The Cornucopia Two - Gas Atmosphere System For Man In Space

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AMONG THE PRESENTLY limiting factors in manned space missions are the weight, complexity and power required for respiratory gas supply and control. Both because of the fire hazard and because of such suspected physiologic hazards as atelectasis, there is growing conviction that prolonged missions will require a two-gas atmosphere. This further emphasizes the constraints and provides a distinct incentive for developing lighter and simpler gaseous atmosphere systems. An additional problem which looms large is the apparent need for purging the spacecraft atmosphere to prevent the build up of contaminants from unknown sources. It is becoming increasingly clear that it will be most difficult always to assure that no physiologic toxin will increase in a sealed capsular environment when the duration of the mission extends beyond a few days. The simplest means of coping with this problem is to flush the capsule on a periodic or slow continuing basis with gases of known purity, but for most atmosphere control techniques and missions this is unacceptable because of the large weight penalties. The Cornucopia process promises a ready solution to all of these atmosphere problem areas including an essentially "free" purge. The unique characteristics which make it such a promising approach are briefly outlined below.

General Description of the Cornucopia Concept:—Cornucopia is the name given to a novel concept for extending the utility of storable rocket bi-propellants to include life support and other essential services in the space environment. The fundamental concept may be embodied in either the hydrogen peroxide/hydrazine system

$$H_2O_2/N_2H_4$$

or the nitrogen tetroxide/hydrazine system

$$N_2O_4/N_2H_4$$

Both of these chemical systems consist of well known earth-storable liquid reactants which burn hypergolically over a wide range of pressures and mixture ratios. Both combinations serve as efficient thrust producers when burned stoichiometrically in a rocket thrust chamber, and yield the same products of combustion

$$H_2O + N_2 + O_2 + \text{heat} + \text{kinetic energy}$$

when burned with an excess of oxidizer in a gas generator.

The thrust obtained from these reactants may be used for propulsion, trajectory adjustment, or attitude control, while the principal products of their off-stoichiometric combinations include potable water, metabolic oxygen, a two-gas replenishment atmosphere, high grade thermal energy for temperature control or power generation, and kinetic energy for a variety of mechani-

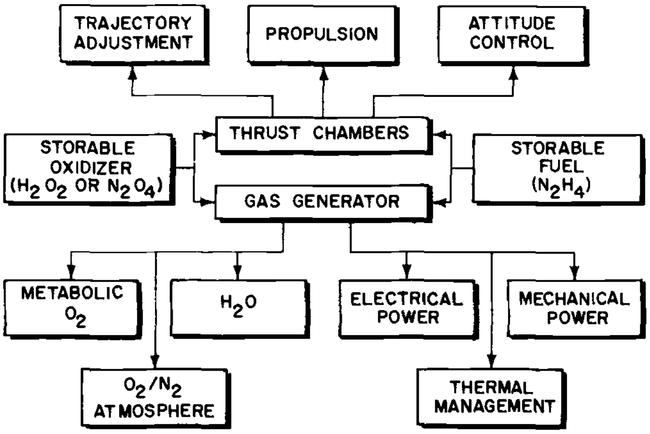

Fig. 1. Representative block diagram

From the Applied Physics Laboratory, The Johns Hopkins University, 8621 Georgia Avenue, Silver Spring, Maryland.

cal functions. Figure 1 illustrates the above in functional block diagram form, as it might typically apply to a manned space vehicle. This profusion of potentially useful products is reminiscent of the horn of plenty from which the Cornucopia concept derives its name.

The foregoing brief description of Cornucopia has presented the most unique aspect of its character—a variety of products and functions are achieved from only two earth-storable liquids. In all but the shortest missions the space vehicle must provide a considerable quantity and variety of vital fluids, including the liquid rocket bi-propellants, potable water, atmospheric oxygen and nitrogen, any necessary coolants, and whatever reactants might be needed for electrical power generation. This situation tends to create a formidable overstorage problem, since the supply of each separately stored fluid must include some individually determined margin for uncertainty or emergency reserve. Also, the inherent inefficiencies of multiple tankage will always incur additional penalties in hardware weight, volume and complexity. Clearly, a substantial consolidation of on-board fluid storage requirements can pay off handsomely in terms of system performance and habitability.

