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Integration of Expected Extraterrestrial Resources Into the Design of Space Transportation Systems

An evaluation of the benefits derived from the utilization of lunar materials as propellants for space systems is based on a logistics study. Various methods and opportunities to supply the materials required by a space program at various locations in space are examined. These include a number of different propellants with several sources and manufacturing processes as well as modes of delivery. The requirements are resolved into launch requirements from Earth and are used as a basis for comparing the alternatives that may be available. The paper integrates the results of previous mission analyses with logistics studies and treats a number of cases, some of which are shown to be promising.

INTRODUCTION

Potential value of lunar material as a source of propellant for space transportation systems is a function of three unknowns:

(1) The resources available on the Moon.

(2) The transportation system that will use the propellant.

(3) The space program of the era during which it first becomes feasible to use lunar material.

In view of the unknowns, any plan made today to exploit lunar material will probably be wide of the mark. However, it is not too early to explore the possibilities, because these can justify and guide the exploratory phase of the lunar program in which we find ourselves today. The Moon's geological history is quite different from that of the Earth, and as a consequence materials suitable for propellant manufacture are apt to differ greatly from material from Earth. Some possibilities are:

(1) Crater bottoms and caves near the poles of the Moon could be very cold, and deposits of ice, solid carbon dioxide, ammonia, etc., could have collected there. There is also the possibility of large permafrost areas containing subsurface ice.

(2) Pockets of helium produced as a radioactive decay product could occur in the interior.

(3) Water of crystallization might be present in certain materials.

(4) Volcanos may still be active, and emissions of water, ammonia, hydrogen sulfide, etc., could supply needed raw materials.

(5) Minerals that do not occur naturally on the Earth might be a suitable propellant source. Metallic compounds, for example, could be better than water as a source of hydrogen.

(6) Basaltic-type materials, whose presence is indicated, could be processed.

(7) Many surface rocks appear highly porous, and the voids are most likely filled with gases (ref. 1).

In view of the uncertainties, this paper will treat many possibilities and will indicate the circumstances under which use of lunar propellant sources will become profitable. In making effectiveness evaluations of propulsion systems based on extraterrestrial resources, one must account for—

(1) Propulsion performance as calculated from specific impulse, structure factors, boiloff, and fuel transfer requirements.

(2) Materiel requirements that support manufacture, storage, and transportation of the propellant to the point in space where it will be used. Production efficiency will depend heavily on the quantities produced.

(3) Facilities to support personnel that include materials, transport, and erection.

(4) Cost of recovery of the propulsion system and the propellant tanks used in delivery from lunar sources.

Methods for evaluating Earth-based systems treat these items independently. This cannot be done here because the most likely benefit comes from lowering the transportation cost listed under (2) above. This must be traded off against degraded values in almost all the other categories. It will also be seen that the possible benefits are highly dependent on the types and numbers of space flights. Therefore the evaluation will be done in the context of a number of scenarios depicting possible space programs of the future.

Much background information on the subject is given in references 1 to 9.

MISSION DESCRIPTIONS

The analysis will be made in the context of two basic space missions with variations given of each. The first is a manned planetary voyage with the spacecraft assembled in Earth orbit. We are not too concerned with what happens at the destination planet or with the details of the spacecraft or its payload. We are concerned with—

(1) The weight breakdown of the space transportation system

(2) Propellants that can be provided from lunar sources and the associated operations.

(3) Assembly and logistic weight burdens.

The other basic mission is the establishment of a lunar base and its resupply. The possibility of using lunar resources for the propulsion of a shuttle is to be investigated and compared with a wholly Earth-based propellant supply.

Much attention will be paid to the method of analysis, and it is convenient to treat both missions in terms of a single framework. Therefore, consider a mission composed of the following maneuvers (see fig. 1):

1. A launch from the Earth's surface E delivering a payload to a rendezvous point R.

2. A launch from the Earth's surface E to the lunar surface L.

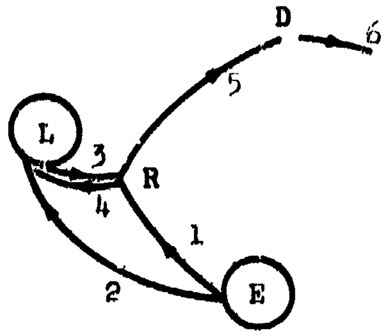

FIGURE 1.—Schematic of maneuvers.

