A Lunar Propellant Supply System

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Abstract

Previous studies have proposed the production of lunar liquid oxygen (LLOX) as an economical cislunar propellant source. Oxygen reduced from ilmenite (mined from lunar regolith) could be liquefied, and launched to lunar orbit collection points in small canisters by a simple electromagnetic mass driver system. It was suggested at the 5th Princeton/SSI Conference that self-maneuvering canisters could avoid the as yet intractable engineering problem of orbiting "mass catchers" to collect the large number of separately launched payloads. Such canisters, once emptied into space-based storage facilities, could be returned en-masse to the lunar surface for reuse. Considered an intermediate step in our understanding of LLOX supply architectures, this paper focuses on engineering the "smart" canister and developing requirements for its handling systems on the Moon and in space. Particular attention is paid to the appropriate avionics, and how maneuvering from mass driver release to canister berthing is accomplished. The canister performs orbit change maneuvers required to rendezvous with the propellant collection space platform. It then maneuvers within berthing range of the platform's robotic loading dock. Inspection and required maintenance are performed at the LLOX recharge facility on the lunar surface. Also discussed in detail is the canister propulsion system, including propellant choice (and source), thruster type, and engineering to withstand launch loads of hundreds of gs. It is proposed that, in the near term, Earth- supplied gaseous hydrogen be used as the canister fuel with the LLOX as oxidizer at a mixture ratio of 1:50. Later, lunar metals or hydrogen may be used as fuel for a totally Earth-independent LLOX supply network.

Nomenclature

e - eccentricity
f - solar flux
HL - allowable heat flux
p - LLOX tank projected surface area
r_a - distance to L2 from Moon, 57000 km
r_m - radius of the Moon, 1738 km
Δr_t - radial distance error
T - temperature
T_{L2} - transit time to L2
ΔT_r - radial arrival time error
ΔT_t - tangential arrival time error
V - LLOX tank exposed surface area
$\Delta V_{maneuver}$ - fine control velocity
ΔV_{KM} - velocity supplied by kick motor
ΔV_L - launch velocity
$\Delta V_{LExcess}$ - excess launch velocity
ΔV_{at} - tangental velocity error
ΔV_r - radial velocity error
ΔV_t - launch velocity error
$\dot{Q}$ - thermal flux

α - absorbtivity
ε - emissivity
μ_m - lunar gravitational parameter, 49000 km^3/sec^2
σ - Stefen-Boltzmann constant
ρ - density

I. Basic System and Requirements

The propellant supply system uses a lunar mass driver, located on the lunar equator, identical to the one described by Snow, Kubby and Dunbar at the 5th Princeton Conference*, to launch a 125 kg canister (75 kg delivered LLOX payload) to an L2 receiving station. The canister is inspired by, but more complex and detailed than, the "smart canister" described by Andrews and Snow, also presented at the 5th Princeton Conference**. The canister launch rate is driven by the LOX needed to support construction of Solar Power Satellites (SPS): a mass requirement of 5835 metric tons (including 875 mt for canister return transport) to L2. For the 75 kg delivered payload, 77,800 canister launches per year to the L2 station are required.

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The sequence of events is envisioned as follows:

Lunar oxygen is reduced from regolith mined on the lunar surface, liquefied, and loaded into a "smart canister", all by automated systems. A full canister is placed on a loading line for insertion into the mass driver for launch to L2. About 3 days after launch, the canister will approach L2 with some excess speed (150-195 m/sec) which will be canceled by retrofiring a 50:1, 111 Newton LO2/GH2 kick motor. Within 10,000 km of the station the station's RF control guidance system locks onto the canister. The station then controls the canister, whose guidance system acts as a slave, aiming and guiding the canister in. At 20 km range, an optical tracking system on the station helps maneuver it within grappling range of the station remote manipulator system (RMS). For this fine controlled approach the canister is equipped with a cold gas jet attitude control system using vapor from the onboard LLOX. The station RMS grapple grips the canister's motor mount. The RMS then carries the canister past several "activity stations", where its GH2 tanks are recharged, its LLOX tank is emptied and it is loaded onto the robot lander for return to the Moon. The canister is at a higher pressure than the refrigerated station LOX receiving tank, allowing quick thermodynamically driven fluid transfer. All operations are automated robotic functions; human intervention will occur only for inspections, contingency control, or in emergency safing and repair conditions as required.

