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SELECTED PAPERS ON ENVIRONMENTAL AND ATTITUDE CONTROL OF MANNED SPACECRAFT

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FOREWORD

This collection of papers includes selected reports containing research information in the areas of life support, stability and control, lunar shelters, and zero-gravity simulation.

These papers were originally presented at the NASA "Conference on Langley Research Related to the Apollo Mission" held at the Langley Research Center June 22 to 24, 1965 and subsequently released in the Confidential NASA SP-101. They are presently being reissued for the purpose of providing the wider dissemination appropriate to the general interest in their subject matter.

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1. DYNAMICS AND CONTROL RESEARCH APPLICABLE TO APOLLO EXTENSION SYSTEMS

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N67 14244

SUMMARY

The disturbance and control aspects of the Apollo extension systems (AES) concept are discussed and studies made at the Langley Research Center of the external and internal disturbances for an earth-orbital mission are outlined. Typical results are presented to illustrate the disturbance profiles and vehicle response for the zero-gravity mode of operation. Experimental programs for possible 90-day and 45-day AES missions are described in terms of requirements and experimental program durations. The fuel consumption required to compensate for the disturbances and to provide control for the experiments is also given.

The disturbance envelope and the experimental program requirements are used to develop an optimum control system. Weight trade-offs of three competitive systems led to the choice of a control-moment gyro-jet system combination as the optimum minimum-weight system for the extended Apollo mission.

Example experimental tasks were simulated to determine the effectiveness of this control system.

INTRODUCTION

An analysis of the dynamics and control research for an Apollo extension system (AES) must be preceded by a brief review of the AES mission and configuration. The base line AES configuration proposed for earth orbital missions is correspondingly shown in figure 1. This AES concept consists of the Apollo command and service modules which are linked to the lunar excursion module (LEM) or to a laboratory module. Power for the spacecraft and its experiments could be produced by fuel cells, by a Brayton cycle system, or by solar panels.

The AES concept assumed for this analysis will have an orbital mission of from 45 to 90 days and will operate in a 200-nautical-mile, 28.5° inclination orbit. It should be pointed out that this assumed AES mission is only one of a number of possible missions that have been under study. (See refs. 1 to 3.) Other missions, for example, include a smaller 14-day AES with a limited experimental mission. However, the dynamics and control problems of all the AES configurations tend to be similar, and the example Apollo assumed here is thus a good measuring stick for determining the impact of these problems on the AES mission.

TECHNICAL APPROACH

After the mission and configuration have been reviewed, an examination of the various aspects of the AES control analysis is made. The technical approach used in this analysis is outlined in figure 2. For any AES concept, the control analysis first necessitates the determination of external and internal disturbances that may act on the spacecraft. These disturbances include aerodynamic and gravity-gradient torques, crew-motion effects and, possibly, moments produced by operation of an onboard centrifuge. After definition of these disturbance characteristics, the uncontrolled motion of the AES may be obtained from computer solutions of the spacecraft equations of motion and from tests with scaled models. Maximum attitude and rate errors can be readily derived from these solutions and instability trends in the AES motion can be detected.

The experimental requirements in terms of allowable attitude and rate errors for the AES are defined next and, together with the disturbance inputs, are used to determine a minimum-weight control system. Both reaction jets and momentum-storage systems, such as control-moment gyros and reaction wheels, are considered. Comparative systems are mechanized to assure their effectiveness and to develop basic control commands and pilot control techniques. The resultant optimum system is then checked in a detailed simulation of normal and experimental tasks.

DISTURBANCE AND EXPERIMENTAL REQUIREMENTS

External disturbances are dependent on the AES orientation and have been determined for three primary orientations; namely, solar, orbit, and inertial orientation. During the solar orientation, the roll axis of the spacecraft points at the sun; during orbit orientation, it is normal to the orbit plane; and during inertial orientation, all three axes are held fixed with respect to an arbitrary inertial reference frame. Characteristic torque profiles for the solar orientation are shown in figure 3. These torque histories consider both aerodynamic and gravity-gradient torques and were calculated by a computer program developed for Langley Research Center (ref. 4). This computer program considers a Harris-Priester atmosphere with diurnal-bulge corrections and could include moving solar panels. The resultant torques for AES have amplitudes of about 0.02 ft-lb for the roll axis, 0.4 ft-lb for the pitch axis, and 0.6 ft-lb for the yaw axis. All three torques also have initial biased components; therefore, the uncontrolled spacecraft response will be a large-amplitude oscillation such as that shown in figure 4. Amplitudes of 50° in roll, 80° in pitch, and 5° in yaw are seen to occur under these disturbances. Control must thus be provided during experiments with rate and attitude-pointing requirements. This control will require an average fuel consumption of about 6.42 lb/day with the present Apollo reaction-jet system.

Internal disturbances, such as crew motions, pose a somewhat different problem. Large attitude errors were produced by crew motions during the Gemini and Voskhod flights. Similar motions will occur during the AES mission. Since these motions occur sporadically, the frequency and magnitude of torques produced by crew motions cannot be definitely established at this time. However, computed maximum errors of about 3^{o} occur for typical crew motions. Even motions equivalent to only one step, or 1-foot displacements, may produce errors on the order of 0.2^{o}. As some of the AES experiments require attitude accuracy of 0.1^{o}, accomplishment of the experimental tasks may well necessitate continuous compensation for crew-motion effects. Such control will lead to large reaction-jet fuel consumption. Characteristic fuel expenditures are about 0.2 lb per single motion and 30 lb/day for periodic unrestricted crew motions during the proposed experimental program.

After the typical effects of the disturbances acting on AES have been considered, a review of the requirements associated with the experimental mission is undertaken. Tables I and II summarize possible control-related experiments assumed for the example AES mission. The experiments have been arranged according to orientation and attitude accuracy within that orientation. The number of experiments per week and the time required for each experiment were then used to derive an equivalent experiment duration in hours per day. For example, the manned coronograph is proposed for 14 experiments per week with an average experiment duration of 1/2 hour per experiment. This proposal gives a total experiment time of 7 hours per 7-day week, or 1 hour per day.

From tables I and II it may be seen that the required spacecraft accuracies range from 0.1^{o} to 1^{o} and that the corresponding commanded slew requirements range from the orbit rate of 0.065^{o} per second to a maneuver rate of about 2^{o} per second. Additional accuracies beyond 0.1^{o} for certain of these experiments are provided by isolating the experiment on a stable platform. From the requirements and from the experiment duration, the fuel consumption for the Apollo reaction-jet system may be determined. This consumption is tabulated in the right-hand column for each experiment. A single three-axis maneuver per day was assumed to provide the orientation changes for the experiments, with an attendant fuel consumption of 11.1 lb/day.

Sequences of experiments with common requirements - as indicated by the numbered braces in the left-hand column of tables I and II - could be performed simultaneously to reduce the required fuel consumption in an optimized experiment scheduling program. In minimizing the fuel consumption, it must be pointed out that two types of programs were taken into consideration; namely, a full experimental program for a possible 90-day mission represented by all the assumed experiments, and a reduced experimental program encompassing only the four experiments listed in sequences 6 and 7. The reduced experimental program corresponds to experiments similar to those tentatively proposed as part of AES flight 516. The optimization process grouped the experiments under the one with the longest duration in a sequence. The result is shown by table III for both the full and the reduced programs. The fuel requirements for the optimized sequences are again shown on the right, and the fuel consumption for the full experimental program is about 43.85 lb/day for a 9.3-hour-per-day experimental program. For the reduced experimental program, the fuel consumption is 12.28 lb/day for a 4-hour-per-day experimental program requiring control. If the fuel required for compensation for aerodynamic and gravity-gradient torques is added, this total becomes 50.27 lb/day for the full experimental program and 16.54 lb/day for the case of the reduced experimental program. Crew-motion disturbances were not considered here since their effects have not, as yet, been adequately defined.

It is thus probable that this fuel estimate is low and that the actual fuel may be considerably greater than the optimized values of 50 lb/day and 16 lb/day. These values should, however, suffice to indicate the trends for the optimization of the AES control system.

CONTROL-SYSTEM SELECTION AND APPLICATION

To develop a minimum-weight system, three types of control systems were studied. These systems are depicted in figure 5. The first system considered is a pure reaction-jet system using the existing Apollo reaction-jet system with additional nozzles on the LEM. The second system is a momentum storage-type system made up of three reaction wheels, one alined with each body axis, and the Apollo reaction jets. Control torques are produced by the reaction moments resulting from acceleration of the flywheels. The third system investigated is also a momentum-storage system. It consists of three double-gimbal control-moment gyros, one alined with each body axis, and of the present Apollo reaction jets. Control torques are now provided by precession of the gyros. Both momentum-storage systems had a reference momentum capacity of 1000 ft-lb-sec per axis. This momentum can compensate for the effects of crew motion, for the cyclic aerodynamic and gravity-gradient torques, and can provide the control for most of the experimental control tasks. Comparative total-system weights for these three means of control are shown by the weight trade-offs of figure 6. The system weight here includes an assumed power penalty of 1 lb/watt for the two momentum-storage systems and uses only minimum jet fuel requirements for both the full and reduced experimental programs being considered.

Several interesting trends can be observed from figure 6. First, the reaction-wheel system is about 1600 pounds heavier than the equivalent control-moment gyro (CMG) system and thus may be eliminated from the comparison. Secondly, the reaction-jet system weight exceeds the gyro system weight after 14 days for the full experimental program and after 35 days for the reduced experimental program. At the end of a 90-day mission, the weight penalty for the present Apollo system is between 600 to 2000 pounds over the gyro system weight for the assumed experiment programs. When one adds the possible fuel requirements to compensate for crew motions, this weight penalty may well become prohibitive for long-term extended Apollo missions.

Since the control-moment gyro system becomes preferable for extended missions, it was decided to proceed with further studies of this system. The base line configuration used for this analysis is shown in figure 7. It consists of three double-gimbal control-moment gyros and the associated electronics and of the present Apollo reaction jets. It should be noted that these gyros can be located anywhere on the spacecraft since the torques produced by these devices are independent of the gyro location.

Each of the three gyros has an angular momentum of 1000 ft-lb-sec, and about 2800 ft-lb-sec of angular momentum can be provided for each spacecraft axis. The gyro weight is 110 pounds, average power is 30 watts per gyro, and maximum torque is 400 ft-lb per vehicle axis.

A preliminary laboratory prototype of a 1000 ft-lb-sec control-moment gyro is currently being built for Langley under Contract No. NAS1-5012 by the Bendix Corporation. A mock-up of this gyro is illustrated in figure 8. This gyro requires approximately 12 cubic feet of volume and will weigh about 110 pounds. Delivery of the gyro is scheduled for early 1966, and static tests of the gyro will begin shortly thereafter.

Desaturation for the gyro and tracking maneuvers could be provided by the existing Apollo jets with their 90-pound thrust level or by smaller thrust engines. Sixteen jets are available for this purpose.

After determining the control-moment gyro-system-hardware characteristics, a number of control commands for the gyro gimbals were investigated. The optimum control law determined by this investigation produced control torques by commanding gimbal rates proportional to the AES attitude and rate errors. The performance of this control law was evaluated by detailed computer simulations of the experiments assumed in this study. As an example of these simulations, consider the earth-surface observation and mapping experiment shown in figure 9. For this experiment, the AES is maneuvered into an orbit orientation, that is, with its long axis normal to the orbit plane. After achieving this orientation, a camera onboard the AES must continuously track a target point on the surface of the earth. Pictures may then be taken when this target point is directly below the spacecraft. During the tracking process, the spacecraft control system must compensate for aerodynamic torque and crew motions. Gravity-gradient torques are small enough to be neglected for the orbit orientation. In the present simulation, aerodynamic torques were continuously applied to the spacecraft. An initial crew motion was also assumed. Attitude accuracies of 0.25° and rate accuracies of 0.01° per second were specified for successful completion of the experiment.

The idealized control-system operation for the earth-mapping mission was determined by computer solutions and is given in figure 10. Both the computed spacecraft rate and attitude are plotted for the duration of the experiment. The target is acquired at -72°, corresponding to the horizon, and is then tracked until the opposite horizon is reached. When the target is directly below the AES, a maximum tracking rate of 1.16° per second occurs.

A crew motion was imposed during the first 1/2 minute to test the response characteristics of the gyro system.

It can be seen that the calculated and the commanded tracking angle and rate curves coincide on the figure. The spacecraft errors about all three axes were kept well within the required experimental accuracies of 0.25° and 0.01° per second. The theoretically determined accuracies were 0.005° or about 18 arc-seconds with similar rate accuracies. During the crew motion, these errors were approximately doubled but still remained considerably below the experimental requirements.

Similar simulations with other experiments have further confirmed the effectiveness of the gyro system. Maneuver rates of about 1° per second in roll and $1/2^\circ$ per second in pitch and yaw were obtained in these simulations; maximum computed inertial-hold accuracies were several seconds of arc. The control-moment gyro system thus appears to be very capable of controlling the spacecraft during its experimental mission - at least theoretically.

CONCLUDING REMARKS

In summarizing, one should note that long-term earth-orbital missions may pose formidable tasks for the spacecraft control system if attitude control of the Apollo is required for onboard experiments. For such control, the Apollo control system must compensate for aerodynamic and gravity-gradient torques, for crew-motion effects, and for other disturbances such as centrifuge operation. It must also be capable of producing large maneuver and tracking torques and, subsequently, of generating very small torques during inertial attitude holds.

Complex experimental missions, such as the one assumed for this analysis, may well lead to prohibitive fuel consumption for missions longer than 45 days. Since most of the control tasks and the applied disturbances are periodic, the Apollo reaction-jet system rapidly becomes inefficient in comparison with control-moment gyro systems. Further studies of the effects of crew motions will also be necessary before the present jet system is used for extended experimental missions.

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3. Anon.: Apollo Extension System Earth Orbit Mission Study. Vol. 2 - Flight Mission and Configuration Descriptions for NASA Experiment Groupings. Grumman Design 378 (Contract No. NAS 9-3681), Grumman Aircraft Eng. Corp., May 10, 1965.

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TABLE I

SUMMARY DATA FOR CONTROL-RELATED EXPERIMENTS

SEQUENCES (1) TO (5)

ORIENTATION	TITLE	DURATION, HR/DAY	ACCURACY, DEG	SLEW REQ., DEG/SEC	FUEL, LB/DAY
SOLAR (1)	SOLAR TELESCOPE	1.0	0.1	NONE	7.69
LOCAL VERTICAL (2)	DRAG STUDIES	0.2	1.0	ORBIT RATE	0.16
	EXTERNAL ATMOSPHERE	0.2	1.0	ORBIT RATE	0.16
	COSMIC-DUST MEASUREMENT	1.6	1.0	ORBIT RATE	0.62
(3)	MULTISPECTRAL SENSING	1.0	0.5	ORBIT RATE	1.53
	ELECTRO - OPTICAL	0.3	0.5	1.1	1.76
	IONIZED-CLOUD OBSERVATION	1 MIN/DAY	0.5		NEGLIGIBLE
(4)	ARTIFICIAL METEORS	0.1	0.2	ORBIT RATE	0.39
	RADIATION MEASUREMENT TECHNIQUES	0.2	0.1		1.27
	ATMOSPHERIC ABSORPTION	NEGLIGIBLE	0.1		NEGLIGIBLE
TRACKING (5)	EARTH SURFACE OBSERVATIONS	1.5	1.0	1.1	7.55
	SIMULATION OF LUNAR MAPPING	0.1	0.3	1.1	6.40

TABLE II

SUMMARY DATA FOR CONTROL-RELATED EXPERIMENTS

SEQUENCES (6) TO (9)

ORIENTATION	TITLE	DURATION, HR/DAY	ACCURACY, DEG	SLEW REQ., DEG/SEC	FUEL, LB/DAY
INERTIAL (6)	*EMISSION LINE RADIOMETRY	0.5	0.1		3.80
	*INTERMEDIATE SIZE REFLECTING TELESCOPE	1	0.1		7.69
	*MANNED CORONOGRAPH	1	0.1		7.69
(7)	*NEARBY SOLAR-LIKE STARS IN X-RAYS	3	0.5		4.59
CENTRIFUGE (8)	BIOMEDICAL EXPERIMENTS	2 EVENTS/DAY	NONE	NONE	1.81
(9)	SPACECRAFT IDENTIFICATION	0.2	0.5	2.0	0.75
	MANEUVER	1 EVENT/DAY		0.5	11.10

*REDUCED EXPERIMENTAL PROGRAM

TABLE III

EXPERIMENTAL SEQUENCE STABILIZATION REQUIREMENTS

SEQUENCE	ORIENTATION	DURATION, HR/DAY	ACCURACY, DEG	SLEW REQ. DEG/SEC	FUEL, LB/DAY
(1)	SOLAR	1.0	0.1		7.69
(2)	LOCAL VERTICAL	1.6	1.0		0.62
(3)	LOCAL VERTICAL	1.0	0.5		1.53
(4)	LOCAL VERTICAL	0.2	0.5		1.27
(5)	LOCAL VERTICAL	1.5	1.0	1.14	7.55
(6)	INERTIAL	1.0	0.1		7.69
(7)	INERTIAL	3.0	0.5		4.59
(8)	OPTIONAL	2 EVENTS/DAY			1.81
(9)		1 EVENT/DAY		0.50	11.10
TOTAL		9.3			43.85
				AERODYNAMIC AND GRAVITY GRADIENT TORQUES =	6.42
				TOTAL	50.27

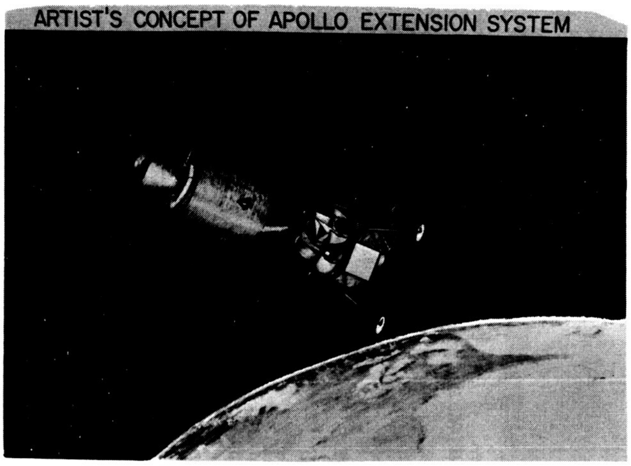


Figure 1 L-2484-1

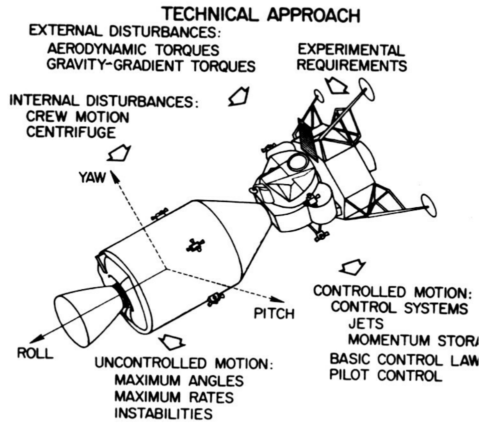


Figure 2

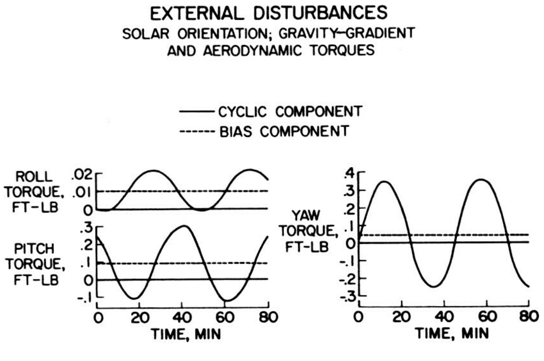
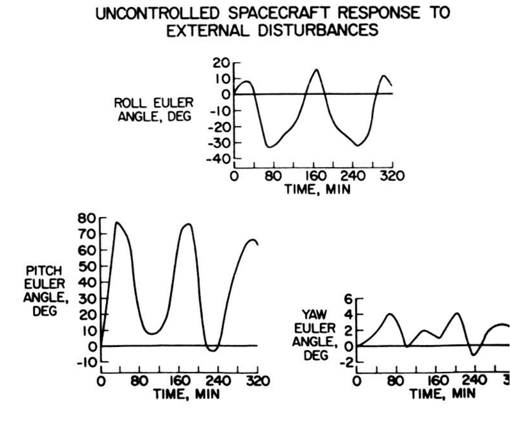


Figure 3



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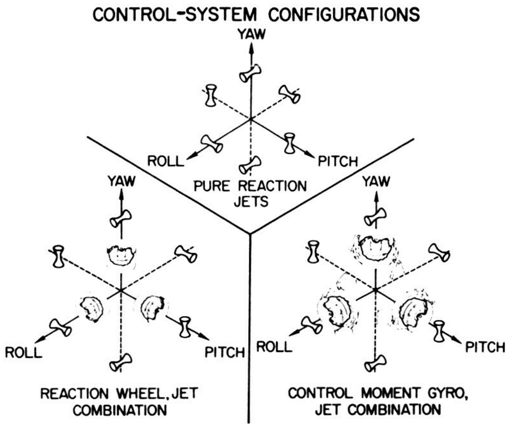

Figure 5

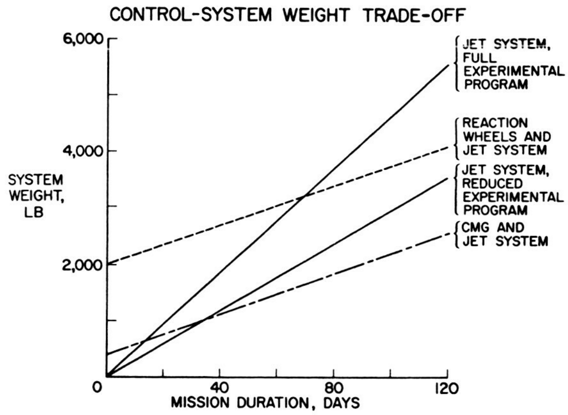

Figure 6

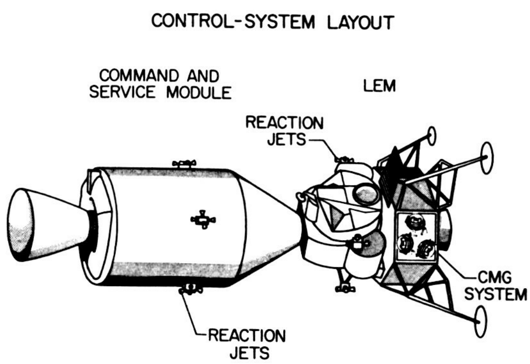

Figure 7

Figure 8 L-2484-13

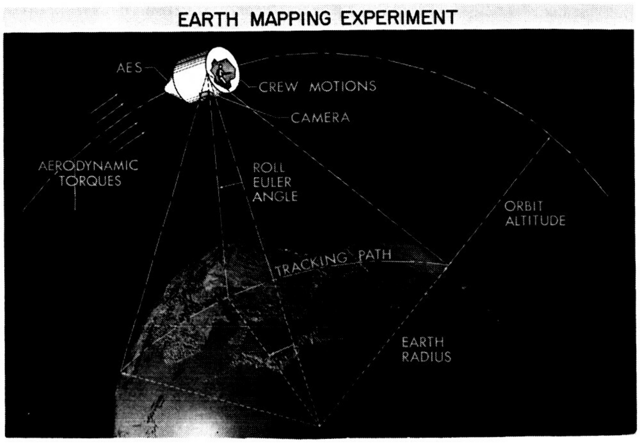

Figure 9 L-2484-14

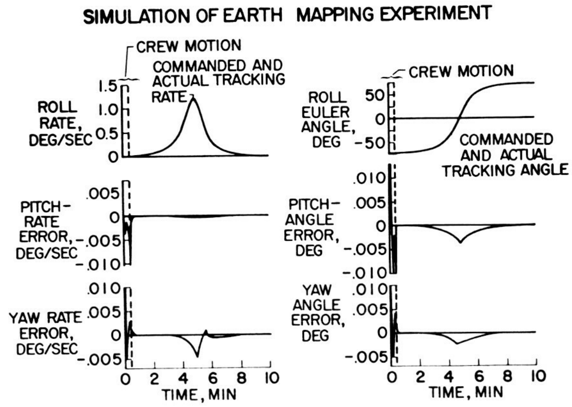

Figure 10

2. CARBON DIOXIDE CONTROL FOR MANNED SPACECRAFT

By Rex B. Martin

SUMMARY

A system-design mission analysis is given for carbon dioxide control for manned spacecraft for missions with durations of 0 to 180 days. It is evident that system expendables such as (1) a nonregenerative sorber, (2) the consumable portion of the fuel-cell power penalty, and (3) moisture, carbon dioxide, and residual air lost in vacuum desorption must be reduced or eliminated for systems designed for missions of increasing duration.

