

# Cornucopia<sup>in</sup> SPACE

*Every space mission involves a vehicle into which is now built a storage capability for the several kinds of fluids needed to support the mission, the vehicle, and its inhabitants. The multiple tankage required is obviously costly in terms of weight, space, and reliability. To greatly enhance the usefulness and success of future missions, a very substantial consolidation of fluid requirements must be achieved.*

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Most space missions that are now being planned, and during which human life must be reliably supported, also involve some impulsive maneuvers by the inhabited space system. These maneuvers, whether for purposes of prime propulsion, attitude control, or trajectory alteration, call for the variable-impulse and multiple-restart capabilities of liquid chemical rockets. Missions will often be of sufficient duration to call for earth-storable propellants and a two-gas cabin atmosphere, but cannot justify a fully regenerative life-support system or a nuclear power source. In such cases the space vehicle must carry a considerable quantity and variety of vital fluids, including the liquid bi-propellants, potable water, atmospheric oxygen and nitrogen, any necessary coolants, and any reactants needed for electrical power generation.

This situation tends to create a formidable over-storage problem since the supply of each separately stored fluid must include some predetermined margin as an emergency reserve. Also, the inherent inefficiencies of multiple tankage will always impose 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 direction was taken in the Mercury program, where a single water tank supplied all fluid for both drinking and capsule

cooling. For the proposed Apollo mission a somewhat more ambitious consolidation of fluid storage is planned, with two cryogenic fluids providing all water, power, and metabolic oxygen. This still represents a fairly modest economy of weight and complexity, considering the total amount of on-board fluid. To obtain a dramatic payoff, we must somehow exploit the presently untapped potentials of the storage propellants that commonly are a large fraction of the total system weight.

*Cornucopia* is the name given to a unique concept developed at APL by the author for extending the utility of storable, rocket bi-propellants to in-

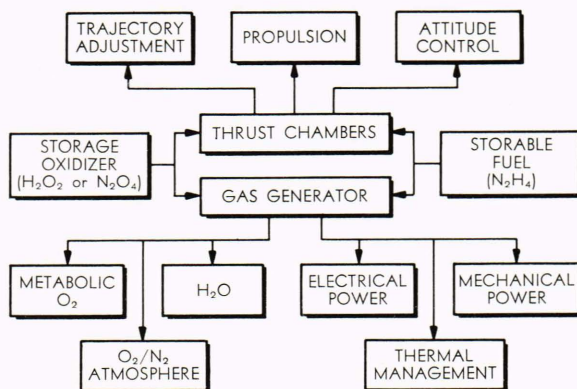
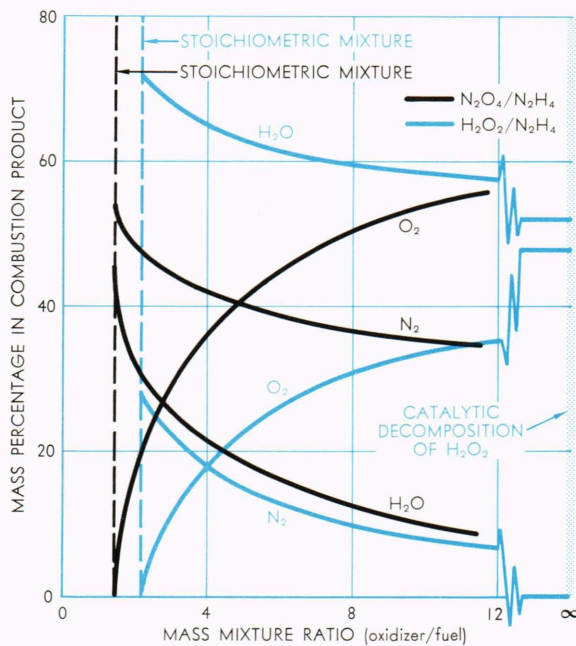


Fig. 1.—Functional block diagram of the Cornucopia concept.



