A Preliminary Appraisal of the Cornucopia Concept

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Initial feasibility studies suggest that the utility of certain storable rocket propellants can be extended to include life support and other essential services in the space environment, thereby improving the habitability and over-all performance of manned systems. Two liquid combinations are considered: hydrazine/hydrogen peroxide and hydrazine/nitrogen tetroxide. Both are good propellants, and their oxidizer-rich combustion in a gas generator theoretically yields potable water, a two-gas atmosphere of controllable composition, and energy for power generation and/or thermal management. The basic thermochemical relationships are presented from which performance in specific areas is derived. Problems of contamination, safety, and reliability are discussed, and possible applications to manned probes, space stations, extravehicular operations, planetary bases, biosatellites, and high-altitude aircraft are explored. The concept is applied in some detail to two hypothetical missions, and its over-all effectiveness is compared with that of more conventional approaches.

Introduction

Many of the manned space missions contemplated at present involve vehicle maneuvers that call for the variable impulse and multiple restart capabilities of liquid chemical rockets. Some of these missions will require earth-storable propellants and a two-gas cabin atmosphere, but cannot justify a fully regenerative life-support system or a nuclear power source. Such cases require a considerable quantity and variety of fluids, including propellants, potable water, atmospheric oxygen and nitrogen, any necessary coolants, and whatever reactants might be needed for electrical power generation. Since the separate storage of each fluid entails individual allowances for uncertainty or emergency, and multiple tanks incur penalties in hardware weight, volume, and complexity, any system that tends to consolidate fluid storage requirements could pay off handsomely in terms of system performance and habitability.

A small step in this direction was taken in the Mercury program, in which a single water tank supplied all fluid for drinking and for capsule cooling. For the Apollo mission, further consolidation is planned, in that two cryogenic fluids will provide all of the water, power, and metabolic oxygen. This still represents a fairly modest economy, however, considering the total amount of onboard fluid. To obtain a dramatic payoff, it appears necessary to exploit the potentials of the storable propellants, which commonly comprise a sizeable fraction of the total system weight.

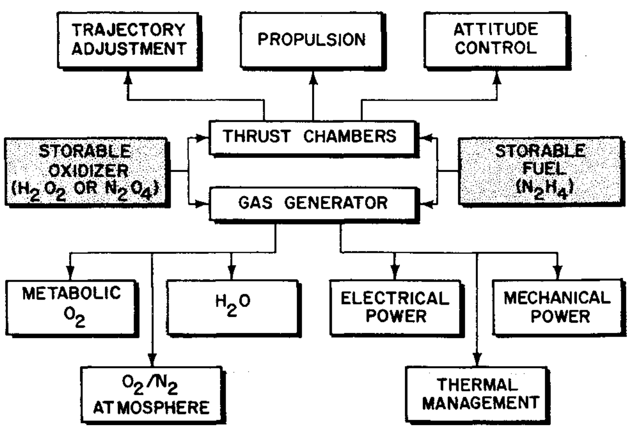

Fig. 1 Representative block diagram.

A promising approach involves the use of the N_2H_4/H_2O_2 system, or, in certain applications, N_2H_4/N_2O_4 system. The use of these liquids for space propulsion and attitude control is well documented, but more exciting is the abundance of potentially useful products from their oxidizer-rich combustion in a gas generator. Always present are large quantities of potable water, plus gaseous oxygen and nitrogen in virtually any desired proportion, depending on the selected mixture ratio. The released energy is available for electrical power generation, thermal management, or mechanical functions. Figure 1 illustrates the foregoing in a representative block diagram reminiscent of the horn of plenty, from which the Cornucopia concept derives its name.