One very small step in this desirable direction was taken in the Mercury program, where a single water tank supplied all fluid for drinking and for capsule cooling. For the Apollo mission a somewhat more ambitious consolidation of fluid storage is planned, in that two cryogenic fluids will provide all water, power, and metabolic oxygen. This still represents a fairly modest economy of weight and complexity, though, considering the total amount of on-board fluid. To obtain any dramatic payoff we must somehow exploit the presently untapped potentials of the storable propellants, which commonly comprise a large fraction of the total system weight. Cornucopia gives promise of such exploitation.

Two-Gas Atmosphere Control:—As seen in Figure 2, the peroxide/hydrazine system can yield gaseous oxygen and gaseous nitrogen in any desired proportion, depending on the selected mixture ratio. With a slight excess of peroxide the cooled and dehumidified product gas has the approximate composition of a sea level atmosphere, while at an infinite mixture ratio (no hydrazine) only water and oxygen are evolved. Figure 3 shows similar yields from the tetroxide/hydrazine system, but with less water production (not necessarily a disadvantage) and with a finite practical upper limit to the oxygen/nitrogen ratio.

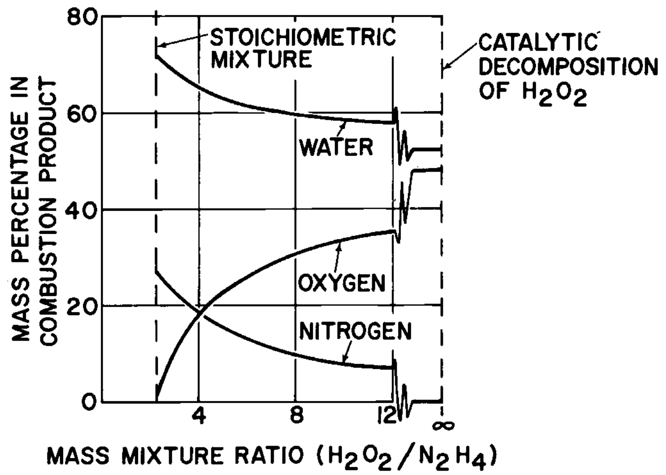

Fig. 2. Products of the hydrogen peroxide/hydrazine reaction

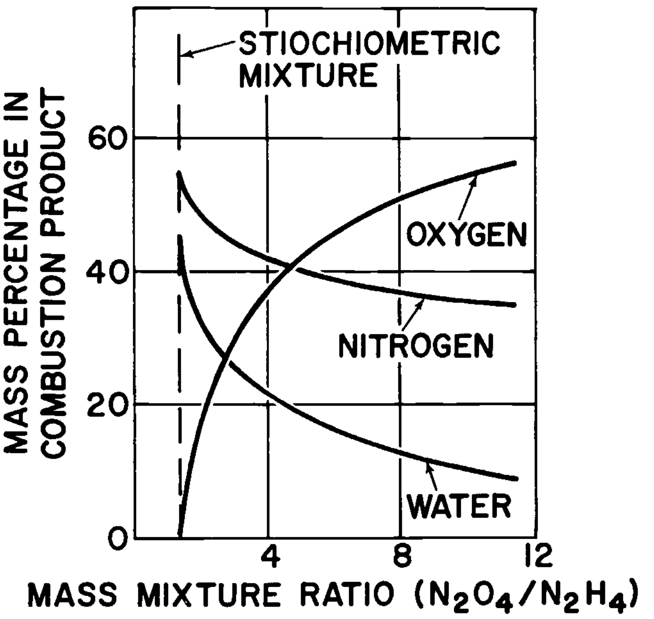

Fig. 3. Products of the nitrogen tetroxide/hydrazine reaction

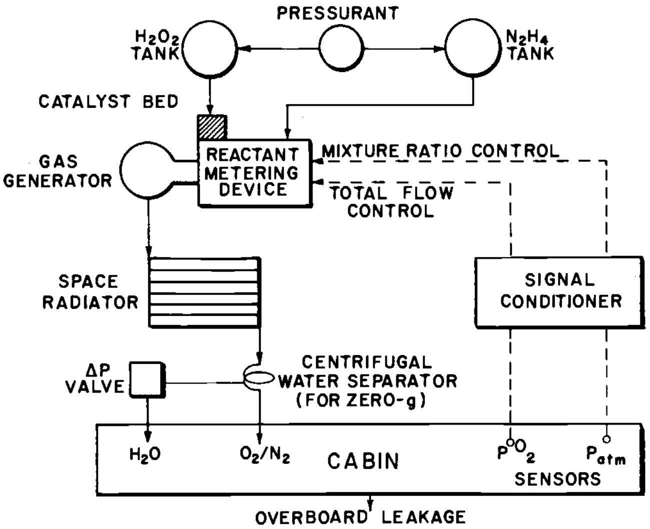

Fig. 4. Representative two-gas atmosphere replenishment system.

Figure 4 schematically depicts a representative Cornucopia system for the generation and control of a two-gas spacecraft cabin atmosphere. The method of CO_2 removal is not specified, since this concept offers no unique solution to that problem, but it is worth noting that the strongly exothermic process might advantageously