The substitution of heat-assisted desorption for vacuum desorption allows a reduction in system expendables at the expense of increased electrical power. However, a net system weight reduction is achieved with increased mission duration. The substitution of waste heat for electrical resistive heating can achieve still further system weight reduction.

Crossover times are indicated for a nonregenerative system and three systems utilizing the regenerative sorber molecular sieve. Potential weight savings are indicated for a regenerative system utilizing an amino acid salt sorber.

The molecular-sieve system provides much flexibility in achieving weight savings with step changes in material conservation; these step changes are particularly appropriate for the intermediate-duration mission in which both fuel-cell and solar-cell electrical power may be considered.

Additional criteria are imposed on the selection and design of the regenerative carbon dioxide system when oxygen reclamation is feasible. Oxygen reclamation is assumed to be feasible in missions of 100 days or more, and for these missions, a regenerative amino acid sorber may then be considered for potential application.

INTRODUCTION

Since man produces about 2 pounds of carbon dioxide per day, means must be provided for removing carbon dioxide from the cabin atmosphere in order to provide a habitable environment. Several methods are considered for this purpose. (See refs. 1 to 7.) Lithium hydroxide, LiOH, for instance, reacts with carbon dioxide, CO_2, and this reaction can be used to remove CO_2 from the atmosphere. The reaction is, for practical purposes, irreversible, and thus a system utilizing LiOH to remove CO_2 is termed a nonregenerative system. Substituting a material for LiOH that can be reactivated and reused many times is the basis for the design of a regenerative CO_2 removal system. The molecular sieve is a sorber for CO_2 which can be regenerated. At this time it is the predominant choice of a regenerative sorber for intermediate-duration missions. A predrying process is necessary to use the molecular sieve effectively for removal of CO_2 and this process encumbers the system somewhat; however, the process does provide considerable flexibility in adapting the system design to the material conservation needs of intermediate-duration missions. Depending upon the material conservation desired, three types of molecular sieve systems are appropriate for consideration: (1) a system in which H_2O and CO_2 are both desorbed to space vacuum, (2) a system in which H_2O is conserved by heat desorption and CO_2 is desorbed to space vacuum, and (3) a system in which both H_2O and CO_2 are conserved by heat desorption.

It may be noted that the criteria for the selection of a CO_2 removal system change somewhat when oxygen reclamation becomes feasible. Oxygen reclamation is assumed to be feasible in missions of 100 days or more. At this time in the mission duration, an amino acid salt sorber is also considered for the purpose of removing and collecting CO_2.

These systems are compared for application for missions with durations to 6 months. Comparison is made on the basis of total-system weight in which total weight includes fixed equipment weight, the weight of appropriate material losses incurred with the system design and operation, and the weight equivalence of electrical power required by the system.

NONREGENERATIVE CO_2 REMOVAL

LiOH is a granular solid which readily absorbs carbon dioxide in air in the presence of water vapor. The reaction is indicated in figure 1. LiOH combines with CO_2 in the presence of some water vapor to become Li_2CO_3 and H_2O and heat is liberated in the process. LiOH may be packed in a replaceable cartridge or canister and located in a loop in the entrance portion of the environmental control system. Filters must be provided to keep LiOH dust from being circulated into the cabin.

The system weight on a pound per man basis is indicated in figure 1 for mission durations to 60 days, and assumes 95-percent utilization of the LiOH. Hardware weight is assumed to be 20 percent of that of the sorber weight. A small weight penalty is incurred for fan power.

Because the fan power is negligible for this small pressure-drop equipment, the power weight penalty is not significantly affected by the type of electrical power system used in the spacecraft. The steep slope shown here is characteristic of a stored or nonregenerative system, and is due to the fact that the quantity of the sorber provided must be in direct proportion to the duration of the mission.

REGENERATIVE CO_2 REMOVAL

The molecular sieve is the furthest developed of the regenerative type of CO_2 removal sorbers and results obtained with its use have been favorable. Much research and development have been accomplished with molecular-sieve systems; thus, the feasibility and the important design parameters of this technique have been established.

A number of investigators have demonstrated that the molecular sieve can be utilized to remove carbon dioxide from air provided the air is sufficiently predried. This drying step is necessary to prevent the molecular sieve from being loaded with moisture instead of with carbon dioxide, because the affinity of the molecular sieve for moisture is far greater than it is for CO_2.

A system utilizing a molecular sieve therefore requires two types of regenerative sorbers, one to remove H_2O and one to remove CO_2. As shown in figure 2, by using two beds of desiccant and two beds of molecular sieve, continuous removal of CO_2 can be achieved. This design utilizes three- and four-way valves to change the air path and thus cycle the four beds between the adsorbing and desorbing modes. In the schematic drawing, the lower desiccant bed and molecular-sieve bed are being desorbed while the upper two beds are removing moisture and CO_2. In this system desorption of both the desiccant and the molecular sieve is accomplished by exposing the sorbers to space vacuum. Thus, the moisture and CO_2 that are removed are lost to space.

When this method is applied to a manned spacecraft, the system should be penalized for the water desorbed to space if solar cells are used for power, but this H_2O is not charged as a loss if fuel-cell electrical power is provided since fuel-cell systems produce large quantities of water. The CO_2 desorbed to space is not considered a loss unless it is feasible to recover oxygen from the carbon dioxide. This recovery of O_2 is assumed to be feasible for missions of 100 days.

Figure 3 shows the weight of this type of regenerative CO_2 removal system as contrasted with the system using LiOH. It is evident that after about 20 days the regenerative molecular-sieve system shows weight savings over the nonregenerative LiOH system.

The system weights obtained with the use of solar cells and fuel cells as power sources are indicated by the dashed and solid lines, respectively. It is well to emphasize that the fuel cell is a stored type of system and incurs a penalty for the expendables it uses. Furthermore, this life-support system does not reflect a direct comparison between the types of electrical power systems for the purpose of their selection. If the fuel cell is selected over the solar cell as the spacecraft electrical power system, the life-support system described benefits by the difference shown between the dashed and solid lines. The power penalty assumed here for these power systems is 500 lb/kW for solar cells and 450 lb/kW plus 1.5 lb/kW-hr for fuel cells.

The preceding regenerative CO_2 system utilized vacuum desorption and results in H_2O and CO_2 as well as some air being lost to space. The regeneration of the molecular-sieve system can be carried a step further and matched more specifically for the solar-cell type of power system by substituting heat desorption of the desiccant for vacuum desorption. With heat-assisted desorption of the desiccant, it is then practical to recover the H_2O that is removed initially to protect the molecular sieve. Thus a material conservation is achieved. A system of this type is shown in figure 4. This system is very similar to the molecular-sieve system represented previously. The CO_2 sorber is still vacuum desorbed. The desorption of the desiccant is achieved by heating all or a portion of the air after it has passed through the sieve bed, and the heat is transported to the desiccant bed by the air. The heat-desorbed moisture is then flushed from the bed by the air and is returned to the cabin atmosphere.

A prototype system of this design is shown in figure 5 which is a photograph of a molecular-sieve system which uses silica gel as a desiccant to dry the air for the sieve beds. It utilizes timer-controlled electrical heating of the process air to desorb the silica gel. The system was designed and built by Hamilton Standard, a division of United Aircraft Corporation (ref. 1) and has undergone extensive testing at the Langley Research Center.

Figure 6 compares the weight and mission duration applicable for this type of regenerative molecular-sieve system and the systems previously described. Of the previously described vacuum desorbed systems, only the vacuum desorbed sieve system with fuel cell power is shown. The crossover time is shown to be 60 days between the two different regenerative systems. Electrical resistive heating is used to provide heat desorption, and thus the trade-off point is very dependent upon the power penalty assumed. If a lower power penalty for solar cells were used (330 lb/kW, for example), the crossover point would be moved back to about 33 days. This range in crossover time of 33 to 60 days points up the dependence of life-support-system design selection upon the electrical power penalty that is assumed; and also, the desirability of minimizing the use of resistive heating in a regenerative system.

OXYGEN RECLAMATION CONSIDERATIONS

A time occurs in a system and mission duration analysis when it becomes feasible to reclaim oxygen from CO_2, and for the purpose of this analysis, this mission duration time is assumed to be 100 days or more. Although this assumption is not discussed here, some of its effects on the selection and design of a CO_2 removal system must be considered. Obviously, such a system makes recovery or conservation of CO_2 necessary. Addition of the collection of CO_2 to the system affects the method used for desorption.

The desorption characteristics of a regenerative CO_2 sorber tend to dominate the design and operation of the CO_2 system when CO_2 collection is required. The most important desorption characteristics of a regenerative sorber are the quantity of heat and temperature required, the effective recovery pressure of the CO_2, and the recovery rate and purity of the CO_2 recovered. In general, the quantity of heat and temperature required to desorb the CO_2 should be as low as possible. The recovery pressure, desorption rate, and the purity of the CO_2 recovered should be as high as possible. Considerations of this type are involved in the integrated life-support systems being investigated by General Dynamics/Astronautics under NASA contract NAS 1-2934. The utilization of molecular sieve now becomes somewhat less of a dominant choice. However, because of the extensiveness of the tests and the state of development of the molecular sieve, it is still the preferred choice.

Recovery and collection of carbon dioxide for oxygen reclamation requires heat-assisted desorption of the sieve. Thus, the system design now includes provisions for complete conservation of material. The power requirement to provide heating for double heat desorption is significantly greater than heat desorption for the desiccant alone. Also, a means for cooling the sieve bed becomes of great importance.

Figure 7 indicates schematically the general molecular-sieve-system design required to achieve complete material conservation insofar as is possible with this type of system. The sieve is heat desorbed of CO_2. The residual air loss is considerably reduced over the vacuum desorption method. Heat desorption of the desiccant with back flush of the desorbed vapor into the cabin is the same as in the sieve system in which desorption is accomplished with heat and vacuum.

Figure 8 shows the system weight and the step increase that occurs for the mission duration when CO_2 must be collected. Note the slight slope change from that of the preceding system. This change is the savings due to reducing the residual air loss. Included in this weight is also a cooling penalty of 0.01 lb/Btu/hr, which is needed to cool the sieve after heat desorption. The electrical power penalty for solar-cell-powered systems assumed for figure 8 is still 500 lb/kW. Heat desorption of the desiccant is provided largely with heat "left over" from the sieve heat desorption. Effective heat desorption of the sieve requires a temperature of at least 300° F, whereas the heat desorption of the desiccant can be achieved at a much lower temperature. The temperature required is in direct proportion to the total process air pressure and the degree of desorption required. A minimum temperature for a half-atmosphere application is about 180° F.

The potential weight savings by substituting waste heat for electrical resistive heating is obvious in the sieve system designed for complete heat desorption. Waste heat with a temperature of perhaps 400° F from a heat-generation source or even from other systems at temperatures up to 180° F could be utilized advantageously. A significant weight savings could be achieved in this manner that would amount to the difference in the electrical power penalty and the waste-heat penalty. The latter penalty may be up to 95 percent less than the electrical power penalty.

Another regenerative sorber which is considered a potential and attractive substitute for the molecular sieve is a system that uses an amino acid salt.

This substance does not require predrying and poses less of a thermal management problem than the molecular sieve. A schematic of this type of system is shown in figure 9. The specific capacity for CO_2 of this sorber is somewhat less than that of the molecular sieve; however, the desorption temperature and heat quantity and management required is less than those required with the molecular sieve. Also, the compatibility of the sorber process with the moisture concentration of the cabin atmosphere is a favorable asset. The lack of a predrying process simplifies the system and reduces the problem of control and management.

The upper canister shown in the schematic diagram of figure 9 is absorbing CO_2, and some H_2O and air is then passed directly back to the cabin. The heat developed in absorption is transferred with a coolant fluid from the bed and with additional heating is then passed to the desorbing bed where desorption is achieved with a temperature of about 175° F and a pressure of about 40 mm Hg. Water is desorbed along with CO_2 and although this characteristic of the system is not assessed here, it is apparent that the potential of such a system would best be achieved by coupling it with an oxygen reclamation system which accepts simultaneously H_2O and CO_2. Definition and control of the function of water-carbon dioxide ratio desorbed with this sorber formulation requires much more research than has been done. The ratio of H_2O to CO_2 processed to balance the oxygen cycle is about 0.15. This ratio is not yet practical for the amino acid salt sorber.

Figure 10 shows a laboratory prototype system using the regenerative amino acid salt sorber (ref. 3). In the schematic diagram the two canisters shown contain the sorber material. The controls are a timer and valves for control of the coolant and heat-transfer fluid. This concept is far less developed than the sieve system. Further investigation and evaluation are necessary before it can be considered with the same level of confidence as is possible with the sieve.

Figure 11 includes a potential system weight savings from the sieve system based on heating requirements and heat management, ease of desorption, and system simplicity in the amino acid salt system.

CONCLUDING REMARKS

Some generalizations can be made from this system mission analysis. It is most evident that losses and expendables must be reduced in order to achieve a reasonable system weight for missions longer than a few days. Such expendables as the nonregenerative sorber itself, the consumable loss portion of the fuel-cell power penalty, and moisture and CO_2 lost in vacuum desorption must be reduced or eliminated as mission time increases. The residual air loss that occurs with vacuum desorption can also be greatly reduced when heat desorption is used. To achieve a reduction and/or elimination of these expendables both the system-fixed equipment weight and the weight equivalence of electrical power required increase. The potential for reducing the system-fixed equipment weight from that included in the analysis is very small. However, the electrical power requirements can be very significantly reduced by the substitution of waste heat from other systems or a heat-generation source for electrical resistive heating.

The molecular sieve is the favored regenerative CO_2 sorber until the mission duration is such that oxygen recovery is feasible. The desiccant sieve system lends itself well to intermediate-range missions because variation in the system design is possible and the system can be adapted to both fuel- and solar-cell power.

The recovery of oxygen from CO_2 greatly influences the selection and design of a CO_2 removal system. Other methods such as the amino acid salt sorber must be reconsidered when the mission duration time is such that recovery of oxygen is feasible. The amino acid salt sorber is considered primarily because of its simplicity and its potential fit with certain types of oxygen reclamation systems.

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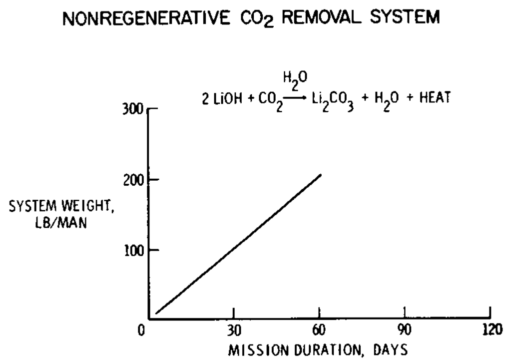


Figure 1

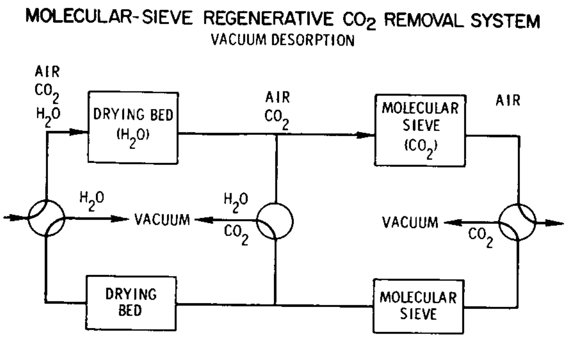
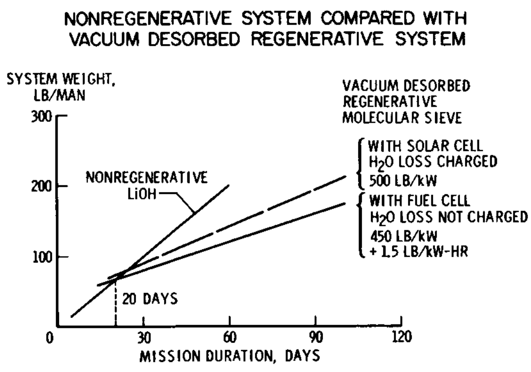


Figure 2



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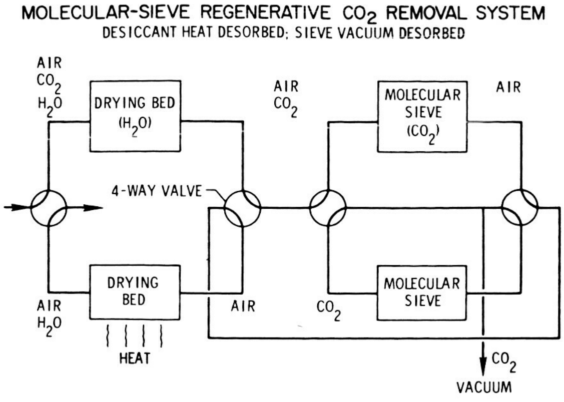

Figure 4

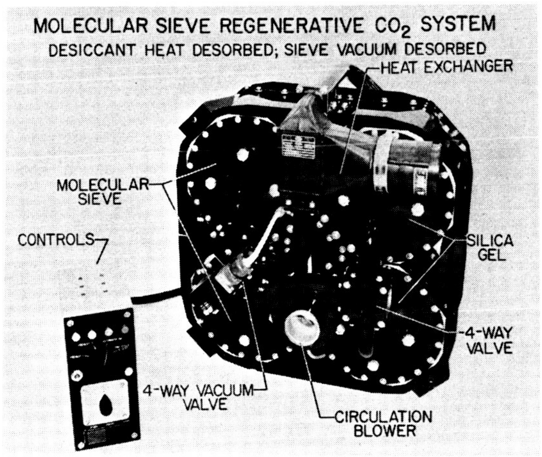

Figure 5

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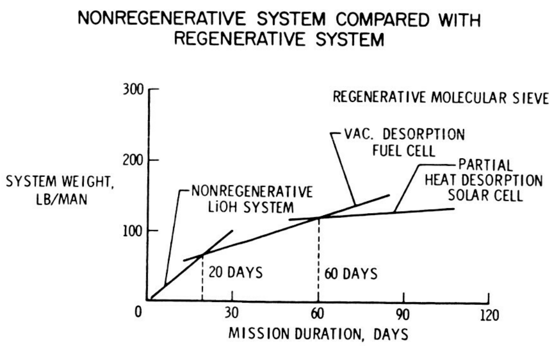

Figure 6

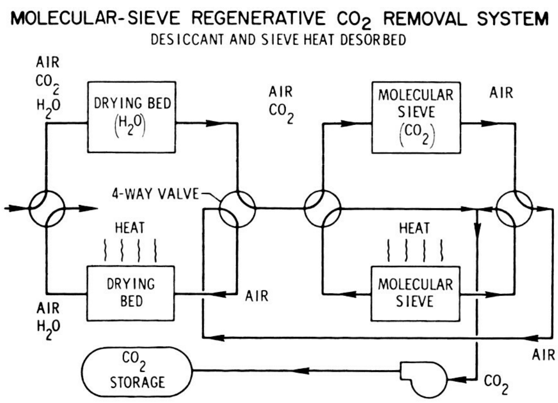

Figure 7

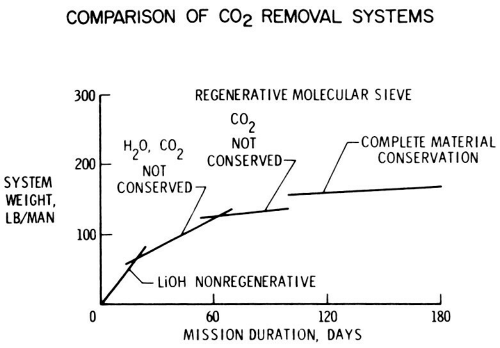

Figure 8

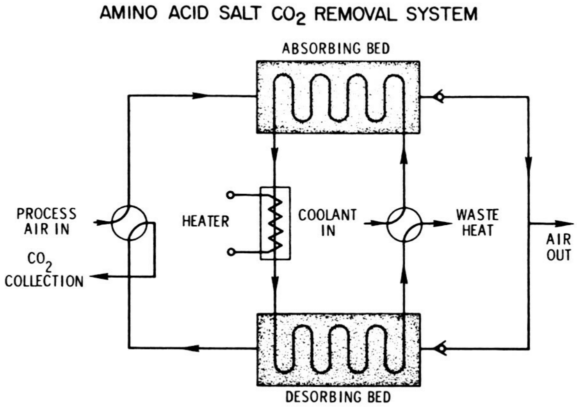

Figure 9

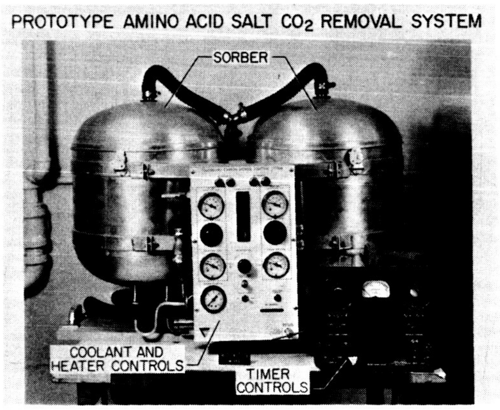

Figure 10

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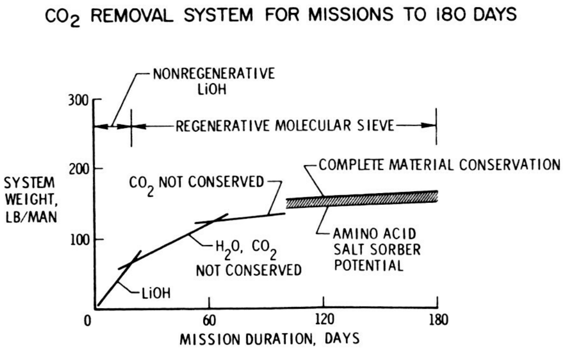

Figure 11

3. WATER AND WASTE MANAGEMENT SYSTEMS N67 14246

By Vernon G. Collins and Robert W. Johnson

SUMMARY

A number of water-reclamation system concepts have been reviewed, and their various advantages and disadvantages discussed. The efforts which are being made at the Langley Research Center are directed toward improving the state of the art. Significant launch-weight savings can be realized by utilizing the proper technique for the reclamation of water and the management of human waste.

