Architecture Study for a Fuel Depot Supplied from Lunar Resources

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Purpose and Agenda

Purpose: Brief the conference attendees regarding a study effort completed in 2015.

Agenda:

- Basic information
- Architecture options
- Design reference missions (DRMs)
- Boiloff and chilldown loss calculations
- Results, Sensitivity analyses, and Conclusions

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Basic Information

- Research questions
- Study question
- Methodology
- Groundrules and assumptions

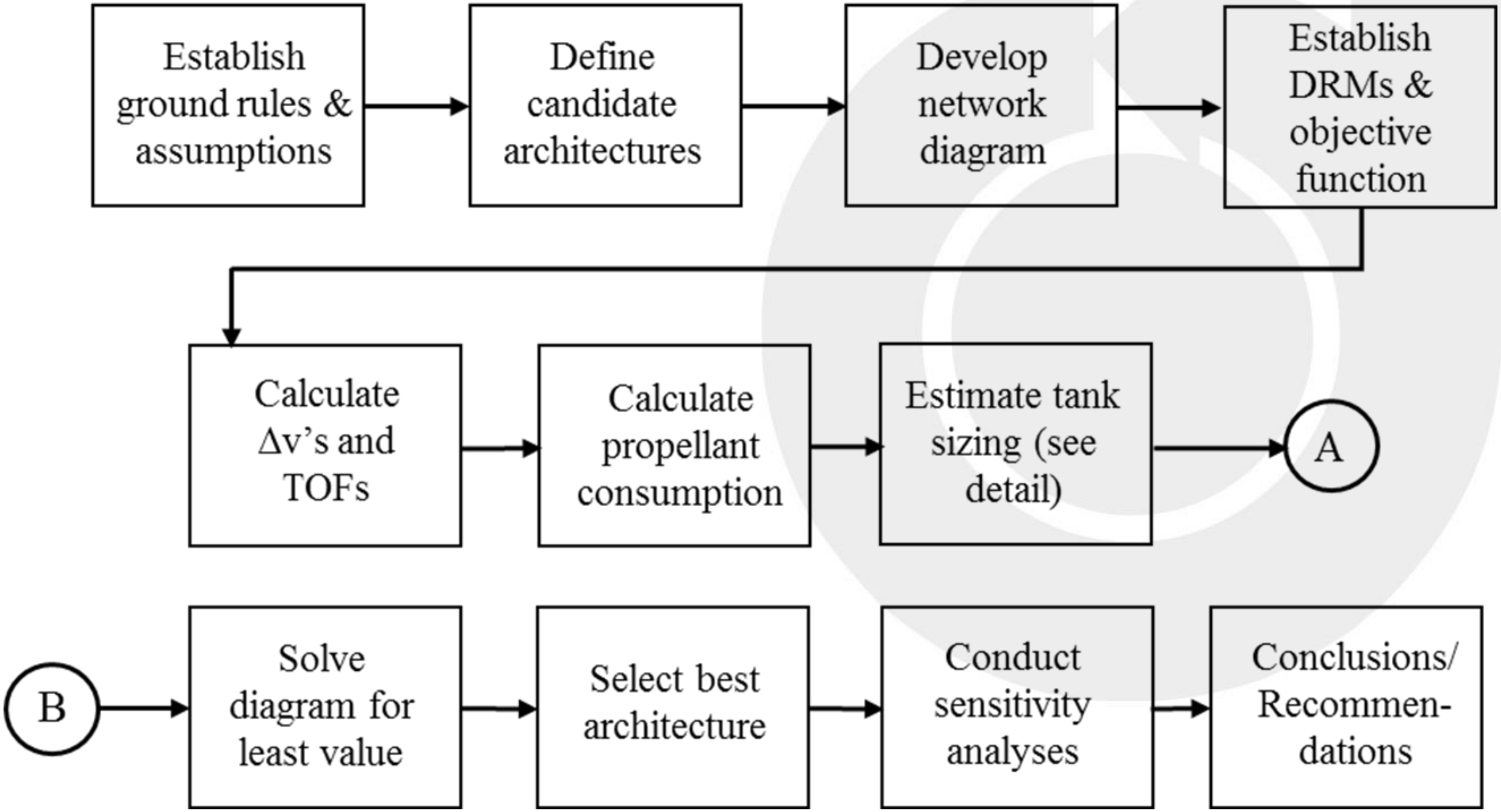
Questions Regarding a Depot Supplied From the Moon

- Where will the processing of lunar water (electrolysis and liquefaction) be performed – on Moon or at the depot?
- Where will the depot be located – On the Moon itself, L1, GEO, LEO?
- Where will fuel transfer be performed?
- What will be the method of fuel transfer?