3. Transportation of supplies (propellant) from the lunar surface L to the rendezvous point R.

4. Return from the rendezvous point R to the lunar surface L.

5. A flight from the rendezvous point R to the destination D, which would be either the vicinity of the planet or a return to Earth.

6. A further maneuver (possibly capture by the planet).

In reference 2, it was shown that the cislunar libration point is well suited for the rendezvous point R, and the high-orbit rendezvous to be treated herein can be considered to take place at this point.

The following notation will be used:

N	The maneuver number, $N=1, 2, 3, 4, 5, 6$
W_{PN}	Weight of payload on maneuver N
W_{PRN}	Weight of propellant on maneuver N
W_{VN}	Weight of vehicle (dry) on maneuver N
W_{TN}	Weight of propellant tanks (dry) on maneuver N
W_{BN}	Weight of burden on maneuver N; a part of W_{PN} (the burden consists of tools and supplies needed for an assembly operation performed after the maneuver)
W_{FN}	The final weight of system after maneuver N; $W_{PN}+W_{VN}$
K_N	The ratio $W_{VN}/W_{PRN}=(W_{FN}-W_{PN})/W_{PRN}$
K'_N	Ratio W_{TN}/W_{PRN}

$H_{1,8}$ Ratio W_{M1}/W_{PM}

a Rate of propellant manufacture needed to supply this mission divided by the rate of propellant manufacture needed to supply all users

M Weight of mining and processing equipment needed to produce propellant

b Logistic requirements needed for propellant manufacture divided by logistic requirements needed for all activities of the base

L Weight of all logistic requirements of the lunar base (so bL is the weight prorated to propellant manufacture)

ΔV_N Change in velocity requirement by maneuver N

I_{SPN} Specific impulse of propulsion system used in maneuver 4.

We shall use set theoretic notation as follows:

$P3 \cap PR5$ that part of the payload P of maneuver 3 that is propellant PR for maneuver 5.

Then the compositions of the transportation systems used on the maneuvers have the appearance shown in figure 2.

The payload weights to be delivered are:

Type	Frequency, mo/yr	Payload, lb
Planetary	1	200,000.
Lunar shuttle	12	28,000 to Moon. 3,000 to Earth.

The planetary payload is an average derived from many studies of a Mars capture mission, and the lunar shuttle is intended to supply a 30-man base.

In figure 2, note that the payload for maneuver 1 is composed of—

(1) Part of the payload $P4$ for maneuver 4
(2) The burden $B1$ (assembly expendables)
(3) The vehicle (dry) for maneuver 5
(4) The payload for maneuver 5

The horizontal separation of the payload of maneuver 2 indicates that the vehicles $V3$ and $V4$, the mining and processing equipment M, and the logistic resupplies L are to be shared with missions other than the one under consideration.

We are faced with some 77 parameters or variables, of which 16 are input parameters and the others are to be calculated. In view of the uncertainty as to resource availability, the many alternative routes that the national space program may follow, and the technology of the era, a narrative encompassing all the situations worthy of analysis would fill a book. Instead of this, table 1 is presented as an overview of the factors influencing the missions (and, hence, influencing the input parameters, which for present purposes describe the mission).

In the same way, table 2 takes the place of a description of all the parameters, their significance, and how their values may be influenced by the inputs.

The analytic methods are a combination of straightforward space flight mechanics, some algebra, and logistic computations. Considerable use was made of the relations derived in reference 2 for the flight mechanics and in reference 3 for the logistics.

Maneuvers 3, 4, 5, and 6 are analyzed with the use of the rocket equation. For maneuver 5, for example, the weight of the initial system

$$W_{15}=W_{P5}\exp(\Delta V_5/gI_{SP5}) \quad (1)$$

Then

$$W_{PM5}+K_5W_{PM5}+W_{P5}=(K_5W_{PM5}+W_{P5})\exp(\Delta V_5/gI_{SP5})$$

where

$$K_N=(W_{FN}-W_{PN})/W_{PMN} \quad (2)$$

and so

$$W_{PM5}=\Phi(5)W_{P5} \quad (3)$$

where one uses the abbreviated notation

$$\Phi(N)=\frac{\exp(\Delta V_N/gI_{SPN})-1}{1+K_N-K_N\exp(\Delta V_N/gI_{SPN})}$$

Requirements for maneuver 6 are calculated in exactly the same way. When velocity requirements are given in terms of hyperbolic excess speeds, the charts in reference 2 can be used.

