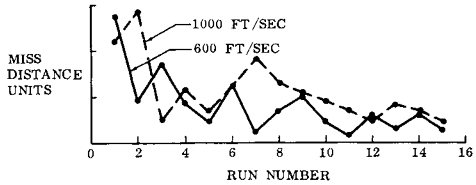

Fig. 5 Learning curves for operators flying missiles at fixed velocities indicated; modified four-degree-of-freedom program.

plot the missile's path projected in horizontal and vertical planes passing through the center of the target. The recorders are optically indexed (zero miss distance) to the target on the scale terrain by driving the reflector to the point at which light source and the center of the target are coincident and by zeroing the recorder pens. A scale of 1 in. of pen movement per 50 ft of missile travel provides very accurate miss-distance measurements but limits the recording to the final 500 ft of the trajectory. However, a continuous strip recorder documents the entire flight-path geometry, body attitude and rates, gusts, and load factors.

Initial flight-control experiments employed a modified four-degree-of-freedom program with simple manual-control systems. Missiles were flown at constant speed and zero roll angle in a wings-level, yaw-to-turn mode. Typical learning curves for two missile speeds are shown in Fig. 5. The miss distances shown are due primarily to error in vertical path, which was more difficult for the operators to control than lateral path; after 15 runs the operators were able to fly the missile with consistent accuracy. This program is continuing with more difficult tests, including effects of cross winds and random gusts.

Space Propulsion by Magnetic-Field Interaction

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Introduction

A MAGNETIC dipole experiences no net translational force in a uniform magnetic field. Instead, the dipole senses a couple until its axis is parallel to the lines of force of the field. On the other hand, in a nonuniform field, the translational force on a dipole in cartesian coordinates can be expressed as follows:

$$F_x = M_x\frac{\partial H_x}{\partial_x} + M_y\frac{\partial H_y}{\partial_x} + M_z\frac{\partial H_z}{\partial_z}$$

$$F_y = M_x\frac{\partial H_x}{\partial_y} + M_y\frac{\partial H_y}{\partial_y} + M_z\frac{\partial H_z}{\partial_y}$$

$$F_z = M_x\frac{\partial H_x}{\partial_z} + M_y\frac{\partial H_y}{\partial_z} + M_z\frac{\partial H_z}{\partial_z}$$

where F is the force, M the dipole movement, and H the magnetic field.

The contention will be made herein that space is permeated with nonuniform magnetic fields and that a dipole of significant magnetic strength will experience accelerating forces of practical magnitude. In a space propulsion system, the dipole is created by means of a current-carrying loop of wire. If this loop is operated as a superconductor, it offers interesting possibilities in efficient space propulsion. The key consideration, whether or not a superconductor is used, is to develop propulsive thrust without dissipating the mass of the space vehicle.

Magnetic-field interaction space propulsion can be likened to sailing uncharted seas while being steered by the winds. The space-sailor captain will have to learn the changing pattern of magnetic fields and to find the maximum gradients, so that he can make use of these forces to propel him on his way. He will enjoy one ancillary advantage from dipole propulsion. Charged particles will be deflected from their normal deadly path when entering the domain of the dipole. Not very much information is available on magnetic fields in space beyond a few geocentric radii of the earth. We know of bands of charged particles around the earth, and we have measured anomalies resulting from particles arriving from the sun. Generally, these factors tell of sharp gradients in the earth's magnetic field. The shrewd space mariner will seek out such gradients for that extra kick.

The earthbound speculator can, however, ignore the anomalies and concentrate on the earth as a giant magnetic dipole. This dipole creates a nonuniform magnetic field. It will be shown that the gradient of this field is sufficient to justify consideration of dipole magnetic-field interaction as a means of propulsion for accelerating the already orbiting vehicle up to escape velocity. That much is claimed for the ion propulsion system, and that system must dissipate its substance in developing acceleration.

Dipole Propulsive Force in Earth's Magnetic Field

In Fig. 1 is shown a dipole, represented by a single loop, which is located at some distance from the earth's surface commensurate with its being in a stable orbit. The net translational force can be expressed as follows:

$$\bar{F} = \frac{5 \times 10^{-11}NIA}{\xi^4}\left[-\hat{r} - (\cos\beta\cos\theta + \tfrac{1}{2}\sin\beta\sin\theta) + \theta(-\tfrac{1}{3}\cos\beta\sin\theta + \tfrac{1}{6}\sin\beta\sin\theta)\right] \quad (1)$$

where N is the number of turns in the coil, I the current in amperes, A the cross-sectional area of the coil, F the force

