tion at increasingly elevated temperatures, and there seems to be theoretical bases for expecting progress in this direction.

There is also reason to expect some improvement in the current density that superconductors can support. Once out of the earth's near magnetic field, the interplanetary field is measured in terms of a few gammas. Gradients would be correspondingly lower, and, therefore, accelerating forces would be much lower. Improvement in current density and reduction in cryogenic equipment would thus extend the useful range of magnetic dipole propulsion.

Conclusion

The magnetic dipole offers good prospects for becoming an efficient space propulsion means. Its outstanding advantage stems from the use of field interaction rather than reaction forces to accelerate the vehicle. Particularly for the longer missions, the elimination of the propulsion medium can be all important.

Nuclear power will apparently offer high-power levels for extended periods of time. In fact, so far as power is concerned, one can project interstellar missions of many years' duration. The current-carrying loop, which is self-forming and which is also self-shielding from charged particles, may take on dimensions more appropriate to the distances to be traveled. The force to be derived from the loop dipole varies with the area of the loop. It is not inconceivable that the interstellar dipole propeller may have dimensions to be measured in the thousands of miles.

Experimental verification of the principle probably is attainable without any superconductor or cryogenic development. An ordinary high-conductivity loop could probably be powered to give a measurable orbital deviation. Superconductivity is essential to the propulsion technique only from the point of view of efficiency for an ultimately practical space vehicle.

Waste-Combustion and Water-Recovery System

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To date, most of the effort devoted to handling human waste for extended space missions has been concentrated on freeze drying or thermal decomposition of solids. The former is wasteful (because the moisture and air contained in the waste container are vented to space to effect drying), and the latter requires much power. The system described here uses a combustor. The required thermal energy is obtained by burning the organics and by heat exchange with the products of combustion. In the process, the organic matter and bacteria are rendered harmless by conversion to normal combustion products.

For a daily input of 6.16 lb of water the following water balance has been estimated for one man:[1]

Intake	6.16	Urine	3.92
Metabolic water	0.84	Feces	0.28
		Insensible loss	2.80
	7.00		7.00

Any excess water over the 6.16 lb of water required per day for consumption could be supplied to a water electrolysis cell.

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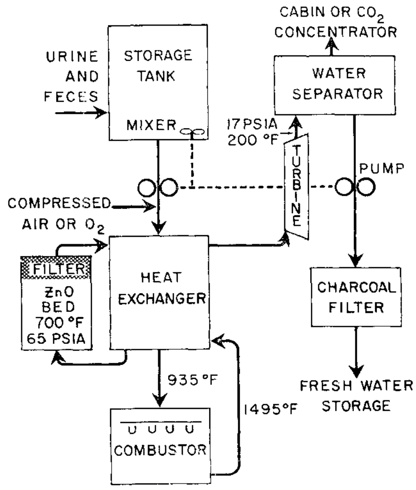
Fig. 1 Human-waste treatment system designed for complete water recovery with solids decomposed by combustion and sulphur dioxide removed with zinc oxide.



This quantity of water should be the difference between the water produced by the reduction of carbon dioxide and that necessary to produce the required oxygen by electrolysis. For a respiratory quotient of 0.85 and a daily requirement of 1.8 lb of oxygen, 0.30 lb of water would supply the necessary additional oxygen above that available in the carbon dioxide. The available water to supply this total water consumption plus oxygen requirement is equivalent to the recovered portion of the water output. If the fecal water is discarded but all of the the insensible water recovered, then 94% of the urine water would have to be recovered to supply the total of $6.16 + 0.30 = 6.46$ lb. Such high recovery from urine is unlikely from a distillation unit. A feasible recovery of 80% leaves a deficiency of 0.52 lb/man-day. On the other hand, if all of the urine and fecal water were recovered and the required 0.30 lb electrolyzed, then there would be an excess of 0.54 lb/man-day which could be used to make up oxygen (0.48 lb) and water-vapor leakage.

In the present system (Fig. 1) human wastes are heated regeneratively and fed with air to a combustor where they burn at approximately 1000°F. The exhaust stream contains principally water vapor, carbon dioxide, nitrogen, oxygen, ash, and sulfur dioxide. The stream, while still hot, is filtered to remove the ash and is reacted with ZnO to remove SO_2. Water is subsequently removed and pumped to storage.