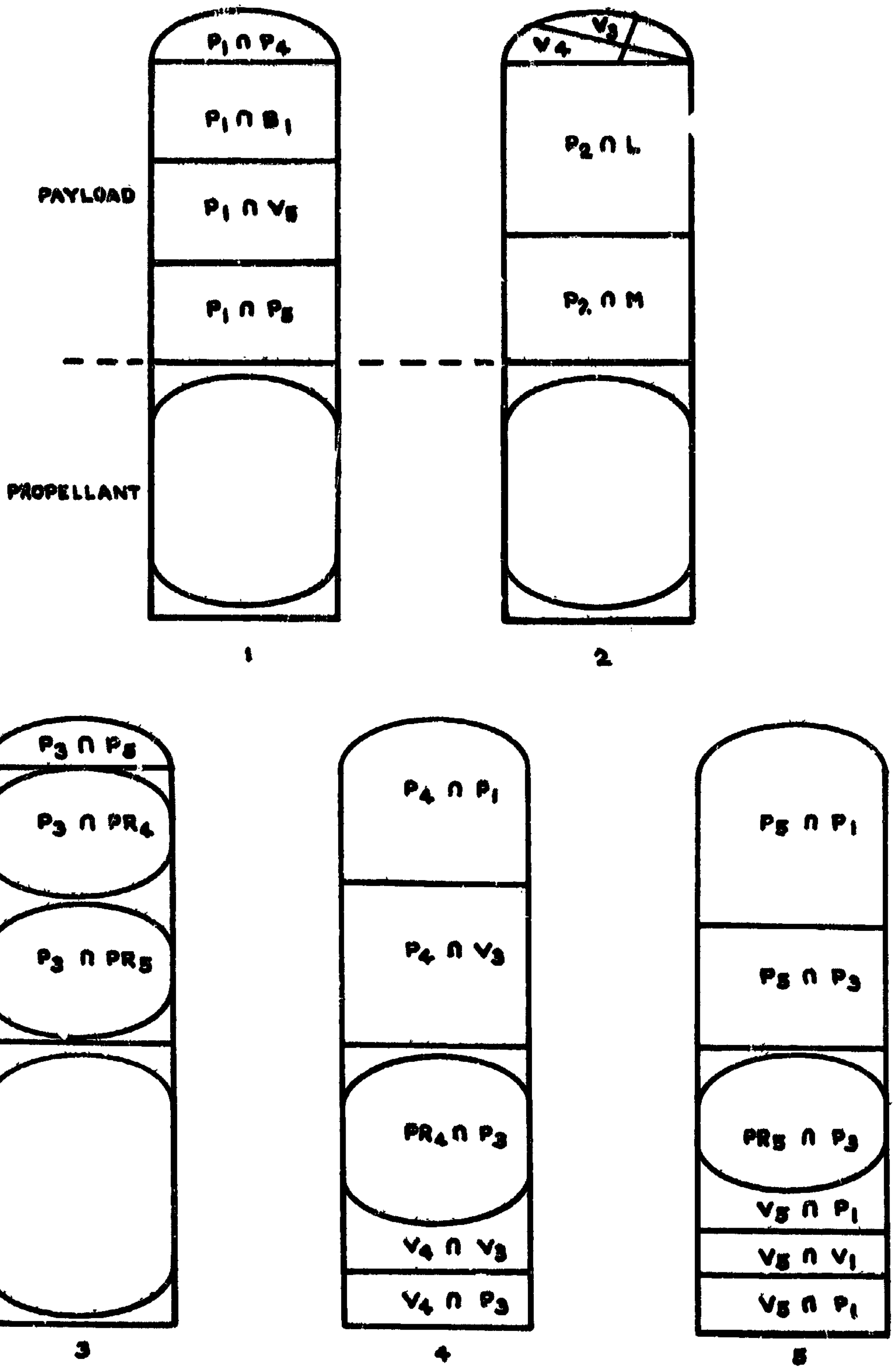

FIGURE 2.—Payload distribution.