INTRODUCTION

An area of major consideration on any manned space mission is water and waste management. (See, for example, refs. 1 and 2.) The water and waste management systems are very important aspects of manned space missions because the selection of a proper technique could reflect significant launch-weight savings on medium- to long-term missions. (See refs. 3 and 4.) Of course, it would be impractical to use water-reclamation techniques on short-term space missions since moderate quantities of stored water can be supplied. On the other hand, if water were supplied from stores to a crew of 4 men on a 100-day mission, over 2 tons of water would be required. A reclamation system that would be capable of doing this job, including its power-weight penalty, however, might weigh no more than 100 pounds. References 5 and 6 discuss this problem in detail.

DISCUSSION

General

A typical materials balance for one man is shown in table I. It might appear ridiculous to have the values shown carried out to the second decimal place because it is known that man's metabolism is not that predictable. The decimals are simply carried to show an exact balance. The values were derived from reference 7; they will vary depending upon man's activity and environment as well as other factors.

Man requires, in addition to an otherwise habitable environment, about $1\frac{1}{2}$ pounds of food, 2 pounds of oxygen, and $4\frac{1}{2}$ pounds of water per day. In exchange, his environment is rewarded with about 2 pounds of humidity water, 3 pounds of urine (95 percent of which is water), 1/4 pound of feces (75 percent of which is water), $2\frac{1}{4}$ pounds of carbon dioxide, and certain other small losses (fingernails, hair growth, and so forth). In addition to the basic requirements, a quantity of water is required for hygienic purposes that has been estimated to be about 4 pounds per day depending upon the health habits of the man. The most attractive sources of water for reclamation are humidity water, urine, and wash water. There are a number of practical techniques that may be employed for the reclamation of water from these sources. Actually though, the choice of technique and extent of reclamation is dictated to a large degree by the nature and type of other systems on board the spacecraft.

Figure 1 illustrates some basic factors that influence decisions concerning the use of water-reclamation systems on space missions. Launch weight in pounds per man is plotted against mission duration in days. The dashed line labeled "Water demand" represents the amount of stored water that would be required. In calculating this water-demand line, the humidity water was assumed to be available for reuse. There would be no need to perform water reclamation on space missions that are of such duration that fuel cells are used for power, since a byproduct of fuel cells is water. When space missions are of such duration that energy supply systems other than fuel cells are used for power, it becomes obvious, from the water-demand curve, that in the interest of minimizing launch weight, some degree of water reclamation should be performed. All need for stored water can be eliminated if there is a system on board that is capable of reclaiming at least 91.5 percent of the available water from man's waste products. Only 91.5 percent is required because man produces metabolic water from the food that he eats. Since some oxygen is also consumed in the production of this metabolic water, when mission durations become of such length that oxygen-reclamation systems are included to balance the oxygen cycle, then some water must be decomposed to make this possible. In other words, when oxygen reclamation is performed, there is an increased water demand and at least 95 percent of the available water from man's waste products must be reclaimed if the need for stored water is to be eliminated.

Curves for two hypothetical water-reclamation systems are shown in figure 1. System A is basically a heavier system than system B because it pushes the recovery efficiency up to 95 percent or higher. Until oxygen reclamation is performed, system B, which can recover 91.5 percent of the available water, is the system of choice, from launch-weight considerations. But, on missions that require oxygen reclamation, system B would have to be penalized for its lower recovery efficiency; then, it would become more economical to fly with system A.

Water Sources

Water-reclamation techniques are generally identified by the basic principle upon which they operate. Table II lists some of the most promising techniques in the first column. The bars in the other columns indicate the area of their most competitive application with respect to water management of humidity water, wash water, urine, and feces. Some generalized statements can be made about these sources and the relative ease with which water can be reclaimed from them.

No great problem is associated with the reclamation of humidity water. It has already undergone a phase change and is therefore in an advanced state of purity except for dissolved gases and aerosols. Some combination of filters would render this water potable. Reclaiming water from wash water and urine is not such a simple process. Wash water is very similar to urine that has been diluted about 25 to 1 with the inclusion of trace quantities of cleanser. Therefore, wash-water-reclamation systems would share the same problems associated with the reclamation of urine, only to a lesser extent. About 5 percent of urine is dissolved solids, the majority of which are organic in nature and have very objectionable characteristics. The primary constituent is urea. This substance decomposes rapidly at temperatures in excess of about 120° F and produces copious quantities of ammonia. Foul odors, like ammonia, that are soluble in water are extremely difficult to eliminate from a water-reclamation system. The easiest way is to avoid forming such gases, if possible. Operating the system at low temperature helps tremendously; but, even at low temperature, some kind of pretreatment is required. (See ref. 8.) Some of these reclamation techniques are a little more dependent on pretreatment processes than others.

There have generally been three basic approaches to the pretreatment problem:

(1) The destruction of urea by chemical or enzymatic means
(2) The fixing or preserving of urea by chemical treatment
(3) The adsorption of urea by activated charcoal

A common objection to each of these techniques is the fact that expendable materials are required. On medium- to long-term space missions, these launch-weight penalties may become excessive. The Langley Research Center is investigating an electrical approach to pretreatment that not only does not require expendables but breaks down urea into nitrogen (which can be used for leakage makeup), carbon dioxide (which is a potential source of oxygen), and hydrogen (which can be vented overboard). This new technique promises launch-weight savings over prior techniques on space missions lasting longer than about 60 days. The reclamation techniques are variously affected by the advent of this new technology. Electrodialysis, for example, is a technique that, by its nature, is dependent upon a pretreatment process that completely removes urea. By conventional methods, such time-dependent weight penalties are prohibitive. Therefore, electrodialysis would not be competitive on certain space missions without this new technology.

Reclamation Techniques

The Langley Research Center has been investigating a few of the best techniques (see table II) that have been proposed for the reclamation of water from man's waste products. Some of these techniques have seemed more promising than others, and, for that reason, they have been investigated more extensively.

Multifiltration.- As table II shows, there is very little competition with multifiltration as a means of recovering humidity water. Multifiltration is one of the simplest as well as one of the most reliable of all the reclamation concepts. Reference 9 discusses such a system for water reclamation.

Figure 2 is a photograph of a multifiltration system that is capable of processing humidity water. The system has no moving parts and consists of no more than a bed of activated charcoal and a particulate filter. Incidentally, the subsystem shown is part of a complete multifiltration system that grew out of a research and development contract with General Dynamics/Electric Boat (Contract No. NAS1-2208). The addition of a canister of mixed-bed ion-exchange resins (see fig. 3) makes a system that is capable of processing wash water. Such a system might be used on medium-term space missions, where reliability could be a greater factor than time-dependent weight penalties.

Vacuum compression distillation.- Distillation is universally recognized as one of the most effective ways of separating water from its contaminants in solution. The primary objection to using distillation as a reclamation technique has been the tremendous amount of energy required owing to the latent heat of vaporization of water, which is about 1000 Btu/lb. (See ref. 10.) One way to operate a distillation system economically is to utilize a vapor compressor. Since the process is usually conducted under vacuum, it is called vacuum compression distillation. The purpose of the vapor compressor in the system is to force water vapor to condense at a higher temperature than when it evaporated. In a practical system, the evaporator and condenser are located on either side of a common heat-transfer wall, and the heat of vaporization can then be recycled or reused in the system. It becomes possible, by this technique, to operate a water still for only about one-eighth the amount of energy that is required to operate a conventional still.

Figure 4 is a photograph of the prototype vacuum compression distillation system that was evaluated at the Langley Research Center. It stands about 2 feet high and weighs about 59 pounds. Such a system, if operated on a near-continuous basis, would be capable of reclaiming approximately 97 percent of all the available water in the urine of 20 men. The extent to which the technology of vacuum compression distillation for urine water reclamation has been advanced, through the study of this system, is illustrated in figure 5. The launch weight of a vacuum compression distillation system, on a per man basis, is plotted against mission duration in days. The projected improvement over the state of the art during the coming year is based on improving the efficiency of the vapor compressor and incorporating passive-phase-separation techniques. This plot reflects the ability to operate a vacuum compression distillation system in such a way as to obtain higher yields and more economical operation, expressed as watt-hours per pound of water recovered.

Advantages of this technique would include its high recovery efficiency (better than 97 percent), its relatively low power consumption (39 watt-hours per pound), and its ability to operate at ambient temperatures. Problem areas are primarily residue removal and zero-gravity phase separation. The system evaluated is basically a batch type; also, the evaporator is lined with a plastic bag that requires periodic removal. The objections to this type of procedure are obvious and the presence of the plastic liner affects heat-transfer efficiency. The system derives its zero-gravity operating capability from rotating components, which consume power and serve to reduce its reliability rating. The Langley Research Center is promoting the research and development of nonrotating-phase-separation techniques that utilize the surface-tension properties of water as well as surface geometry.

Air evaporation.- Air evaporation is as simple in concept as hanging clothes out on the line to dry. However, when this sort of process has to be conducted within a small confined area on board a spacecraft, has to consume a minimum amount of power, and has to be capable of operation under zero-gravity conditions, the process can get rather complicated. The Langley Research Center is evaluating this technique to the extent that two such subsystems will be included in the integrated life-support system discussed in paper no. 6 by Hypes, Bruce, and Booth. One subsystem will process wash water; the other will process urine.

Membrane permeation.- Membrane permeation utilizes the selective diffusion properties of a membrane to separate water from a waste stream. This technique (described in ref. 11) is currently being evaluated by Langley through a contract to Radiation Applications, Inc. (Contract No. NAS1-4373). The contractors are to design, fabricate, and deliver a prototype, membrane-permeation, water-reclamation system that requires no expendables and has a moderate power requirement.

Distillation by waste heat.- Distillation by waste heat is a technique that can be made to operate on the waste-heat energy that is given off from electronic and other power-consuming devices on board a spacecraft. When distillation can be effected in this manner, it becomes attractive as a reclamation technique. The Langley Research Center has recently contracted (NASA Contract No. NAS1-5312) with Hamilton Standard, Division of United Aircraft Corp., for the design and construction of a prototype waste-heat distillation system that is pneumatically operated and has no moving parts.

Electrodialysis.- Electrodialysis is a technique that utilizes an electric field to separate ionic constituents from a waste stream. (See ref. 12.) It does not separate nonionic constituents such as urea; therefore this technique is dependent upon a pretreatment that completely removes urea. But with the advent of electrical pretreatment, electrodialysis becomes very competitive. Unlike the other techniques, the energy requirements for electrodialysis are primarily dependent upon the quantity of solutes removed and not so much upon the quantity of water processed.

Vacuum drying.- Vacuum drying is a technique that has been proposed for the suitable disposition of fecal matter on board a spacecraft. (See ref. 13.) The Langley Research Center has obtained and evaluated a piece of prototype hardware (fig. 6) that provides for the simultaneous and separate collection of urine and feces. Due consideration was given in the design of this system to providing a means of waste elimination and subsequent processing that is both sanitary and aesthetically acceptable to the flight crew members. Zero-gravity capability is incorporated through the use of a seat-belt arrangement coupled with induced airflows that are directed into the waste receptacles. The system provides for the vacuum drying of feces. Tests have shown that feces dried in this manner can be stored at room temperature for periods of time in excess of 75 days without contaminating the surrounding atmosphere. Apparently, no appreciable bacterial decomposition occurs under these conditions.

CONCLUDING REMARKS

Various techniques for water reclamation from man's waste products and the extent to which they have been investigated have been discussed. Table III summarizes the state of the art for a few of the most competitive techniques. The water-reclamation techniques are air evaporation, distillation by waste heat, electrodialysis, membrane permeation, multifiltration, and vacuum compression distillation. Vacuum drying is a practical technique for the suitable disposition of fecal matter on space missions. The length of the bars shown in table III indicate the extent to which the Langley Research Center has carried the investigation of these techniques. Langley has determined the feasibility of all these techniques and contracted for prototype hardware. Prototype hardware for several of the most promising of these techniques has already been obtained and evaluated. It is anticipated that during this next year, Langley will be evaluating all the better techniques for the reclamation of water from urine on space missions of extended duration. In addition, advanced engineering concepts will be incorporated into the construction of better water and waste management systems.

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TABLE I

MAN'S DAILY BALANCE

INPUT		OUTPUT	
FOOD	1.50 LB	HUMIDITY WATER	2.20 LB
OXYGEN	1.92 LB	URINE (95% H_2O)	3.24 LB
WATER	4.69 LB	FECES (75% H_2O)	0.29 LB
		CARBON DIOXIDE	2.24 LB
		OTHER LOSSES	0.14 LB
TOTAL	8.11 LB	TOTAL	8.11 LB

ADDITIONAL REQUIREMENT (NOT ESSENTIAL TO LIFE)

4.00 LB ← WASH WATER → 4.00 LB

TABLE II

WATER MANAGEMENT ON MANNED SPACE MISSIONS

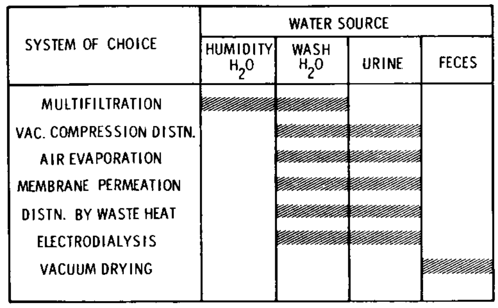
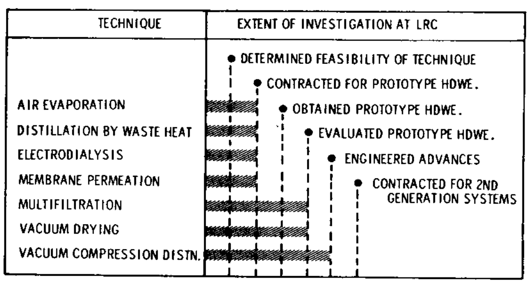


TABLE III

WATER RECLAMATION



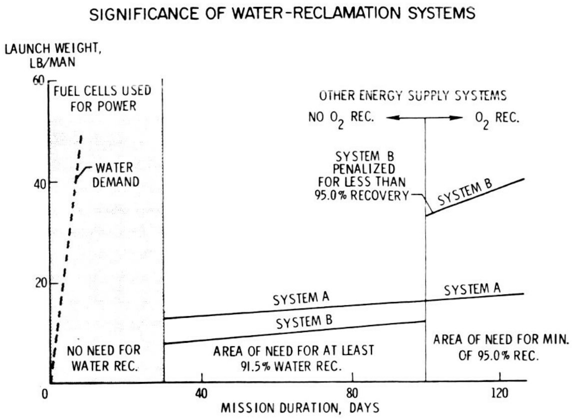


Figure 1

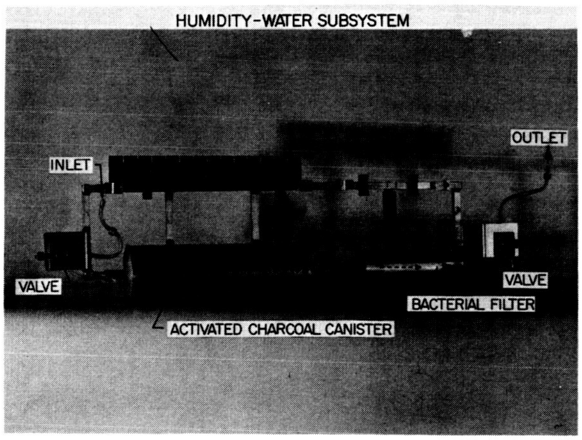


Figure 2 L-2489-8

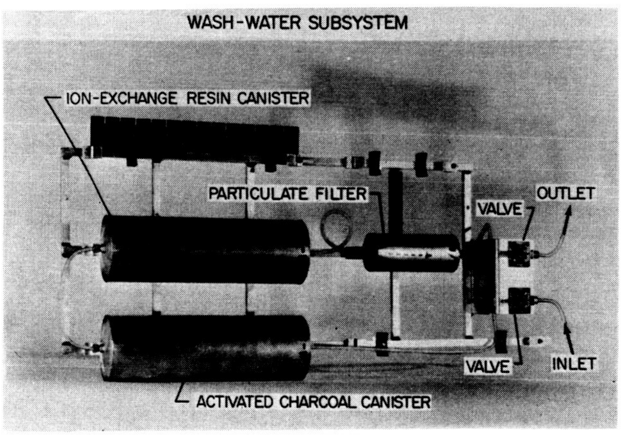


Figure 3 L-2489-9

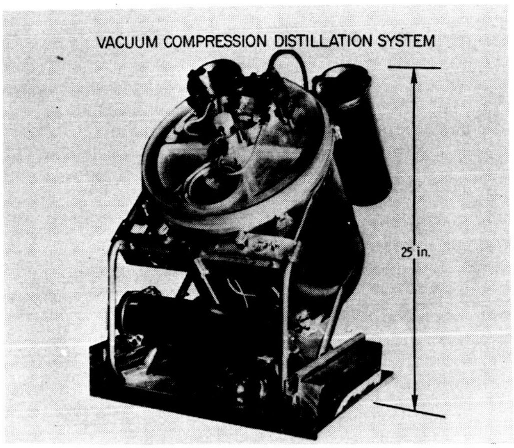


Figure 4 L-2489-5

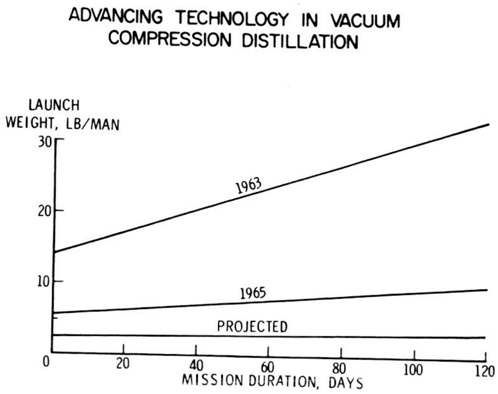


Figure 5

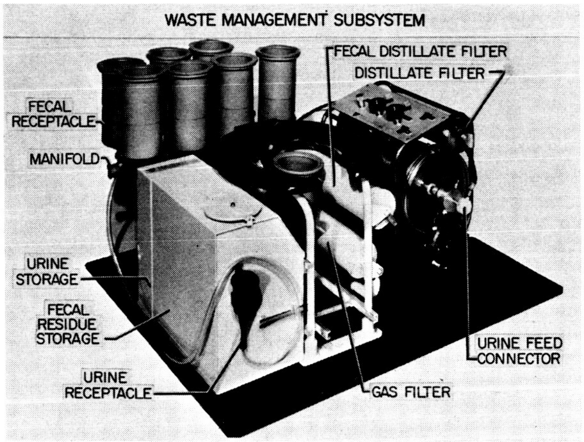


Figure 6 L-2489-10

4. CONTAMINANT COLLECTION AND IDENTIFICATION N67 14247

By Robert M. Bethea, Iris C. Anderson,
and Robert A. Bruce

SUMMARY

The portion of the manned spacecraft contaminants problem involving contaminant collection, identification, and biological effects is discussed. A specialized laboratory chromatograph for the detection and identification of permanent and low-molecular-weight gases present as trace contaminants in manned spacecraft and spacecraft simulators is described. This apparatus includes a special sampling device for use with manned simulators such as the integrated life support system test bed. The development of an inhouse integrated analytical system using combined gas chromatography, infrared spectrophotometry, and mass spectrometry techniques for contaminant identification is described. A tissue culture system for rapid screening of effects of toxic contaminants on biological systems is discussed, and some details of the operating procedures are given. Techniques of contaminant control by proper selection of materials and removal devices are presented.

INTRODUCTION

Contaminants are those chemical compounds found in trace amounts in air or water which might be harmful to man if present in high concentrations. They are likely to build up during long-term manned space missions in which the atmosphere is being regenerated. There are three principal sources of these contaminants: the metabolic processes of the inhabitants that result in saliva, urine, feces, flatus, and expired air; gassing products from food and supplies stored and used aboard the spacecraft; and gassing products resulting from the operation of the various systems within the spacecraft. Two other sources of contaminants are the materials from which the spacecraft is made and any reaction products of individual gassing components.

Before further improvements can be made in the design of water and atmospheric purification systems, detailed knowledge must be available concerning the nature and amount of the compounds likely to be present at any time. For long-term manned missions, it is even more important to be able to estimate the effects of the trace contaminants on the human body.

This report outlines current efforts aimed at developing techniques for trace-contaminant collection and identification, tissue testing to estimate the toxic effects of these contaminants on human systems, and contaminant control by proper selection of materials and removal devices.

EXPERIMENTAL

Table I shows a list of the contaminants found in manned and unmanned spacecraft simulation tests (refs. 1 to 3 and NRL Letter Rept. 6110-96A:RAS), in the Mercury orbital missions (NRL Letter Rept. 6110-143A:RAS), and in a manned simulation test of the third Gemini shot (private communication from Maxwell W. Lippitt of NASA Manned Spacecraft Center). This information is only qualitative and was obtained by analyzing the materials desorbed from activated carbon contaminant filters. The presence of these compounds has, except in the case of one manned test which had to be aborted (NRL Letter Rept. 6110-2A:RAS) because of the illness of the test subjects, produced no detectable harm on the astronauts or test subjects in manned simulation tests. Many of these compounds can produce serious harm or even death if allowed to build up in long-term missions.

Sample Collector

The list of contaminants given in table I is far from complete. Activated charcoal will not trap such compounds as methane and carbon monoxide, and all the contaminants trapped by activated carbon filters cannot be completely desorbed (ref. 2). In order to obtain a more realistic picture of the contaminants spectrum, a movable sample collection system has been designed and built. This sample collector is shown in figure 1. The basic system contains two whole-air samplers, two particulate-type biological filters, two adsorbent filters, and two cold traps. One cold trap is maintained at -78° C by a dry-ice—acetone bath; the other is kept at -196° C by liquid nitrogen.