furnish the heat for a thermally regenerative CO_2 absorption system. Operation in a weightless environment would be assured by positive expulsion tanks and by centrifugal separation of the condensed water, as shown. Although a simpler all-peroxide version might suffice in the unlikely situation of zero overboard losses, where only the metabolically consumed oxygen need be replaced, the more demanding requirement for two-gas atmosphere replenishment is probably unavoidable.

From an analysis of the peroxide/hydrazine and tetroxide/hydrazine reactions shown in Figures 2 and 3, it can be shown that for any combination of leak rate, metabolic oxygen consumption, and maintained oxygen percentage there exists a unique combination of mixture ratio and total reactant flow. Figure 5 illustrates the sensitivity of total reactant flow to cabin outflow (or leakage rate) for various maintained atmosphere compositions. The system of Figure 4 could maintain nearly any desired combination of oxygen partial pressure and total atmospheric pressure by appropriate modulation of the mixture ratio and total reactant flow. The two pressures could be monitored by presently available techniques to close the control loop after suitable conditioning of the sensed deviations from nominal. If flows greater than those required for gaseous atmosphere control might be demanded for other purposes, such as power generation, an overboard relief valve could limit overpressure while the percentage of oxygen would be maintained by mixture ratio control. A fallout benefit in such cases would be the reduced contaminant level assured by high bleed rates.

Contaminant Control by Purging:—The energy release which accompanies gaseous atmosphere control could be used to generate power for a variety of uses, and might in some cases supply all of the mission needs. Figure 5 shows the rates of raw thermal energy production from which such power would be derived. Where