TABLE 1.—*Input Parameters*

Uncertainty	Parameters	Symbols	Remarks
Space program level of activity.	Mission-dependent factors.	W_{P5}	Large value for ambitious manned planetary mission, additional maneuvers.
		ΔV_1 to ΔV_6	Depends on rendezvous point, destination, lunar launch site, etc. Large for fast missions.
	Space-program-dependent factors.	a	Small if resource is used widely in addition to use for propellant by this mission.
		b	Small if propellant manufacture is small part of total lunar effort.
		M	Increases with rate of propellant production. Large for difficult or inefficient processes. (Silicate reduction).
		L	Increases with size of lunar base.
		W_{P4}, W_{P5}	Increases with size of lunar base.
Era during which mission takes place.	Propulsion technology.	I_{SP1} to I_{SP5}	Large for a variety of nuclear developments.
			Small for low-performance propellants such as H_2O, NH_3.
	Design	K_1 to K_5; K'_1, K'_4 K'_5	Small for efficient design, advanced materials. Large for nuclear systems, artificial gravity.
	Mining and processing technology.	M	Small for efficient processes of fluid handling as opposed to solids. Make use of vacuum. Depends strongly on resource availability.
			Small for automated processes.
	Space operations	$H_{1,2}$	Small for efficient assembly, propellant transfer.
Resource availability.	Mining and processing technology.	M, b	Small for readily available, readily usable materials.

TABLE 2.—*Mission Parameters*

Symbol	Represents—	Maneuver	Significance	Influenced by—	Equation
W_{P1}	Payload weight	1	Relates to number of space vehicle launches required.	Choice of R, W_{P4}, assembly needs.	(15)
W_{P2}	Payload weight	2	Relates to number of space vehicle launches required.	Prorating among lunar base activities; processing and mining weight M.	(12)
W_{P3}	Payload weight	3	Focus of study	Propellant needs at R; Moon-to-Earth traffic rate.	(4)
W_{P4}	Payload weight	4	Tank recovery lunar transport.	Structural efficiency; base resupply rate.	(5)
W_{P5}	Payload weight	5	Scopes mission	Mission objectives; payload delivered to destination.	Input
W_{PR3}	Propellant weight	3	Tradeoff variable	Transportation system I_{SP}, ΔV, boiloff, leakage, cooldown.	(8)
W_{PR4}	Propellant weight	4	Recovery penalty	Transportation system I_{SP}, ΔV, boiloff, leakage, cooldown.	(7)
W_{PR5}	Propellant weight	5	Focus of study	Transportation system I_{SP}, ΔV, boiloff, leakage, cooldown.	(3)

TABLE 2.—*Mission Parameters*—Continued

Symbol	Represents—	Maneuver	Significance	Influenced by—	Equation
W_{F3}	Final weight (dry)	3	Weight delivered to *R* from Moon.	Degree of automation, propellant transfer methods.	
W_{F4}	Final weight (dry)	4	Shuttle system weight landed on Moon.	Degree of automation, propellant transfer methods, tank structure.	
W_{F5}	Final weight (dry)	5	Mission effort	Payload, structural efficiency, propellant density, insulation.	
W_{I3}	Initial system weight.	3	Launch weight from Moon.	Propellant requirements of final mission manuevers.	(1)
W_{I4}	Initial system weight.	4	Moves back to Moon.	Lunar shuttle, tank recovery scheme.	(1)
W_{I5}	Initial system weight.	5	Orbital launch weight.	Fixed by mission and choice of transportation system, boiloff.	(1)
K_3	Empty vehicle to propellant ratio.	3	Accounts for structural weight.	Design efficiency, propellant density, max. acceleration, insulation engine size.	(2)
K_4	Empty vehicle to propellant ratio.	4	Accounts for structural weight.	Design efficiency, propellant density, max. acceleration, insulation engine size.	
K_5	Empty vehicle to propellant ratio.	5	Accounts for structural weight.	Design efficiency, propellant density, max. acceleration, insulation engine size.	(2)
W_{B1}	Weight used in assembly at *R*.	1	Part of Earth lift-off weight.	Assembly methods, degree of modularity.	
K'_4	Ratio of propellant tank weight to propellant weight.	4	Determines payload for maneuver 3.	Design, propellant density, insulation.	(4)
K'_5	Ratio of propellant tank weight to propellant weight.	5	Determines payload for maneuver 3.	....	(4)
$H_{1,5}$	The ratio W_{B1} to W_{PR5}.	1	Payload on 1 can be related to propellant on 5.	Assembly operations at *R*	(15)
a	The ratio of propellant used in this mission to all propellant produced by the base.	....	Prorates mining and processing equipment.	Level of lunar-base activity using resource, other missions using resource.	(13)
b	Logistic requirements ratio propellant production to total.	....	Prorates logistic weights transported to Moon.	Overall lunar activity; manpower required for propellant production.	(13)
M	Weight of supplies sent to Moon.	2	Weight delivered to Moon.	Type of production process, rate of production.	(12)
L	Weight of supplies sent to Moon.	....	Weight delivered to Moon.	Lunar-base activity	(13)
ΔV_1	Change in velocity	1	Energy requirement	Assembly point *R*	Input
ΔV_2	Change in velocity	2	Energy requirement	Location of lunar base *L*	Input
ΔV_3	Change in velocity	3	Energy requirement	*R* and *L*	Input
ΔV_4	Change in velocity	4	Energy requirement	*R* and *L*	Input
ΔV_5	Change in velocity	5	Energy requirement	*R* and mission final destination *D*.	Input