System Operation

Based on the forementioned water balance, the total amount of solids in urine (4.8% solids) and feces (25% solids) is 0.29 lb/man-day. Using Babbitt's[2] heating value of 7600 Btu/lb of dry solids, the heat of combustion available is 2200 Btu/man-day. (Spector's data[3] on the heat of combustion for unconsumed food matter would give only 1200 Btu/man-day. But since this does not include the heat of combustion for bacteria or cellulose in feces, Babbitt's estimate[2] was used. However, the combustion scheme discussed is compatible with the lower heat of combustion. The

Table 1 Calculation of heat of combustion for nutrients in human excrement for 3000 kcal/day diet

Nutrients	Protein	Carbo-hydrate	Fat
Diet, kcal, %	15	52	33
kcal/day	450	1550	1000
kcal/gm	5.6	4.1	9.5
gm/day	80	378	105
Feces, kcal/gm	0.85	0.15	0.95
kcal/day	68	57	100
Urine, kcal/gm	1.1	...	...
kcal/day	88	...	...

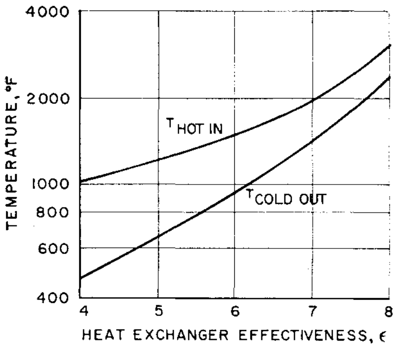


Fig. 2 Relationship between waste-combustion system temperatures and heat-exchanger effectiveness.

calculation of heat of combustion based on Spector[3] is shown in Table 1.) To assure complete combustion, the required air was estimated to be 150% of the stoichiometric requirement, i.e., 8 lb air/man-day or 1.7 lb O_2. The flow into a human-waste combustion system per man-day is then composed of 4.2 lb water, 0.29 lb solids, and either 1.7 lb O_2 or 8 lb air. Although combustion of garbage along with human wastes was not considered, this could easily be included. (Garbage has 72% moisture and a higher heating value of 8800 Btu/lb dry solids.[4] The heat of combustion is therefore 2460 Btu/lb of garbage. A representative analysis on a dry basis is: fixed carbon, 12.2%; volatile, 75%; and ash, 12.8%.)

In Fig. 1, air and wet wastes are separately pumped up to the required pressure and passed through a regenerative heat exchanger. The water is completely vaporized before it enters the combustor, in which the organic material and bacteria in the waste stream are completely burned at approximately 1000°F. The burned gas re-enters the regenerative heat exchanger, where it is cooled, partially condensing the water vapor. At a temperature of approximately 700°F, the stream is routed through a zinc oxide bed and a solids filter. (The ZnO-SO_2 reaction occurs best at $\backsim$700°F.) The filter is located here as a compromise solution to the problems of filtering at high temperature and of removing solids that are in solution with water. There can be no liquid water present in the filter, and consequently all solids will be dry. The stream is next passed through a turbine, which extracts work from the stream before it enters the water separator. The turbine drives the mixer in the storage tank and also the two fluid pumps. The separated water is passed through a charcoal filter to remove dissolved components and is then directed to a storage tank. The gas stream leaving the water separator is either directed to the cabin for mixing with the cabin air directly, or it is directed to the environmental control system for cooling and reduction of carbon dioxide concentration.

An alternative system was also considered in which SO_2 removal would be accomplished by an adsorbent bed (synthetic zeolites or silica gel) downstream of the water separator, rather than by the ZnO reaction. Since the maximum pressure in this system would only be 30 psia, the turbine would not be used. Hence, electrical power would be provided for the mixer and pumps and a blower provided for the adsorbent loop. Also, since SO_2 adsorbents show a preferential affinity for water, the stream must be predried prior to removal of SO_2. Such a system would require additional cooling and condensation in the water separator. Two SO_2 adsorbent beds would be used, one adsorbing while the other was being desorbed to space vacuum. A small amount of CO_2 will be adsorbed along with the SO_2, and it will also be lost. Table 2 shows that both systems would require approximately the same input power—15 w/man-day. Both systems would also have approximately the same weight for a 4-man-yr operation. Because of its greater simplicity and lack of vacuum connections, the system using zinc oxide is preferred.