II. System Sections

Mass Driver

The mass driver used here is the one presented by Snow, Kubby, and Dunbar, but with several differences. Our canister version uses an internal guidance system and an attitude control system, because spin stabilization would hinder maneuvering, we do not spin the canister prior to launch. Spin stabilization helps primarily in the initial launch accuracy and does not permit large flight path corrections or maneuvers. The canister, however, may require a down range correction station for initial launch accuracy. Indeed, it may be desirable to have such a station to increase the accuracy of the trajectory to L2. This would reduce the probable number of canisters that may be in the vicinity of the L2 station at any one time, and the consequent number of canisters that the station canister guidance system must handle. Otherwise, with a +/- 1 degree pointing error and a 10 cm/sec tangential launch velocity error, the station must be able to track and control up to 150 canisters at a time, since their terminal approaches may overlap.

Another difference is the power source for the launcher and automated plant. Due to the launch rate to support SPS construction, the mass driver must operate "around the clock". This includes the lunar night, and would require a very large solar array / energy storage system (with a high mass penalty), if such a system were used. We favor a nuclear power supply, large enough to support more than one mass driver. At present we are considering two mass drivers, for uninterrupted duty cycle despite routine maintenance. We used the parameters in Table 1 for our reference (not optimized) mass driver.

TABLE 1. Mass Driver Parameters

Launch velocity	2.331 km/sec[†]
length	655 meters + 3 meter correction section
acceleration	4834 m/sq sec (493 g's)
acceleration time	0.539 sec
caliber	0.60 meters
canister loaded mass	125 kg
period between launches	6.78 minutes for (1 mass driver) 13.56 minutes for (2 mass drivers)
number of launches per year	77800
LLOX delivered to orbit	5835 m tons /yr
Mass Driver position[†]	0 deg latitude, 45 deg longitude, 0 deg elevation, 90 azimuth
Tangential launch error	10 cm/sec
Pointing error	+/- 1 degree

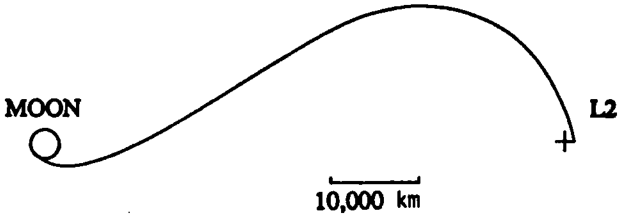

Figure 1. Trajectory To L2

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[*] Snow, W.R., Kubby, J.A., and Dunbar, R.S., "A Small Scale Launcher for Early Lunar Material Utilization", Space Manufacturing Facilities 4, Proceedings of the Fifth Conference, Princeton, NJ, May 18-21, 1981, AIAA, New York

[**] Andrew, D.A., and Snow, W.R., "The Supply of Lunar Oxygen to Low Earth Orbit", Space Manufacturing Facilities 4, op. cit.

[†] The mass driver position parameters were used to predict the velocity to L2 using a Boeing in-house computer program called CISLUN for examining lunar launches. This program predicted the 2.331km/sec velocity to the vicinity of L2 with an excess arrival velocity of 154 m/sec and a flight time of 2.97 days. The form of the trajectory flight path is shown in Figure 1.

Using the CISLUN program's predicted velocity of 2.331 km/sec and the formulas noted in Table 2, deviations from the nominal trajectory in position, velocity and time can be considered.