TABLE 2.—*Mission Parameters*—Continued

Symbol	Represents—	Maneuver	Significance	Influenced by—	Equation
I_{SP1}	Specific impulse	1	Determine propellant weight.	Propulsion system technology.	Input
I_{SP2}	Specific impulse	2	Determine propellant weight.	Propulsion system technology.	Input
I_{SP3}	Specific impulse	3	Determine propellant weight.	Type of resource available	Input
I_{SP4}	Specific impulse	4	Determine propellant weight.	Type of resource available	Input
I_{SP5}	Specific impulse	5	Determine propellant weight.	Type of resource available	Input

The payload for maneuver 4 includes the vehicle for maneuver 3 and the payload of maneuver 3 contains the tanks and propellant for maneuver 4. Consequently a pair of simultaneous equations must be solved. Consider first the case where the tanks carrying propellant for maneuver 5 are not returned to the Moon but become part of vehicle $V5$.

$$W_{P3}=W_{PR4}+W_{T4}+W_{PR5}+W_{T5}=(1+K_4')W_{PR4}+(1+K_5')W_{PR5} \quad (4)$$

where

$$K_4'W_{PR4}=W_{T4}$$

Also

$$W_P=W_{T3} \quad (5)$$

Using the rocket equation again

$$W_{PR3}=\Phi(3)W_{P3}=\Phi(3)[(1+K_4')W_{PR4}+(1+K_5')W_{PR5}]$$

and assuming $K_4'=K_5'$ (i.e., the same structure factor for the two maneuvers)[1]

$$W_{PR3}=\Phi(3)(1+K_4')(W_{PR4}+W_{PR5}) \quad (6)$$

and if the tanks carrying propellant for maneuver 5 become part of vehicle 5

$$W_{PR4}=\Phi(4)W_{P4}=K_3'\Phi(4)W_{PR3} \quad (7)$$

Then substituting equation (7) into equation (6) and setting $K_3'=K_4'$.[1]

[1] This assumes that the ratios of tank to propellant weights are the same for maneuvers 3, 4, and 5; this is not a bad assumption since the propellants are the same in each case.

$$W_{PR3}=\frac{\Phi(3)(1+K_4')}{1-(1+K_4')K_3'\Phi(3)\Phi(4)}$$

$$W_{PR5}=\frac{(1+K_3')\Phi(3)\Phi(5)}{1-(1+K_3')K_3'\Phi(3)\Phi(4)}W_{P5} \quad (8)$$

If the tanks carrying propellant for maneuver 5 are returned to the Moon (and the propellant is transferred to other tanks), instead of equation (5), we have $W_{P4}'=W_{T3}+W_{T5}$, and, instead of equation (7), we have, using W_{PR3}' as the new propellant for maneuver 3,

$$\begin{aligned} W_{PR4}' &= \Phi(4)(W_{T3}+W_{T5}) \\ &= \Phi(4)(K_3'W_{PR3}'+K_5'W_{PR5}) \\ &= K_3'\Phi(4)(W_{PR3}'+W_{PR5}) \end{aligned} \quad (9)$$

Setting $K_3'=K_4'$ and $\Phi(3)=\Phi(4)$ (the return trip has the same ΔV, I_{SP}, and K factor), we get instead of equation (8)

$$W_{PR3}'=\Phi(3)(1+K_3')\frac{1+K_3'\Phi(3)}{1-(1+K_3')K_3'\Phi(3)}2$$

$$W_{PR5}=[1+K_3'\Phi(3)]W_{PR3} \quad (10)$$

which is a convenient form because we intend to calculate W_{PR3} prior to W_{PR3}'.