**Fig. 2.—Products of the nitrogen tetroxide/hydrazine and hydrogen peroxide/hydrazine reactions.**

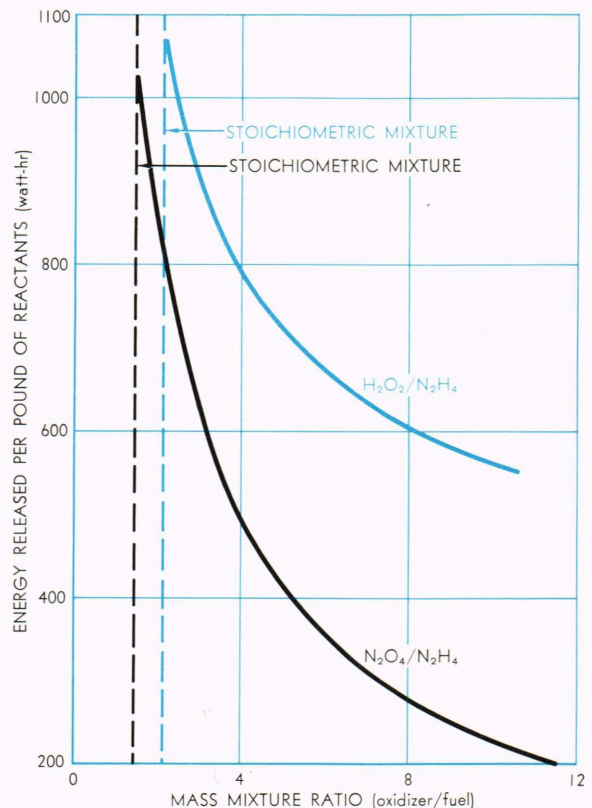
clude life support and other essential services in the space environment. The fundamental concept may be embodied in either the hydrogen-peroxide/hydrazine system ( $\text{H}_2\text{O}_2 + \text{N}_2\text{H}_4$ ), or the nitrogen-tetroxide/hydrazine system ( $\text{N}_2\text{O}_4 + \text{N}_2\text{H}_4$ ). Both are composed of well-known earth-storable liquid reactants that 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 both yield the same products of combustion, i.e.,  $\text{H}_2\text{O} + \text{N}_2 + \text{O}_2 + \text{heat} + \text{kinetic energy}$ , when burned with an excess of oxidizer in a gas generator. The thrust obtained from these reactants may be used for propulsion, trajectory alteration, or attitude control, while the potential 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 mechanical functions. Figure 1 illustrates the above as it might apply to a manned space vehicle. This profusion of potentially useful products represents the horn of plenty—the Cornucopia concept.

## Performance

Figures 2 through 4 illustrate the basic thermochemical relationships from which estimates of performance in specific areas may be derived. Figure 2 presents the proportional yields of water,

free oxygen, and free nitrogen from the hydrogen-peroxide/hydrazine and nitrogen-tetroxide/hydrazine reactions at various mixture ratios. Figure 3 compares the total energy release for these two chemical systems, and Fig. 4 plots their computed reaction temperatures. All data are 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. This assumption is sufficiently valid for the present purposes since the essential chemistry is unaffected and the performance figures can readily be adjusted by an appropriate “wetness” factor.

**GASEOUS ATMOSPHERE CONTROL**—The peroxide/hydrazine system can yield gaseous oxygen and gaseous nitrogen in any desired proportion, depending on the selected mixture ratio, as seen in Fig. 2. 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 2 also shows similar yields from the tetroxide/hydrazine system,



**Fig. 3.—Total energy production of nitrogen tetroxide/hydrazine and hydrogen peroxide/hydrazine reactions.**



but with less water production (not necessarily a disadvantage) and with a finite practical upper limit to the oxygen/nitrogen ratio.

Figure 5 depicts schematically a representative Cornucopia system for the generation and control of a two-gas spacecraft-cabin atmosphere. The method of  $\text{CO}_2$  removal is not specified because this concept offers no unique solution to that problem. It is worth noting, however, that the strongly exothermic process might furnish the heat advantageously for a thermally regenerative  $\text{CO}_2$  absorption system. Operation in a weightless environment would be assured by the 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 would need replacing, the more demanding need for two-gas atmosphere replenishment can seldom be avoided.