Thermochemical Relationships

Figures 2–4 illustrate the basic thermochemical relationships, from which estimates of performance in specific areas may be derived. The left-hand plot of Fig. 2 presents the theoretical yields of water, oxygen, and nitrogen from the hydrogen peroxide/hydrazine reaction at various mixture ratios, as computed from the expression

$$nH_2O_2 + N_2H_4 \rightarrow (n + 2)H_2O + N_2 + [(n - 2)/2]O_2 \quad (1)$$

where n is the molar ratio of oxidizer to fuel. It presupposes a reaction that goes to completion in the combustor of a gas generator, with subsequent cooling to room temperature at shifting equilibrium. The right-hand plot similarly depicts

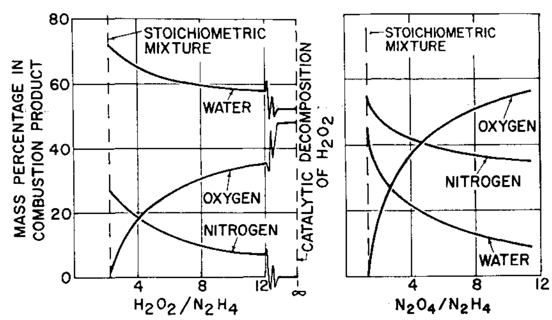

Fig. 2 Reaction product concentrations vs mixture ratio (weight) for the two systems.

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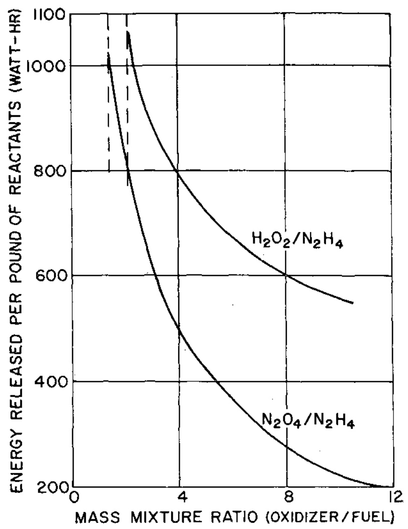

Fig. 3 Energy release.

the end products of the nitrogen tetroxide/hydrazine reaction from

$$nN_2O_4 + N_2H_4 \rightarrow 2H_2O + (n + 1)N_2 + (2n - 1)O_2 \quad (2)$$

The energy release and combustion temperatures for these two chemical systems are compared in Figs. 3 and 4, respectively, as machine-computed using the program of Ref. 1. All of the data presented in Figs. 2–4 are also based on the convenient assumption of anhydrous reactants, although the hydrogen peroxide would, in fact, be a concentrated water solution, and the hydrazine might profitably be slightly hydrated. That assumption appears valid for this discussion, since the essential chemistry is presumably unaffected, and the performance figures can readily be adjusted by appropriate "wetness factors." It is conservative from the standpoint of engineering design, in that reaction temperatures would actually be somewhat lower than those indicated in Fig. 4. For the N_2O_4/N_2H_4 reaction, a further temperature reduction (not evident from the computations) might be encountered because of the persistence of undecomposed oxides of nitrogen.[2]

Atmosphere Replenishment

Figure 2 shows that the H_2O_2/N_2H_4 system can yield gaseous oxygen and gaseous nitrogen in any desired proportion, as governed by the selected mixture ratio. With a slight excess of H_2O_2, the cooled and dehumidified product gas has the approximate composition of a sea-level atmosphere, whereas, at an infinite mixture ratio (no hydrazine), the catalytic decomposition of hydrogen peroxide produces only water and oxygen. It is clear that such a process could maintain any specified cabin atmosphere composition under widely varying conditions of metabolic oxygen usage and overboard losses. From Eq. (1) we can write this balance as

$$N_2 + [(n - 2)/2]O_2 = (1 + p)N_2 + O_{2M} \quad (3)$$

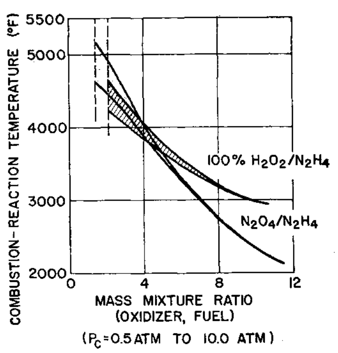

Fig. 4 Reaction temperatures.

where O_{2M} is the metabolically consumed oxygen, p is the maintained molar ratio of oxygen to nitrogen in the cabin atmosphere, and $(1 + p)N_2$ represents outflow from the cabin.