The particulate-type biological filters and the adsorbent filters have been designed with sufficient surface area to maintain collection characteristics over a 10-hour sampling period. The traps and filters are equipped with quick-connect couplings and are inserted in the system as bypass samplers. During operation, any one or all four of the filters may be used or changed at will.

In figure 1, the sample inlet is at the upper right. The sample enters, passes through one of the particulate filters, through an adsorbent filter, through the dry-ice—acetone trap, through the liquid nitrogen trap, and then through the vacuum pump to the flow meter and gas volume meter. The purpose of the evacuated sampling bottles is to allow samples of the inlet atmosphere and the final decontaminated atmosphere to be collected for separate analysis.

Gas Chromatography

The materials contained in the sampling bottles and the cold traps will be subjected to analysis in a highly versatile research gas chromatograph. Gas-liquid chromatography is a physical separation method in which a solute is distributed between a stationary sorbent phase of large surface area and a mobile gas phase flowing over the stationary phase. The sorbent is a thin layer of a relatively nonvolatile substance coated on a finely divided inert solid support material. The coated solid support, or packing, is placed in a tube of appropriate dimensions to make a column. All separations take place in the column.

In the gas chromatograph, the materials in the different traps are fractionated into a series of peaks containing ideally only one component. It is quite possible that some of these peaks will contain more than one component. In order to make maximum use of the rapid analytical capabilities of the dual-column, dual-detector gas chromatograph, each sample will be run through four general purpose columns. These columns are designed to give quantitative separations, in the 10 parts per million (ppm) range, of about 90 percent of the expected contaminants in less than 2 hours. These columns are used for the identification of the ethers, ketones, esters, nitriles, alcohols, and halogenated hydrocarbons from C_1 through C_8; the alkanes, alkenes, and alkynes above C_5; the alkylbenzenes and multisubstituted toluenes, pinenes, and carenes through C_{12}; the C_2 and higher aldehydes; the C_2 and higher sulfides, mercaptans, and thiophenes; and various other miscellaneous compounds.

Freons; formaldehyde; the low-molecular-weight hydrocarbons; the low-molecular-weight mercaptans and sulfides; organic acids; cresols; phenols; amines; amides; isocyanates; and the corrosive gases such as the oxides of nitrogen and sulfur, HF, HCN, and HCl are not separated by these general purpose columns. For these specialized separations, other columns have been designed which separate these types of material preferentially.

After the samples from the collection system have been run through the general purpose columns and the identity of the majority of the components has been determined by matching their respective retention times in at least three of the columns, any unidentified peaks will be trapped from the effluent stream from the chromatograph and subjected to infrared and/or mass spectral analysis at the same time that the fractions are being checked on the special purpose chromatographic columns.

Fraction Collector

An inlet system has been constructed whereby the effluent from the gas chromatograph can be taken directly to an infrared spectrophotometer or a time-of-flight mass spectrometer without the possibility of contamination from outside sources. This sample transfer system is shown in figure 2. The two outlets from the thermal conductivity cells in the chromatograph are connected to this system through the tee at the bottom of the figure. The effluent can be sent directly to the infrared spectrophotometer, to the mass spectrometer, or to a fraction collector. In the fraction collector, the separated fractions can be trapped and held for subsequent analysis in the mass spectrometer or in the infrared spectrophotometer. The fraction collector is shown in figure 3. It consists of a machined aluminum block containing three 5-stopcock manifolds with male Luer lock adapters (ref. 4). The manifolds are connected by rotating ring adapters. The effluent from the chromatograph comes in through the 1/8-inch-tubing adapter on the right. In this view, the manifold is positioned to collect a sample in the 15th sampling position which is on the extreme left.

This entire assembly, except for the fraction collection tubes and bottles, is wrapped with heating tape and maintained at a sufficiently high temperature so that no sample components will condense anywhere except in the tubes or bottles. The sample transfer system is similarly heated. In operation, the sample tubes, needles, and bottles are immersed in liquid nitrogen which fills the large, double-wall, evacuated stainless-steel tank shown in figure 3. The inside dimensions of this tank are 2 by 8 by 30 inches. The tank is placed in a wooden box with $1\frac{1}{2}$-inch-thick foam plastic insulation around it. The tank has a foam plastic top through which liquid nitrogen can be poured and the needles and sample receivers can be inserted. These holes are large enough so that the boiloff of the liquid nitrogen will not be impeded. This system presents no cryogenic safety hazard.

The fraction collection manifold is fitted with two collection tubes, three hypodermic needles of different lengths, and two sample collection bottles. The sample collection bottles are 10-milliliter serum bottles partially filled with crushed glass and capped with a serum cap through which are inserted two hypodermic needles for the sample inlet and the helium vent.

The bottles are used with preparative-scale chromatography columns to trap selectively the major components of materials used for calibration standards. This is necessary because the majority of the chemicals required for calibration purposes are not commercially available in the desired purity. By use of the preparative-scale columns and this collection device, adequate amounts of materials can be purified for calibrations to 99.9+ mole percent or better.

Figure 4 shows a detailed sketch of the fraction collection manifold and the fraction collection tubes. The bottom port of each of the three-way stopcocks is fitted with an adapter to which a stainless-steel hypodermic needle is attached. This needle pierces the self-sealing rubber serum cap on the top of the fraction collection tube.

Helium and the sample component flow into the fraction collection tubes through the inlet hypodermic needles. The helium vents through the 3/4-inch, 22-gage stainless-steel needle cemented in the bottom of the tube. The sample component condenses on the crushed glass which partially fills the tubes. Because the amount of the fraction in each collection tube is in the microgram range, the only practical method of concentrating the sample is by centrifugation.

After the samples are collected in the tubes, they are then placed in brass centrifuge holders. Figure 5 shows a centrifuge holder. The holder contains an infrared microcell in the small window. The tip of the vent needle of the fraction collection tube projects through the upper portion of the centrifuge holder and rests on the top of the microcell. The microcells are tapered to increase efficiency in the infrared spectrophotometer. The microcells are approximately 5/8 inch long and 1/8 inch wide. They are made of two NaCl crystals cemented between two thin glass wafers to form a sample cavity that is triangular in vertical cross section. The width of the cavity varies uniformly from 0 to 0.3 millimeter.

Automatic Gas Chromatography System

At the present time, it is not feasible to attempt to identify the permanent gases and the light hydrocarbons by infrared techniques as Langley does not have a rapid-scanning infrared spectrophotometer. Instead, an automatic gas chromatographic system for the analysis of these gases has been designed. This system is shown in figure 6 and consists of three columns and four 4-way valves. The first column separates CO_2, NH_3, H_2S, and SO_2. The second column separates the C_2 to C_4 hydrocarbons. The third column separates the permanent gases: H_2, O_2, N_2, CH_4, and CO. These separations are shown in figure 7. Three columns are necessary, as no one of the columns will give the desired separations in the ppm region without serious peak overlap.

In this automatic analysis system, the linear sampling valves are operated individually by solenoids. The solenoids are activated by a stepping switch and a timer. The solenoids, switch, and timer are not shown in figure 6. The operating procedure for this analyzer is to absorb the sample on the first column where part of the separations occurs. By proper switching of the valves, the remainder of the sample can be routed to the other two columns where the permanent gases and the light hydrocarbons can be separated with maximum efficiency. Any of the original sample remaining in column 1 is then "backflushed"; column 2 is backflushed through the detector for the determination of the C_5 and higher hydrocarbons in the original sample. Backflushing means to reverse the direction of the carrier gas flow through a column in order to clean it in a minimum of time. The necessity for having a three-column switching system for these compounds is demonstrated in figure 8, which shows the sample components eluted from columns 1 and 2. A comparison of these chromatograms with the chromatogram shown in figure 7 shows that each individual column operates poorly when used alone for the analysis of the atmospheric sample. Note the many overlapping peaks, unresolved groups of compounds, and the absence of NH_3 and H_2S (peaks 3 and 4) in the column 2 chromatogram. A similar chromatogram on column 3 has not been shown as that column acts as a trap for all compounds other than the permanent gases.

Toxicity Testing

It would be most desirable to determine a space threshold limit value of those contaminants likely to accumulate in a spacecraft habitable environment. Unfortunately, it has been estimated that it would take up to a year or even longer to determine the threshold limit value for continuous exposure of animals to the contaminants (ref. 5). It has been suggested that animals be exposed for at least 90 days to each contaminant and that several concentrations of each contaminant be tested. This would require more money, trained personnel, and equipment than are presently available. The questions that will need to be answered are what tests should be run, how often these tests should be run, and what data are statistically significant.

Discussions at the "Conference on Atmospheric Contamination in Confined Spaces" held at Wright-Patterson Air Force Base indicated that there is little agreement among toxicologists as to what tests should be run. Some scientists advocated taking multipoint data throughout the exposure; others seemed to think that this would subject the test animals to so much physical and emotional stress that no meaningful data could be obtained. Even data on the space threshold limit value for animals would have to be extrapolated to obtain such estimates for man.

Contaminant Screening Technique

It will be impossible to specify an accurate space threshold limit value for each of the many possible contaminants in the habitable spacecraft environment by the time of the first Apollo flight. A rapid screening procedure is needed. Such a procedure may not be very precise, but it will indicate which contaminants will be toxic to man. Work on such a project is in progress. The screening system entails the continuous exposure of human cells in tissue culture to contaminants at various concentrations.

In order to get data on specific cell lines that may be compared with data on a living animal or human system, studies will be made on only the cells of those basic pathways involved in the metabolism of such nutrients as carbohydrates, proteins, and fats that are found in the whole system. If such basic systems are the sites of attack by toxic materials, then tissue cultures will not only show the effects, but will also allow the mechanism of the effect to be studied. Those contaminants which show an effect in tissue cultures can be further studied in tests of animals under continuous exposure.

Figure 9 shows one of the methods being tested for exposing tissue culture cells to contaminants. The cells are grown in a chemically defined nutrient medium in spinner flasks at 37° C. Fresh nutrient medium is continuously pumped in, and the spent medium and cells are pumped out at the same rate. In this way, the cultures can be grown continuously under optimum conditions. The contaminant is introduced into the spinner flask as shown. An example is ethyl nitrite, which is a gas at a temperature of 37° C. The parameters to be followed as endpoints of the effect are growth rate and appearance, the rate of protein synthesis, the rate of nucleic acid synthesis, and the rates of enzyme catalyzed reactions. Growth rate and appearance are monitored by observation under a phase contrast microscope. The rates of protein and nucleic acid syntheses are measured by the incorporation of specific C^{14} materials in the nutrient medium. The rates of the enzyme catalyzed reactions are measured by the most convenient assay method available, preferably spectrophotometric. It is felt that a change in the rate of an enzyme catalyzed reaction will be one of the most significant signs of toxic effect. Enzymes have often been called biological catalysts, because they allow complex reactions, such as those involved in the metabolism of carbohydrates, fats, and proteins, to take place at body temperature.

Table II gives a partial list of the enzymes proposed for study. These enzymes were chosen mainly because they occur in major metabolic systems; they are important in the metabolism of carbohydrates, fats, proteins, and phosphates, and in respiration. These enzymes are found in the specific areas listed. They may also be found in other body fluids. If such enzymes are affected in tissue culture, it is hoped that similar effects can be studied in animals.

Contaminant Control

No mercury will be used in thermometers, switches, or other equipment in the integrated life support system test bed. There will be no chlorinated solvents used for cleaning purposes. No volatile toxic liquids will be used in the thermometers or any other equipment which will be exposed to the habitable environment of the test bed.

For the removal of contaminants generated within the test bed, several techniques will be followed. The airstreams through the air conditioning and waste management systems pass through activated carbon filters in which the heavier hydrocarbon contaminants are removed. There are, in addition to these filters, two catalytic burners in the test bed, which are used to oxidize any contaminants in the chamber atmosphere which were not removed by the activated carbon filters.

More than 30 sampling points are in the test bed. Some of these are located upstream and downstream of each contaminant removal device. Three gas chromatographs will be used to provide real-time analysis of the contaminants in the test bed. One of the gas chromatographs is an automatic unit with a 12-position sampling capability. It will be used for determination of the majority of the contaminants in the 1 to 10 ppm range. The second automatic gas chromatograph uses thermal conductivity cells for the routine, sequential analysis of 10 sample streams. It is designed to monitor these streams for the following gases: H_2, O_2, N_2, H_2O, CH_4, CO, and CO_2. In addition, there is a Karmen detector in a separate gas chromatograph for monitoring the CO content down to the 10 ppm range of the output from a Bosch reactor.

CONCLUDING REMARKS

The problems in collection and identification of contaminants have been discussed. A brief description of a tissue culture system for rapid screening of the effects of these contaminants on human systems has been presented. A brief review of contaminant control in the test bed by material selection and contaminant removal techniques has been given. Much has been done toward solving some of the problems in these areas, but a great deal remains to be done.

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TABLE I

CONTAMINANTS FOUND IN MANNED AND UNMANNED SIMULATION TESTS AND ORBITAL MISSIONS

ACETIC ACID	n-BUTYRALDEHYDE	ETHYL CHLORIDE	FREON 114	METHYLENE CHLORIDE	PROPIONIC ACID
ACETONITRILE	ISOBUTYRALDEHYDE	ETHYLENE	n-HEXANE	METHYLETHYL KETONE	ISOPROPYL ACETATE
ACETALDEHYDE	n-BUTYRIC ACID	ETHYL MERCAPTAN	HYDROGEN	METHYLISOBUTYL KETONE	ISOPROPYL ETHER
ACETONE	ISOBUTYRIC ACID	ETHYLENE CHLORIDE	HYDROGEN CHLORIDE	2-METHYLPENTANE	ISOPROPYL FORMATE
ACETYLENE	CARBON DIOXIDE	ETHYLENE GLYCOL	HYDROGEN CYANIDE	3-METHYLPENTANE	PROPYLENE
ALLYL ALCOHOL	CARBON DISULFIDE	ETHYLENE OXIDE	HYDROGEN SULFIDE	MONOCHLOROACETYLENE	SKATOLE
AMMONIA	CARBON MONOXIDE	ETHYL ALCOHOL	INDOLE	NITRIC OXIDE	SULFUR DIOXIDE
BENZENE	CARBON SULFIDE	ETHYL ETHER	ISOPRENE	NITROGEN DIOXIDE	1, 1, 1-TRICHLOROETHANE
n-BUTANE	CHLORINE	ETHYL FORMATE	METHANE	n-PENTANE	1, 1, 2-TRICHLOROETHANE
ISOBUTANE	p-CRESOL	ETHYL SULFIDE	METHANOL	ISOPENTANE	TOLUENE
1-BUTANOL	CYCLOHEXANE	FORMALDEHYDE	METHYL ACETATE	2-PENTANONE	VINYL CHLORIDE
1-BUTENE	DICHLOROACETYLENE	FORMIC ACID	METHYL CHLORIDE	PHOSGENE	VINYLIDENE CHLORIDE
CIS-2-BUTENE	DIMETHYLPENTANE	FREON 11	METHYL CYCLOHEXANE	2-PROPANOL	o-XYLENE
TRANS-2-BUTENE	1, 4-DIOXANE	FREON 12	METHYL SULFIDE	PROPIONALDEHYDE	m-XYLENE
ISOBUTYLENE	ETHYL ACETATE	FREON 22			

TABLE II

ENZYME ACTIVITY AS AN INDICATOR OF TOXICITY

ENZYME	METABOLIC SYSTEM INVOLVED	SITE OF ENZYME			
		BLOOD	LIVER	KIDNEY	URINE
TRIOSE PHOSPHATE ISOMERASE	CARBOHYDRATE	X			
GLUCOSE-6-PHOSPHATE KINASE	CARBOHYDRATE	X			
FUMARASE	CARBOHYDRATE		X	X	
GLUTAMIC OXALACETIC TRANSAMINASE	PROTEIN	X	X	X	
HISTIDASE	PROTEIN		X		X
ACETYL CoA TRANSACETYLASE	FAT		X		
CHOLINE ESTERASE	FAT	X	X		
CATALASE	RESPIRATION	X	X		
ALKALINE PHOSPHATASE	PHOSPHATE	X	X		X

SAMPLE COLLECTION SYSTEM

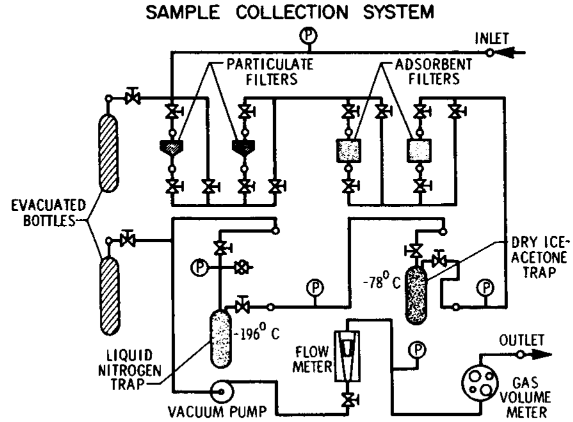

Figure 1

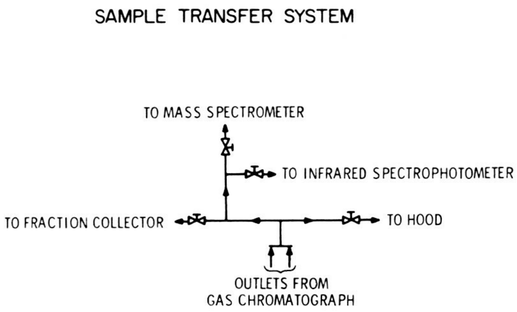

Figure 2

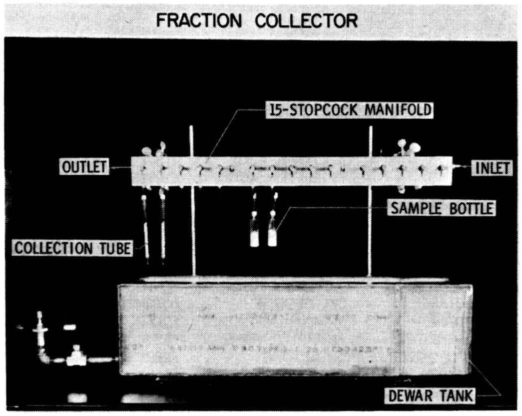

Figure 3 L-2488-6

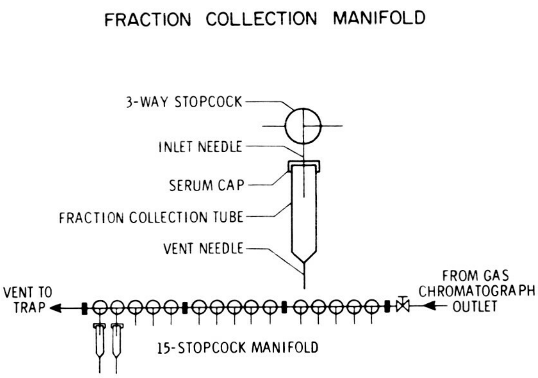

Figure 4

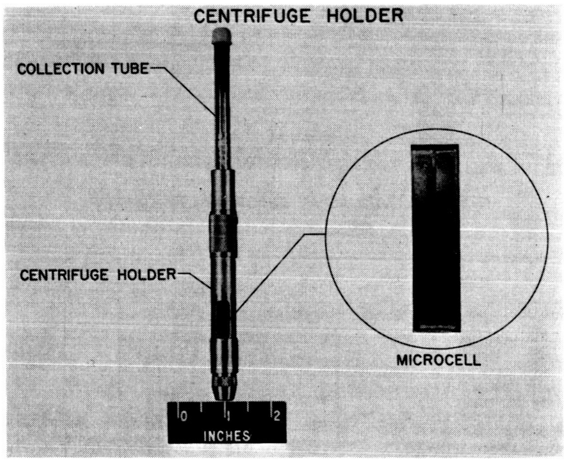

Figure 5 L-2488-8

COLUMN SWITCHING SYSTEM FOR AUTOMATIC GAS CHROMATOGRAPHIC ANALYZER

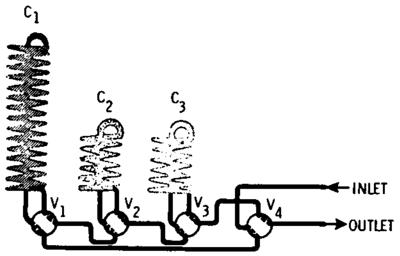

Figure 6

CHROMATOGRAM OF TYPICAL GAS SAMPLE

1. COMPOSITE	6. H_2	11. C_2H_6	16. C_4H_{10}
2. CO_2	7. O_2	12. C_2H_4	17. C_5H_{12}
3. NH_3	8. N_2	13. C_3H_8	18. $CH_3CH_2CH(CH_3)_2$
4. H_2S	9. CH_4	14. C_2H_2	19. $CH_3CH(CH_3)_2CH_3$
5. SO_2	10. CO	15. $CH_3CH(CH_3)_2$	20. $CH_2CHCH_2CH_3$

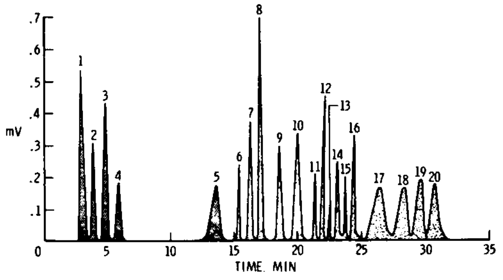

Figure 7

CHROMATOGRAMS FROM INDIVIDUAL COLUMNS

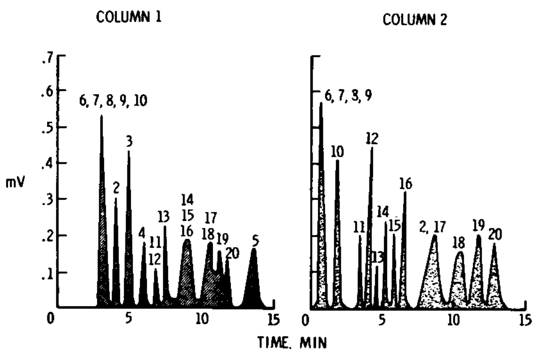

Figure 8

CONTINUOUS SCREENING TECHNIQUE

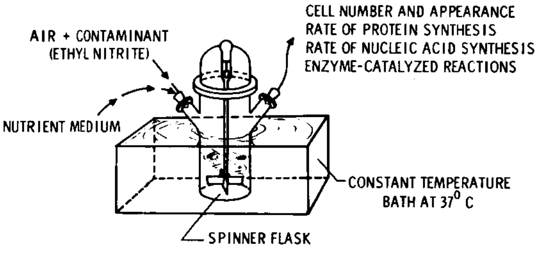

Figure 9

5. CONTAMINANTS FROM MANNED SPACECRAFT SIMULATIONS

By E. Eugene Mason and Charles H. Wilson

SUMMARY

The Langley Research Center recently participated in two different series of simulator experiments involving trace contaminant studies. One series was performed by the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, and was concerned with certain nutritional and personal hygiene problems. The contaminants found during these studies were identical with those reported in other tests, with the exception of ethyl mercaptan, which is reported in the present experiments for the first time. The other experiments were performed by the Boeing Company in Seattle, Washington, and were concerned with testing a completely enclosed, integrated, chemical, physicochemical, biological life-support system for five men for 30 days. The events leading to the aborted first test stress the need for careful material selection, improved analytical techniques, and thorough appraisal of the systems used for trace contaminant removal. The second test, though successful, points out that a potentially hazardous bacteriological condition may result from a very clean atmosphere and emphasizes the need for further study in this area.