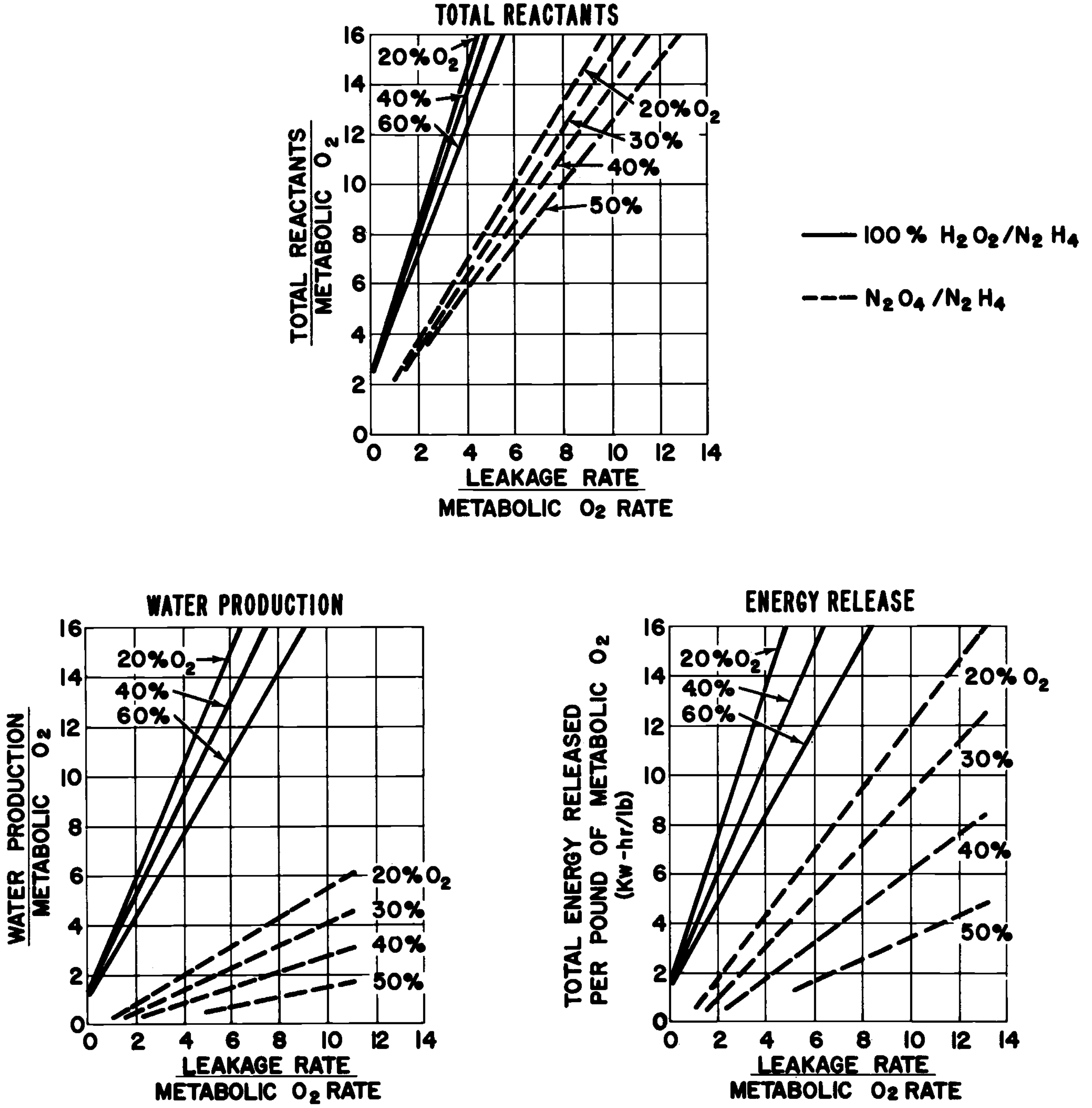

Fig. 5. Effects of relative leakage rate.

the need for power exceeds the available "free" supply (after conversion losses) any deficit could be made up by allowing power demand to govern the total throughput. As shown later such an approach is competitive on an overall systems basis even where the deficit is quite large. When the power requirement is relatively large compared to that which normally results from atmosphere production and control, the correspondingly large volume of gas production becomes available for purging the spacecraft atmosphere. Such a liberal purging schedule is perhaps the best means of assuring acceptable contaminant levels. This overboard leakage might also produce a continued low thrust for orbit maintenance or for periodic orbit adjustment. Other atmosphere control techniques impose too large a weight penalty to justify atmosphere control by such a purging technique. In the Cornucopia system this means of contaminant control can be an essentially free by-product of power production.

Available Water:—From Figures 2 and 3 it was clear that water can be made available in practically any needed percentage of the total reactant flow. Purely from the standpoint of water production, the peroxide/hydrazine system would be favored where it is not feasible or desirable to recycle a large percentage of the metabolic throughput. Where water replacement needs are relatively low the tetroxide/hydrazine system shows to advantage. Figure 5 illustrates the sensitivity of water production to the atmospheric leakage rate and to the maintained cabin oxygen concentration, when gaseous atmosphere control is the governing requirement. Certainly an over-abundance of water could be produced in some situations, particularly where the total reactant flow exceeds that required for gaseous atmosphere control. Such situations are analogous to that anticipated for the Apolla mission, where the considerable excess of water from fuel cell operation is made available for evaporative cooling or stored for later use.

Thermal Environment Control:—Since the metabolic heat production is at a relatively low temperature, the radiative rejection of this thermal energy from a spacecraft is often a difficult problem. The varying amounts of high grade thermal energy constantly released as a by-product of Cornucopia atmosphere production, may be exploited for thermal management. Since this surplus of thermal energy is hot enough for good control and amply large to span any fluctuations in metabolic heat generation, it presumably can be employed for cabin temperature control. A simple design philosophy could apply. The spacecraft might be appropriately configured with an α/ϵ such that the cabin would normally be too cool, even under conditions of maximum solar exposure and metabolic activity. The cabin would then be heated to the desired temperature by diverting more or less heat to it fram the Cornucopia combustion process, which energy would otherwise be rejected to space or used for other purposes.