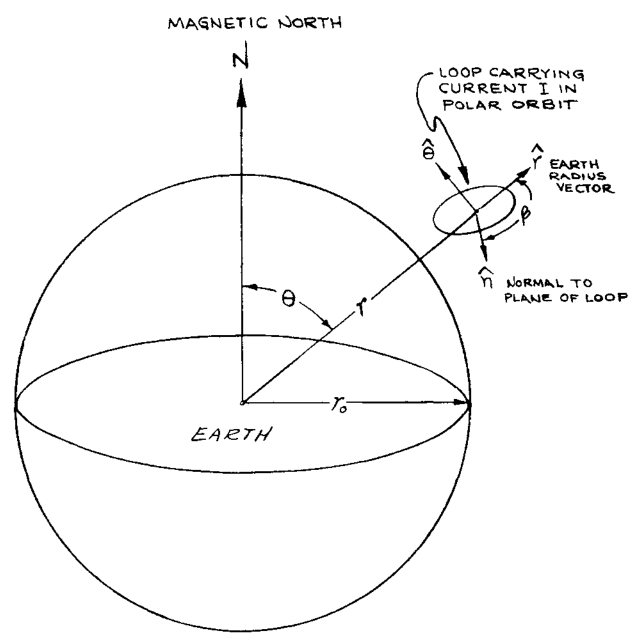

Fig. 1 Acceleration of magnetic dipole in polar orbit.

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* President.

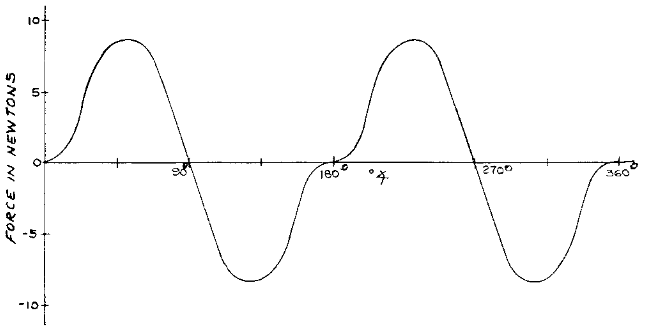

Fig. 2 $\hat{\theta}$-directed force on magnetic dipole in earth polar orbit: loop radius = 10,000 m, current = 4000 amp, altitude = 200,000 m.

in newtons, and ξ is a normalized altitude ($\xi = r/r_0$, where r_0 is the earth's radius in meters).

Figure 1 presumes a polar orbit. In an equatorial orbit there would be no net force in the direction of motion. In the polar orbit the θ-directed force component, not the r-directed component, must be utilized; θ is measured from the North Pole, and β is the angle between the radius vector r from the center of the earth and the normal to the current-carrying loop.

In the polar orbit the current-carrying loop will everywhere experience a torque that aligns the normal to the coil with the earth's dipole field. Under these circumstances Eq. (1) describes a θ-directed force which goes through zero at the poles and at the equator and which reverses in alternating quadrants. The angle β is evidently predetermined for every θ by the field of the earth's dipole:

$$\tan\beta = \tfrac{1}{2}\tan\theta \tag{2}$$

If the θ-directed force reverses every quadrant, the net acceleration in the direction of travel is zero. A simple approach to attaining a net acceleration is to reduce the current in the coil to zero during travel through those quadrants in which the force would be decelerating. (Mechanisms for accomplishing current reduction and the possibilities for tumbling the coil and reversing the current will be discussed later.)

The term $5 \times 10^{-11}\ NIA/\xi^4$ of Eq. (1) is the maximum force that is experienced by the coil as a radial force when $\theta = \beta = 0$. We can evaluate the magnitude of this term for an arbitrary 200,000-m-altitude orbit where $\xi^4 = 1.14$. Let us denote the result, $4.4 \times 10^{-11}\ NIA$, as F_0. It is preferable first to calculate F_0/M where M is the minimum mass of the coil (no cryogenics, mechanical support, etc.). In this case $M = \rho V_{\text{coil}}$, where ρ is the density and V_{coil} is the volume of the coil.