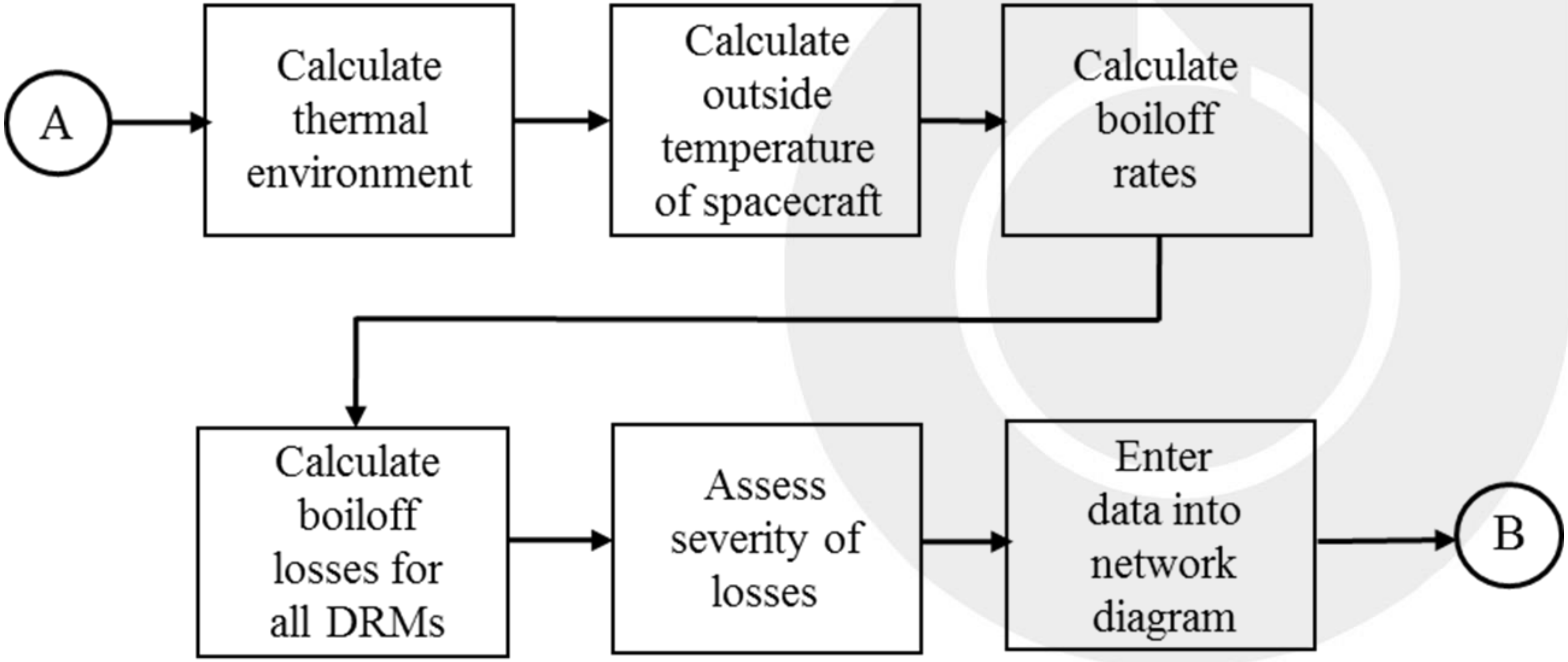
Research Question

What is the optimum architecture for a fuel depot supplied from lunar resources? *That is, which architecture satisfies the Design Reference Missions (DRMs) for the least amount of LO2 and LH2 consumed in flight or lost due to boiloff?*

General Methodology



Calculating Boiloff Losses



Groundrules and Assumptions

- Circular, coplanar orbits for the Earth, Moon, Mars, and depot. Coplanar with the Sun.
- Restricted two-body techniques used for orbital mechanics.
- Assume “zero boiloff” (ZBO) technology (active cooling) is used on the depot.
- The mass of propellant tanks is not considered.
- The amount of time needed to transfer bulk propellants or to exchange propellant canisters is not considered.
- All operations are controlled robotically.
- Except for MCV bulk fuel tanks, all other tanks are spherical.