The atmosphere-replenishment potential of the peroxide/hydrazine and tetroxide/hydrazine systems are seen in Figs. 6 and 7, respectively. We see 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. All of the curves are normalized for a unit rate of metabolic oxygen consumption. It is evident from these curves and from Fig. 8 that the system in Fig. 5 could main-

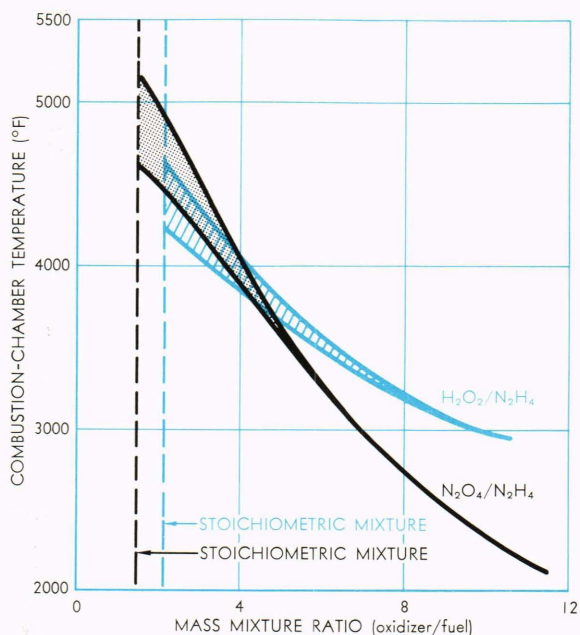


Fig. 4.—Reaction temperatures of nitrogen tetroxide/hydrazine and hydrogen peroxide/hydrazine reactions for all chamber pressures from 0.5 to 10.0 atm.

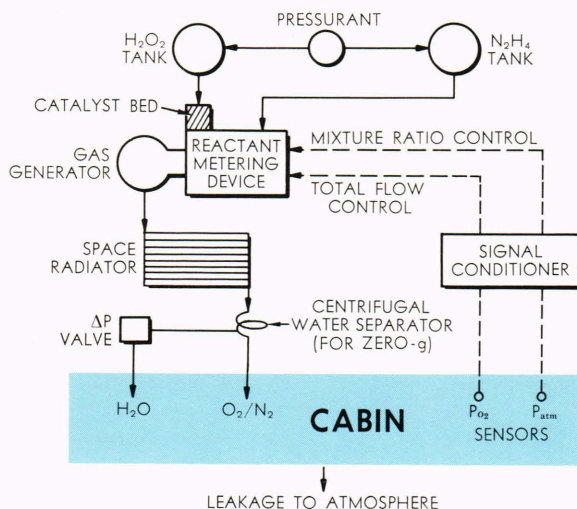


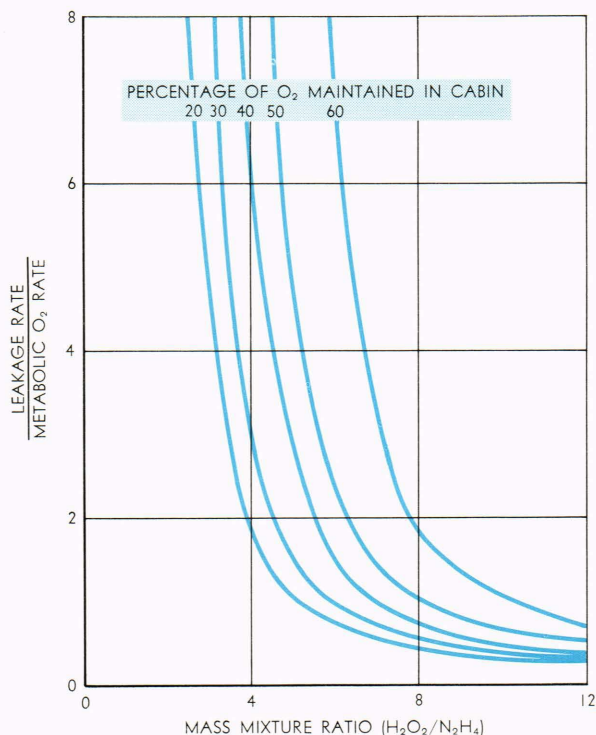
Fig. 5.—Representative two-gas atmosphere control system for the Cornucopia concept.

tain nearly any desired combination of oxygen partial pressure and total atmospheric pressure. This would be done by appropriate modulation of the mixture ratio and total reactant flow. The two pressures could be monitored by known techniques to close the control loop after suitable conditioning of the sensed deviations from nominal. If flows greater than those needed for gaseous atmosphere control were demanded, an overboard relief valve could limit overpressure while the percentage of oxygen would be maintained by mixture ratio control; a reduced contaminant level would then be assured by high bleed rates.