INTRODUCTION

The Langley Research Center expects, during the summer of 1965, to install an Integrated Life Support System test bed (fig. 1), which is intended to be used in the evaluation of various integrated life-support systems under both unmanned and manned conditions. In preparation for such testing, and as part of a continuing program to develop experience in the area of trace contaminants during manned testing, the Langley Research Center has recently participated in two different manned-spacecraft-simulation experiments. The first experiment, which was conducted by the Aerospace Medical Research Laboratories (AMRL) at Wright-Patterson Air Force Base, Dayton, Ohio, in conjunction with the Manned Spacecraft Center of Houston, Texas, was concerned with the first three of a series of four-man 28-day tests. These tests were primarily concerned with certain nutritional and personal-hygiene problems. Langley's participation in this program was limited to furnishing atmospheric sampling devices and analyses of the samples collected.

The second experiment, which was conducted by the Boeing Company under Contract NASw-658 and designated as "Manned Environmental Systems Assessment" (MESA), was concerned with investigating the many aspects of a closed-operation life-support system capable of supporting five men for 30 days. The Langley Research Center was responsible for the overall technical direction of the program. The systems selected for this test were not optimum with respect to mission length, zero gravity, or weight but instead were based on obtaining a mixture of chemical, physicochemical, and biological systems which would furnish broad interface data when tested as an integrated system. The first attempt to conduct a five-man 30-day test was begun in July, 1963, but was aborted after 4.5 days as a result of the onset of illness in the crew. This period of time from program start to the end of the abort is referred to as MESA I. The period from July, 1963, through redevelopment and subsystem testing and the subsequent successful 30-day test in April, 1964, is referred to as MESA II.

This paper, then, describes the sampling device and analytical results obtained in the AMRL program and discusses the MESA problems that led to the abort of MESA I, the resolution of these problems, and the results of the successful 30-day test of MESA II.

DISCUSSION

The nutritional and personal hygiene studies at AMRL were performed in their life-support-systems evaluator. The unit, which is shown in figure 2, is a double-walled two-compartment chamber that is 27.5 feet long and 7.5 feet in diameter. The evaluator provides instrumentation, accommodations, service connections, and support facilities for carrying out programs to investigate life-support systems, nutritional balance, personal hygiene, waste management, trace contaminants, biomedical instrumentation, and other associated problems, in which from one to six men can be tested for extended periods of time. Each test, involving four men, was for 28-day periods. The participation of the Langley Research Center in these tests was limited to furnishing charcoal sampling devices and obtaining the analytical results from the analyses of these samples. The sampler (fig. 3) is a charcoal canister approximately 5.5 inches in diameter by 27 inches long and houses a small blower that is capable of drawing 60 cubic feet of air per minute through the 3-pound activated charcoal bed. Sampling devices were furnished for the first three tests of the series but, as yet, the analytical results of only the first two tests are available. These results are compiled and presented in table I:

TABLE I

AEROSPACE MEDICAL RESEARCH LABORATORIES EVALUATOR CONTAMINANTS

Methyl ethyl ketone	Isopropyl acetate	Di-isopropyl ether
Methane	Acetone	Trichloroethylene
Ethyl mercaptan	Ammonia	Isopropyl formate
n-Pentane	Allyl alcohol	Freon-11
Isopentane	Benzene	Freon-12
Dimethyl pentane	n-Butane	n-Hexane
Propane	Isobutane	Cyclohexane
Propylene	Butene	Methyl cyclohexane
Isopropanol	Ethane	Cyclohexanol
Toluene	Ethylene	Isoprene

There is nothing startlingly significant in any of the findings except for the presence of ethyl mercaptan. This compound is one of the products of human flatus and, although it is fairly conclusive that this gas is present in any environment inhabited by man, it is the first time that the Langley experimenters have seen it reported in spacecraft simulation studies.

The second manned spacecraft simulation test in which Langley participated (project MESA) was intended to demonstrate the capability of a mixed chemical, physicochemical, and biological integrated life-support system to support five men for a period of 30 days. The overall program, which is reported in reference 1, yielded specific data in many areas including those of psychology, biochemistry, microbiology, medicine, and toxicology. This paper, however, is concerned only with the toxicological or trace contaminant data and its associated problems.

The experiments of both MESA I and MESA II were performed in the high-altitude chamber of the Boeing Company. The chamber was divided into two sections, as illustrated in figure 4. The long rectangular base of the T-shape is approximately 20 feet long, 10 feet wide, and 8 feet high. The section designated as the sleeping area is cylindrical in shape and measures about 8 feet in diameter and 16 feet in length. The chamber was chosen not because of its shape, but because its volume (approx. 2400 ft^3) approximated that of a then-current space-station proposal, and its leakage rate was less than 1 pound of air per day.

Since the history of MESA I indicated that the crew illness of that experiment was due to toxic material in the atmosphere, a review of the air purification system (fig. 5) is in order. The heart of the system was the sodium superoxide (NaO_2) beds for the oxygen generation and carbon dioxide removal and the catalytic oxidizer for the oxidation of most gaseous hydrocarbons to carbon dioxide and water. Briefly, the system worked as follows:

(1) Air from the chamber was passed through an air conditioner for temperature and humidity control.

(2) Part of the output from the air conditioner passed through an ultraviolet light for sterilization purposes, through a silica gel bed for drying purposes, and through a blower to the entrance of the sodium superoxide (NaO_2) beds.

(3) The dry air was mixed at this point with air pumped through the aerobic biological waste reactor. As this mixture passed through the yellow granular NaO_2, water present in the air from the waste reactor reacted with NaO_2 to produce oxygen (gas) and sodium hydroxide (solid NaOH). Any carbon dioxide (CO_2) in the chamber air then reacted with the NaOH to form mixtures of sodium bicarbonate ($NaHCO_3$) and sodium carbonate (Na_2CO_3).

(4) A fraction (1/5) of the air from the NaO_2 beds was routed through the catalytic oxidizer (fig. 6) where it was heated to 600° F and then passed over a metal catalyst to oxidize any hydrocarbons present.

(5) The heated air, recombined with the bypassed air, passed through another silica gel bed (in a desorption mode) through a second ultraviolet light and back into the chamber.

Objectionable odors and problems in the air purification system began to appear on the second day of the test. First, the concentration of hydrogen began to increase. This hydrogen increase was a result of a reaction between the NaOH formed in the NaO_2 beds and the aluminum used in the construction of the beds. A second problem was concerned with the overproduction of oxygen in the chamber. This problem was due to a greater concentration of water in the air from the waste-management system than was originally estimated.

In an effort to diminish the buildup of hydrogen in the chamber, the system was altered so that all air passing through the NaO_2 beds passed directly into the catalytic oxidizer. This alteration served to convert all hydrogen formed to water, but it also lowered the operating temperature of the oxidizer to about 350° F, as the heat exchanger had been designed for only 20 percent of the flow.

Since the waste reactor was the prime suspect as the source of odors, the airstream from the waste-management system was temporarily rerouted so that it, too, passed directly into the catalytic oxidizer. It was believed that this procedure would stop the overproduction of oxygen and, at the same time, would eliminate the source of the nauseating odors. After the equipment had operated in this mode for approximately 6 hours, no discernible difference could be noticed in the odors present. It was observed, however, that the operating temperature of the oxidizer had dropped below 250° F and the concentration of hydrogen was again increasing. In order to bring the operating temperature up to 350° F, the line from the waste-management system was disconnected from the oxidizer and allowed to vent into the chamber. During this period of time additional odors were produced from overheating in other systems. Finally, on the fifth day, 4.5 days into the mission, a gasket on the sight glass of the waste-management tank ruptured and allowed approximately 5 gallons of raw waste to flow onto the chamber floor. The nauseated condition of the men, coupled with the waste-management malfunction, resulted in the decision to abort the test.

After the abort, whole-air and charcoal samples were taken from the chamber and sent to a number of laboratories for analyses. The results of these analyses are given in table II. Unfortunately, the symptomology of the crew illness did not fit any known toxicological pattern for the contaminants listed, and it was concluded that it was not possible to trace the nausea and vomiting to any one particular compound. (Recent research has indicated that as little as 1/4 part per million of the dichloroacetylene ($ClC \equiv CCl$), listed in table II, may have been responsible for the crew illness. It is suspected that certain halogen compounds such as trichloroethylene may dissociate and recombine in a catalytic burner to produce various other halogenated compounds, including phosgene and both monochloroacetylene and dichloroacetylene.) A decision was then made to remove everything from the chamber and to sandblast the interior to insure removal of all paint and other contaminants. Each system was critically reviewed and, where necessary, was redesigned and refabricated before being replaced in the chamber.

TABLE II

MESA I CONTAMINANTS

Trichloroethylene	Carbonyl sulfide
Monochloroacetylene	Carbon disulfide
Dichloroacetylene	Isopentane
Ethyl chloride	Isobutylene
Vinylidene chloride	n-Butane
Phosgene	Propylene
Freon-12	n-Pentane
Methyl chloride	2 Methyl butane
p-Cresol	Ethanol
Hydrogen	Methanol
Carbon monoxide	Acetaldehyde
Ammonia	Methyl ethyl ketone
Nitrogen dioxide	Ethyl ether

The development of the air purification system for MESA II was based on a very conservative engineering philosophy. The prime objective in this philosophy was to eliminate as many sources of contaminants as possible through material selection and equipment redesign. A comparison of the MESA I and II waste-management systems (figs. 7 and 8) is indication of the extent of redesign done on the various systems. A second objective was to remove completely all airborne contaminants as rapidly as they were generated. One method of accomplishing this goal was to fit systems with known contaminant-removal devices. For example, a silica gel filter was fitted to both the waste-management system and the water-management system to act as an ammonia scrubber. Other devices, shown in the MESA II schematic (fig. 9), were the separate charcoal filters near the electronic equipment and on the exit side of the catalytic oxidizer.

The second method of removing contaminants was to install a filter that was capable of handling the entire flow of the air conditioning system (600 cu ft/min). The unit selected for this purpose was a chemical-biological-radiological (CBR) filter with a capacity of 1000 cubic feet per minute (CFM). The entire assembly (fig. 10) measured 24 inches wide, 24 inches high, and 22.25 inches deep and consisted of a fiber-glass filter element for particulate matter and a chemical element for gaseous matter. The particulate filter was a self-supporting "honeycomb" type fabricated by pleating a continuous sheet of an all-glass, microfiber, water-resistant medium. The filter was certified to remove a minimum of 99.97 percent of 0.3 micron aerosols. The chemical element was a folded perforated steel sheet containing approximately 43 pounds of activated coconut base charcoal in a uniform bed depth of 3/4 inch. The charcoal was "iodized" with 4-percent potassium iodide and 2-percent iodine to improve its effectiveness against inorganic acid gases. This filter was located at the inlet to the air conditioner unit and, at the prescribed flow rate of 600 cubic feet per minute, effectively filtered the entire volume of the air in the chamber every 4 minutes. It is believed that the addition of this filter, together with the catalytic oxidizer, was responsible for the exceptionally clean atmosphere provided for the 30-day test.

The air, in fact, was so clean that the test subjects developed extremely sensitive senses of smell. This quality was noticed in the first few days of the test when the subjects complained that everyone inside the chamber was reeking with body odor and halitosis. Actually, the odors were no worse than usual. The fact that they were more noticeable was due to the absence of the normal masking odors, which had been removed by the air purification system. Another example of how keen the sense of smell had become was noticed during the use of the small-equipment airlock (fig. 11). The subjects could tell whether the person who had placed material in the airlock was a smoker or a nonsmoker and on several occasions could not only detect, but identify, the shaving lotion that may have been applied as much as 7 hours earlier.

Besides being highly effective at removing contaminant gases, the air purification system also kept the air very free of bacteria (less than 1/3 bacteria content per cubic foot for airborne bacteria). This condition may have been responsible, at least in part, for an unusual condition that developed in the bacterial floras of the noses and throats of the test subjects. This condition is graphically shown in figure 12. The percentage of pathogens (in each case staphylococcus aureous) increased from a normal 10 to 15 percent to an abnormal 85 to 100 percent. At day 37, the final day the subjects were tested, all five subjects showed pure cultures of staphylococcus aureous. While the cause of this abnormal condition is not fully understood at this time, it has been suggested that: (1) The atmosphere was so clean that there was little chance for the nonpathogens to repopulate through normal respiration and as a consequence the pathogens could overgrow; (2) there was some bactericidal contaminant present in the atmosphere that was specific for the nonpathogens but not for the pathogens; and (3) some contaminant was affecting both the nonpathogens and the pathogens but at different rates.

Regardless of the cause, this deviation from normal raises the question of whether such a condition should be considered potentially hazardous. To date, there has been no positive answer to this question, but those who have reviewed these data have indicated that a danger may exist, as certain phage types of the staphylococcus aureous may manifest themselves as either brain or lung abscesses. These bacteriological results may have been due to peculiarities of the MESA II test, but they are presented here to emphasize that such a condition may arise and should be the subject of examination on future long-term tests.

CONCLUSIONS

The experiments at both the Aerospace Medical Research Laboratories and the Boeing Company have contributed to the field of toxicology. The AMRL program lends credence to the existence of some of the contaminants already reported in other manned simulators and, in addition, reveals an analytical capability of detecting some of the products of human flatus in charcoal sampling.

Specifically, the first manned environmental system assessment (MESA I) of the Boeing Company demonstrated the necessity of using careful material evaluation and selection. MESA I also showed that systems designed to purify the air, such as the catalytic oxidizer, may, instead, further contaminate the atmosphere with byproducts more toxic than the contaminants originally present. Both MESA I and MESA II cite a continuing need for more sensitive and more reliable, real-time analytical equipment.

Finally, MESA II reported, for the first time, a marked change in the normal bacterial floras in the noses and throats of the test subjects. The cause and significance of this change remain to be proven, but its potential danger must be considered in future testing.

REFERENCE

1. Anon.: Manned Environmental System Assessment. NASA CR-134, 1964.

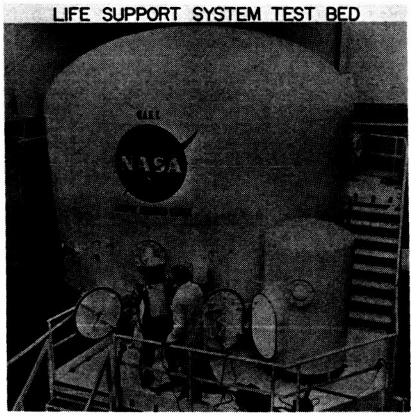

Figure 1 L-2487-1

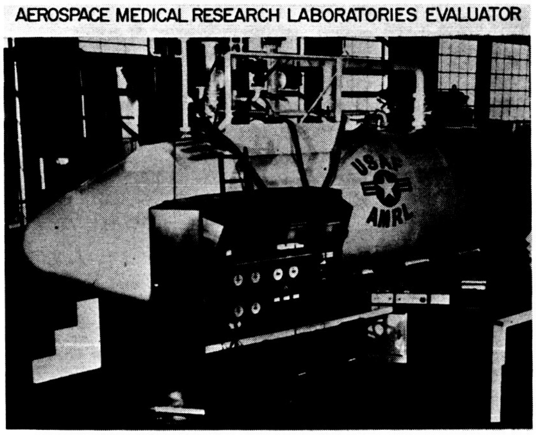

Figure 2 L-2487-2

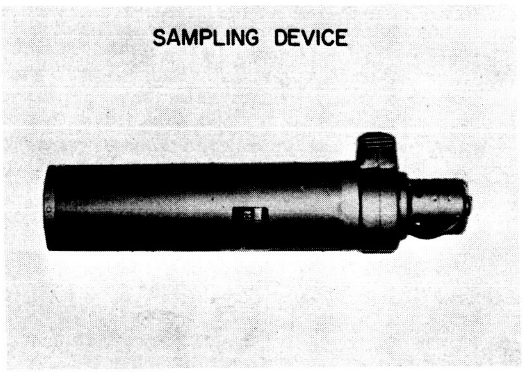

Figure 3 L-2487-3

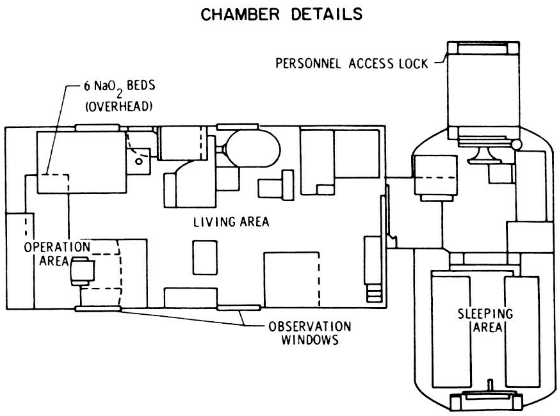

Figure 4

MESA I AIR PURIFICATION SYSTEM

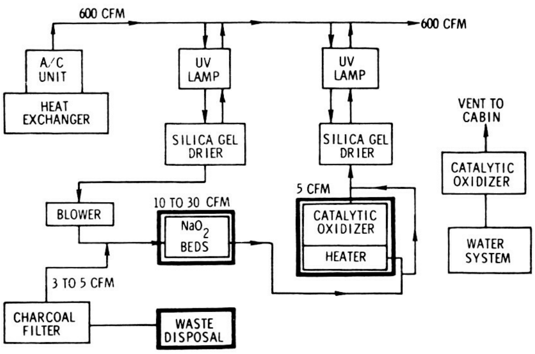

Figure 5

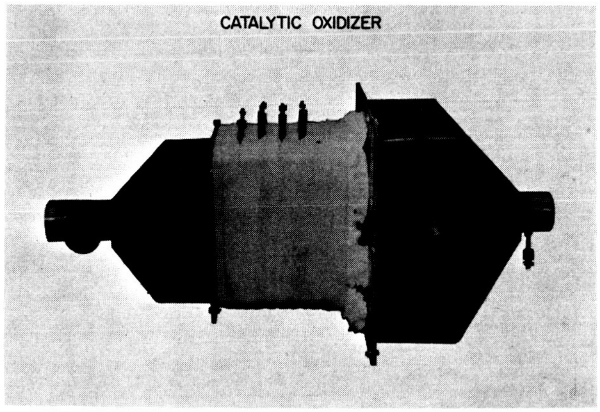

Figure 6 L-2487-10

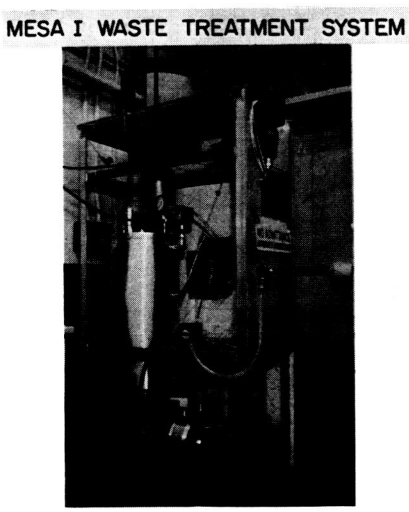

Figure 7 L-2487-11

Figure 8 L-2487-16

MESA II AIR PURIFICATION SYSTEM

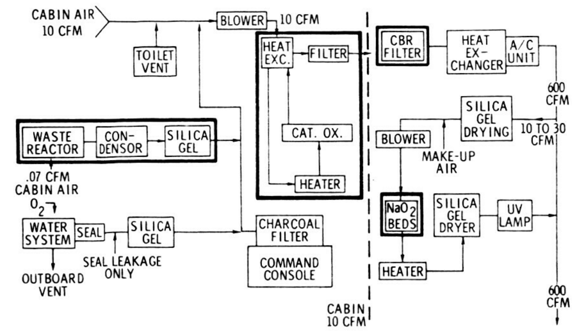

Figure 9

CHEMICAL, BACTERIOLOGICAL, AND RADIOLOGICAL (CBR) FILTER

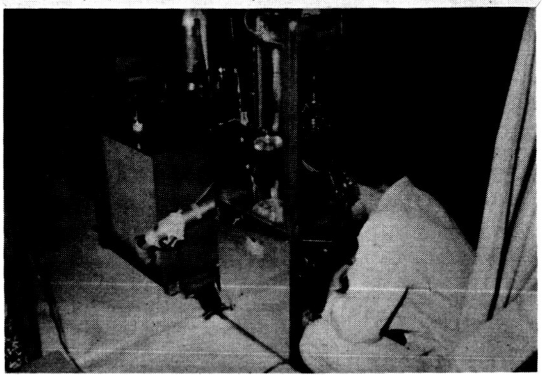

Figure 10 L-2487-17

CHAMBER AIRLOCK

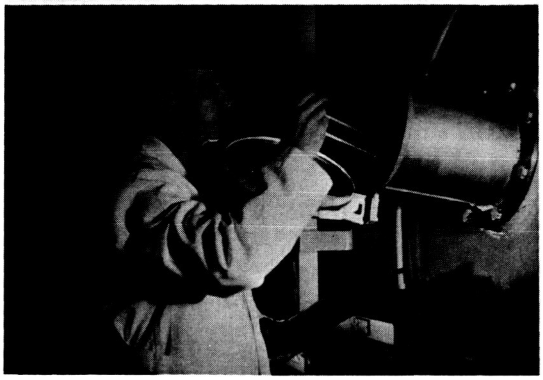

Figure 11 L-2487-18

NASAL FLORA

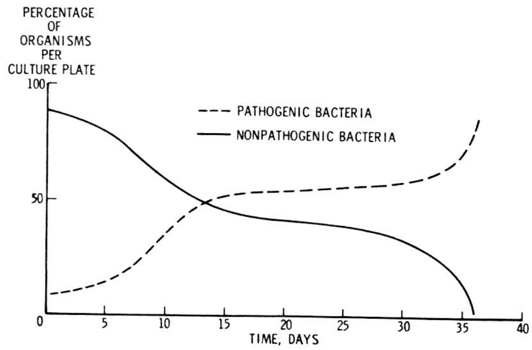

Figure 12

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6. INTEGRATED REGENERATIVE LIFE SUPPORT SYSTEM FOR EXTENDED MISSION DURATIONS

By Warren D. Hypes, Robert A. Bruce,
and Franklin W. Booth

SUMMARY

The objective of the Integrated Life Support System (ILSS) project was to select, design, and develop a working model of a regenerative life support system capable of supporting a 4-man crew in a zero-gravity environment for a period of 1 year. Resupply at 60- to 90-day intervals was assumed.