Table 2 Energy balances for the two combustion systems

Power-using component	Power, w/man-day	Source of power
ZnO System (Fig. 1)		
Air compressor	15	Electrical
Pumps	0.15	Turbine
Mixer	0.35	Turbine
Turbine	−0.5	Fluid stream
Net external power	15	
Adsorbent System		
Air Compressor	5	Electrical
Pumps	0.05	Electrical
Mixer	0.35	Electrical
Adsorption Loop	10	Electrical
Net external power	15.4	

Thermal Balance and Zinc Oxide Bed

In the waste-combustion system that we have analyzed, combustion was assumed to take place at 1000°F and supply at 88°F and 15 psia. The liquid is pumped up to 80 psia and mixed with compressed air at 90°F before entering the heat exchanger. The power requirement for a compressor with an over-all efficiency of 50% is $\backsim$15 w/man-day.†

The heat exchanger effectiveness ϵ is defined by

$$\epsilon = (T_{\text{cold out}} - 90°\text{F})/(T_{\text{hot in}} - 90°\text{F})$$

where $T_{\text{cold out}}$ is the temperature of the fluid leaving the heat exchanger prior to entering the combustor, and $T_{\text{hot in}}$ is the fluid stream temperature leaving the combustor and entering the heat exchanger. $T_{\text{hot in}}$ may also be determined by $T_{\text{cold out}} + Q/Wc_p$, where Q is the total heat of combustion of W lb of waste. These two equations were solved simultaneously to determine the temperatures as a function of ϵ. The relation between ϵ and the temperatures is plotted in Fig. 2. To sustain a combustion temperature of approximately 1000°F, $\epsilon = 0.6$ was selected. This corresponds to a temperature of 935°F entering the combustor and 1500°F leaving the combustor. (Corresponding calculations for the lower heat of reaction of 1200 Btu/man-day indicate a required effectiveness of 0.75, giving temperatures of 1000°F entering and 1300°F leaving the combustor.) The heat exchanger functions as a boiler for the entering stream and as a condenser for the leaving stream. To permit operation of the ZnO bed at 700°F, the flow leaving the combustor is routed through the heat exchanger into the bed and back into the heat exchanger for further cooling. If a 10% efficiency is assumed for the pumps and turbine, the power balance of Table 2 obtains.

The recommended conditions for the ZnO reaction, $2ZnO + 2SO_2 \rightarrow 2ZnS + 3O_2$, are 65 psia and 700°–750°F. Approximately 0.0033 lb S/man-day is excreted.[3] This is equivalent to 0.0375 lb-moles/man-yr, which requires 0.0375 lb-moles of zinc oxide or 3.04 lb/man-yr. The calculated heat of reaction is 425 Btu/lb-moles of zinc sulfide or 4.4 Btu/lb. On a daily basis, 10^{-4} lb-moles of ZnS is formed, with a total heat of reaction of 0.0425 Btu/day. This will cause the stream temperature to change by less than one-tenth of a degree and has therefore been neglected.

A comparable regenerable solid-adsorbent system to remove the SO_2 (based on 10-man capacity) would weigh approximately 12 lb/man-yr, thus providing a break-even at 4 yr. However, an adsorbent such as synthetic zeolite will also adsorb significant quantities of CO_2. This, together with the large amount of water in the stream to be removed ahead of the adsorbents, makes the adsorbent system appear less attractive than the ZnO system.

† If the heat of compression were included in the air, its temperature would be 760°F for a compressor efficiency of 50%. This would show the waste-treatment system to greater advantage, but, to be conservative, it has not been included here. Of course, use of stored pressurized oxygen would also cancel this energy input.

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Impact Force per Crater Area Related to the Tensile Strength

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Many efforts have been made to relate the extent of impact damage to the properties of the target material. These efforts probably started in 1742 with the resistance-to-penetration theory of Robins.[1] Between 1835 and 1845 the French conducted a series of experiments to measure the velocity of cannon-ball fragments. The fragment velocity was computed by assuming a constant cratering efficiency, i.e., a constant ratio of crater volume to the kinetic energy of the fragment. One of the earliest correlations of cratering data was made by Helié,[2] who observed that the crater volume was approximately proportional to the kinetic energy of the impacting projectile where the constant of proportionality is a function of the target material. Later investigators,[3–7] in general, have agreed with Helié's conclusions.

