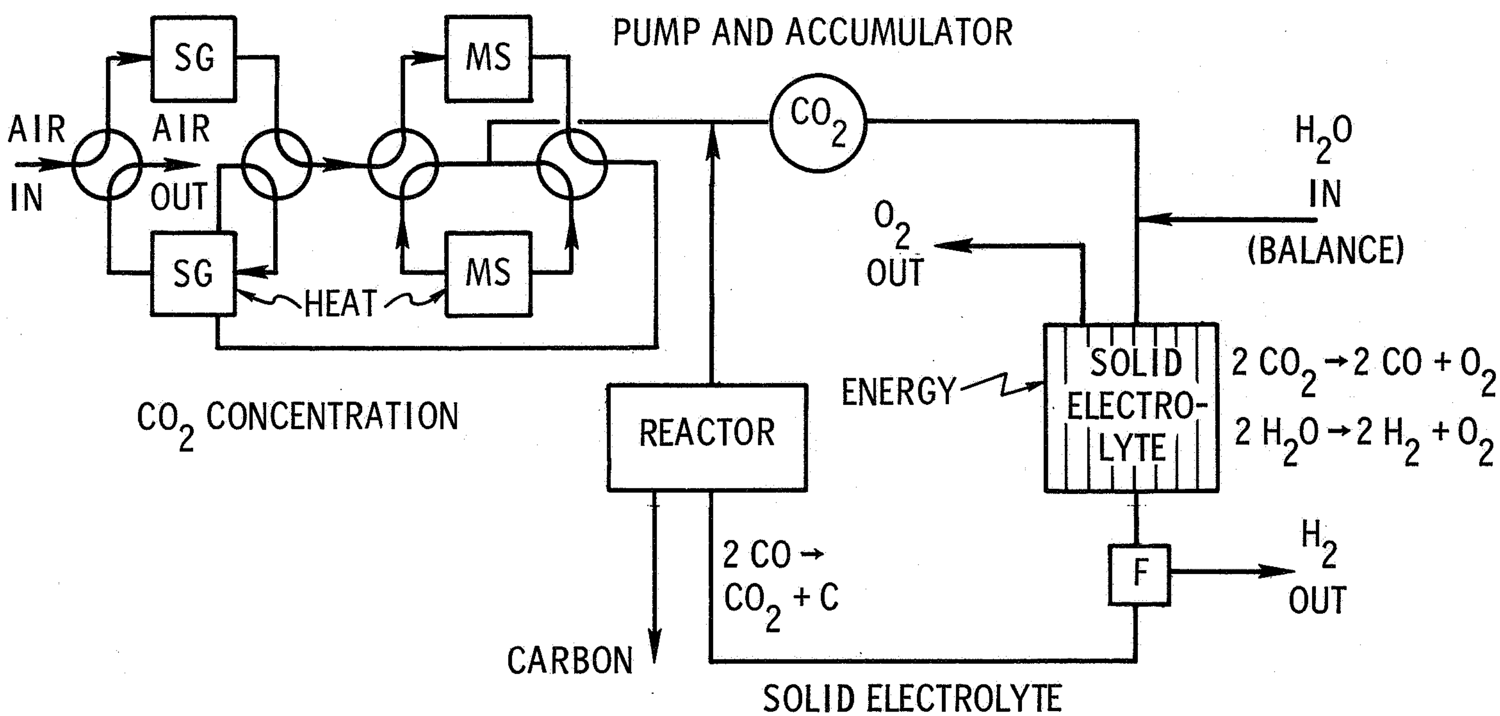

Figure 10.- Solid electrolyte oxygen reclamation.

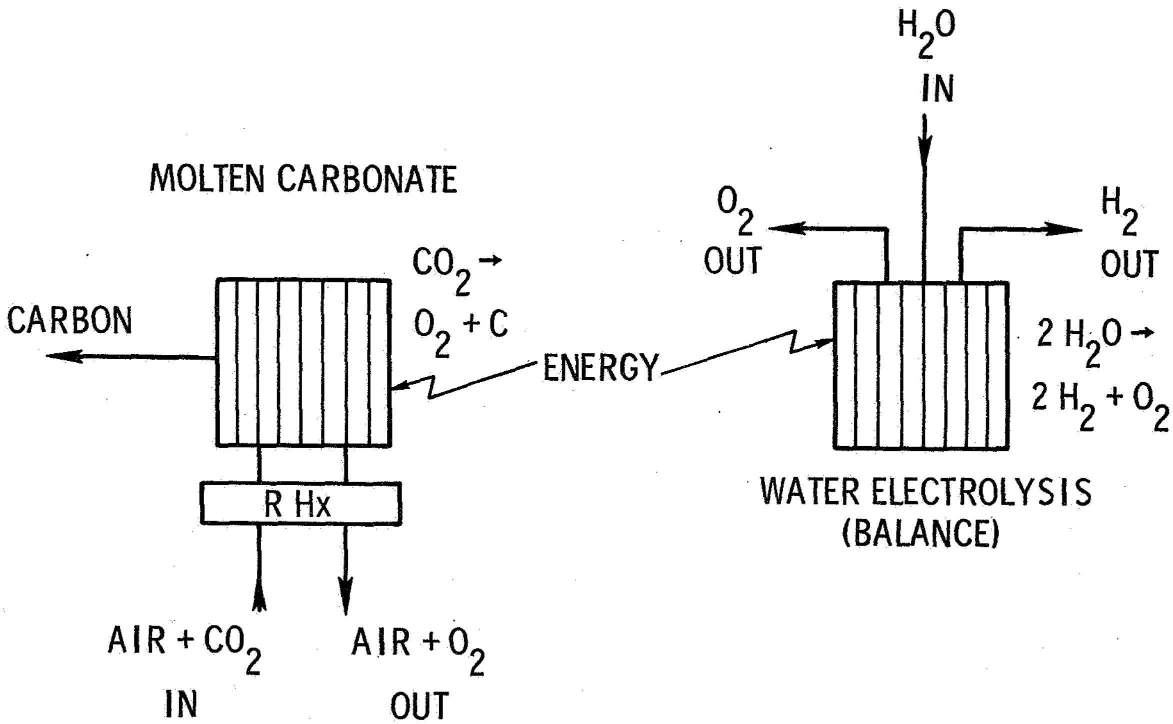

Figure 11.- Molten carbon oxygen reclamation.

NASA-Langley, 1967