A trade-off of all techniques of life support was made at the component, subsystem, and system levels. The selected system utilizes a waste heat loop to supply process heat. An oxygen recovery loop based on regenerable carbon dioxide adsorption, hydrogen reduction of carbon dioxide, and electrolysis of water was selected. Closed-loop air evaporation was chosen to recover useful water from waste water. Vacuum-thermal dehydration with subsequent storage at cabin temperature was chosen for processing solid waste products.

The development effort has indicated that the system is feasible; however, a final assessment awaits a detailed evaluation which will be conducted during a planned research program.

INTRODUCTION

During the past 10 years, government research laboratories and private industry have been cooperating in research efforts directed toward finding techniques and processes that can regenerate useful products from the waste products available in manned spacecraft. Most of these research efforts have consisted of a study of a promising physicochemical technique followed by the development of a laboratory model which was used to demonstrate feasibility of the technique. The majority of the laboratory models were individual units designed for specific inlet conditions of mass flow rate, purity of flow, pressure, and temperature. These inlet conditions were accurately controlled and, therefore, the efficiencies of the models were not subject to frequent change due to variations in inlet conditions. Although this type of research is necessary to uncover and evaluate new approaches to regenerative life support processes, the true feasibility of the technique and embodying component cannot be established until it has been integrated into a total system where its inlet conditions are established by the output of a previous component. To demonstrate feasibility as a part of an integrated life support system, the component must be integrated into such a system for functional check-out. The purpose of the project discussed in this paper was to examine the large number of available life support techniques and to select a combination of the techniques which could be integrated into a working system. By design, development, and testing of this system, the feasibility of a regenerative life support system can be established. The system will also provide a technological base from which flight hardware can be developed.

This project has been a cooperative effort between the Langley Research Center and General Dynamics/Convair, San Diego, California, under contract NAS 1-2934.

SPACECRAFT AND MISSION

In order to select and design a regenerative life support system, a typical spacecraft and mission had to be selected. It was desirable that the spacecraft and mission be representative of those likely to evolve in the NASA manned space program. The Manned Orbital Research Laboratory (MORL) concept developed by Langley Research Center meets this requirement. An examination of the MORL spacecraft and mission revealed that the type of life support system required by the MORL would embody the physicochemical regenerative techniques applicable to any extended mission duration. Therefore, the MORL concept was used as a focal point for the selection and design of the integrated life support system.

Based on the MORL concept, the spacecraft and mission models developed are defined as follows:

Spacecraft model:

Diameter, in.	220
Length, in.	215
Volume, cu ft	4150
Allowable leakage, lb/month	33.5
Power source	Radioisotope dynamic
Maximum power available, kW	5
Power for life support, kW	2.5
Power penalty, lb/kW	290
Heat rejection penalty -	
Sensible, lb/Btu/hr	0.01
Latent, lb/lb H_2O/hr	28
Cabin total pressure, psia	10 to 15

Mission model:

Operational period	1967
Mission duration, yr	1
Resupply period, days	90 (plus 17-day emergency supply)
Gravity mode	Zero
Crew	4

These models, along with the proposed configuration of the MORL vehicle at the time the Integrated Life Support System (ILSS) project was initiated, resulted in the test-bed configuration shown in figure 1.

CRITERIA FOR SYSTEM SELECTION

With the spacecraft and mission models defined, the next step in the development of the ILSS was to select the techniques and components to be integrated into the total system. A review of the state of the art in regenerative life support techniques was made. All potential techniques were listed. After elimination of those techniques which were obviously unsuitable for consideration because of a technical or practical deficiency, the remaining ones were analyzed by a detailed trade-off study. The trade-off criteria and weighting factors used are listed in the following table:

Criterion	Weighting factor
Design:	
Confidence in success Degree of development Performance margins	22
Advance to state of the art	3
Weight:	
Fixed	7
Expendable	8
Volume	2
Reliability	20
Maintainability	10
Safety	10
Power	18
Total	100

The techniques scoring highest on the trade-off study were then evaluated for integration potential. This potential was evaluated at all possible levels, that is, at the component, subsystem, and total-system level. The end purpose of the integration study was to choose and define an optimized total system of minimum weight and minimum power demand. Although an optimized system concept was sought, the actual hardware system was not optimized to the extent that a flight model would result. The system was, however, based on principles that would operate in a zero-gravity environment.

There were two requirements on the integration phase of the project that had an important impact on system selection and on the operating modes of the system. The first of these requirements was that a source of waste heat would be utilized to supply a portion of the heat required for the life support processes. The source of waste heat was a simulated radioisotope dynamic auxiliary power system which is a potential system for flight vehicles of the MORL type.

By employing this source of waste heat, the requirement for electrical power was reduced approximately 800 watts. The integration of the system and the process heat circuit is illustrated in figure 2. The second of the requirements was that the system would be integrated in such a manner that a failure in a primary mode of operation would not create an abort situation. The requirement stated that when a primary mode failure occurs, the system degrades gracefully into a secondary mode of operation which permits continuation of the mission with only a partial loss in regenerative capability. This concept will be discussed in more detail in a subsequent section of this paper.

DESCRIPTION OF THE SELECTED SYSTEM

Atmosphere Control Subsystem

The atmosphere control subsystem is one of the major integrated loops in the total system. It is within this subsystem that oxygen is recovered from carbon dioxide, makeup gases are added, and the atmosphere is purified to maintain a habitable environment.

Carbon dioxide concentration unit.- The first unit in the oxygen recovery loop is the regenerable carbon dioxide concentrator shown in figure 3. The concentrator receives a continuous flow of approximately 30 cubic feet per minute of cabin air direct from the cabin air-conditioning unit. The flow to the concentrator exits the air-conditioning unit immediately downstream of the heat exchanger and air-water separator. At that location, the air is at its lowest temperature and dewpoint which are favorable conditions for the adsorption phenomenon that follows. Adsorption occurs in silica gel and molecular sieve beds. The silica gel beds remove remaining traces of moisture, and the molecular sieve beds selectively adsorb carbon dioxide. During operation, one silica gel and one molecular sieve bed are adsorbing while a second pair of beds is being desorbed. The silica gel bed is being desorbed back into the cabin airstream to prevent loss of water. In the primary mode of operation, the molecular sieve bed is being desorbed thermally by a hot fluid from the waste heat process loop. The hot fluid enters the desorbing bed at a temperature of 375° F. The concentration unit also contains a cooling fluid loop for maintaining proper thermal conditions in the adsorbing beds and associated heat exchangers. The desorbed carbon dioxide is stored in an accumulator tank from which it is available for processing in the carbon dioxide reduction unit. As a secondary mode of operation, the molecular sieve beds can be desorbed by a simulated space vacuum. In this mode, the carbon dioxide concentration unit remains a regenerable adsorber, but the adsorbed carbon dioxide is lost during desorption.

Carbon dioxide reduction unit.- From the accumulator tank carbon dioxide is transferred by pressure demand regulation to the reduction unit shown in figure 4. It is mixed with hydrogen and passed into a reactor where it is reduced over iron catalyst plates at a temperature of approximately 1100° F. The reaction is the Bosch type represented by the chemical equation

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

The carbon that results from this reaction is a waste product and is collected in a filter which must be periodically replaced. The product gases are then cooled, and the water vapor produced by the reaction is condensed and separated from the gas stream by means of a passive, capillary type of separator. The gas stream, enriched with additional carbon dioxide and hydrogen, is then recycled through the reactor. The recycle gas consists of unreacted carbon dioxide and hydrogen, together with the reaction byproducts methane, carbon monoxide, and nitrogen which is present as an impurity in the carbon dioxide feed. The buildup of nitrogen in the reaction mixture is controlled by bleeding a small flow of the recycle gas out of the reduction system through a catalytic burner where the hydrogen, methane, and carbon monoxide are oxidized to water and carbon dioxide and released to the cabin. A secondary mode of carbon dioxide reduction is available in the system. This capability for a secondary mode of operation is an example of the concept of graceful degradation mentioned in the previous discussion of the integration-study phase of the project.

If trouble occurs in the more complex but more efficient high-temperature Bosch reactor, the process flow can be directed to a low-temperature Sabatier reactor where hydrogen reduction of carbon dioxide takes place as represented by the chemical equation

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

The waste product now becomes methane which is vented to a simulated space vacuum. Figures 5 and 6 illustrate the practical differences between the two modes of operation. It can be observed that, of the 8.42 pounds of water required per day for oxygen regeneration, the Bosch reaction yields 7.6 pounds and the Sabatier reaction yields 4.21 pounds. Neither reaction yields all the water required by the electrolysis cell and, therefore, a quantity must be added on a daily basis from the water management subsystem.

Water electrolysis unit.- The water electrolysis unit is shown in figure 7. The unit includes 3 modules, each of which contains 16 cells. The cells contain a 25-percent solution of sulfuric acid electrolyte and water between two ion-exchange membranes. The electrodes are made by coating the outer surfaces of the membranes with a platinum black catalyst powder in contact with a current-distributing screen mesh. The oxygen produced at the positive electrodes is released into the cabin for crew consumption. The hydrogen evolved at the negative electrodes is used in the carbon dioxide reduction unit. Figures 5 and 6 illustrate the utilization of hydrogen and the figures also illustrate the materials balance associated with the entire oxygen recovery loop.

Stored gases.- Quantities of stored oxygen and nitrogen must be supplied to furnish makeup gases for the following requirements during a 90-day resupply cycle: leakage, one cabin repressurization, five air lock repressurizations, and a 17-day emergency supply of metabolic oxygen. The system studies indicated that this storage would be most desirable in the form of subcritical cryogenic liquids. The tankage for these fluids was not procured under the contract mentioned previously.

Contaminant control.- There are three types of contaminant control devices in the system. Fiber-glass particulate filters are located at the inlets of the upper and lower floor cabin ventilation ducts. They remove particulate matter and aerosols from the cabin air. Activated charcoal filters are located immediately downstream of the particulate filters to remove the high-molecular-weight organics. Activated charcoal filters are also located in the airstreams in the water recovery and waste management process loops. Two catalytic oxidizers are included as a final contaminant control technique. They oxidize many of the potential contaminants into water and carbon dioxide. Oxidation takes place across a catalyst bed maintained at approximately 750° F by a regenerative heat exchanger which greatly increases the efficiency of the process. The oxidizers, called burners, can be operated independently, in series, or in parallel. Three different catalysts are being furnished with the two oxidizers.

Water Management Subsystem

The water management subsystem is another of the major integrated loops in the total system. It is within this subsystem that usable water is recovered from urine, wash water, and humidity condensate. This subsystem also serves a collection, holding, and dispensing function for water throughout the entire system. The total water required and water recovered for the entire system on a daily basis is listed in the following table:

	Quantity, lb/day/4 men
Water required:	
Drinking and food preparation	30.0
Wash water	13.2
Electrolysis makeup	0.8
Total	44.0
Water recovered:	
Urine water	13.2
Wash water	13.2
Humidity condensate	19.6
Total	46.0

The data in the table apply only if the primary mode of operation is successful and if 100 percent of the recovered water is of sufficient purity for use. The entire water management subsystem is shown in figure 8.

Wick-type air evaporation units.- The water recovery process occurs in the wick-type air evaporation units, one of which is shown in figure 9. A flow of air heated to approximately 180° F is passed over a wick saturated with waste liquids. The water in the liquids is vaporized, condensed, and separated by a centrifugal separator. The water is then pumped to the holding tanks for purity analysis. The airstream is reheated and passed into the wick for another cycle. Pretreatment chemicals, chromic acid and sulfuric acid, are added to the waste water prior to processing to lower the pH, fix ammonia, and prevent the growth of micro-organisms.

Multifiltration unit.- A multifiltration unit is included in the system as a standby for emergency mode operation. This unit uses activated charcoal filters and ion-exchange resin beds to process humidity condensate to potable water. The unit is sized for a 17-day capacity.

Modes of operation.- The two types of recovery units discussed are capable of three modes of operation. The normal processing mode is represented in figure 10. In this mode of operation, one air evaporation unit is processing urine to wash water and the other unit is processing wash water and humidity condensate to potable water. Thus, to process urine to potable water two processing cycles must be completed. A second mode of operation, the minimum continuous mode, is represented in figure 11. In this mode of operation, one air evaporation unit has failed and the other unit is processing urine, humidity condensate, and a portion of the wash water. There is only one process cycle from urine to potable water, and the amount of water for personal hygiene is reduced. The third mode of operation, the emergency mode, is represented in figure 12. In this mode of operation only the humidity condensate is processed by the emergency multifiltration unit and makeup water is added from the stored supply. Water for washing is no longer available.

The capability of the water management subsystem for the three modes of operation is an example of the concept of graceful degradation discussed previously.

Nutritional Support Subsystem

Nutritional support is provided by freeze dried, stable conventional, and frozen foods. These foods are to be stored, prepared, and dispensed with the aid of the console shown in figure 13 and a supplementary freezer not currently a part of the system. The diet requires warm water at 180° F and cool water at 40° F for reconstitution of the dried foods. The reconstitution takes place in small plastic packages which are used as dispensing aids.

The diet provides a caloric value of 2,800 kcal/day/man and is composed of 60 percent carbohydrate, 15 percent protein, and 25 percent fat. Two percent of this diet is crude fiber.

Waste Management Subsystem

The waste management subsystem provides for the collection of all wastes, the processing of solid body wastes, and the storage of waste solids for the entire system. The waste collection and processing unit is shown in figure 14. Urine is collected in a relief tube with the aid of a small flow of cabin air.

After being separated from the airstream, the urine is pumped to the water management subsystem for processing. The airstream is returned to the cabin. The fecal material is collected in a permeable bag placed in a metal canister. During the collection process (in a zero-gravity environment), a small flow of cabin air prevents escape of noxious odors and helps to direct the fecal material into the bag. Since the bag is permeable, the airstream passes through the bag. The air is then filtered and returned to the cabin. The bag containing the fecal material and cleaning tissue is manually transferred to a processing canister in which it is vacuum dried by a simulated space vacuum with the aid of heat from the waste-heat process circuit. The dried material is then placed in a nonpermeable bag and stored in one of the large storage containers placed adjacent to the collection unit. The vacuum drying canisters and the storage containers are also used to process solid waste materials from the nutritional support and personal hygiene subsystems.

The functions provided and the quantity of wastes handled by the waste management subsystem are as follows:

Waste	System function	Quantity handled, lb/day/4 men
Feces	Collection, processing, storage	1.3
Urine	Collection, transfer	13.2
Refuse:		
Food and packaging . . .	Processing, storage	1.6
Personal hygiene	Processing, storage	0.5
Carbon from reactor . . .	Storage	2.5

Personal Hygiene Subsystem

The personal hygiene subsystem provides sponge bathing facilities and essentially conventional dental cleansing and shaving facilities. Warm water treated with benzalkonium chloride at a dilution of 1:2000 is furnished for body cleansing and rinsing of personal hygiene aids. A cylindrical chamber with a thumb-operated removable piston provides a container for wetting, drying, and cleansing the sponges. Dental cleansing is provided by a conventional toothbrush and ingestible dentifrice. Shaving is accomplished with a conventional electric razor although, in a flight system, the razor would be modified to house a small induction blower and whisker collection bag.

Thermal Control Subsystem

The thermal control subsystem includes three separate, but integrated, fluid loops. They are the process heat circuit previously discussed, the primary cooling circuit, and the cabin air circuit. The integration of these circuits is illustrated in figure 15.

Primary cooling circuit.- The primary cooling circuit utilizes a heat transport fluid which is a mixture of 40 percent propylene glycol and 60 percent water. Heat is rejected by a simulated space radiator which acts as a heat sink. The cooling circuit provides coolant fluid, and therefore heat exchange capability, at numerous locations throughout the system. The cooling circuit provides a means of rejecting heat generated from electrical power, the waste heat process circuit, and crew metabolic heat loads.

Cabin air circuit.- The cabin air circuit shown in figure 16 provides a transfer function for many of the materials associated with the process loops; however, as part of the thermal control subsystem, its primary function is to transfer sensible and latent heat loads from the cabin atmosphere to the cabin air heat exchanger. The cabin environment is maintained at a selected temperature in the range from 68° F to 80° F and a relative humidity between 40 and 60 percent. Condensation and removal of excess humidity is accomplished in the cabin air circuit with the heat exchanger and a passive type of air-water separator which utilizes capillary action across porous plates as the phase separation technique.

CONCLUDING REMARKS

Much of the advance in technology to be gained from the Integrated Life Support System (ILSS) project was gained during the study and development phases of the project. These phases represented a first attempt to select, design, and develop a working model of an integrated, regenerative life support system. The development effort has proved that regenerative techniques can be successfully integrated into a working system. An oxygen recovery loop based on regenerable carbon dioxide adsorption, hydrogen reduction of carbon dioxide, and electrolysis of water appears feasible. The feasibility of using a source of waste heat to supply process heat for the life support system has been demonstrated although a final assessment of this technique cannot be made until a functional evaluation has been completed. The development effort has proved that an integrated system can be designed to operate in secondary modes with only a slight degradation in performance.

The ILSS project has greatly advanced the technology on regenerative life support systems. Additional advances will result from the detailed engineering evaluations and the man-system relationship studies that will be conducted during the research program to follow.