TABLE 2. Flight Path Deviations

formula *	result
from CISLUN program	V_{L2} = 2.331 km/sec
from CISLUN program	T_{L2} = 2.97 days
Tangential launch error	ΔV_t = 10 cm/sec
$e = \frac{r_a - r_m}{r_a + r_m}$	e = .943
$\Delta V_{at} = \frac{2(r_m + 2r_a)}{r_a + r_m}\Delta V_t$	ΔV_{at} = 0.394 m/sec
$\Delta T_t = 3/4\pi(r_a + r_m)^2\sqrt{a/r_m}\,\Delta V_t$	ΔT_t = 17.04 minutes
$\Delta V_r = \gamma(V_{L2})$	ΔV_r = 40.79 m/sec
$\Delta L = r_a L\frac{1}{r_a - r_m} \times \sqrt{\frac{2r_a r_m(r_a + r_m)}{\mu_m}}\,\Delta V_r$	ΔL = 1.465 km
$\Delta T_r = \left(\frac{r_a - r_m}{r_a + r_m}\right)\left(\frac{r_a^2 - r_m^2}{\mu_m}\right)\Delta V_r$	ΔT_r = 8.46 hr
(compared to 7.75 hr from CISLUN)	
$\Delta r_t = \sqrt{\frac{2r_a\,(r_a + r_m)^3}{\mu_m r_m}}\,\Delta V_t$	Δr_t = 174.7 km

Using the above calculations an unoptimized estimate of a change of velocity (delta V) budget needed for the canister is given in Table 3.

TABLE 3. Canister Delta V Budget

individual delta v's	purpose	how handled
ΔV_L = 2.331 km/sec	launch	done by Mass Driver
ΔV_t = 0.394 m/sec	correction	done by cold gas jet
ΔV_r = 40.79 m/sec	correction	done by kick motor
$\Delta V_{LExcess}$ = 154 m/sec	arrival	done by kick motor
ΔV maneuver= 0.3 m/sec†	approach	done by cold gas jet

Total delta v's	how handled
V_{L2} = 2.331	Mass Driver
ΔV maneuver~=0.7 m/sec	cold gas jet
ΔV_{KM} = 195 m/sec	kick motor

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* Formulas are those that are used by Snow, Kubby and Dunbar

† ΔV maneuver includes the fine control thrusting prior to the station RMS grapple contact and an end exchange maneuver to orient the kick motor for retrofiring to slow the canister for capture.

Canister Configuration

With the delta velocity budget established and the physical limits of the mass driver known, the canister physical configuration can be designed, and is shown in Figure 2. Our "smart"canister differs from the Andrews and Snow, and Snow, Kubby and Dunbar "smart" canisters by the addition of a guidance and "communications" system for the canister, the use of 8 attitude control (ACS) cold gas jets using vapor from the available, warming LLOX propellant supply, and the use of a hydrogen-oxygen kick motor also using the available LLOX propellant. All the LLOX will be stored in one tank with the ACS and kick motor prevented from dumping the liquid oxygen payload by vapor filters in their feed lines. Pressure is expected to build in the canister, but be restrained by the 2mm thick tank walls designed to withstand the 493 g launch loads that the mass driver would produce. We calculate the pressure buildup in the canister over the three day trip by evaluating the heat flux through it. As a benchmark estimate the allowable heat flux that would rase the LLOX tank pressure to 3448000 N/sq.m (500 psi) is calculated as follows:

Assume: 13% of the tank is ullage
Volume of the liquid V_l = 0.088 m^3
Volume of the vapor V_v = 0.011 m^3
Initial pressure p_i = 101400 N/sq.m (14.7psi)
Final pressure p_f = 344800 N/sq.m
Initial temperature T_i = 89 deg. K
Final temperature T_f = 144 deg. K
Initial gas density ρ_{ig} = 4.486 kg/m^3
Initial liquid density ρ_{il} = 1153 kg/m^3

From this information the density of the liquid and gas at 344800 N/sq.m (500 psi) was calculated to be