- Architecture options
- Architecture network diagram
- Objective function

Architecture Defining Parameters and Potential Values

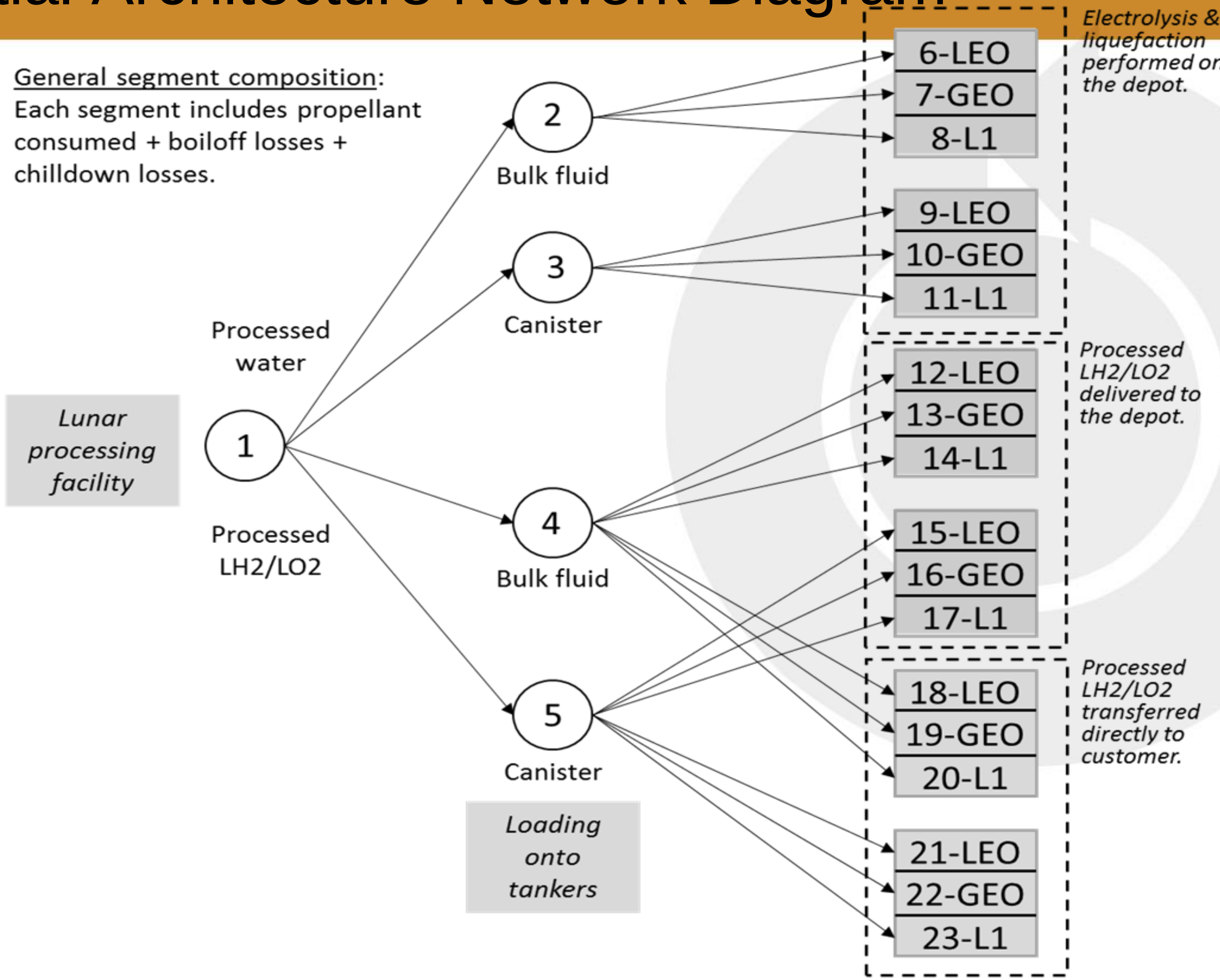
Parameter	Possible Values	Remarks
Location of depots	On Moon, L1, GEO, LEO	Locations mentioned in technical literature.
Location of electrolysis/ liquefaction	On Moon; On-board orbiting depot	Electrolysis is performed daily in microgravity onboard the ISS. The technology is suitable for scaling.
Location of fuel transfer to customer	L1, GEO, LEO	Transfer at depot location, except for Moon.
Method of fuel transfer	Bulk fuel (BF), canister exchange (CX)	Canister exchange would require standardization of tank sizes and connecting hardware.

Candidate Architectures Defined

Location of processing	Location of depot	Location of transfer	Method of transfer	Remarks
In orbit	L1	L1	BF	Water is shipped from the lunar processing facility to the depot. Electrolysis and liquefaction take place on the depot.
In orbit	L1	L1	CX	
In orbit	GEO	GEO	BF	
In orbit	GEO	GEO	CX	
In orbit	LEO	LEO	BF	
In orbit	LEO	LEO	CX	
Moon	L1	L1	BF	Fuel is shipped from the lunar processing facility to the depot.
Moon	L1	L1	CX	
Moon	GEO	GEO	BF	
Moon	GEO	GEO	CX	
Moon	LEO	LEO	BF	
Moon	LEO	LEO	CX	
Moon	Moon	L1	BF	Electrolysis/fuel processing takes place on the Moon, and the depot is also on Moon. A tanker vehicle delivers fuel and oxidizer directly to the customer.
Moon	Moon	L1	CX	
Moon	Moon	GEO	BF	
Moon	Moon	GEO	CX	
Moon	Moon	LEO	BF	
Moon	Moon	LEO	CX	

Initial Architecture Network Diagram

General segment composition: Each segment includes propellant consumed + boiloff losses + chilldown losses.