Typical Impurities and Contaminant Control:—Any stored atmosphere source will deliver with the product gas some residua from a manufacturing process, deposition from the storage container, or deliberately introduced chemical inhibitors. In addition to these intrusions via the replenishing gas supply, other atmospheric impurities will arise from within the cabin itself, notably as outgassing of volatile substances at subnormal atmospheric pressures. In the presence of a high enough leak rate the equilibrium concentration of any contaminant can be held acceptably low, but in a tightly sealed cabin the continual build up of impurities might quickly reach physiologically intolerable or sensibly repugnant levels.

Although many of the usual trace contaminants can be removed or adequately controlled by chemical or mechanical means, exclusive reliance on this approach appears questionable. It is in any event obviously worthwhile to minimize the amount of undesirable contaminants which are introduced with the makeup atmosphere, plus those which are released from within the cabin. Control of the latter might be accomplished partly by appropriate materials selection and partly by the maintenance of as high an atmospheric pressure as is consistent with structural and leakage considerations. Some atmosphere outflow to space, whether as deliberate bleed or as unavoidable leakage, is certainly desirable and probably necessary for the reasons stated earlier. The extra weight required to replenish this outflow need not be considered purely as a penalty; it might well cost as much or more in added structural weight (round trip) to provide the savings in stored fluid (expended) which would result from tighter sealing.

Typical impurities in several atmosphere sources, including Cornucopia fluids[1] and liquefied gases,[2] are shown in Figure 6. As seen here there are no impurities that are dangerous or would be carried over into the combustion products providing the reaction is allowed to go to completion in the gas generator. The hydrocarbons would be converted to CO_2 and water, putting some extra load on the CO_2 removal facilities, therefore this source of contamination should be kept as low as possible in the Cornucopia fluids.

ANHYDROUS HYDRAZINE	PARTS PER MILLION
ANILINE & HYDROCARBONS ⟶	2000
CL	100
SO_4	50
Fe	10
90% HYDROGEN PEROXIDE	
CARBON	10
PO_4	0.2
SO_4	0.2
Cl	0.2
Al	0.1
NITROGEN TETROXIDE	
CL	70
ASH	5
LIQUID OXYGEN	
HYDROCARBONS	100
CO_2	20
N_2O	5
FREONS	0.5
LIQUID NITROGEN	
HYDROCARBONS	2
CO_2	0.5
CO	1
N_2O	0.1

Fig. 6. Typical impurities.

The Cornucopia combustion processes appear unlikely to introduce physiologically significant amounts of any other unwanted chemical species, even though such will exist briefly in the gas generator. Since the cooling process is relatively slow (compared to the extremely rapid expansion cooling in a rocket motor) a shifting equilibrium (as opposed to the partially frozen equilibrium typical of rockets) can confidently be postulated. Under such conditions the delivered concentration of all such species would be vanishingly small. Verification of this analytically established but extremely crucial point should be an early experimental goal. Equally important is the need to demonstrate complete reaction in the combustor, particularly to provide assurance against NO_2 carryover when nitrogen tetroxide is the oxidizer.

Applicable Missions:—The Cornucopia concept could be exploited to fullest advantage for missions which are of sufficient duration to require earth-storable propellants and a two-gas atmosphere, but which cannot justify fully regenerative life support or a nuclear power source. Its competitive position is enhanced with increased spacecraft propulsion requirements, up to some point where the benefits of consolidation might be offset by the higher specific impulse of more exotic propellants. Always favoring it would be large overboard losses of cabin atmosphere (whether by intent or inability to prevent) and a high ratio of crew size to electrical power demand. It would compare quite favorably in overall performance with the present Apollo design, which employs cryogenically stored oxygen and hydrogen for life support and power generation, and would presumably include a separate supply of cryogenic nitrogen for conversion to a two-gas system. The Cornucopia process could provide equivalent services (a two-gas atmosphere for 28 man days, and 17.5 kw-days of electrical power) plus a continuous purge nine times greater than the metabolic oxygen usage rate, with a net gain in overall spacecraft performance. Even though more fluids would be consumed, the substantial hardware economies would assure a sufficiently low end-of-mission weight to override that penalty. If further integration with spacecraft propulsion were to be considered, i.e., sharing a common propellant reserve, the benefits would be even more convincing.