Final gas density ρ_{fg} = 160.2 kg/m^3
Final liquid density ρ_{fl} = 761 kg/m^3

The mass of the gas that vaporized is

$$m_{Tg} = m_{fg} - m_{ig}$$

where: $m_{ig} = \rho_{ig} \times V_g$ = 0.0478 kg
$m_{fg} = \rho_{fg} \times V_g$ = 1.708 kg

The heat of vaporization is

$H_{vg} = m_{Tg} \times h_{vap}$
H_{vg} = 1.660 kg x 213100 J/kg sec
H_{vg} = 353.69 kJ/sec

@ 259200 seconds of flight :

The vaporized liquid heat load is

353690/259200 = 1.365 Watts

The remaining liquid heat capacity is

12.75 cal/mol K (55.6 k) = 7542.92 kJ/sec

The remaining liquid heat load is

7542920/259200 = 29.101 Watts

The original vapor heat capacity is

4.651 J/kg sec x 1.660 kg = 7.7208 kJ /sec

The original vapor heat load is

7720.8/ 259200 = 0.00298 Watts

The allowable heat leak for 3448000 N/sq.m is therefore

HL = 1.365 +29.101 + 0.00298 Watts

HL = 30.469 Watts

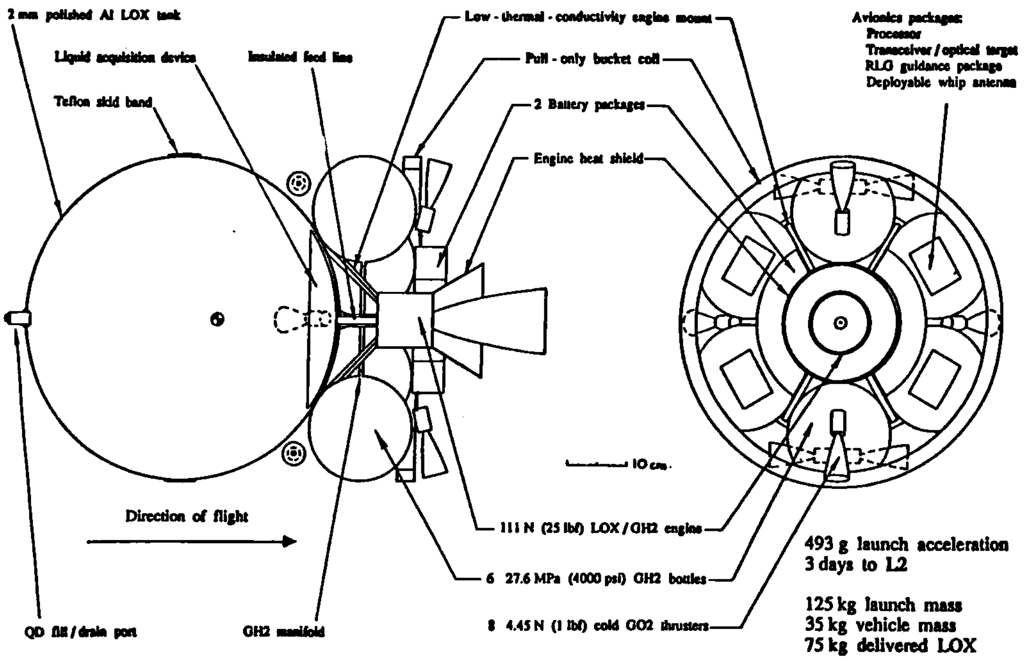

Figure 2. "Smart" Mass - driver LLOX Canister

The actual heat flux for a tank surface with emissivity of 0.04 and an absorptivity of 0.1 (polished aluminum) is

$$\dot{Q} = f \alpha p = 32.063 \text{ Watts}$$

where: solar flux f = 1400 W/m
absorptivity α = 0.1
projected area p = 0.229 m

The reradiated flux for the tank is

$$\dot{Q} = V \varepsilon \sigma T^4 \quad = 0.2755 \text{ Watts}$$

where :
3/4 viewed surface area V = 0.687 m
emissivity = 0.04
Stefan Boltzmann constant = 5.729×10^{-8} W/m²K
average surface temperature difference =115 deg K