As is also shown in Fig. 2, the N_2O_4/N_2H_4 reaction produces a higher nitrogen yield and less water, with a finite practical upper limit to the oxygen/nitrogen ratio. It therefore requires some outflow of cabin atmosphere to enable oxygen production. The atmosphere replenishment balance for this reaction can be written from Eq. (2) as

$$(n + 1)N_2 + (2n - 1)O_2 = (1 + p)N_2 + O_{2M} \quad (4)$$

Figure 5 depicts schematically a representative system for the generation and control of a two-gas spacecraft cabin atmosphere. The indicated reactants could also provide any or all of the other services indicated in Fig. 1, but side processes other than water production are omitted for the sake of clarity. The method of CO_2 removal is not described, since the Cornucopia concept offers no unique solution to that problem. It is worth noting, however, that the strongly exothermic process might economically provide heat for a thermally regenerative CO_2 absorption system, and that any associated flushing would tend to reduce the requirement for CO_2 removal. Operation in a weightless environment would be assured by positive expulsion tanks and by centrifugal separation of the condensed water, as shown. Any desired combination of oxygen partial pressure and total atmospheric pressure would be automatically maintained by appropriate modulation of the mixture ratio and total reactant flow. If higher reactant flows were required for reasons other than atmosphere replenishment, an overboard relief valve could limit overpressure, whereas the oxygen partial pressure would be maintained by mixture ratio control. The total reactant consumption would depend strongly on the ratio of cabin atmosphere outflow (or leakage) to metabolic oxygen consumption as shown in the upper plots of Fig. 6. Engineering estimates of this ratio range generally from 0.5 to 2.5 for unavoidable leakage, with additional allowances for purge, airlock operation, and emergency pressurization.[3–7] Since each crew member would consume about 2 lb of metabolic oxygen in 24 hr, the ordinate values also represent roughly one half of the total reactants burned per man-day.

Water Production

The atmosphere replenishment process would produce byproduct water as shown in the left-hand plots of Fig. 6. An estimated requirement of 6 lb/man-day[8] (human consumption plus personal hygiene) corresponds to a value of 3 on the ordinate scale. Purely from the standpoint of water production, the peroxide system would be favored in situations

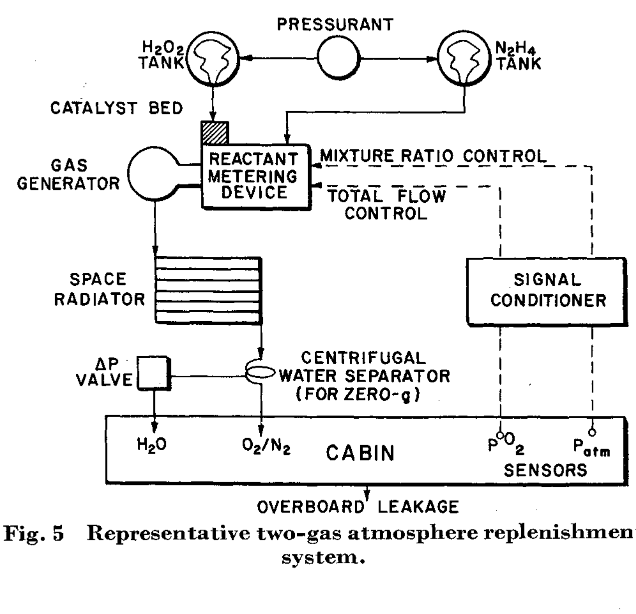

Fig. 5 Representative two-gas atmosphere replenishment system.

where it is not feasible or desirable to reprocess a large percentage of the waste water. Certainly an overabundance of water would be produced in some situations, particularly when the reactant flow exceeds that required solely for atmosphere make-up. Such situations are comparable to that anticipated for the Apollo spacecraft, where the fuel cell will generate substantially more water than is required for life support, and the excess water will be made available for evaporative cooling or stored for later use.