Architecture Study Objective Function

Objective Function: Minimize: $X_{ijk} = P_{LTV} + B_{LTV} + B_{P/L} + C_{P/L} + P_{CSSV} + C_{CSSV} + B_{CSSV} + P_{MCV} + C_{MCV} + B_{MCV}$

Where X_{ijk} maps to a unique candidate architecture (unique path in the network diagram), and

P_{LTV}	=	Propellant consumed by the LTV
B_{LTV}	=	Boiloff losses of the LTV's own propellant
$B_{P/L}$	=	Boiloff losses for the LTV payload
$C_{P/L}$	=	Chilldown losses transferring the LTV payload to the depot
P_{CSSV}	=	Propellant consumed by the CSSV
C_{CSSV}	=	Chilldown losses when the CSSV receives propellants
B_{CSSV}	=	Boiloff losses on the CSSV
P_{MCV}	=	Propellant consumed by the MCV
C_{MCV}	=	Chilldown losses when the MCV receives propellants
B_{MCV}	=	Boiloff losses on the MCV

- Design reference missions (DRMs)
- Delta-v/Time-of-flight calculations
- Fuel consumption calculations

DRM#1: Commercial Satellite Servicing Vehicle (CSSV)

- In-space vehicle docked at the ISS; periodically resupplied with parts and hydrazine for servicing customer satellites.
- General concept of operations: CSSV departs ISS, achieves GEO orbit, rendezvous with satellites and the CSSV payload robot services/repairs the satellites. CSSV vehicle then maneuvers to the depot, refuels, and returns to the ISS.
- Ten satellites per mission; one mission per month.
- Initial sizing based on publicly available data for the proposed MacDonald-Dettwiler & Associates (MDA) satellite servicer.

CSSV Characteristics

- Dry mass: 4000 kg
- Payload (robotic servicer): 500 kg
- Additional payload: 2000 kg N2H4
- Powered by single RL10B-2 engine; I_{sp} = 465.5 sec
- Mass of fuel developed from delta-v and TOF calculations.

DRM#2: Gov't-sponsored Mars Cargo Vehicle (MCV)

- Based on NASA Exploration Systems Architecture Study (ESAS), which envisioned heavy lift vehicles to pre-position equipment/ habitat/ supplies on Mars prior to crew arrival.
- This MCV is configured like the ESAS EDS configuration to go to the Moon. The EDS was to have been placed in LEO at 200 km circular orbit. After docking with its payload, it would execute trans-lunar-injection (TLI).
- The MCV will be assumed to be placed in LEO. The MCV will dock with its payload, then rendezvous with the fuel depot and refuel, and will depart on its journey to Mars.
- The DRM assumes four vehicles; one vehicle launch every 6 months.

MCV Characteristics

- The MCV will use a conjunction class trajectory from the Earth to Mars, estimated at 288 days.
- The MCV must retain enough fuel to permit a final burn to enter Martian orbit.
- Dry mass: 24,000 kg
- Powered by single J2-X engine; I_{sp} = 449 sec
- Max fuel mass capacity: 250,000 kg
- Remaining fuel mass after launch: 103,350 kg

DRM #3: Lunar Tanker Vehicle (LTV)

- Any fuel depot architecture requires some sort of tanker vehicle(s) to supply the depot with propellant.
- The Lunar Tanker Vehicle (LTV) fills this role.
- The LTVs would be based on the Moon. They would deliver LO2/LH2 or water to the fuel depot, and return to the Moon.
- For a few of the candidate architectures, the LTVs could deliver fuel directly to the CSSV or MCV. These architectures represent the alternative of locating the depot on the Moon.