The total heat flux is

$$\dot{Q} = 32.063 - 0.2755 \text{ Watts}$$
$$= 31.79 \text{ Watts}$$

This is very close to our estimated allowable heat leak rate for a 3448000 N/sq.m (500 psi) rise in tank pressure. In fact, iteration shows that the heat flux of 31.79 Watts will yield a pressure rise to 3861000 N/sq.m (~560 psi) for the tank over the three day journey to L2. The tank is sized to withstand 5020000 N/sq.m (728 psi). **Thus radiation shields do not even appear necessary; in any case they would be extremely light.**

This pressure buildup will be used in discharging the LLOX payload into the L2 station's colder receiving tanks, through a quick disconnect valve at the canister aft end. This process is expected to take about a minute . The hydrogen gas is stored in six high-pressure bottles mounted to the engine support struts. A GH2 fill valve is located in a recessed port on the side of the canister. The ohmic bucket coil is located forward of the canister mass center, to accomodate the pull-only mass driver centering feature. The canister is launched nozzle first. Aft of the LLOX and hydrogen tanks the electronics package in an annular ring around the kick motor nozzle. Small avionics packages containing the control processors, ring-laser-gyro guidance sensors, radio transcever electronics and antenna are mounted directly to the forward faces of four of the GH2 bottles. The antenna is a whip dipole, deployed after the launch by a spring release. The station electronics will do the work of acquiring the communications link with the canister, to keep the canister as simple and light as practical. The power requirements of the canister thus consist primarily of the operation of valves, gyro lasers and some communications feedback. We have used silver-zinc batteries rated at 56 Watt-hours, configured in two annular segments around the main engine. A mass statement appears in Table 4.

TABLE 4. Canister Mass Statement

LLOX :	delivered	75 kg	
	propulsion	12.6 kg	
	ACS	0.2 kg	
	2% residuals	1.7 kg	
total			89.5 kg
Tanks:	LLOX	5.0 kg	
	six 4000psi GH2 tanks	3.0 kg	
total			8.0 kg
Thrusters:	Main thruster+ (25 lb) GH2/LO2	3.6 kg	
	eight ACS thrusters (1 lb) cold GO2	2.2 kg	
total			5.8 kg
Ohmic coil:			4.0 kg
Processers, RF transceiver gyros, antennas, wiring Fluid lines + ports Misc. structure and fittings			
total			6.3 kg
Growth **and** : **reserves**			11.4 kg
Total mass			125 kg