Thermal Management

A useful amount of high-grade thermal energy is released by the atmosphere replenishment process, as shown in the right-hand plots of Fig. 6. In most cases, the heat released would far exceed the astronauts' metabolic production of roughly 100 w/man. Figure 4 shows that the reaction temperatures would always be high enough for efficient radiative heat rejection to space and for good heat transfer to other fluids. This surplus of thermal energy offers some attractive opportunities for cabin temperature control. A simple design philosophy could apply, wherein the spacecraft would be coated and configured to keep its interior too cold, even under conditions of maximum solar exposure, metabolic rate, and electronic heat dissipation. The cabin would then be heated to the desired temperature by diverting more or less heat to it from the Cornucopia reaction, which energy would otherwise be rejected to space or used for other purposes. Figure 7 is a simplified schematic diagram illustrating one of the many possible methods of implementing such a thermal management concept.

Power Generation

The energy release that accompanies atmosphere production could also be converted to electrical or mechanical power and might, in some applications, provide all of the mission needs. If the need for power exceeds this "by-product" supply (after conversion losses), any deficit could be made up by allowing power demand to govern the total throughput. It will be shown later that such an approach could be competitive on an over-all systems basis even where the deficit is large.

Peltier cooling could provide reliable and inexpensive supplementary power, even though thermoelectric conversion

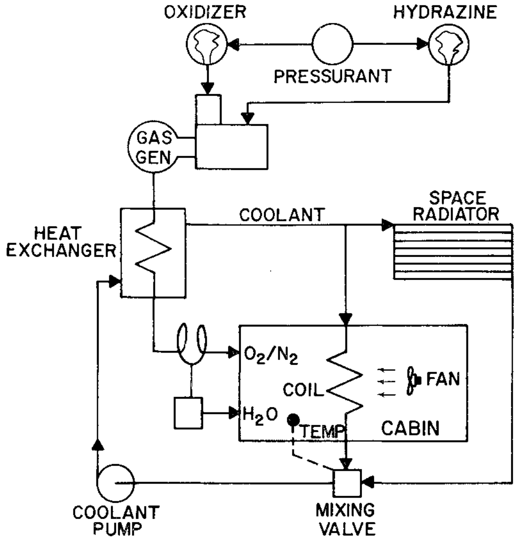

Fig. 7 Representative thermal management system.

efficiencies of only a few percent can be expected, whereas various mechanical functions might directly utilize the available kinetic energy. More ambitious exploitations are worth investigating whenever the product gas flow is high enough for the efficient use of piston engines or turbogenerators. This would apply more generally than is immediately apparent from examination of Fig. 6, since the gases must first be cooled to an acceptably low inlet temperature. The cooling would in large part be provided by recycling a portion of the condensed water, thus increasing the effective mass flow (and engine efficiency) at no cost in energy but at some additional expense in radiator size and weight. Figure 8 illustrates such a process, for which over-all conversion efficiences of 40% appear possible[8] with present technology. The interrelationships between power and other performance parameters are presented for selected cases in Fig. 9.

Thrust Production

Concentrated H_2O_2 and N_2O_4 are among the better earth-storable oxidizers that can be classed as "man rated," and their use with hydrazine is well documented.[9] Although some question remains concerning the maximum safe concentration of H_2O_2 in certain applications, it is still an attractively energetic oxidizer even at the 90% strength used for attitude control of the Mercury capsules. Reservations might also remain concerning the unqualified use of anhydrous hydrazine, despite its successful use on the Venus probe, but there seems to be no doubt concerning its suitability as a rocket fuel, provided that it is not used as a regenerative coolant. If

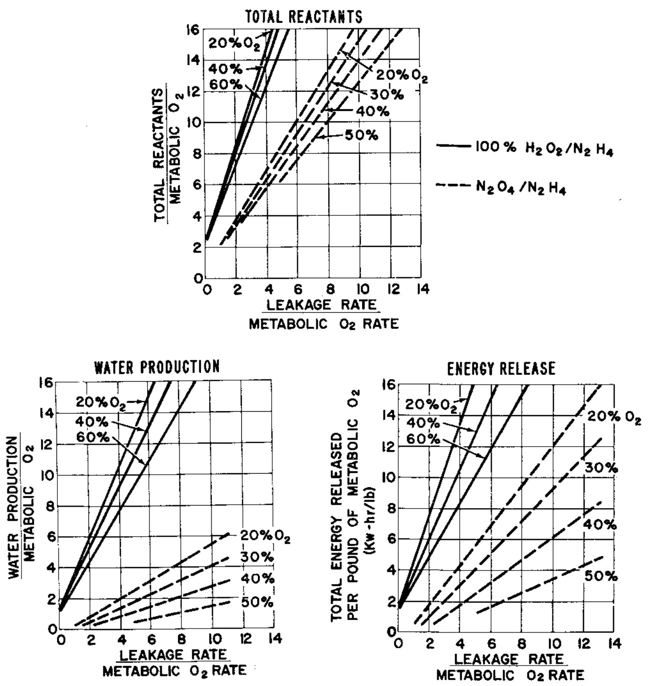

Fig. 6 Effects of relative leakage rate.