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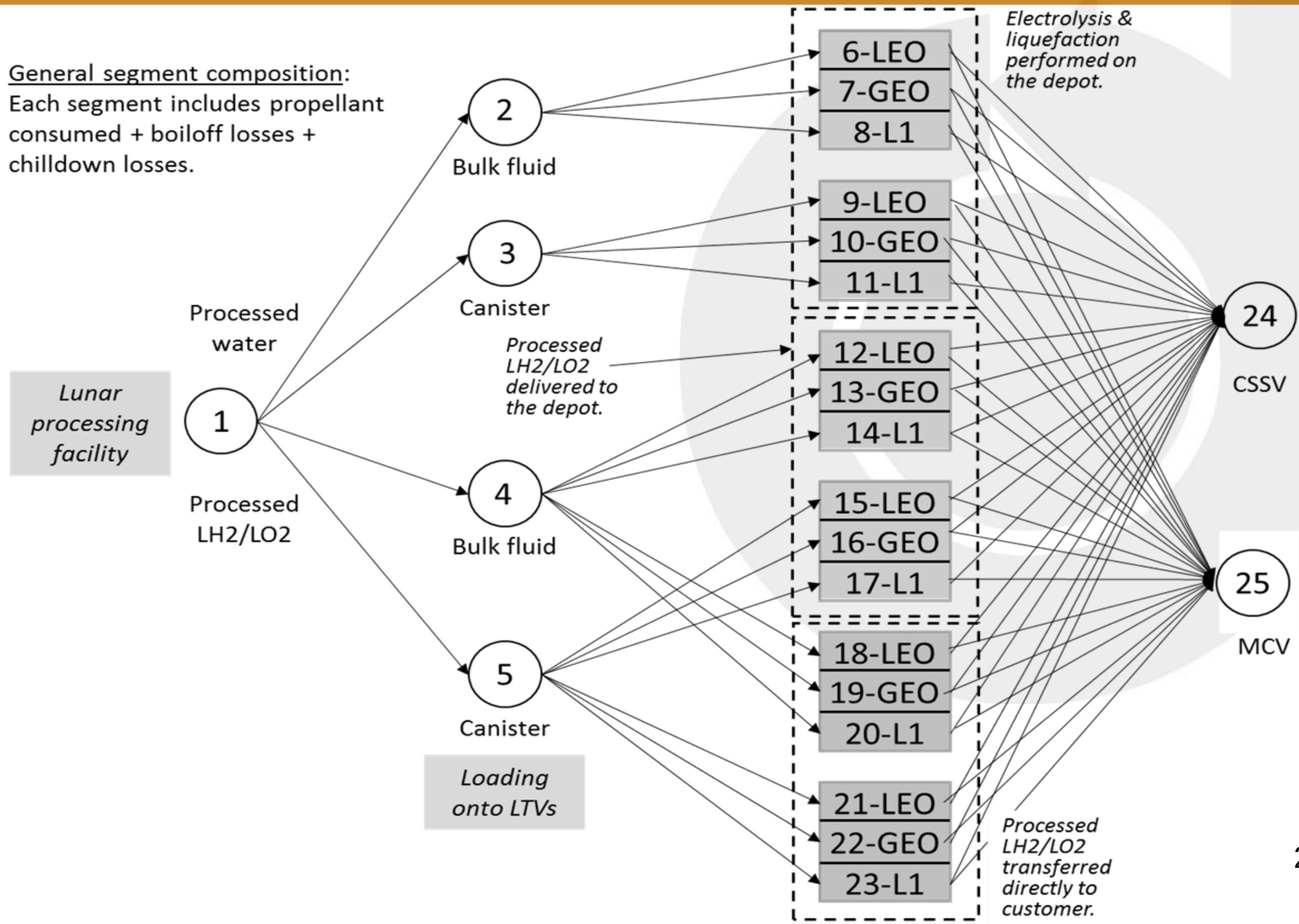
LTV Characteristics

- Dry mass: 22,470 kg (20,000 kg structure + 2,470 kg engine)
- Powered by a single J-2X engine:
  - I_{sp} = 449 seconds
  - Thrust = 1,307 kN (294,000 lbf)
- Max vehicle takeoff weight* = 268,071 kg**

** Includes tanker dry mass, tanker propellant mass, and payload (propellant) mass. Fuel needed by the tanker to deliver to depot/customer and return to the Moon by definition reduces the allowable payload mass.*

*** Based on 3:1 thrust-to-weight ratio.*

Complete Architecture Network Diagram



Delta-v and Time of Flight Calculations

Mission	Delta-v (km/s)	Time of Flight (hrs)
CSSV departs ISS, flies to GEO, services satellites, refuels, and returns to ISS.		
Depot in LEO	17.695	226.7
Depot in GEO	13.902	237.9
Depot in L1	12.301	420.3
MCV flies to depot from its LEO parking orbit, refuels, and departs for Mars.		
Depot in LEO	9.559	0.74 + travel to Mars[1]
Depot in GEO	8.569	17.2 + travel to Mars[1]
Depot in L1	8.107	92.1 + travel to Mars[1]
LTV departs Moon, travels to depot/customer, transfers fuel, and returns to Moon.		
Depot in LEO	14.605	241.5
Depot in GEO	9.899	284.3
Depot in L1	4.684	131.3
Notes: [1] 288 days (conjunction class trajectory)		

Fuel Consumption

Vehicle	Depot in LEO	Depot in GEO	Depot at L1
CSSV Fuel Required (kg) [1]	243,621	110,229	77,803
CSSV Payload (kg)	2,500	2,500	2,500
MCV Fuel Required (kg) [2]	191,075	102,740	126,978
MCV Payload (kg)	48,850	38,600	52,000
LTV Fuel Required (kg)	571,796 [3]	231,065	126,320
LTV Payload (kg)	---	14,520	119,275

Notes:

[1] CSSV fuel is that needed for one mission – departing from the ISS, servicing satellites, refueling, and returning to the ISS.

[2] MCV fuel is that needed to depart LEO and refuel at the depot, perform TMI to Mars, and have enough fuel remaining to enter Martian orbit. The fuel remaining after achieving initial LEO orbit limits the payload that can be taken forward.

[3] LTV fuel required to deliver in LEO is greater than its total lift capacity.