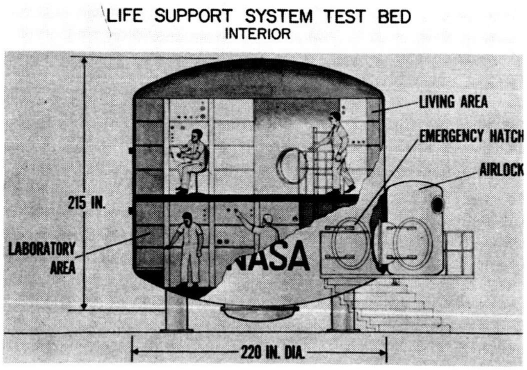

Figure 1 L-2490-2

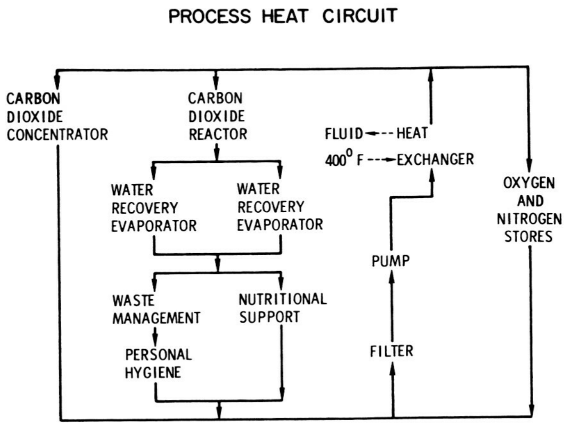

Figure 2

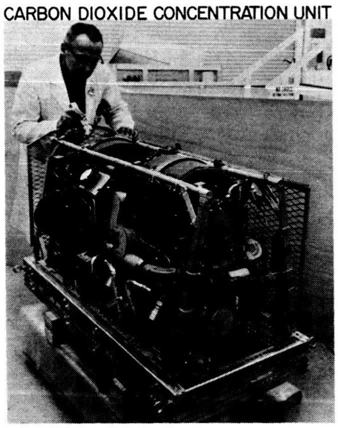

Figure 3 L-2490-9

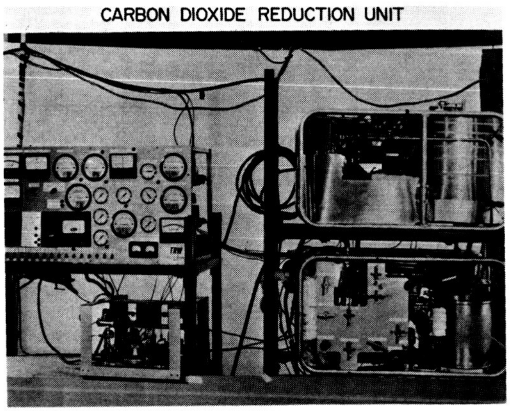

Figure 4 L-2490-10

OXYGEN REGENERATION - BOSCH MODE

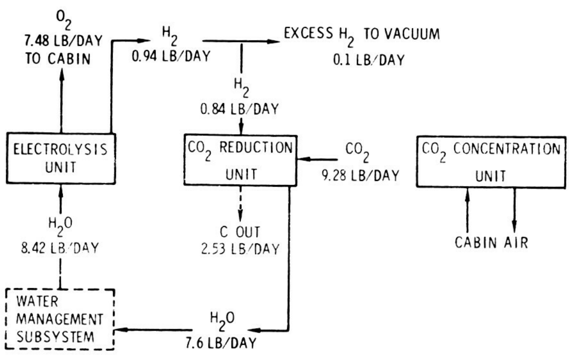

Figure 5

OXYGEN REGENERATION - SABATIER MODE

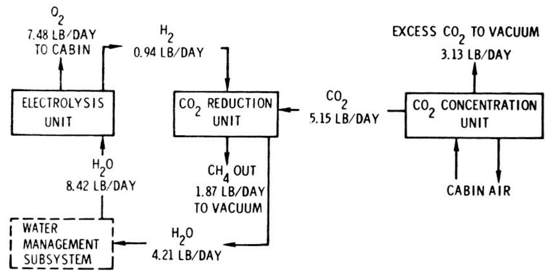

Figure 6

WATER ELECTROLYSIS UNIT

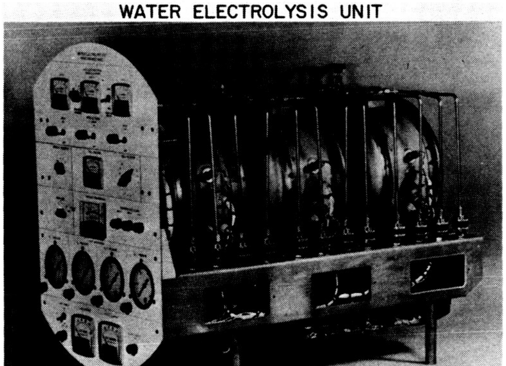

Figure 7 L-2490-11

WATER MANAGEMENT SUBSYSTEM

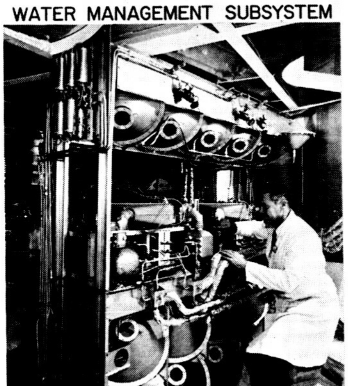

Figure 8 L-2490-16

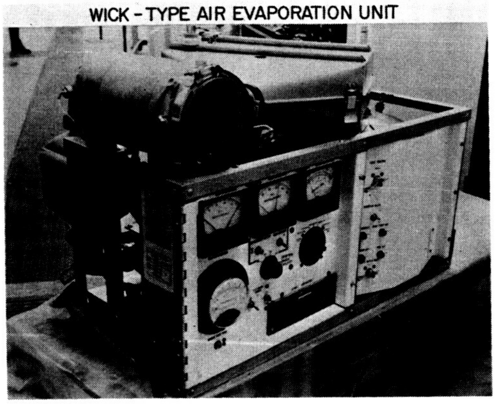

Figure 9 L-2490-12

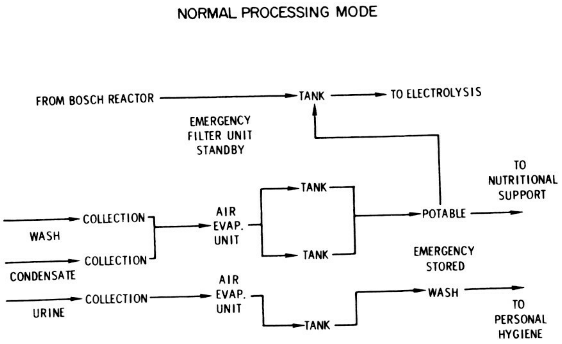

Figure 10

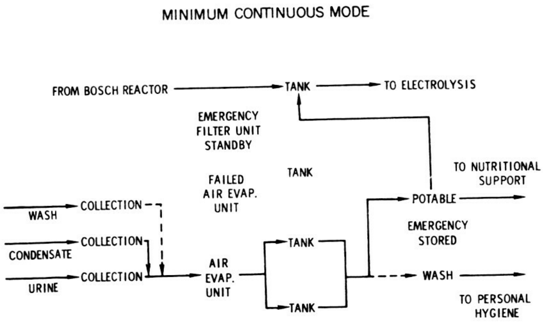

Figure 11

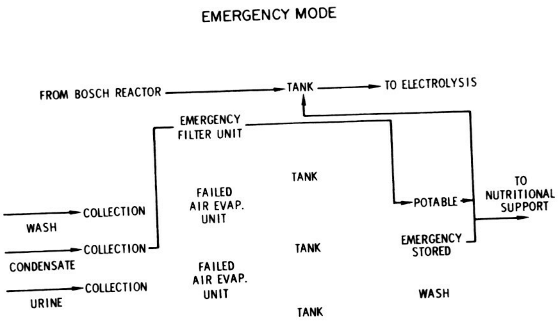

Figure 12

NUTRITIONAL SUPPORT CONSOLE

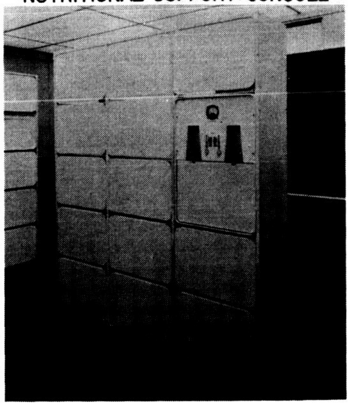

Figure 13 L-2490-6

WASTE COLLECTION AND PROCESSING UNIT

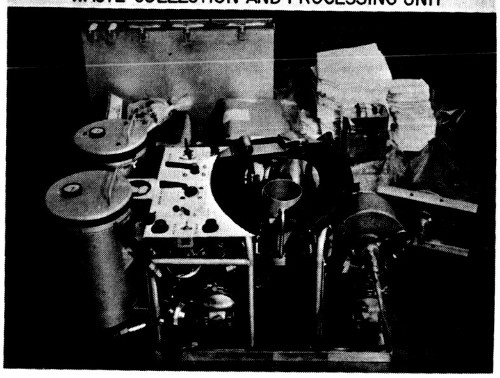

Figure 14 L-2490-7

INTEGRATION OF THE THERMAL CONTROL CIRCUITS

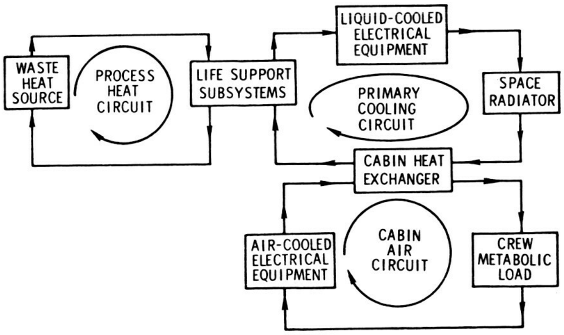

Figure 15

CABIN AIR CIRCUIT

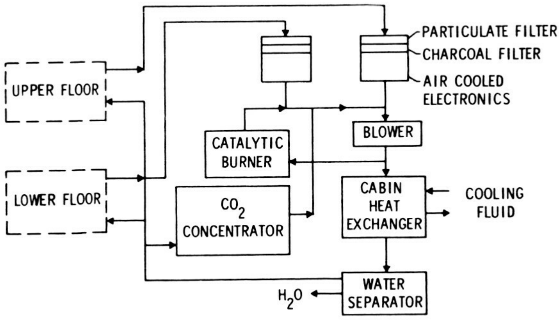

Figure 16

7. LUNAR STAY TIME EXTENSION MODULE

By Charles I. Tynan, Jr.

SUMMARY

A contractual and inhouse research effort to develop the technology for extending man's stay time on the lunar surface is discussed. Parameters such as the lunar environment, crew size, stay time, mission objectives, and integration with logistic vehicles have been considered with respect to their effect on the configuration and design of expandable modules and supporting subsystems. An expandable lunar shelter, referred to as a stay time extension module (STEM), has been designed and a full-scale laboratory model of the shelter is being fabricated. The shelter structure, subsystems, and expendables to support two men on the lunar surface for 8 days should weigh 1,276 pounds and be capable of being packaged in canisters attached to the base of a manned lunar excursion module (LEM) for transportation to the lunar surface. Test programs to be conducted with the full-scale shelter model and samples of its wall structure should make significant contributions to the advancement of expandable structures technology for lunar shelters and other space structures applications.

INTRODUCTION

Advanced lunar programs indicate a requirement for portable lightweight modules to house personnel and equipment on the lunar surface for extended periods of time. These modules could be used for the following functions:

(1) Extending Apollo stay time
(2) Emergency shelter for the Apollo crew
(3) An astronaut suit changing facility
(4) Emergency shelter for the crew of a large lunar roving vehicle
(5) Supplement to a larger permanent shelter
(6) Equipment storage facility
(7) Maintenance hangar
(8) Experiment facility to be left on the lunar surface for some period of time.

Previous research on expandable structures for manned earth-orbiting space stations demonstrated a possible application of this fabrication technique to the lunar shelter requirement.

In order to develop the technology for extending man's stay time capability on the lunar surface, Contract No. NAS1-4277 was awarded to the Goodyear Aerospace Corporation in August 1964 for a feasibility study and systems integration effort which would lead to the conceptual design and construction of a full-scale laboratory model of an expandable lunar module.

The three phases of the contractor's study are presented in figure 1. Certain study requirements and constraints were specified in the environmental, mission, and logistics areas. A particularly significant logistic constraint was that the lunar shelter should be capable of being packaged so that it could be carried in canisters to the lunar surface by a manned LEM. Studies on the shelter-airlock, life support, power, and communications subsystems were conducted. A systems integration effort insured that the selected subsystems were compatible with, and adequate to meet, the study constraints. Phase I of the study ended with the conceptual definition of the STEM design.

The LEM subsystems were investigated in phase II in order to compare a completely independent STEM with a STEM that could be connected to the manned LEM by umbilicals in order to utilize the LEM life support, thermal control, power, and communications systems. Supporting analyses were conducted in the thermal, structures, logistics, materials, and environmental effects areas. The subsystems definition and systems integration efforts of phase I were continued in phase II. The STEM preliminary design was based on a system which could support two men on the lunar surface for 8 days. Parametric analyses investigated the STEM system required to support a crew of two to six men on the lunar surface for periods up to 30 days.

The contractor is now in phase III of the study and the fabrication of the full-scale laboratory model of the STEM should be completed in July 1965. This module will undergo minimum-leak-rate acceptance tests at the contractor's plant. Test procedures are now being developed for programs to be carried out at the Langley Research Center when the full-scale STEM is received from the contractor.

DISCUSSION

STEM Operational Concept

Figure 2 shows a manned LEM on the lunar surface and two of the four STEM packaging canisters can be seen attached to the base of the LEM. The largest canister would have a volume of 80 ft^3 and contain the shelter-airlock, a thermal mat, and stabilizing chocks. One 54-ft^3 and two 27-ft^3 canisters would contain the remainder of the STEM equipment and supplies. The heaviest canister would weigh 300 earth pounds, equivalent to 50 pounds on the lunar surface. Therefore, one man should be able to erect the STEM and have it operational within 2 hours.

In figure 3, the method of deploying the shelter-airlock on top of the 44-foot-diameter thermal mat is illustrated. The stored potential energy of the compressed foam in the wall structure of the shelter would cause the shelter to erect itself without internal pressurization.

In figure 4, the shelter-airlock is deployed and an astronaut is placing the stabilizing chocks on one side of the shelter. Overall length of the shelter-airlock is 17.5 feet and the diameter is 80 inches. Internal volumes of the shelter and airlock are 410 ft^3 and 105 ft^3, respectively.

Attachment of the three communications antennas is illustrated in figure 5. Communications would be provided (1) to the earth by means of the deep-space instrumentation facility (DSIF) network, (2) to an orbiting command module, and (3) to an astronaut walking about on the lunar surface. The storage of cryogens outside the shelter is also illustrated in figure 5. The cryogenic canister on the left would contain oxygen for the life support system and the other two canisters would contain oxygen and hydrogen for the fuel-cell power supply. A fully operational STEM is illustrated in figure 6.

Although the structural aspects of the lunar shelter are of primary interest, it was necessary to consider all its major subsystems in order to determine the effect of these subsystems on the design of the structure itself. All the selected subsystem components are essentially state of the art.

Wall Construction

A cross-sectional view of the composite wall structure is presented in figure 7. The outer surface thermal coating of zinc oxide in silicone resin would provide a diffuse reflectance for thermal control. The outer bumper of Dacron fabric and Mylar film laminate would provide micrometeroid protection. The 2-inch-thick layer of flexible polyurethane foam would provide additional micrometeoroid protection. Since the foam would be an excellent insulator, 5-mil-diameter copper drop threads embedded in the wall structure would provide thermal conductivity from its inner surface to its outer surface. The structural layer of stainless steel would be filament wound over the inner pressure bladder which is the first layer of the composite structure to be applied to a mandrel of rigidized foam. The resultant composite structure would be flexible and weigh only 0.613 lb/ft^2.

Inhouse test programs have been initiated at the Langley Research Center using samples of the proposed STEM wall structure which have been provided by the contractor. These test programs will investigate (1) the effectiveness of the structure to withstand micrometeoroid impacts, (2) the thermal conductivity through the shelter wall, (3) the effect of a vacuum environment on the self-erection capability on the lunar surface of the compressed foam in the wall structure, and (4) the effects of folding and compression on the structural integrity of the wall structure.

Thermal Control

The lunar temperature environment varies from 250° F to -300° F. A unique approach to the thermal-control problem has been incorporated into the STEM design. This threefold approach would be to (1) moderate the 250° F temperature of the lunar surface, (2) insulate the shelter against the -300° F lunar night, and (3) design the shelter as a space radiator. The thermal-control concept is presented in figure 8. The thermal mat, with a maximum temperature on its upper surface of 71° F, would insulate the shelter from the heat of the lunar surface. The shelter thermal coating would control the exterior surface temperature to a maximum of 49° F. The previously mentioned copper drop threads imbedded in the wall structure would permit the transfer and rejection of the internal heat load. An exterior insulation blanket composed of superinsulating material would be folded alongside the base of the shelter during the lunar day and during the cold lunar night would be pulled up and over the shelter walls to hold the internally generated heat within the shelter. Movement of the insulation blanket would be manually controlled by cables and a hand crank within the shelter. Position of the insulation blanket would vary the shelter exposure area and thereby maintain a comfortable interior temperature.

Life Support System

The STEM would utilize a 100-percent oxygen atmosphere at 5 psia. Two gas systems were investigated but 100 percent oxygen was selected because of its light weight and compatibility with the present Apollo life support system. Lithium hydroxide would be used to remove carbon dioxide. A waste-water evaporator would be used for humidity control. An alternate means of humidity control would utilize a space radiator which can be seen resting on the thermal mat in the shadow of the shelter in figure 6. Activated charcoal would be used for odor control and trace contaminant removal. A temperature of 75° F and a relative humidity of 50 percent would be maintained. Water consumption would be 41.2 pounds per day and water production would be 24.4 pounds per day. Planned water management is presented in table I. A 3,000-calorie diet (1.5 pounds of food per man-day) would be provided. Feces and urine would be stored in sealed containers.

Power System

STEM power requirements for cooking, communications, lighting, instrumentation, and the environmental control system would total 290 watts per day. After consideration of several power systems, it was concluded that storage batteries would be too heavy, solar power systems would be incompatible with day-night operation, and nuclear systems would be beyond the limit of current technology. A hydrogen-oxygen fuel-cell power system was therefore selected to be utilized in the STEM. Two 300-watt fuel cells would be provided for 100-percent redundancy. Reactant consumption for continuous output of 300 watts would be 6.8 pounds per day of oxygen and 0.8 pound per day of hydrogen. Fuel-cell operation would provide 7.6 pounds per day of drinkable water. A membrane-electrolyte-type cell was selected over a liquid-electrolyte-type cell because of a lower operating temperature and self-starting capability. The selected fuel-cell operating temperature would vary between 80° F and 140° F, and the cell would have a self-starting capability at temperatures as low as 40° F. Since the fuel cell would be located inside the shelter, it would reject heat to the shelter interior at a rate of about 2,000 Btu per hour.

STEM Weights

From table II it is seen that the total weight of a STEM system supporting 2 men on the lunar surface for 8 days would be 1276 pounds. Parametric analyses were conducted to determine the weight of a STEM system that would be required to support 2, 4, and 6-man crews for lunar surface stay times from 6 to 30 days.

The results of these analyses are presented in figure 9. A STEM system weight of 6,100 pounds would be required to support a 6-man crew for a stay time of 30 days. For longer stay times there would be crossover points at which changes in the base line design 2-man, 8-day subsystems would be made - for example, molecular sieves would replace lithium hydroxide for carbon dioxide removal because of their weight advantage for the longer stay times.

Umbilical STEM

The umbilical STEM system is illustrated in figure 10. A comparison was made between the independent STEM and a STEM which would be connected with the manned LEM by umbilicals so that the shelter-airlock would utilize the LEM environmental control, power, and communications systems. A weight summary for the umbilical STEM is presented in table III. From a comparison of tables II and III, it is seen that the fixed weight of the umbilical STEM is less than that of the independent STEM. However, the expendable weights for the umbilical STEM are considerably higher than those of the independent STEM. The large difference in expendable weights is due to the fact that the independent STEM was considered to use the previously described quasi-passive thermal control system, whereas the umbilical STEM was considered to rely completely on the active environmental control system of the LEM. The weight differential between the two systems is illustrated in figure 11 from which the weight advantage of a quasi-passive thermal control system is seen. An optimized STEM system incorporating the quasi-passive thermal control system and an umbilical attachment to the LEM will be investigated.

CONCLUDING REMARKS

Operationally, an independent lunar shelter would have a safety advantage over a shelter which would utilize the subsystems of its logistic vehicle for environmental control, power, and communications. A breakdown in the logistic vehicle subsystems would most likely place further operation of both the shelter and its logistic vehicle on an emergency basis. An independent shelter would provide redundant habitable living quarters in the event of a subsystem breakdown in either the lunar shelter or its logistic vehicle.

The STEM concept has potential for fulfilling the requirement for portable lightweight lunar shelters. The full-scale module now under construction will be used to study packaging and deployment techniques and to determine its structural integrity. The inhouse test programs with the full-scale STEM and the small samples of its wall structure should make significant contributions to the advancement of expandable structures technology for lunar shelters and other space structures applications.

TABLE I

WATER MANAGEMENT

[2 men; 8-day stay time]

Water production:	
Potable water	
Fuel cells	60
Contaminated water	
Expired and transpired	36
From lithium hydroxide cartridges	14
Urine	53
Sanitation	32
	195 lb
Water consumption:	
Potable water	
Drinking	35
Food reconstitution	43
Sanitation	32
Back pack cooling*	96
Perspiration lost while outside shelter**	24
Contaminated water	
Waste-water evaporator***	100
	330 lb
Water balance:	
Potable water at start of trip	170 lb
Contaminated water at end of trip	35 lb
Potable water at start of trip	10.6 lb/man-day
Contaminated water at end of trip	2.2 lb/man-day

*Each astronaut on one outside trip each day would use 80 percent of the 7.5-lb water supply of back pack.

**During lunar exploration, water generated by perspiration and respiration at approximately 1.5 lb per trip is not recovered. This water loss is replaced when the astronauts return to the shelter.

***Waste-water evaporator, 50 percent efficient.

TABLE II

WEIGHT SUMMARY FOR INDEPENDENT STEM

Fixed weights:	
Shelter-airlock	326
Furnishings	67
Life-support	116
Power system	86
Communications	32
Thermal control	70
Packaging canister (shelter-airlock)	52
Packaging canister (equipment)	68
	817 lb
Expendable weights (57.4 lb/day):	
Life support	
Oxygen	113
Lithium hydroxide	50
Food	24
Water	189
Power	
Oxygen	64
Hydrogen	19
	459 lb
Total weight (2-man, 8-day system)	1,276 lb

TABLE III

WEIGHT SUMMARY FOR UMBILICAL STEM

Fixed weights:	
Shelter-airlock	326
Furnishings	30
Umbilical equipment	39
Packaging canister (shelter-airlock)	52
Packaging canisters (expendables)	90
	537 lb
Expendable weights (≈135 lb/day):	
Thermal control	
Water and tanks	632
Hydrogen and tanks	84
Life support	
Oxygen and tanks	113
Lithium hydroxide	50
Food	24
Water and tanks	105
Power	
Oxygen and tanks	57
Hydrogen and tanks	18
	1,083 lb
Total weight (2-man, 8-day system)	1,620 lb