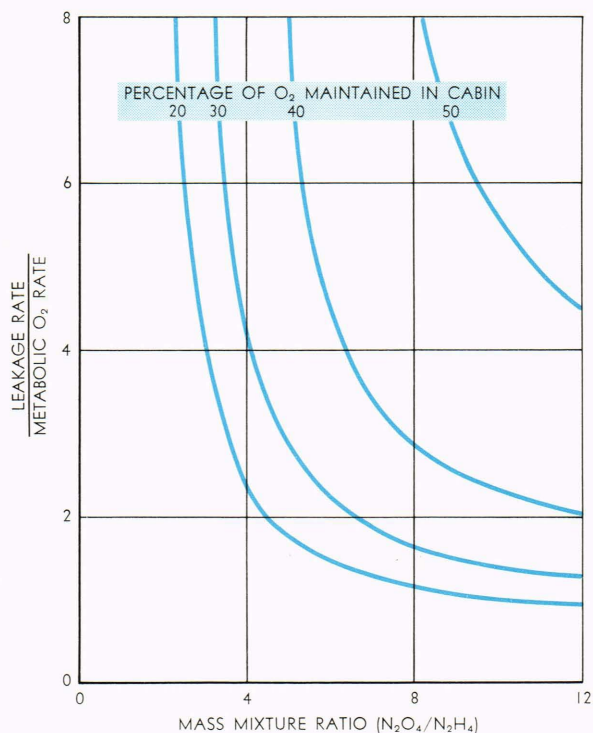
**WATER PRODUCTION**—It is clear from Fig. 2 that water can be made available in practically any needed percentage of the total reactant flow. Purely from the standpoint of water production, the peroxide/hydrazine system would be favored where it is not feasible or desirable to recycle a large percentage of the metabolic output. Where water-replacement needs might be relatively low, the tetroxide/hydrazine system would be advantageous. Figures 8A and B illustrate the sensitivity of water production to the atmospheric leakage rate and to the maintained oxygen concentration, when gaseous atmosphere control is the governing requirement. Certainly an overabundance of water would be produced in some situations, particularly where the total reactant flow exceeded that required for gaseous atmosphere control. Such situations are analogous to that anticipated for the Apollo mission; in this case the considerable excess of water from fuel-cell operation is made available for evaporative cooling or is stored for later use.

**THERMAL-ENVIRONMENT CONTROL**—Varying amounts of high-grade thermal energy are con-





**Fig. 6.—Maintenance of cabin atmosphere composition by the hydrogen peroxide/hydrazine reaction.**



**Fig. 7.—Maintenance of cabin atmosphere composition by the nitrogen tetroxide/hydrazine reaction.**

stantly released as a by-product of Cornucopia atmosphere production. Figure 3 shows for both chemical systems the effects of mixture ratio on the heat released per unit rate of total reactant flow. Figure 8C was derived from these curves and the data of Figs. 5 and 6 to show more directly the relationship between gaseous atmosphere control and thermal-energy production. It is evident that the heat generated by the atmosphere-control process for one astronaut will in nearly any situation be substantially greater than his metabolic rate. Reference to Fig. 4 shows that Cornucopia reaction temperatures are always high enough for efficient radiative heat rejection to space and for good heat transfer to other fluids. At the same time they are low enough over the more likely ranges of mixture ratio and combustor pressures to permit the general use of conventional materials and cooling methods.

Since this surplus of thermal energy is big enough for good control and can span any fluctuations in metabolic heat generation, it presumably can be employed for cabin-temperature control. A simple design philosophy could be applied. The spacecraft might be configured appropriately with such a ratio of solar absorptivity to emissivity that the cabin normally would be too cool, even under conditions of maximum solar exposure and metabolic activity. The cabin could then be heated to the desired temperature by diverting more or less heat to it from the Cornucopia combustion process, which energy would otherwise be rejected to space or used for other purposes.