Fuel Consumption Implications

- LTV propellant delivery
- LTV Capacity to Service CSSV & MCV
- Fuel depot sizing
- LTV flights to support the depot

LTV Propellant Delivery Calculations

Depot Location	LTV Fuel Required (kg)	Qty Fuel Delivered (kg)	Remarks
LEO	571,796*	---	Amount of fuel needed for round trip exceeds capacity of LTV.
GEO	231,065	14,520	LTV uses more fuel than it delivers
L1	126,320	119,215	LTV uses more fuel than it delivers

**LTV max capacity (fuel + payload) = 245,601 kg*

LTV Capacity to Service CSSV and MCV

DRM	Fuel Needed for mission (kg)	Mass LTV can deliver (kg)	Remarks
Commercial Satellite Servicing Vehicle (CSSV)			
Depot in LEO	243,621	---	LTV cannot service CSSV/depot in LEO.
Depot in GEO	110,229	14,520	LTV capacity is less than fuel required; impractical to service CSSV directly.
Depot in L1	77,803	119,275	LTV capacity is greater than fuel required; can service the depot or CSSV directly.
Mars Cargo Vehicle (MCV)			
Depot in LEO	191,075	---	MCV has enough fuel remaining after launch to fly to a depot in LEO, but LTV cannot service MCV or depot in LEO.
Depot in GEO	102,740	14,520	LTV capacity is less than fuel required; impractical to service MCV directly.
Depot in L1	126,978	119,275	LTV capacity is less than fuel required; impractical to service MCV directly.

Fuel Depot Sizing

Depot Location	CSSV Fuel Required (kg)	MCV Fuel Required (kg)	Suggested Depot Size/ Remarks
LEO** (400 km/0 Deg)	243,621 (once per month)	191,075 (once every 6 months)	434,696 kg, based on having to fuel both vehicles every 6th month.
GEO	110,229 (once per month)	102,740 (once every 6 months)	212,969 kg, based on having to fuel both vehicles every 6th month.
L1	77,803 (once per month)	126,978 (once every 6 months)	204,871 kg, based on having to fuel both vehicles every 6th month.

*** It has been shown that the LTV is not capable of servicing a customer vehicle or depot in LEO. The fuel needed for the round trip exceeds the total lift capacity of the vehicle, even with no payload.*

LTV Flights to Supply the Depot

Depot Location	DRM-driven throughput (kg) per 6 months	Mass LTV can deliver per flight (kg)	Raw number of flights to service the depot
LEO*	1,653,401	---	---
GEO	764,114	14,520	52.625 → 53
L1	596,796	119,275	5.003 → 6

** It has been shown that the LTV is not capable of servicing a customer vehicle or depot in LEO. The fuel needed for the round trip exceeds the total lift capacity of the vehicle, even with no payload.*

- Boiloff Calculations
- Chilldown Calculations

Thermal Environment

Heat (Watts/m^2)	LEO	GEO	L1
- Solar heating	1,367	1,367	1,367
- Earth emitted infrared	350.3	9.1	0.16
- Earth reflected heating	444.2	11.5	0.20
Total (Watts/m^2) [1]	2,161.5	1,387.6	1,367.36

Notes:

[1] This represents the energy deposited on the cross section of the spacecraft propellant tanks.

Tank Sizing

Delivery Location	Delivery Method	LTV Propellant	LTV Payload	CSSV	MCV
LEO	(ALL)	The LTV cannot service the CSSV, MCV, or depot in LEO. The round trip from the Moon to LEO takes more fuel than it carries.			
GEO	BF	LH2: 4.80 m LO2: 3.41 m	LH2: 1.91 m LO2: 1.36 m	LH2: 3.75 m LO2: 2.66 m	LH2: 10 x 6.36m LO2: 10 x 2.29m
	CAN	LH2/LO2: 1.35 m			
L1	BF	LH2: 3.92 m LO2: 2.79 m	LH2: 3.85 m LO2: 2.73 m	LH2: 3.34 m LO2: 2.37 m	LH2: 10 x 6.41m LO2: 10 x 2.29m
	CAN	LH2/LO2: 1.35 m			

Propellant Boiloff Calculations

Step 1: Outside temperature of a propellant tank is calculated as follows*:

$$\sigma T^4 = [(\alpha/\varepsilon)(S) + (\alpha/\varepsilon)(RH) + E] \times (A_p/A)$$

where

T	=	spacecraft temperature (K)
σ	=	Boltzmann's constant = 5.67051×10^{-8} W/m^2T^4
α	=	absorptivity *(= 0.14 for outer layer of MLI)*
ε	=	emissivity *(= 0.6 for outer layer of MLI)*
S	=	solar constant (1,367 W/m^2)
RH	=	Earth-reflected heating
E	=	Earth infrared
A_p	=	projected area of the propellant tank
A	=	total surface area of the propellant tank

* *Adapted from Wertz, J. and Larson, W. (Eds.) Space Mission Analysis and Design, 3d Ed. New York: Springer, 1999, p.435.*

Propellant Boiloff Calculations, cont.