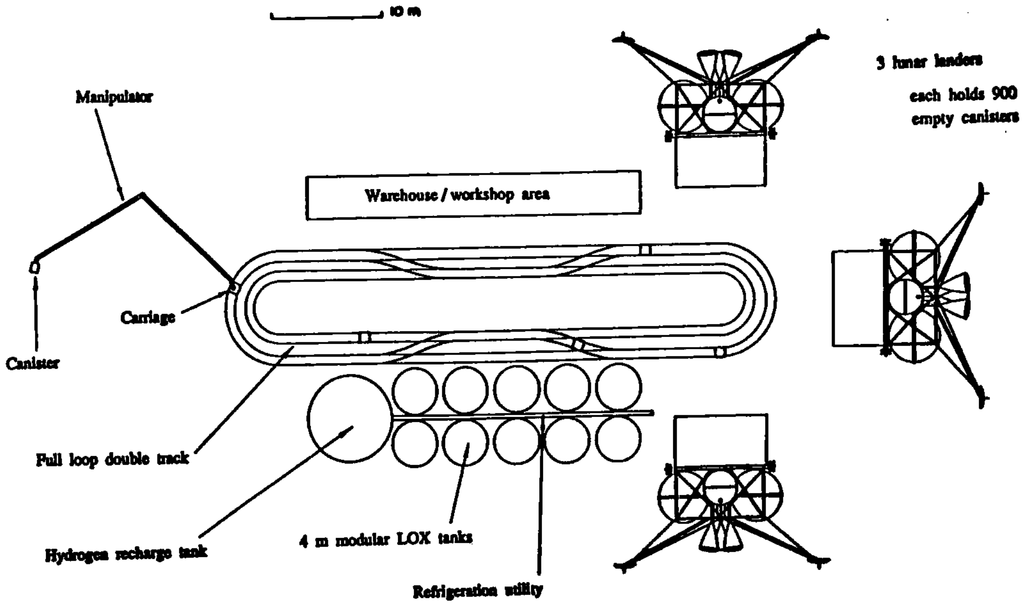

Figure 3. Conceptual Design of L2 LLOX Receiving Facility

L2 LLOX Receiving Station Systems

The use of this type of canister, with external terminal guidance control, allows it to be directed to a "soft" grapple catch without severely penalizing its size and mass. A conceptual design of the LLOX receiving facility on the L2 station is shown in Figure 3. This receiving facility may be part of an L2 "port" station, since ore from the Moon and H2 from Earth must be transferred also. It supports at least six 20-meter RMSs equipped with the grapple end-effectors, which may be changed out for repair end- effectors for maintenance operations. The RMSs have access to a warehouse of spare parts and a workshop area for robotic maintenance. Each of the six RMS arms moves independently on its own carriage around a full loop double track to reach any portion of the receiving facility. These tracks have two crossover points to prevent a stationary or busy RMS from blocking movement around the loop by any other RMS.

The hydrogen recharge tank, and four-meter diameter modular LOX tanks (sized to be interchangeable with the lander propellant tanks) are shown serviced by a refrigeration utility (helium coolant).

The thirty metric ton lunar cargo lander will be the transport vehicle which returns the empty LLOX canisters to the lunar surface. An empty lander would dock at one of three available ports to refuel and load empty canisters. Considering 25 % of the cargo capacity as retaining structure, each lander is capable of returning 900 canisters to the lunar surface. At the reference rate of canister launches, 87 trips per year must be made to the surface averaging one every four days. Three lander docking ports accommodate both an empty and a full lander, as well as an offline lander or manned transport. Several times a year, a shipment of hydrogen would be received and a LLOX load shipped out to LEO or GEO.

The L2 station computer navigation system must be sophisticated enough to track, direct and time the arrival of up to 150 canisters approaching the station simultaneously, and track the station's own position and drift. This number derives from the launch rate, and possible 8 hour arrival time error that a 1 degree launch position error yields. The navigation capability required is thus an inverse function of the mass driver launch accuracy. Subsequent study should better show how to trade these off against each other, and may serve to drive mass driver specifications.

Final close-approach canister maneuvers would be guided by processing units at the base of each RMS; thus the computer handling the canister acquisition must assign each incoming canister to a particular RMS.

The onboard computer would also be needed for the detection of faults and to guide the robots in inspection and repair.

III. Conclusions

By studying in increasing detail all the parts of a LLOX supply system, the total viability of the concept will be identified. Certain critical aspects, including receiving the LLOX in space, require much more work before they can be as well defined as ilmenite reduction and electromagnetic launchers, as part of the overall LLOX transport concept.

While the systems presented here have not yet been optimized, and several trades are yet to be performed, the basic scenario seems workable. It particularly avoids "hard" impact catching methods or net catchers at the L2 station. A "smart" canister, relying on terminal guidance control from the remote L2 station, can be maneuvered and slowed to within the grappling capability of its receiving facility.

References

1. Snow, W.R., Kubby,J.A., and Dunbar, R.S., "A Small Scale Launcher for Early Lunar Material Utilization", SpaceManufacturing Facilities 4, Proceedings of the Fifth Conference, Princeton, NJ, May 18-21, 1981, AIAA, New York

2. Andrew,D.A., and Snow, W.R., "The Supply of Lunar Oxygen to Low Earth Orbit", Space Manufacturing Facilities 4, op. cit.