If additional payload W_{P4} is delivered on maneuver 4 in addition to the return of tanks W_{T3} and the shuttle W_{V3}, equation (10) becomes

$$W_{PR3}''=\frac{\Phi(3)\{(1+K_3')[\Phi(4)(K_3'W_{PR3}+W_{P4})+W_{PR5}]+W_{P3}\}}{1-\Phi(3)\Phi(4)K_3'(1+K_3')} \quad (11)$$

The propellant requirements for maneuvers

3, 4, and 5 can now be expressed in terms of the payloads to the destinations. Relations between propellant manufacturing rates and mining, basing, and processing weights are given in reference 3. In order to use these charts to calculate the weight of material to be delivered to the Moon, two things must be done:

(1) Total requirements for propellant must be translated into rates of production.

(2) Production rates must be prorated to various requirements.

These depend on the ability and cost of storing propellant and the total activity at the lunar base. Instead of attempting to solve these problems, we introduct the notation a, M, b, and L listed in table 2 and then treat these terms parametrically.

Then the payload for maneuver 2 becomes

$$W_{P2}=aM+abL+c(W_{V3}+W_{T4})$$

where

$c=1\div$the number of uses of the vehicle used in maneuver 3

The relations in reference 3 are linear, so by introducing a proportionality constant J to relate propellant production to weight of equipment used to produce that propellant and by introducing a constant K to relate propellant production to logistics requirements, we get

$$\begin{aligned} J(\overline{W}_{PR3}+\overline{W}_{PR4}+\overline{W}_{PR5})&=M \\ K(\overline{W}_{PR3}+\overline{W}_{PR4}+\overline{W}_{PR5})&=bL \end{aligned} \qquad (12)$$

where $\overline{W}_{PR3}$ denotes the yearly rate of propellant consumed by maneuver 3. Then

$$W_{P2}=a(J+bL)(\overline{W}_{PR3}+\overline{W}_{PR4}+\overline{W}_{PR5})+c(W_{V3}+W_{T4}) \qquad (13)$$

Instead of using the rocket equation to determine the initial weight (weight at launch), we use performance curves for the launch vehicle, in this case the Saturn V, to determine the number of launches required. Using the lunar logistics vehicle on top of the Saturn V, 28 500 pounds can be landed on the Moon (ref. 4). Therefore dividing W_{P2} by 28 500 gives the number of launches required. Fractional launches make sense in this context because we assume other lunar activities that would use up the additional payload capacity. The number of Saturn V launches used on maneuvers 1 and 2 to be ascribed to the missions are:

$$N_2=W_{P2}/28\,500 \qquad (14)$$

A lunar landing vehicle other than the one envisioned gives a different constant as a divisor. The consequence will be discussed later.

The payload of maneuver 1 consists of the mission payload, the vehicle used in maneuver 5, and the weight burden needed to carry out the assembly operations at the rendezvous point R. This is given by

$$\begin{aligned} W_{P1}&=W_{P5}+W_{V5}+W_{B1}+W_{P4}=W_{I5}-W_{PR5}+W_{B1}+W_{P4} \\ &=W_{P5}+K_5W_{PR5}+H_{1,5}W_{PR5}+W_{P4} \\ &=[1+(K_5+H_{1,5})\Phi(5)]W_{P5}+W_{P4} \end{aligned} \qquad (15)$$

The Saturn V can deliver about 100 000 pounds to the cislunar libration point. If this point is chosen for the rendezvous point R, the number of Saturn V launches required for maneuver 1 is

$$N_1=W_{P1}/100\,000$$

However, W_{P4} should not be ascribed to the planetary mission, so that the number of Saturn V launches to be assigned to this mission is

$$N_1=(W_{P1}-W_{P4})/100\,000$$

SCOPE

One purpose of this paper was to treat cases other than those already appearing in the literature and to give something more specific than a parametric treatment. Therefore these propellants were considered:

Liquid hydrogen-oxygen-chemical:
$I_{SP}=444$ sec

Methane-nuclear:
$I_{SP}=400$ sec

Ammonia-nuclear:
$I_{SP}=400$ sec

Water-nuclear:
I_{SP}=300 sec
Helium-nuclear:
I_{SP}=600 sec
Hydrogen-nuclear:
I_{SP}=830 sec

The methane and ammonia yield values of I_{SP} that are close and overlap in some cases depending on the temperature of the reactor (ref. 5); therefore, they were treated as one case. The water-nuclear system proved to be inferior for the planetary mission and was not investigated in depth.