**POWER GENERATION**—The energy release that accompanies gaseous atmosphere control could be used to generate power for a variety of uses, and might in some cases supply the total needs of a mission. Figure 8C shows the rates of raw thermal-energy production from which such power would be derived. Where the need for power exceeds the available "free" supply (after conversion losses), any deficit can presumably be removed if power demand is allowed to govern the total fluid usage.

Whatever the primary electrical power supply may be, it might prove worthwhile to employ some Peltier-effect cooling in the Cornucopia process. Although thermoelectric conversion efficiencies of only a few percent can be expected, this would provide a reliable and inexpensive supplementary or standby power source. Also available in any event would be kinetic energy for mechanical power. Such continuous functions as air circulation and coolant flow might be powered profitably by simple turbines or venturi-type devices. This would reduce electric-power requirements.

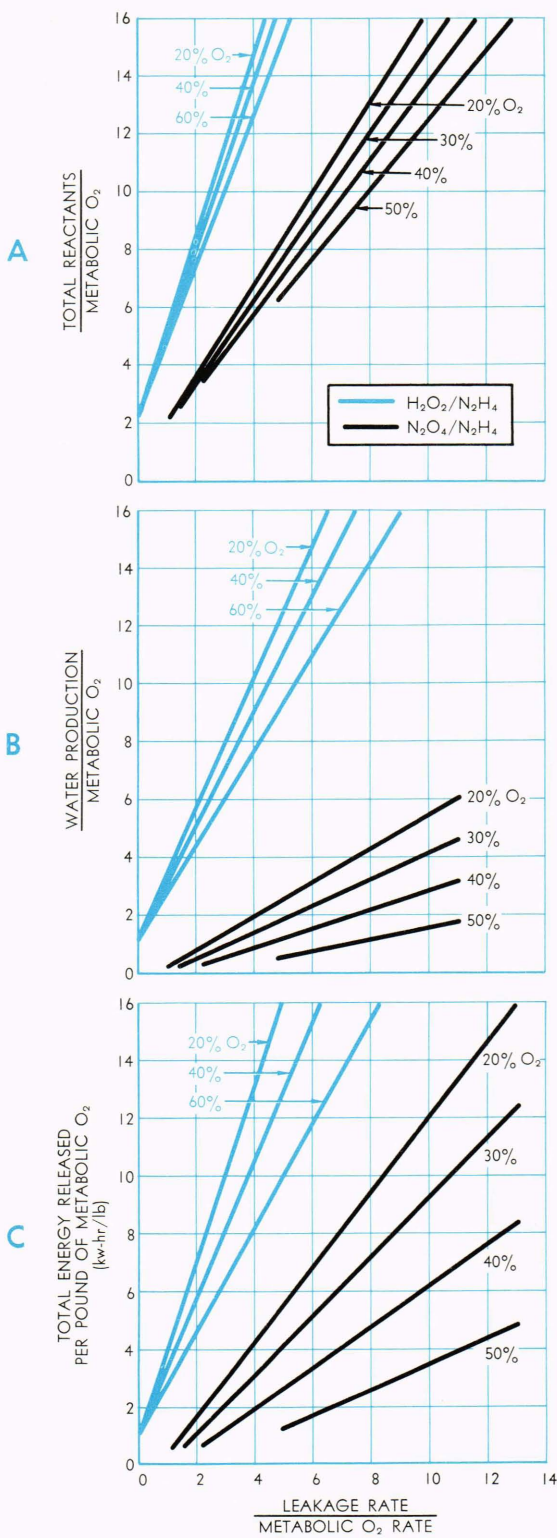
Much more ambitious exploitations are worth

investigating whenever the gas flow can be made suitably high for good turbine efficiencies. Such would be the case less frequently than is immediately apparent from Fig. 8A thanks to turbine-inlet-temperature limitations. The product gas will always require substantial cooling to an acceptably low blade-inlet temperature, as can be seen from Fig. 4. This cooling presumably can be accomplished by recycling a portion of the condensed water. Thus, the increased flow and lowered temperature could be obtained at no cost in energy, but at some added cost in radiator size and weight.