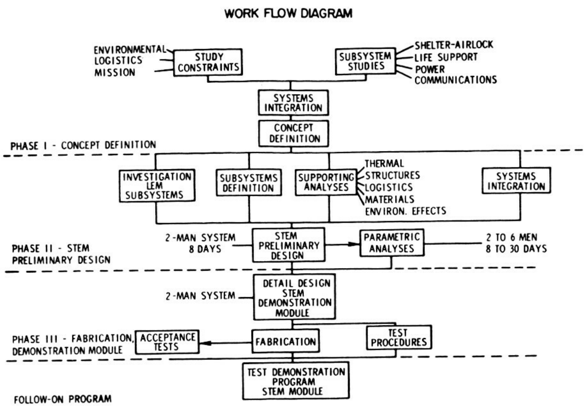

Figure 1

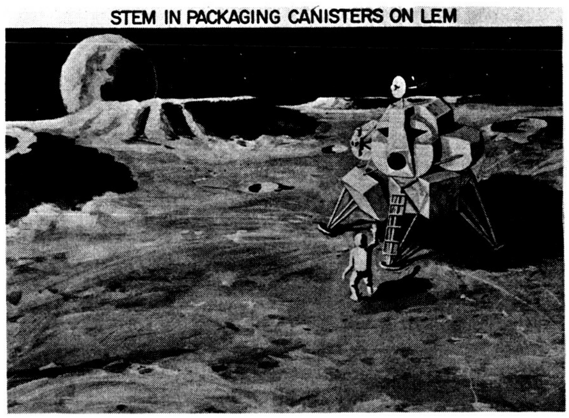

Figure 2 L-2485-3

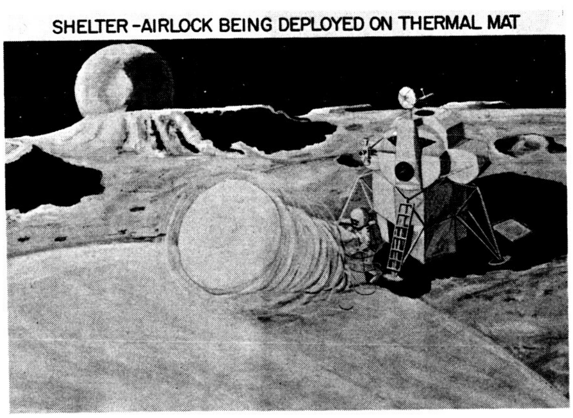

Figure 3 L-2485-4

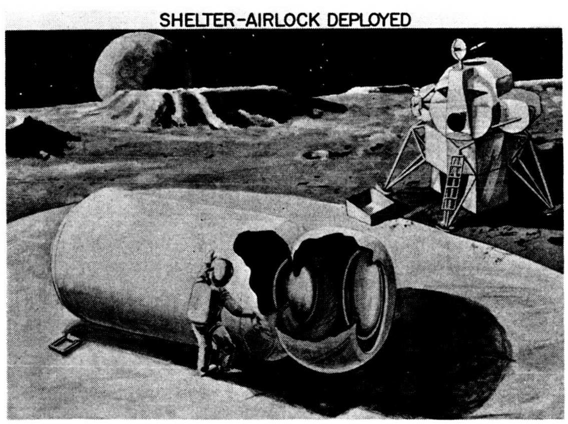

Figure 4 L-2485-5

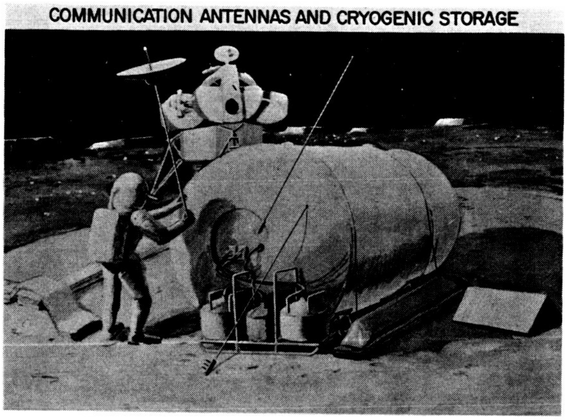

Figure 5 L-2485-6

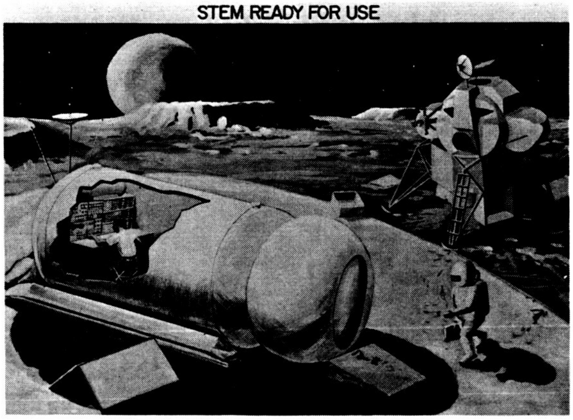

Figure 6 L-2485-7

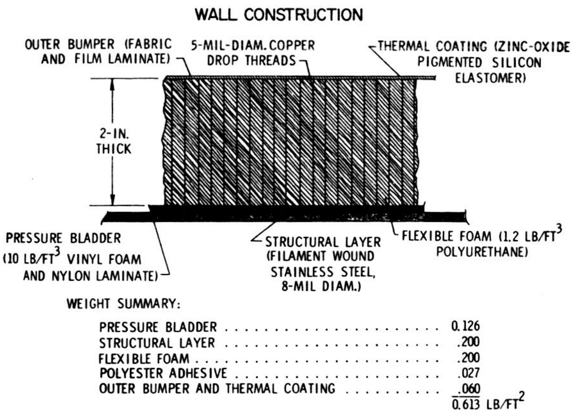

Figure 7

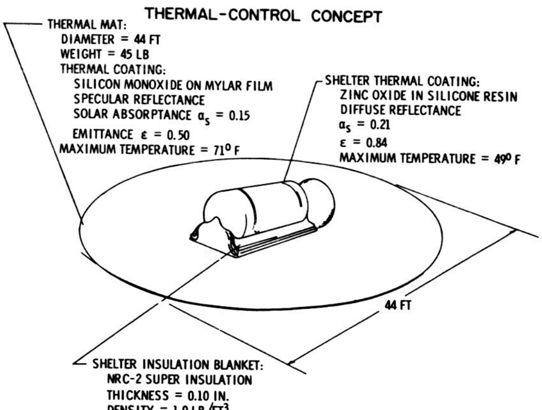

Figure 8

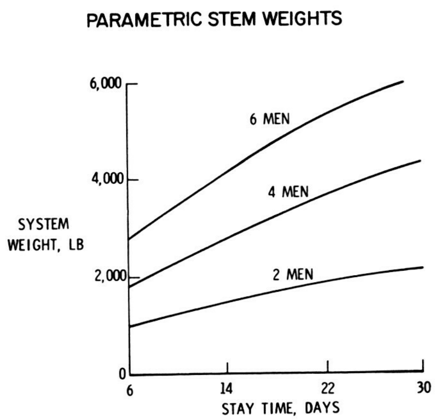

Figure 9

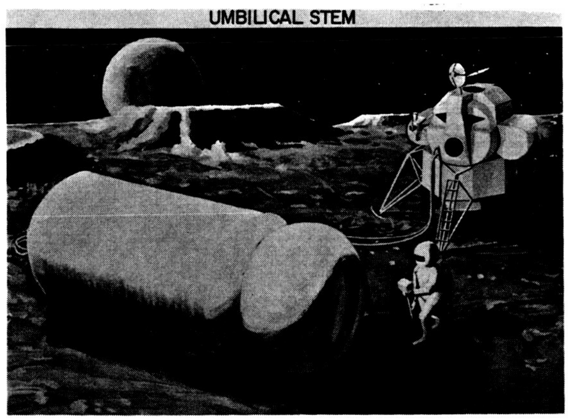

Figure 10

L-2485-15

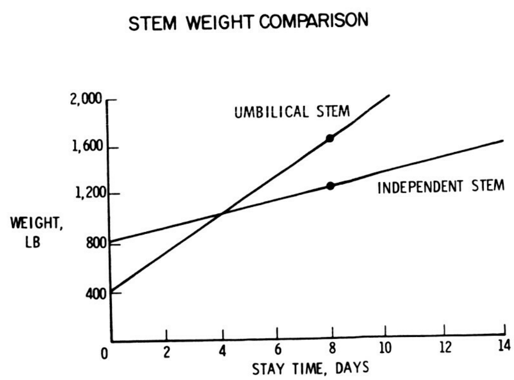

Figure 11

8. WATER-IMMERSION TECHNIQUE FOR SIMULATION OF INGRESS-EGRESS MANEUVERS UNDER CONDITIONS OF WEIGHTLESSNESS

By Otto F. Trout, Jr.

SUMMARY

A water-immersion technique has been developed whereby a pressure-suited subject, unrestrained by connecting lines and hoses, can simulate maneuvers under conditions of weightlessness in six degrees of freedom. This simulation has been applied to a series of ingress-egress experiments, and some of the results are described in this paper. The results of these experiments indicate that the technique has application to the study of human factors and capabilities in extravehicular space operations and to a determination of design criteria for advanced manned space vehicles and related equipment.

INTRODUCTION

Current NASA studies of manned space stations and other extended-mission space vehicles include requirements for extravehicular astronaut performance in the hard-vacuum, zero-gravity environment of space while encumbered by a full pressure suit. These tasks will include ingress-egress through airlocks, intervehicular crew and cargo transfer, assembly of external equipment and experimental hardware, inspection and maintenance of equipment, and performance of various extravehicular scientific tasks and measurements.

Assessment of available means of simulation of these tasks has shown a definite need for the development of additional techniques. An investigation was therefore undertaken to examine the feasibility of a pressure-suited subject operating in a neutrally buoyant condition in water to study weightless ingress-egress maneuvers through airlock systems. The feasibility of the technique was demonstrated and used to determine problem areas associated with ingress-egress operations. It has proven to be a valuable research tool for zero-gravity simulation where the pressure-suited subject is required to work in confined spaces and where the velocities of the subject are low.

This simulation technique is primarily designed to investigate the external motion performance characteristics of the suited subject in a weightless state, in six degrees of freedom, unrestrained by connecting lines and hoses but does not provide for assessment of internal physiological effects at zero gravity.

The simulation has been applied to a number of ingress-egress problems that include operation through airlock systems, examination of problem areas, motion aids, workspace limitations, equipment sizes, and the study of human factors and astronaut capabilities in a weightless environment.

ZERO-GRAVITY SIMULATION TECHNIQUES

The recent Gemini and Voskhod flights have shown some of the value and feasibility of operations of an astronaut on the exterior of a vehicle. Figure 1 is an artist's concept of an astronaut making egress from the airlock of a manned space vehicle into the hard-vacuum environment in a pressurized suit. The extravehicular operations in which man can effectively be utilized on extended missions include ingress and egress operations through airlock systems, assembly and maintenance of equipment, crew and cargo transfer functions, observation and inspection tasks, and manned experimentation in research endeavors. An important factor in the success of extended manned space missions will be the extravehicular operational performance of suited astronauts in both the routine and emergency modes.

The operational characteristics and work output capabilities of the suited astronauts in the zero-gravity and partial-gravity environments need to be assessed in order to define and develop operational procedures, to obtain anthropometric data for design purposes, to provide specifications for systems design, and to determine man-machine relationships. The interaction of vehicle systems, the size and configuration of airlock systems, the choice of supporting hardware, and the design of extravehicular equipment cannot be specified until the capabilities of the pressure-suited astronaut are determined.

Examination of manned experiments has shown an apparent lack of facilities to develop design data and to simulate the suited astronaut in a tractionless or reduced-traction environment. The principal means of simulation available for studying these extravehicular operations include aircraft Keplerian trajectory, cable and suspension systems, air-bearing platforms, and water-immersion neutral buoyancy. Each of these means of simulation is a valuable tool but has definite limitations. The aircraft flying a Keplerian trajectory is limited to test durations of 10 to 30 seconds. Cable suspension systems and air-bearing platforms restrict performance, in confined spaces, to single planes or to limited degrees of freedom. Water immersion is limited to low velocities because of drag effects. Actual orbital experiments are obviously too costly and complex for obtaining preliminary data. The several means of simulation are often complementary, and valuable data may thus be obtained by performing similar tests by more than one method.

APPARATUS AND TESTS

Because the water-immersion technique appeared to offer advantages for studying ingress-egress operations and was the least developed, an investigation was undertaken to assess the feasibility of operating a pressure-suited subject neutrally buoyant in water with a self-contained breathing apparatus. This research has resulted in a successful technique wherein a subject using a modified Navy Mark IV pressure suit has been able to operate under water in six degrees of freedom for extended periods of time up to $1\frac{1}{2}$ hours, unrestrained by connecting lines and hoses. Weightless simulation by water immersion has often been suggested in the past, but this effort is believed to be the first time that it has been successfully used with a test subject in a fully pressurized suit.

Figure 2 illustrates the pressurization and breathing system of the suit used in these tests. The Navy Mark IV suit was used because of its availability. It was modified by blocking the ventilation system and replacing the oxygen system with a self-contained air supply. High-pressure air is supplied by a 2500-psi storage bottle on the subject's back to which first- and second-stage regulators are connected. A demand regulator in the helmet provides a flow of air into the facial area of the helmet when the subject inhales. Exhalation by the subject causes the demand regulator to close, and air is expelled into the torso of the suit by a valve located in the neck seal. This expelled air acts to pressurize the suit to the level preset on the relief valve. This system effectively provides for breathing and suit pressurization both under water and on the ground.

The validity of the water-immersion simulation was examined by performing a series of water-immersion experiments and comparing them with similar experiments by zero-gravity aircraft flights and ground tests. The aircraft-test results were shown to be comparable to the water-immersion-test results when the movements of the subject were not rapid. Comparable experiments on the ground at full-gravity conditions with the same subjects and equipment have shown that the ground results are not comparable for studies of the weightless ingress-egress problems, yet much of the design data for equipment used by pressure-suited astronauts is presently obtained from full-gravity ground tests.

The water-immersion tests were made in a swimming pool approximately 11 feet deep. A transparent test model of an airlock 4 feet in diameter and 6 feet long with hatch doors at each end was used to provide simulation of ingress-egress performance. (See fig. 3.)

During the water-immersion tests the subject was balanced to neutral buoyancy and stabilized in pitch and roll. A scuba-equipped safety man accompanied the test subject during each experiment.

A complete photographic record of the subject's maneuvers was made by an immersed 16-millimeter camera positioned normal to the airlock. A standard frame rate of 24 frames per second was used in all tests. An optical grid positioned behind the airlock and dimensioned markings 2 feet apart on the outside of the airlock test model were used in conjunction with the motion pictures to measure velocities of the test subject, time to perform specific tasks and subtasks, and body position. The dimensioned markings but not the optical grid were used also in the ground and aircraft tests.

DISCUSSION

A comparison of tests performed on the ground, aboard a zero-gravity aircraft, and by water immersion was provided from the motion pictures of the subject undergoing the tests. The discussion that follows is based on these film sequences (Langley Research Center film No. L-879).

For the ground tests, the subject performed various tasks at full gravity in the same transparent model of a space-vehicle airlock previously described. The tasks assigned may simulate those of an astronaut working in an artificial-gravity field aboard a space vehicle. The subject had difficulty in moving his hands and knees with $3\frac{1}{2}$ pounds of pressure in the suit. In one task he was required to pass over a 6-inch ledge to enter the airlock through the hatch and found it necessary to perform a pushup to get his legs over the ledge; even then, he scraped the legs of the suit. Forward motion on the hands and knees required considerable effort. Because the pressure tends to straighten out the knees of the suit, the subject reported that he had the feeling that he was going to be thrown on his face if he relaxed. A turnaround in the cylindrical airlock was obviously a strenuous maneuver. Fifteen minutes of operation on the ground tired the subject more than a similar period working under the water.

The subject also used the same airlock model to perform a similar set of maneuvers aboard the C-131 airplane at Wright-Patterson Air Force Base during zero-gravity trajectories. Because of the short duration of each trajectory, the ingress-egress tests were broken down into six test sequences. The subject showed greater incentive in these tests to move rapidly to avoid being draped over a sharp edge on the $2\frac{1}{2}$g pullout. During the pullout at this acceleration he lay on his side. He appeared to have some difficulty in making a turnaround during another trajectory. He was sometimes unable to complete this maneuver in the allotted time.

In the tests performed under water, before the maneuvers are attempted the subject is balanced to neutral buoyancy and neutral in pitch and roll. In the sequences showing the subject making a passage through the same airlock underwater, he tended to move forward in an inclined position in order to maintain forward vision through the helmet, as illustrated in figure 4. Motion through the water appeared almost effortless in these tests. The subject in making an exit through the hatch eases his grip on turning around and floats off in the water. This maneuver illustrates the necessity of tethering an astronaut to the exterior of the vehicle. The subject's ability to swim is very poor in the pressurized suit. In one test, the subject attempted to apply torque on a hatch handle which was tightened, but his body turned instead of the hatch handle.

In another assignment, the subject, in making an exit, caught one of his suit straps on the hatch. In this test, the safety man had to rescue him, since he was not capable of loosening himself in the pressurized suit. This limitation on maneuverability might have serious consequences in a space vehicle, since it is conceivable that the entire vehicle might have to be depressurized in order to perform a rescue on the outside hatch of an airlock. Once, when the subject was attempting an egress maneuver without the use of motion aids, he tried, in desperation, to use the hatch to control his body position. Because the hatch was not fixed he had only partial control of his body position.

The hands are not the only useful part of the body for the suited astronaut. The subject in one test learned to use his feet to execute a turnaround on exit. In the weightless environment of space the astronauts will quickly learn to perform acrobatic maneuvers, because such maneuvers are not limited by gravity and the movements need not be rapid.

A turnaround executed by the subject with the use of an interior handhold indicated that such handholds gave him only slightly more control than he could normally get by bracing himself between two surfaces, as shown in figure 5. On two occasions, the subject damaged the helmet or faceplate of the suit in performing a turnaround. In one test the subject made use of a handrail on exit from the airlock. In this maneuver, the subject appeared to have excellent control over his body position; he was able to maneuver with relatively little effort and in some cases could change his attitude merely by the use of his wrists. Hand rails on the exterior of a space vehicle will permit easily controlled physical positions and postural attitude of the crewmen during extravehicular task performance.

A test was made to demonstrate the use of a safety tether line during egress. The line is fastened to the end of the airlock and the subject shoves off. The line was drawn between his legs when he attempted to reel back; then he worked himself into such an awkward position that he almost smashed his helmet into the side of the airlock, but he was able finally to maneuver himself out of this position without help. This test showed that it is possible to attain a dangerous velocity and attitude on reeling in.

A task that the subject performed successfully was that of fastening his safety line on an eye on the exterior of the lock.

One assignment given the subject was that of examining the workspace limitations and his ability to reach control points. This problem was studied by requiring the subject to insert a phone jack in various locations on the inside of the airlock. By this means, workspace limitations, task allocation times, work cycles, and control locations can be established. During the water-immersion tests the subject was able to reach all positions within the airlock model, but during similar ground tests he was not able to reach some of the overhead positions.

EVALUATION OF TECHNIQUE

The validity, advantages, and disadvantages of the water-immersion technique will be discussed briefly. Figure 6 presents a plot of the maximum and minimum whole-body drag as a function of velocity as observed from the subject's performance of ingress-egress maneuvers similar to those just discussed. During these maneuvers the average velocity was about 0.5 foot per second, with the maximum seldom exceeding 1.3 to 1.8 feet per second. Subjective comments indicated that the forces necessary to overcome the resistance of the pressure suit were much greater than those required to overcome the drag of the water. When the velocities are low, this technique appears to be suitable for evaluating astronaut capabilities.

The advantages of the water-immersion simulation are its simplicity, relatively low cost, the ability to work in six degrees of freedom, and the additional time available to conduct detailed studies.

The results of the present ingress-egress studies can be summarized according to the following categories:

(1) Astronaut capability: The water-immersion simulation technique has been shown to be a useful tool in studying the capabilities of the pressure-suited astronaut under conditions of weightlessness. The test subjects were able to perform most ingress-egress tasks with relative ease and to develop quickly new skills and procedures.

(2) Spacecraft configurations and sizes: The airlock used in these simulations was 48 inches in diameter, which was marginal for turnaround by the pressure-suited subject, who was 5 feet 10 inches tall. Measurements from the photographs of the 6-foot-long airlock showed that a turnaround could be executed within a length of $4\frac{1}{2}$ feet, which would leave sufficient space for an inward opening hatch. This type of hatch offered few problems to the subject if it could be opened 90°. Substantial structural weight savings and reduced latching complexity are possible on airlock systems if hatches can be opened inward and seated with pressure. The 32-inch-diameter circular hatch was sufficiently large for easy passage of the subject in the weightless state and did not begin to pose a problem with this pressure suit until the diameter was reduced to less than 26 inches. The outward opening hatch was often in the way for maneuvers on the exterior of the airlock.

(3) Handholds, handrails, and motion aids: The experiments have shown that handholds are not advantageous in confined spaces where traction can be attained by other means. Protrusions in a confined space are a definite hazard from the standpoint of entanglement with the suit straps and damage to the helmet. However, handholds on the exterior are a necessity, since no other means of traction are available. Handrails are advantageous for easy locomotion and for controlling body attitude. It is conceivable that handrails could be a most desirable motion aid to frequently visited locations on the exterior of a space vehicle. For torque application, hand or foot braces are a necessity if body orientation is to be maintained.

(4) Tether lines: Experiments with the safety tether line have shown that the subject is able to reel himself back to the attachment location; however, he has no axial control of attitude perpendicular to the tether. In the present studies the line was considered only as a safety device to prevent loss of the astronaut. Total simulation of the dynamics of a tethered astronaut is not possible with this technique because of the damping effects of the water; however, comparison of these tests with recent flight experiments shows considerable similarity in attitude control and the capability of the astronaut to recover on a short safety line. Cargo transfer by the astronaut on a tether line appears to be a real problem and requires further study.

(5) Workspace limitations: The study of workspace limitations indicated that working in a confined space in the weightless state is less of a problem than anticipated. The location of controls in an airlock can be determined by similar tests. Working with pressurized gloves requires handles of at least 1-inch diameter to provide the necessary feel and dexterity.

(6) Operational procedures: It is apparent from these studies that many operational procedures can be developed by the water-immersion simulation technique. During the early experiments the subjects made little or no use of their legs or feet; however, they quickly learned to perform maneuvers with their feet and to brace themselves with their legs in applying torque.

This continuing experimental program shows promise of providing a better understanding of human factors and capabilities in extravehicular operations; it contributes data applicable to future configurations, to manipulation and control devices and safety-design features for airlock systems, and to other extravehicular equipment for advanced manned space vehicles.

CONCLUDING REMARKS

A technique has been developed and validated wherein a pressure-suited subject is immersed in water and maintained in a neutrally buoyant condition to simulate the external tractionless characteristics of the zero-gravity environment in six degrees of freedom.

The water-immersion technique can be applied in many current and future studies of extravehicular space missions and tasks, such as the ingress or egress through airlocks, evaluation of the astronaut's extravehicular work capabilities, development of procedures for crew and cargo transfer techniques, and provision of design data for future vehicles and related equipment.

Similar experiments performed by water immersion and from zero-gravity aircraft flights have shown that the water-immersion and aircraft tests are comparable when the velocities are low. The two simulation techniques are complementary and information from each should supplement that from the other to increase understanding of the overall problem.

ASTRONAUT EGRESS

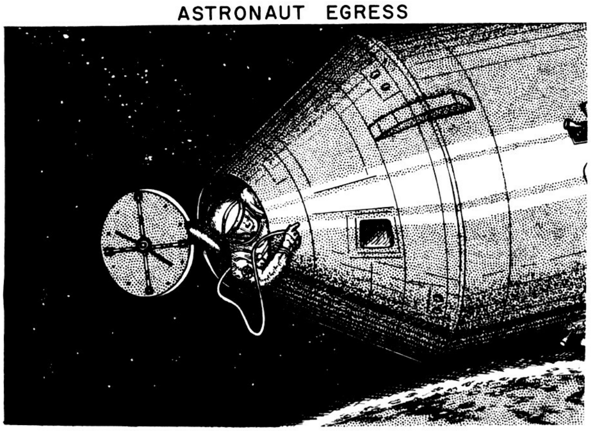

Figure 1 L-2491-1

SUIT PRESSURIZATION AND BREATHING SYSTEM

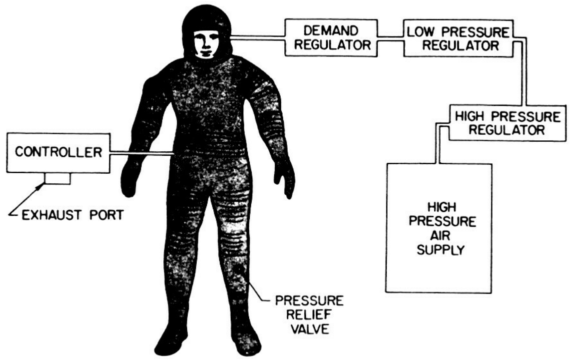

Figure 2

MODEL AIRLOCK WITH SUITED SUBJECT

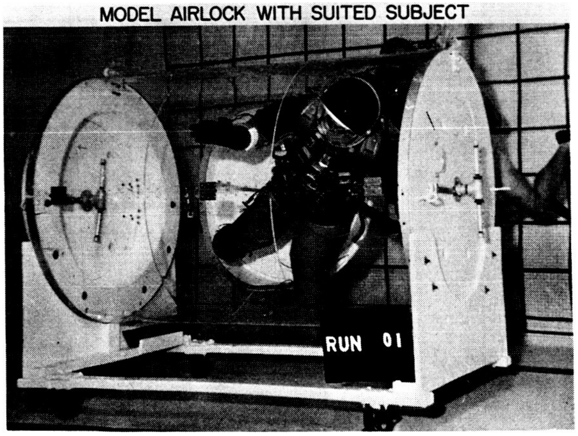

Figure 3 L-2491-7

SUBJECT MAKING INGRESS

Figure 4 L-2491-8

SUBJECT PERFORMING TURNAROUND

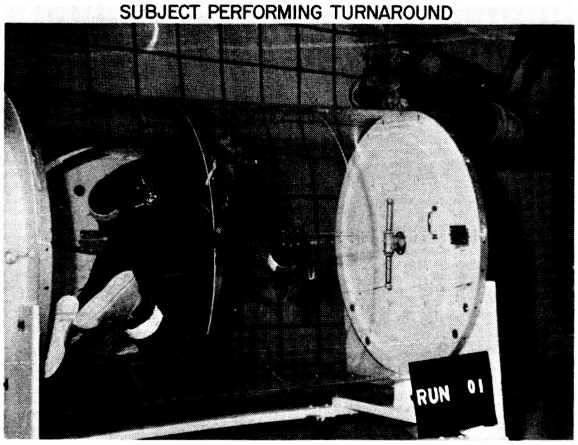

Figure 5

L-2491-9

WHOLE-BODY DRAG PLOTTED AGAINST VELOCITY

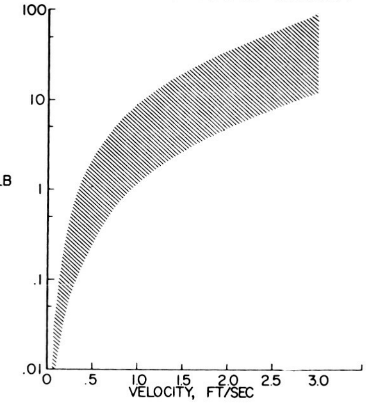

Figure 6