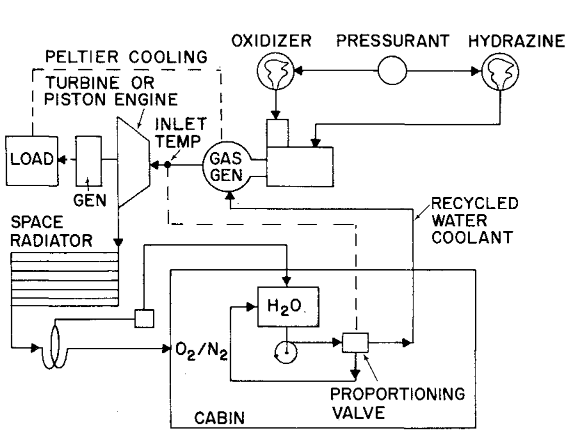

Fig. 8 Representative power generation system.

Table 1 Comparison of typical impurities in Cornucopia reactants vs cryogenic liquids

Reactant	Impurity	Concentration, ppm
Anhydrous N_2H_4	Aniline and hydrocarbons	2000
	Cl	100
	SO_4	50
	Fe	10
90% H_2O_2	C	10
	PO_4	0.2
	SO_4	0.2
	Cl	0.2
	Al	0.1
N_2O_4	Cl	70
	Ash	5
LOX	Hydrocarbons	100
	CO_2	20
	N_2O	5
	Freons	0.5
LN_2	Hydrocarbons	2
	CO_2	0.5
	CO	1
	N_2O	0.1

found necessary, a slight hydration could improve stability with little attendant penalty in propulsive performance. Realistic performance comparisons with other storable propellant combinations, from the standpoints of specific impulse and density, must await positive determination of the required dilutions and some empirical data from rocket firings.

A more readily established performance advantage is associated with tankage weight. Since the tankage for storable propellants can be designed for noncryogenic temperatures, modest pressures, and no vent losses, the hardware weight of such storage systems is a very small percentage of the stored fluid weight. This is contrasted with the much heavier, supercritical cryogenic storage systems. Coupled with the evident savings in hardware weight would be less apparent but equally compelling reductions in the over-all space envelope and in the overstorage associated with variously accumulated individual margins for uncertainty and emergency reserve. Perhaps most significant of all are the enhanced performance and increased flexibility associated with the postburnout utilization of unburned propellant reserves

Contamination

Any stored atmosphere source will contain some impurities inherited from its manufacture or introduced by the onboard system. Table 1 compares the typical purities of commercially available Cornucopia reactants with cryogenic sources being used at present. In evaluating this comparison it is important to remember that the hydrocarbons in stored oxygen carry over directly to the cabin atmosphere, whereas those in the Cornucopia reactants are burned first and enter the cabin as CO_2 and water.

If the Cornucopia reaction goes to completion in the gas generator, none of the transient species listed in Table 2 is likely to persist in significant concentration through the relatively slow (compared to a rocket motor) cooling and expansion process. In the case of the N_2O_4/N_2H_4 system, it is not known whether the N_2O_4 decomposition would follow equilibrium predictions, because the NO bond is strong, and the reaction rates are slow. This could still be a problem,[2] even if the combustor were designed to provide good mixing and long dwell time. In the case of the H_2O_2/N_2H_4 system, excessive oxides of nitrogen would not be expected to be a problem.

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 these 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 outgassing problem by maintaining as high an atmospheric pressure as is consistent with structural and leakage considerations, and to assure some atmosphere outflow to space. The extra weight required to replenish this outflow would not necessarily be a penalty; it might 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.