Cratering involves shock compression of the target material to very high pressure, and the subsequent motion involves high strain and stress. Although the initial phase of the motion resulting from high-velocity impact may be adequately described by hydrodynamic principles, the stresses rapidly decay due to geometrical divergence and dissipation to the point where material strength becomes important. Pressures operative immediately after impact are clearly not representative for the greater part of the cratering process and cannot serve as a valid basis for neglecting the strength of materials. The bulk of the crater formation is caused by a process of energy dissipation and target deformation, during which the only restraining forces are the target properties. The final phase of the motion will involve a certain amount of elastic "springback." Because of this springback, the final crater depth was observed[10] to be 25% less than the maximum depth that occurred during the peak pressure pulse.

It has been observed that the ratio of impact energy to final crater volume‡ (reciprocal of the cratering efficiency) is directly proportional to the following:

Method A: Brinell hardness number§ of the target material which, in turn, is approximately proportional to the yield strength.[6]

Method B: Shear strength of the target material.[7]

The inherent limitations with these approaches to predict the crater damage sustained by a target can be attributed to the following:

Method A: The difficulty in relating other physical properties to the indentation hardness. The Brinell hardness number is *roughly*[8] proportional to the yield stress, at least within the scatter usually associated with empirical correlations. When the yield stress is known, the proportionality constant can be determined accurately, but, due to the approximate proportionality of yield stress to hardness, the crater dimension can be only *roughly* predicted.

Method B: The proportionality constant can be determined only when the shear strength is known, although it has an *approximate* value of 10 for all materials except lead.

The hypervelocity impact force per crater surface area is equal to the ultimate tensile strength,[9]¶ when the measured crater dimensions in aluminum are corrected (25%) for relaxation. Equations for uniformly accelerated rectilinear motion are applicable. The computed ultimate strength for the hemispherical craters is 3.2×10^9 dynes/cm^2 which can be compared to the measured tensile strength** of 2.97×10^9 dynes/cm^2. Nylon, glass, and aluminum projectiles with a mass range of 0.075–0.800 g were used to impact aluminum (6061-T6) targets with velocities in the range of 3.78–5.43 km/sec. Two additional experiments have been made with 0.075-g projectiles with impact velocities of 3.66 and 4.80 km/sec. The computed strength, with the two data points, was unchanged. Thus, the comparison can be made of the computed strength (3.2×10^9 dynes/cm^2), the experimentally determined tensile strength (3.0×10^9 dynes/cm^2), and the handbook value of the tensile strength (3.1×10^9 dynes/cm^2). The concordance is astounding, especially in the light of the assumptions made in computing the area, the averaging of the pressure, and the different material properties that are important during the various stages of crater formation.

In order to further corroborate the force per unit area concept, the data reported by Gehring[10] were used to compare the computed strength with the tensile strength. The 0.10-g steel projectile†† impacted the aluminum (2S-O) target at 5 km/sec and produced a 2.5-cm-diam crater that was 1.2 cm deep. However, the maximum depth of penetration was 1.5 cm as observed by flash x-radiography during the cratering process. The computed strength of 1.05×10^9 dynes/cm^2 can be compared to the tensile strength of 0.9×10^9 dynes/cm^2 or to the compressive‡‡ yield strength[7] of aluminum (alloy not specified) of 1.02×10^9 dynes/cm^2.

Comparison of the ultimate tensile strength with the strength computed from springback corrected data reported by two different laboratories and with different combinations of materials for the projectile and target shows excellent concordance. Thus, the maximum depth of penetration depends upon the force produced by the impact, and the measured (postmortem examination) depth of penetration depends on the amount of elastic recovery or springback.

It is significant that crater damage via hypervelocity impact can be predicted from the tensile strength established by standard metallurgical techniques. Future correlations of impact damage with material properties may be more productive, and better concordance may be achieved between theoret-

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‡ The final crater volume refers to that volume observed after "springback."

§ The ratio of E/V was observed[9] to be 2.1×10^3 joules/cm^3 which can be compared to the value of 2.5×10^3 joules/cm^3 computed from the relationship reported by Gehring.[10] The measured hardness was 93.8 on the Rockwell E scale which can be converted to the approximate Brinell hardness number of 97.

¶ Theoretically, the value of the pressure P is obtained by equating the sum of the pressures over the contact area A to the compressive force F. Then the hemispherical pressure distribution $P = 3F/2\pi r^2$.

** Standard tensile specimens were cut from the material used as targets.

†† This mass refers to the actual or impact mass.

‡‡ Static compressive yield strength or tensile strengths have, in general, about the same value. Yield strengths generally increase with the rate of strain, and the true value of the yield strength would be somewhat larger than the value given.