more favorable than D1L2. Korolev Basin is generally pocked with kilometer-sized craters, unlike the smooth lava-filled basins constituting nearside maria; but detailed photographic studies may disclose isolated sites smooth enough to permit construction. R2L1, though requiring a closer restriction on allowed ΔV_T, may be able to take advantage of the nearby crater Riccioli for site location, since that crater has a smooth marelike floor.

Deprit and Henrard[6] have shown that in the Earth-Moon system, bodies leaving L1 with near-zero velocity follow a 5:2 resonant orbit. This is also very nearly true[3] for bodies departing L2 with small velocity. Hence the arguments of Ref. 3, proposing that if mass-catching is done near L2 then the manufacturing facility should be in a 2:1 resonant orbit, apply as well when catching is done near L1.

The popular legend of an L5 space colony finds little support from the present results. While one may arbitrarily adopt decision criteria favorable to the D3L5 or D3L5-A mode, such criteria can appear only as ad hoc assumptions. When using a mass-driver and mass-catcher in lunar material transport, the difficulty is the sensitivities at launch; from this perspective, the launch modes to L4 or L5 are entirely unsuitable. Nor is it desirable to transport mass from L2 to L4 or L5.[3] Hence, any proposal to locate a space colony at L5 must involve an alternate mode for resource transport, e.g., the use of rockets. Such a proposal must then show advantage for L5 vs such alternatives as lunar orbit, geosynchronous orbit, or a stable "giant-halo" orbit of L1 or L2,[7] all of which may be conveniently reached by rockets.

Conclusions

An evaluation of some 34,000 test achromatic trajectories has yielded ten well-defined modes for lunar material transport. These have been compared from the standpoints of arrival velocity, launch side topography and location, and sensitivities with respect to errors in components of launch velocity. This comparison favors the D1L2 mode treated in previous papers.[1-4] However, the possibility of using relatively smooth terrain in the Korolev Basin and in the crater Riccioli suggests that the D1L1 or R2L1 modes may prove usable. All other modes involve high arrival velocity, very rugged launch-site terrain (often on the lunar farside), or high-launch sensitivities, and thus presently appear inferior to D1L2.

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Flight Instability Produced by a Rapidly Spinning, Highly Viscous Liquid

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A NEW type of flight instability has been observed for spin-stabilized projectiles filled with a liquid whose viscosity is approximately 100,000 times larger than water. The stability of liquid-filled projectiles is a well documented problem. Stewartson[1] provided a description of one physical mechanism for instability as a matching of a natural frequency of oscillation of the liquid (an eigenfrequency) and the fast frequency of motion of the projectile and calculated the eigenfrequency spectrum and the amplitude behavior of the carrier vehicle for an inviscid liquid. Wedemeyer[2] then provided viscous boundary-layer corrections to the Stewartson solution. The range of application of these corrections is controlled by the Ekman number ($E=\nu/a^2p$, where ν is the kinematic viscosity of the liquid, a is the radius of the cylindrical payload compartment, and p is the spin of the projectile). Good agreement between the Wedemeyer theory and a liquid-filled gyroscope is obtained for $10^{-4}>E>10^{-6}$.[3] The Stewartson-type instability directly depends upon the liquid fill ratio and the geometry of the payload compartment as any eigenvalue problem would.

Such is not the case for a recently observed instability which is apparently controlled by the viscosity of the liquid when E is much larger. Laboratory experiments with a spin fixture stimulated interest in high Ekman number flows. The laboratory spin fixture causes a full-scale cylindrical payload container for a 155-mm projectile to undergo simultaneous spin and precession and measures the canister despin due to the action of a nonrigid payload fill. Spin fixture results and flight data have shown good qualitative agreement on a variety of nonrigid payload configurations.[4] A series of spin fixture tests were conducted with cylindrical containers completely filled with homogeneous liquids of various viscosities. Figure 1 shows spin fixture despin moment data as a function of liquid kinematic viscosity. Note that the despin moment approaches zero at both low and high viscosity extremes and achieves the largest value at a kinematic viscosity of about 100,000 centistokes. Subsequently, a series

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Table 1 Round-by-round data[a]

Round number	Type of liquid	Kinematic viscosity[b] cs	Muzzle velocity m/s	Ekman number	Range, m	FMA,[c] deg	Comments
E1-9391	corn syrup	1.92×10^5	317.1	8.4×10^{-2}	3447	14	unstable
E1-9392	glycerol	1.03×10^3	321.4	4.6×10^{-4}	6955	12	stable
E1-9393	corn syrup	1.92×10^5	317.6	8.4×10^{-2}	3691	...	unstable
E1-9394	corn syrup	1.92×10^5	316.3	8.4×10^{-2}	3392	14.5	unstable
E1-9395	corn syrup	2.14×10^6	319.9	9.4×10^{-1}	7217	10.5	stable
E1-9396	glycerol	6.34×10^3	320.4	2.8×10^{-3}	6557	13	constant yaw

[a]All projectiles were conditioned to 22°C except for E1-9395 and E1-9396 which were conditioned to 4°C. Canister internal dimensions of height and diameter were 0.508m and 0.117m, respectively.
[b]Water has a kinematic viscosity of approximately 1 centistoke (cs) at 22°C.
[c]First maximum angle (FMA) of yaw is half of the first recorded peak-to-peak excursion of σN.