Safety and Reliability

The handling and storage of nitrogen tetroxide, anhydrous hydrazine, and hydrogen peroxide in concentrations up to 98% is already state of the art. Hazard to the astronauts from explosion or toxic leakage could presumably be held within currently acceptable limits largely by adherence to existing safety criteria, since the problems appear comparable to those which are faced at present. Some unique problems of carry-over prevention are anticipated, but all of them appear

Table 2 Transient species in combustor

Oxidizer/fuel mixture ratio, Molar	Oxidizer/fuel mixture ratio, By weight	Combustor pressure, atm	H	O	OH	NH	NO	NO_2	H_2
			Concentration in combustor, ppm by weight						
Hydrogen peroxide/hydrazine									
2	2.12	0.5	752	4,250	32,050	15	7,170	0	6778
		10.0	302	1,775	23,700	15	7,680	0	4692
4	4.25	0.5	86	2,650	21,300	0	7,910	0	862
		10.0	17	928	13,400	0	9,200	46	302
8	8.50	0.5	3	320	5,200	0	3,330	0	58
		10.0	0	80	2,670	0	3,510	46	14
Nitrogen tetroxide/hydrazine									
0.5	1.44	0.5	1743	10,440	41,900	45	14,280	0	8126
		10.0	379	5,400	35,800	90	17,000	0	65
1.0	2.88	0.5	252	9,400	30,550	0	22,530	0	984
		10.0	68	4,060	22,450	0	28,450	92	440
3.0	8.60	0.5	0	16	425	0	3,210	0	0
		10.0	0	0	204	0	3,240	92	0

amenable to straightforward engineering and in-hand techniques. Since most system elements would be small and light, any needed redundancy could be inexpensively provided.

Potential Applications

Table 3 summarizes a comparison of four technical approaches to the problem of maintaining four men in a near-earth space station for one month. In each case a maintained sea-level atmosphere is lost overboard at an average rate at least equal to the metabolic oxygen consumption of 2 lb/man-day, and the water requirements (no recycling) are three times that rate. The total impulse requirement represents a minimal propulsive capability for orbit maintenance, which is provided by a small liquid bipropellant rocket in the first three cases, and the directed bleed of excess atmosphere production in the last case.

The average power of 2 kw is provided in the first case solely by a solar cell/battery combination and in the second case by an O_2/H_2 fuel cell at a total reactant rate of 1.0 lb/kw-hr. In the Cornucopia process employing 90% H_2O_2, one-quarter of the power is continuously generated by a gas expansion engine at an over-all energy conversion efficiency of 40%, and the total reactant rate is only that needed for atmosphere replenishment. The final case is based on all-solar power during the sunlit phase of each orbit, when the Cornucopia process with N_2O_4 provides only for life support. During periods of eclipse, the Cornucopia reaction produces the entire 2 kw, while generating all of the required orbit maintenance thrust and flushing the cabin atmosphere at nearly six times the presumed minimum rate. Where life-support fluids must be stored separately, as in the first case, a 25% margin is provided.

The results of this rather cursory comparison for a space station are by no means conclusive, but they clearly indicate that some form of the Cornucopia process might, in such applications, be competitive with more conventional techniques. The comparison appears even more favorable in view of the intriguing opportunities that might exist for integration with the shuttle vehicles, wherein the periodic resupply fluids might consist in part of unburned reserve propellants from each vehicle.

Table 3 Monthly supply comparison for 4-man space station with sea-level atmosphere

Service or item	Solar power	Fuel cell	Cornucopia H_2O_2	Cornucopia N_2O_4
Service				
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
Storable fluids, lb				
N_2H_4	...	...	281	638
MMH	85[a]	85[a]	...	...
N_2O_4	170[a]	170[a]	...	1714
90% H_2O_2	...	...	1342	...
H_2O	900[b]	...	...	...
Cryogenic fluids, lb				
O_2	366[b]	1573	...	...
N_2	234[b]	234[b]	...	...
H_2	...	160	...	...
Total fluids, lb	1755	2222	1623	2352
Hardware, lb				
Tankage	196	570	95	140
Elec. generators (2)	...	380	100	100
Solar array	300	...	240[c]	200[d]
Batteries	700	...	560[c]	...
Total hardware	1196	950	995	440
Total supplied weight, lb				
Initial	2951	3172	2618	2792
Monthly resupply	1951	3172	1718	2492

[a] For orbit maintenance.
[b] Includes 25% margin.
[c] 0.5 kw generated chemically.
[d] 2 kw generated chemically during eclipse.