If the coil is assumed to have a major radius of a m and a core radius of b m, then

$$V_{\text{coil}} = 2\pi a \times \pi b^2\ (m^3) \tag{3}$$

At present, niobium-tin appears to be a superior candidate for the coil material. The density of Nb_3Sn is 8.4×10^3 kg/m^3, and we can set the maximum current density at 3×10^{10} amp/$\overline{m}^2$. Then

$$M = \rho V_{\text{coil}} = 8.4 \times 10^3 \times 2\pi^2 ab^2 (\text{kg})$$
$$NI = 3 \times 10^{10}\pi b^2 \tag{4}$$

Hence

$$F_0 = 4.4 \times 10^{-11} \times 3 \times 10^{10}\pi b^2 \times \pi a^2 \cong 13 b^2 a^2 (\text{N}) \tag{5}$$

and

$$\frac{F_0}{M} = \frac{15 b^2 a^2}{2\pi^2 ab^2 \times 8.4 \times 10^3} \cong 1 \times 10^{-4} a (\text{N/kg or m/sec}^2) \tag{6}$$

The acceleration F_0/M is evidently independent of the number of turns in the coil, but it does depend linearly on the radius of the coil. Unless a is very large, the acceleration will be small compared with $1.0\,g$ (9.8 m/sec^2). Yet, appreciable forces can be delivered if one presumes that a large diameter coil can be erected in orbit. As an example, we might assume a coil of major radius a equal to 10,000 m (about 13 miles in diameter) and a wire radius b of 2×10^{-4} m (about 10 mils in diameter). From Eq. (5), $F_0 \cong 50$N, or 5000-g force, and from Eq. (4) the coil would carry a current of $\cong$ 4000 amp. The mass of the coil would be $\cong$ 65 kg.

Now 10 lb of propulsive force from a coil weighing under 150 lb certainly sounds interesting, but many other factors must be considered. First, we have weighed only the Nb_3Sn wire and given no thought to the problem of maintaining cryogenic temperatures, which will certainly introduce weight.

Next, F_0 is the peak force and the θ-directed force not only is smaller but also waxes and wanes vs θ. Using Eq. (1), the plot of Fig. 2 has been developed to show the variations of F_θ in its polar orbit. In the negative quadrants the force is decelerating. To utilize only the accelerating forces, one must collapse the current in the loop during passage through the decelerating quadrants. An effective technique might be to dump the energy into a condenser bank during the negative quadrants. Such a condenser bank, as well as the prime source of electrical power, must be included in the propulsion system weight allowance.

Some Application Considerations

A loop that is 13 miles in diameter poses the formidable problem of erection in space. However, there are possibilities for simple erection. If the wire with its cryogenic envelope is reasonably flexible, it might be coiled up for delivery to orbit. Once in orbit, the coil would be discharged from the vehicle, and the hoop forces resulting from current flowing would result in formation of the circular loop.

The major components of the propulsion system are the loop, the temporary energy-storage equipment, and the electrical generator. When the loop passes into the decelerating quadrants, the superconducting circuit must be opened up and the energy stored until the next accelerating quadrant is reached. If the storage system were a capacitor bank, the current in the loop would be converted into charge on the capacitor.

It must be remembered that work is being done while the loop is carrying current. Accordingly, the amount of energy dissipated must be replenished regularly from the spacecraft's electrical generator. With a capacitor bank this can readily be done by trickle-charging. Or, more energy could be introduced into the superconducting loop by magnetic coupling.

In the earth's polar orbit, the loop has only one stable orientation with respect to the earth's dipole field. This orientation results in decelerating forces through two quadrants of travel. One can consider reversing the current to utilize forces in these quadrants to contribute to the spacecraft's acceleration. If the current is reversed, a tumbling couple is introduced which will swing the loop once again into a decelerating orientation. Considering the inertia of the loop, however, one can visualize a technique wherein the loop current is pulsed on a relatively long-time base and the loop is allowed to tumble in its orbit. Naturally, current and its direction would be coordinated with loop orientation.

The most severe problem in development is the need for attaining the extreme cryogenic temperatures necessary to keep the loop superconducting. The only mitigating circumstance is the vacuum of space, which will help in providing insulation. The pumping of liquid helium around such a long path does stagger the imagination, but even in this regard there are possible solutions—as research with superconducting materials progresses, we can hope for operation 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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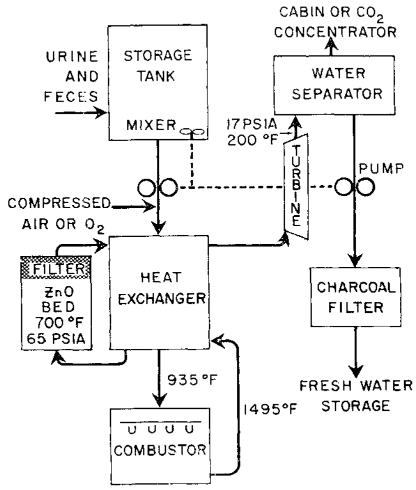

Fig. 1 Human-waste treatment system designed for complete water recovery with solids decomposed by combustion and sulphur dioxide removed with zinc oxide.

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	Carbohydrate	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	...	...