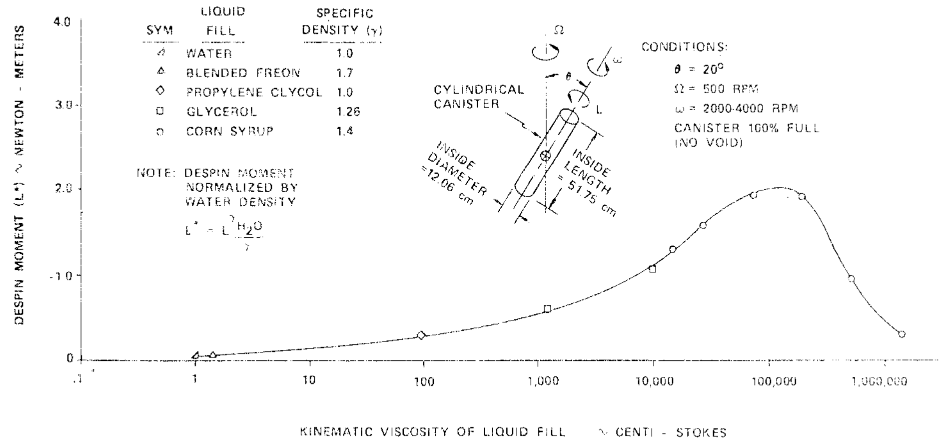

Fig. 1 Laboratory spin fixture data.

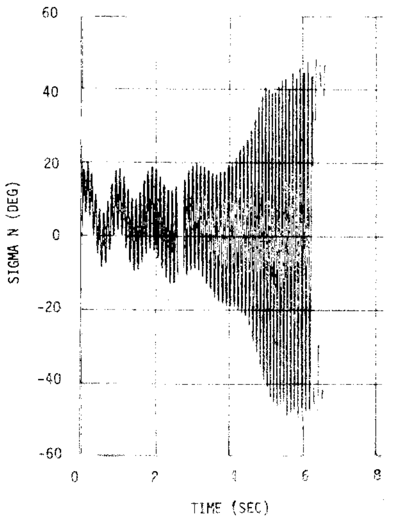

Fig. 2 σ/N vs time round E1-9394.

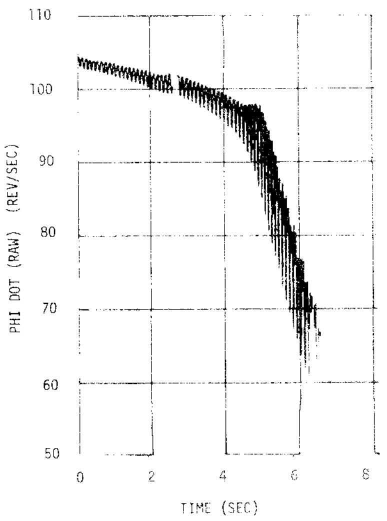

Fig. 3 $\dot\phi$(raw) vs time round E1-9394.

of full-scale, instrumented flight tests were conducted to evaluate this effect further.[5]

Six 155-mm projectiles were fitted with completely filled cylindrical containers. Yawsonde data were obtained for five shell,[6,7] while all shell were tracked by a time-position radar. The single projectile for which yawsonde data were not obtained was determined to be unstable from the radar data. Table 1 provides a round-by-round summary of the flight program. A modified muzzle brake was used to induce yaw. Yawsonde data yielded a one-dimensional projection of the angular motion of the projectile and a spin history. The angular motion is viewed in terms of the complementary solar aspect angle, σN. σN is the complement of the angle between the longitudinal axis of the projectile and a vector to the Sun. These data will show directly the fast and slow precessional motion of the projectile. The spin is viewed in terms of $\dot\phi$ (raw) which is the derivative of the Eulerian roll angle of the projectile. For small angular motion $\dot\phi$ (raw) is an accurate representation of the spin, but for large angular motion the fast precession motion will modulate an ordinarily smooth spin history. The mean of the data should then be regarded as the spin. The yawsonde data for E1-9394 are presented in Figs. 2 and 3. The solar angle data show that the fast mode motion grows rapidly and a circular coning motion larger than 40 deg in peak-to-peak amplitude occurs within 4 s, which is atypical for liquid-filled projectiles when $E \ll 1$.

Data beyond 4 s indicate a strong coupling between the spin and the yaw that is characteristic for payload/projectile interactions. As Table 1 indicates, two other projectiles with an Ekman number similar to E1-9394 were fired, and unstable flights were recorded. Three other projectiles with larger and smaller Ekman numbers were fired and were stable. One projectile, E1-9366, exhibited a constant yaw envelope of 20 deg for the entire trajectory. For these six projectiles all canisters were of the same dimensions. The only variable was the kinematic viscosity of the payloads.

The flight-test results show good qualitative correlation with the laboratory test fixture results in that the limiting cases of vanishing small viscosity (an inviscid liquid) and infinite viscosity (rigid-body motion) would not produce flight instabilities and the worst behavior is observed for a viscosity 100,000 times that of water. The mechanism of the instability is not completely understood, but one hypothesis proposed by Vaughn[8] considers that small perturbation velocities are induced in the liquid by the spin and precession. Further tests have been performed and also have shown instability for large viscosity payloads at smaller levels of launch yaw.

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