Step 2: The temperature determined in Step 1 is used as T_h in the "Modified Lockheed Model"*

$$q = 0.00024*(0.017+7E\text{-}6(800-T) + 0.0228*\ln(T))*(N^*)^{2.63}(T_h-T_c)/N_s$$

$$+ 4.944E\text{-}10*\varepsilon*(T_h^{4.67}-T_c^{4.67})/N_s + 1.46E4*P*(T_h^{0.52}-T_c^{0.52})/N_s$$

Where
- q = heat transfer rate
- ε = emissivity of the inner layers of MLI = 0.035
- T_h = temp on outside tank surface
- T_c = propellant temperature
- T = $(T_h+T_c)/2$
- N^* = number of layers/cm of MLI
- N_s = number of layers of MLI, and
- P = pressure between layers of MLI

* *NASA/TM –2004–213175: Analytical Modeling and Test Correlation of Variable Density Multilayer Insulation for Cryogenic Storage, p. 25.*

Chilldown Loss When Transferring Propellant

- When transferring cryogenic propellants, the transfer pipe must be chilled. This is accomplished by filling the line with the cryogen and allowing it to boil off, thus cooling the line. The mass of the sacrificed cryogen is equal to the volume of the transfer pipe times the density of the cryogen.
- For this study, a 0.1 m diameter transfer pipe 10 meters long was assumed.

Volume = $\pi r^2 h$, where h = length of the pipe
Transfer loss (LH2) = π x $(.05m)^2$ x 10m x 70.99 kg/m^3 = 5.6 kg
Transfer loss (LO2) = π x $(.05m)^2$ x 10m x 1191.6 kg/m^3 = 93.6 kg

- Results
- Sensitivity analyses
- Conclusions

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Results

Architecture/ LTV Flights	Location of transfer	Method of transfer	Propellant Spent (kg)	Boiloff Losses (kg)	Chilldown Losses (kg)	Total Pro-pellant (kg)
1-2-8/ 6 (water)	L1	BF	1,225,396	2,162	696	1,228,254
1-4-14/ 6	L1	BF	1,225,396	2,217	1,292	1,228,905
1-5-17/ 6	L1	CX	1,267,347	4,857	0	1,272,203
1-3-11/ 6 (water)	L1	CX	1,270,350	4,739	0	1,275,088
1-4-20/ 7 DD	L1	BF	1,308,801	2,236	794	1,311,830
1-5-23/ 7 DD	L1	CX	1,362,925	4,908	0	1,367,832
1-2-7/ 53 (water)	GEO	BF	13,010,559	5,464	696	13,016,719
1-5-16/ 53	GEO	CX	13,010,559	8,023	0	13,018,582
1-4-13/ 53	GEO	BF	13,010,559	5,736	5,953	13,022,248
1-3-10/ 74 (water)	GEO	CX	16,991,500	8,974	0	17,000,474

Statistics

Candidate Architecture	LTV losses % fuel consumed	CSSV losses % fuel consumed	MCV losses % fuel consumed	Boiloff % fuel consumed	Boiloff % fuel shipped
1-2-8 BF H2O L1	0.015%	0.260%	1.220%	0.233%	0.481%
1-4-14 BF prop L1	0.015%	0.260%	1.220%	0.286%	0.591%
1-5-17 CX prop L1	0.015%	0.327%	2.438%	0.364%	0.821%
1-3-11 CX H2O L1	0.016%	0.327%	2.438%	0.357%	0.798%
1-4-20 BF DD L1	0.013%	0.260%	1.298%	0.231%	0.510%
1-5-23 CX DD L1	0.017%	0.327%	2.438%	0.360%	0.826%
1-2-7 BF H2O GEO	0.027%	0.203%	1.491%	0.047%	0.806%
1-5-16 CX GEO	0.027%	0.293%	2.380%	0.062%	1.050%
1-4-13 BF GEO	0.027%	0.202%	1.491%	0.090%	1.530%
1-3-10 CX H2O GEO	0.028%	0.293%	2.380%	0.053%	1.174%

Sensitivity Analyses

- Sensitivity analyses were performed in two areas:

  -- LTV with two engines, instead of one (LTV2)

  -- Investigated boiloff results for 30 layers of MLI instead of 60 (MLI-30)

LTV2

- Two J-2X engines; thrust doubled from 1,307 kN to 2,614 kN
- Dry mass increased from 22,470 kg to 34,940 kg
- Max lift increased from 245,601 kg to 501,202 kg
- GEO flights reduced from 53 to 18.

  L1 flights reduced from 5 to 3.
- Losses from boiloff and chilldown reduced (fewer flights)
- Overall fuel consumption across all architectures: no significant change.

MLI-30

- Focused on CSSV and MCV fuel tanks.
- Reduced MLI from 60 layers to 30 layers.
- Calculated the change in boiloff mass and the change in MLI mass and compared the two.
- In both cases (BF and CX), the increase in boiloff losses was significantly less than the decrease in MLI mass:
  - BF: 2,066 kg increase in boiloff <<3,945 decrease in MLI mass
  - CX: 4,622 kg increase in boiloff << 8,976 decrease in MLI mass
- Further investigation is needed to determine the best compromise between predicted boiloff and MLI mass.