Many of the considerations which apply to manned space probes apply also to space stations, but with some changes in emphasis. Although thrust production will generally be limited to station keeping and attitude control, propellants must be stored in sufficient quantity for the entire period between re-supplies. Atmospheric replenishment rates are likely to be deliberately higher than for shorter duration probes, to keep contaminant levels at a lower level. Also tending to increase overboard losses would be the high leakage associated with the sea level atmospheres which are being considered with increasing seriousness for orbiting laboratories. A particularly intriguing opportunity would also exist for integration with the shuttle vehicles, wherein the periodic re-supply fluids might consist largely of the unburned reserve propellants from each vehicle. Figure 7 is a summary tabulation of several alternate approaches to the problem of monthly re-supply for a 4-man space station. More extensive performance comparisons appear in another paper.[3]

		SOLAR POWER	FUEL CELL	CORNUCOPIA	
SERVICE				H_2O_2	N_2O_4
METABOLIC O_2 (LB)		240	240	240	240
FLUSHING GASES (LB)		240	240	240	1392
WATER (LB)		720	1440	936	720
AVERAGE POWER (KW)		2	2	2	2
TOTAL IMPULSE (LB-SEC.)		80,000	80,000	80,000	81,000
STORED FLUIDS (LB.)					
N_2H_4	STORABLE	---	---	281	638
MMH		❶ 85	❶ 85	---	---
N_2O_4		❶ 170	❶ 170	---	1714
90% H_2O_2		---	---	1342	---
H_2O		❷ 900	---	---	---
O_2	CRYOGENIC	❷ 366	1573	---	---
N_2		❷ 234	❷ 234	---	---
H_2		---	160	---	---
TOTAL FLUIDS		1755	2222	1623	2352
HARDWARE					
TANKAGE		196	570	95	140
ELEC. GENERATORS (2)		---	380	100	100
SOLAR ARRAY		300	---	❸ 240	❹ 200
BATTERIES		700	---	❸ 560	---
TOTAL HARDWARE		1196	950	995	440
TOTAL SUPPLIED WEIGHT					
INITIAL		2951	3172	2618	2792
RE-SUPPLIES		1951	3172	1718	2492

KEY

- ❶ FOR ORBIT MAINTENANCE
- ❷ INCLUDES 25 MARGIN
- ❸ 0.5 KW GENERATED CHEMICALLY
- ❹ 2 KW GENERATED CHEMICALLY DURING ECLIPSE

Fig. 7. Monthly supply comparison for 4-man space station with sea level atmosphere.

Lunar or planetary bases might profitably employ some version of the Cornucopia concept on an interim basis, before going "on stream" with permanent nuclear power stations or closed ecological systems. Even after such facilities are functioning, attractive applications might remain for surface conveyances.

Extravehicular life support and protective devices might also use this concept to advantage, particularly if some "flying belt" feature is required. For short solo operations, where the need for a two-gas atmosphere is not very compelling, an all-peroxide system might suffice for all functions including propulsion.

The cockpit capsules of very high performance and high altitude aircraft might use Cornucopia reactants for two-gas atmosphere replenishment, especially in view of the high leakage rates which can be expected from such enclosures. This approach appears competitive with cryogenic or stored gas systems from a weight standpoint, for mission duration of more than a few hours, and logistically seems much superior to the non-storable liquefied gas systems.

REFERENCES

1. Personal communications from representatives of Food Machinery Corp., E. I. duPont de Nemours & Co., Olin Mathieson Corp., and Nitrogen Division of Allied Chemical Corp.
2. "Statistical Analysis of LOX Constituents," NAS Alameda Overhaul and Repair Dept., April 1961.
3. Swet, C. J. : "A Preliminary Appraisal of the Cornnucopia Concept" presented at the First Annual Meeting of the American Institute of Aeronautics and Astronautics, Washington, D. C., 29 June—2 July, 1964, paper No. 64-213.