Also plausible is the use of a peroxide/hydrazine or tetroxide/hydrazine fuel cell instead of the gas generator plus rotating machinery. The problems of integrating such a device with gaseous atmosphere control appear rather forbidding, however.

**THRUST PRODUCTION** — Concentrated hydrogen peroxide and nitrogen tetroxide are the two highest-performance earth-storable oxidizers that can be classed as “man rated,” that is, acceptable for use in manned missions. Their adequacy in bi-propellant combination with hydrazine is well documented. Although there is some question of the maximum safe concentration of hydrogen peroxide in certain applications, it is still an attractively energetic oxidizer at the 90% strength currently used in the Mercury capsules; there might also be some question concerning the unqualified use of anhydrous hydrazine, despite its successful use on the Venus probe. However, there seems to be no doubt concerning its suitability as a rocket fuel as long as it is not used as a regenerative coolant. In any event a slight hydration would provide an effective safeguard with little loss 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 small-rocket firings.

A more readily determined performance advantage is associated with tank weight. Since tankage for storable propellants can be designed for non-cryogenic temperatures, modest pressures, and no vent losses, the hardware weight of such storage systems is typically less than a tenth of the weight of the stored fluid. This is contrasted with the 100% or more that is representative of super-critical oxygen-storage systems. The weight savings from such a consolidation as the Cornucopia process offers are obvious, and in some applications could be overriding. Coupled with the evident savings in hardware weight would be the equally important reductions in both the overall space envelope and in the excess storage capacity required for various reserves.



**Fig. 8.—Effects of relative leakage rate on (A) total fluid requirements, (B) water production, and (C) energy release.**



Even where no propulsion capability exists, there often will be other requirements for thrust production such as trajectory alteration, attitude control, and spin-up. These smaller thrust-production systems might require fluid storage in the same order of magnitude as those for life support or power generation, and would require a zero-g start capability. Such applications would permit the efficient multiple use of one set of positive expulsion devices, besides affording the more obvious opportunities for weight and volume reduction.

Another latent, although admittedly speculative, opportunity for the production of thrust is the low-cost velocity control that might be obtained by suitably directional use of an intentional high bleed of cabin atmosphere. Although extremely inefficient from a purely thrust-production standpoint, all of the potential in-process accomplishments of such a bleed (contaminant flushing, etc.) might well conspire to favor its use.

### **Contamination Control**

Any source of stored atmosphere 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 levels or become repugnant.

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 obviously worthwhile, in any event, to reduce the amount of contaminants that are introduced with the replenishment atmosphere, plus those 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 needed to replenish this outflow need not be considered purely as a penalty; it might well cost as much or more in added structural weight to provide the savings in stored fluid that would result from tighter sealing.

The Cornucopia reactants are believed to contain trace quantities of various potentially harmful impurities. However, we must further investigate the nature and amount of such substances before any comparison can be made with compressed gas and cryogenic storage systems now in use. Also uncertain is the extent to which these trace impurities in the liquid reactants might carry over through the combustion, cooling, and dehydrating processes into a cabin atmosphere. It is quite clear, though, that the Cornucopia process provides an exceptionally economical source of flushing gas in connection with its other functions, thereby permitting good control over the build-up of contaminants from all sources.

Since the rate of cooling in the combustion chamber is relatively slow compared to the extremely rapid expansion cooling in a rocket motor, a shifting equilibrium can confidently be postulated. Under such conditions the delivered concentration of any short-lived species would be infinitesimal. Verification of this crucial point should be an early experimental goal.

### **Applicable Missions**

**MANNED SPACE PROBES**—The Cornucopia concept could be exploited to fullest advantage for missions 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 a point where the benefits of consolidation might be offset by the higher specific impulse of more exotic propellants. Always favoring Cornucopia 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.

**SPACE STATIONS**—Many of the considerations that apply to manned space probes apply to space stations also, but with various changes in emphasis. Although thrust production will generally be limited to intermittent orbit adjustments 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 the shorter-duration probes in order to keep contaminant levels lower. Also tending to increase overboard losses would be the higher leakage associated with the sea-level atmospheres that are being considered for space laboratories. A particularly intriguing possibility would be to use as re-supply fluids unburned reserve propellants from the shuttling re-supply vehicles.