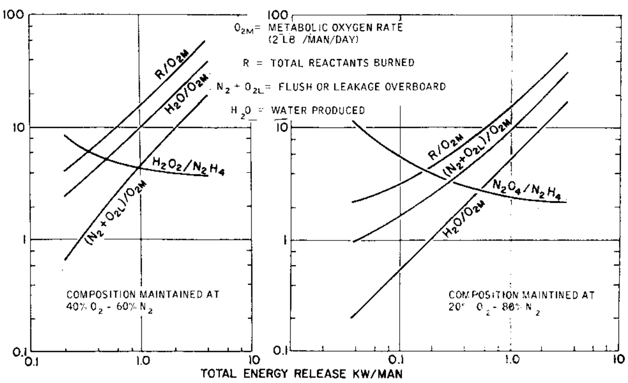

Fig. 9 Parametric tradeoffs.

A hypothetical lunar mission is grossly outlined in Fig. 10, indicating the principal changes in mass and velocity, the effects of small weight changes on propulsive performance, and the amount of unburned propellant reserve that would be accumulated under normal conditions. Figure 11 presents a more detailed mission profile for the life-support and power-supply functions, indicating a net performance advantage for the Cornucopia process over that of an all-cryogenic system despite a higher initial weight and without capitalizing on the likely availability of unburned propellant reserves. It will be noted that the weight of unburned propellants would normally be nearly three times the reactant consumption for life support plus electrical power generation and represents an unused emergency reserve rather than an expected spread about nominal.

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 systems could also use this concept to advantage, particularly if some "flying belt" feature is required; for short solo operations with 100% oxygen, an all-peroxide system might suffice for all of the functions including propulsion. It could also be used for atmosphere replenishment in the cockpits of high-performance aircraft, especially in view of the high leakage rates that can be expected from such enclosures; this approach appears competitive with cryogenic or stored gas systems for mission durations of more than a few hours, and it is logistically superior to any liquefied gas system. Finally, biosatellites

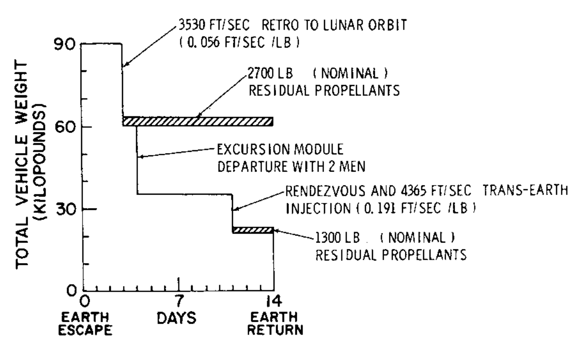

Fig. 10 Vehicle weight and velocity profile for lunar mission.

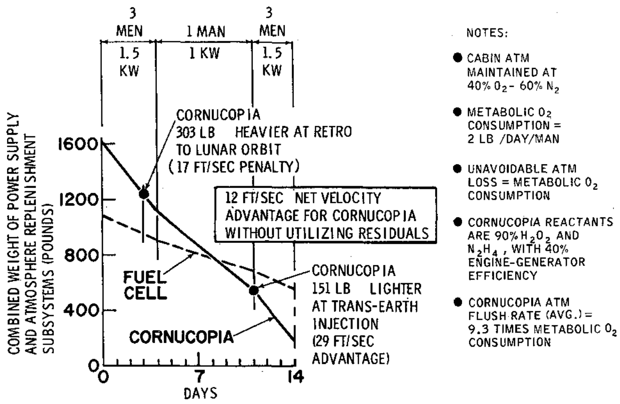

Fig. 11 Subsystem weight profile for lunar mission.

would benefit particularly from the ability to generate economically a high atmosphere flushing rate, and by the opportunities for integration with a deorbit rocket propulsion system.

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