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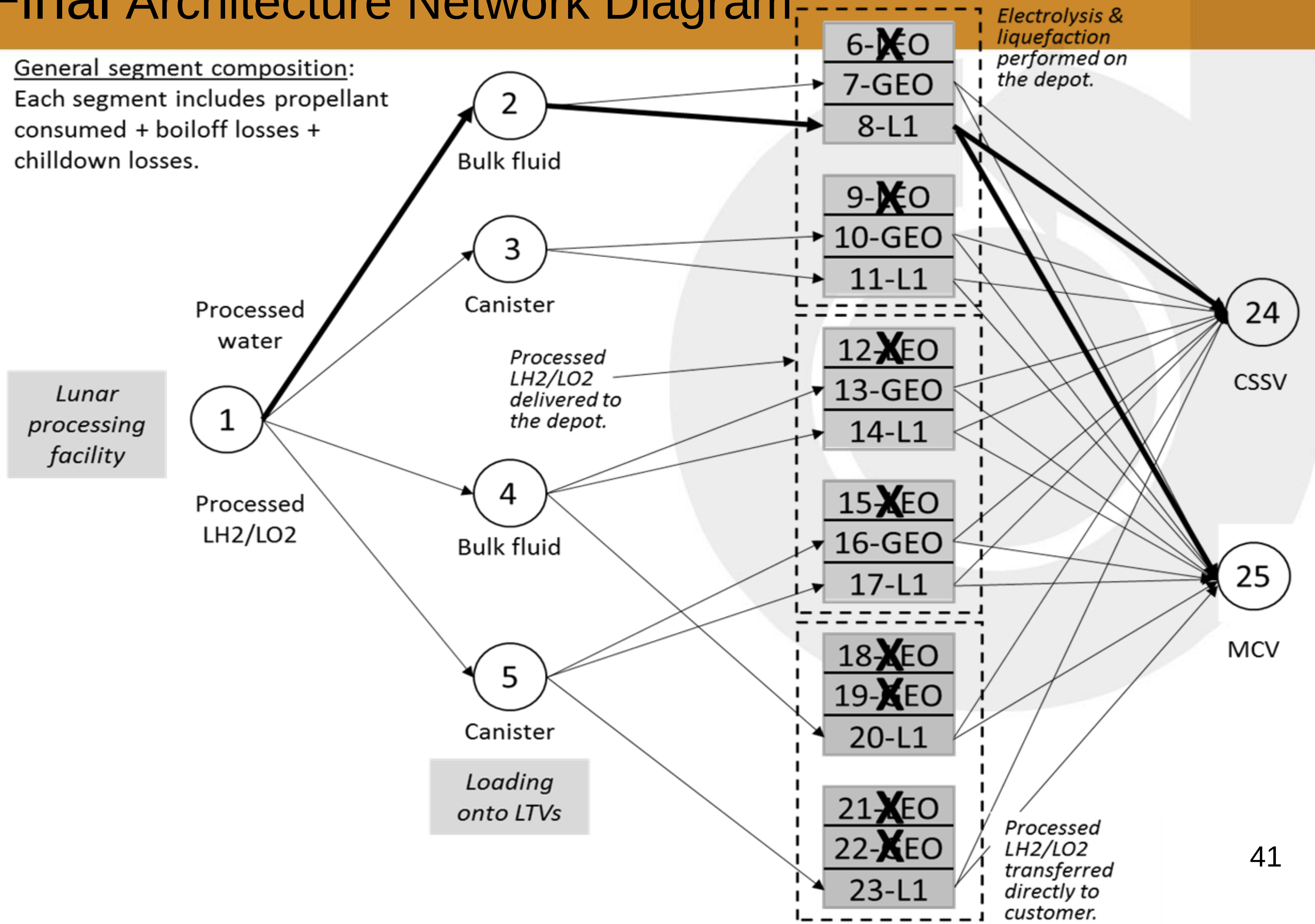
Final Architecture Network Diagram

General segment composition: Each segment includes propellant consumed + boiloff losses + chilldown losses.



Conclusions

- Of the potential methods for judging candidate architectures, calculating fuel consumption and losses gives the greatest credible insight into potential fuel depot operations.
- Earth-Moon L1 is the best location for an orbiting depot (thesis statement unsupported); Low Earth Orbit is not a viable location for a depot supplied from the Moon.
- Boiloff would not be the primary factor in choosing among competing architectures.

Conclusions, cont.

- For the propellant tank configurations used, and the fuel transfer pipe dimensions of 10 meters by 0.1 meters, canister fuel tanks appear to offer a competitive alternative to bulk fuel transfers.
- The use of canisters often limits the use of the full payload capacity of the host vehicle.
- Optimization of the DRM vehicles for their assigned tasks is both possible and necessary.

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