The planetary mission had two versions, a slow and a fast trip with the following velocity requirements:

(1) Slow: two impulses with V_∞ of 0.1 EMOS each

(2) Fast: two impulses with V_∞ of 0.15 EMOS each

The propellant for the return trip was considered part of the payload of the final maneuver. No essential difference would occur if the total excess velocity V_∞ (0.2 EMOS, slow, and 0.3 EMOS) were partitioned in different ratios between the two impulses.

The departure from Earth was considered in three modes:

(1) HO, departure from a high orbit, specifically the cislunar libration point.

(2) LO, departure from a low circular orbit, specifically a 250-kilometer altitude.

(3) EO, departure from an eccentric orbit, specifically a 60×1.1 Earth radii ellipse.

Rendezvous of the lunar and Earth originating stages was assumed to take place in the departure orbits. This poses operational difficulties in the EO case. However, the penalty paid for rendezvous at the cislunar libration point and transferring the entire transportation system into the elliptic orbit is not too large. Figure 3 illustrates the three alternate Earth departure orbits.

The lunar mission was treated in three versions in which—

(1) The lunar shuttle and Earth shuttle rendezvous at the cislunar libration point

(2) The shuttles rendezvous in low Earth orbit

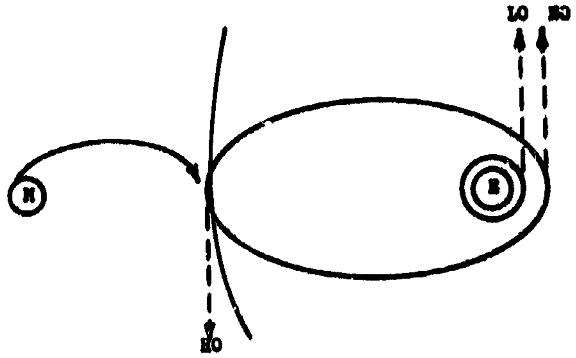

FIGURE 3.—Orbital launch modes.

(3) One shuttle operates between the Moon's surface and the Earth's surface

Version (2) was ruled out as too wasteful of propellant and version (3) was used mainly with the no-lunar-material baseline mode.

Four processes for obtaining propellant were considered:

(1) Oxygen by silicate reduction (refs. 3 and 8).

(2) Hydrogen and oxygen from electrolysis of permafrost water (ref. 3).

(3) Hydrogen and oxygen from pure water (ref. 3).

(4) Ammonia, methane, water, or helium from a gas drilling operation perhaps supplemented with a nuclear underground blast to open up the rock.

In order to carry out the analysis outlined in the previous section, values of J and L are needed. These were derived from 1-, 2-, and 5-year equipment lifetime from charts given in reference 3 as shown in table 3.

Benefits from the 5-year life of equipment are limited by a maximum of 2-year life of the powerplant fuel elements. Figures 4 to 6 give the processing equipment weight as a function of propellant production rates. If the propellant is used at the production, the process must be represented by a point below the broken 45° line shown in these figures. If the propellant must be transported prior to use, the point must lie considerably below the 45° line. The values for L in table 3 represent the resupply requirements for 1 year, in pounds.

TABLE 3.—*Processing Coefficients*

Process	Coefficient, lb/lb/yr, for—			[a] L, lb
	J (1 yr)	J (2 yr)	J (5 yr)	
1	1.06	0.51	0.48	27 000×NM[a]
2	.78	.40	.33	27 000
3	.45	.22	.19	27 000
4	.31	.16	.13	27 000
5	.017	.008	.003	27 000

[a] NM = number of men used in process.

RESULTS

Table 4 shows the propellant requirements for different versions of the planetary mission. Weight is given in kilopounds. The departure from low orbit was set up to calculate direct Earth supply only and has been omitted from several of the versions which apply to lunar refueling. As expected, the hydrogen-nuclear system provides the best performance.

By using totals given in table 4 and the relations in figures 4 to 6, we can calculate equipment weights that must be delivered to the Moon if we use the various propellant manufacturing processes. Results are shown in table 5 with the equipment sized to take care of the mission versions indicated.

A summary of the lunar-shuttle mission propellant weights is given in table 6 for the cislunar rendezvous mode only when this proved superior to the other modes. Again the hydrogen-nuclear propulsion is superior, but, of course, the processing penalties have not

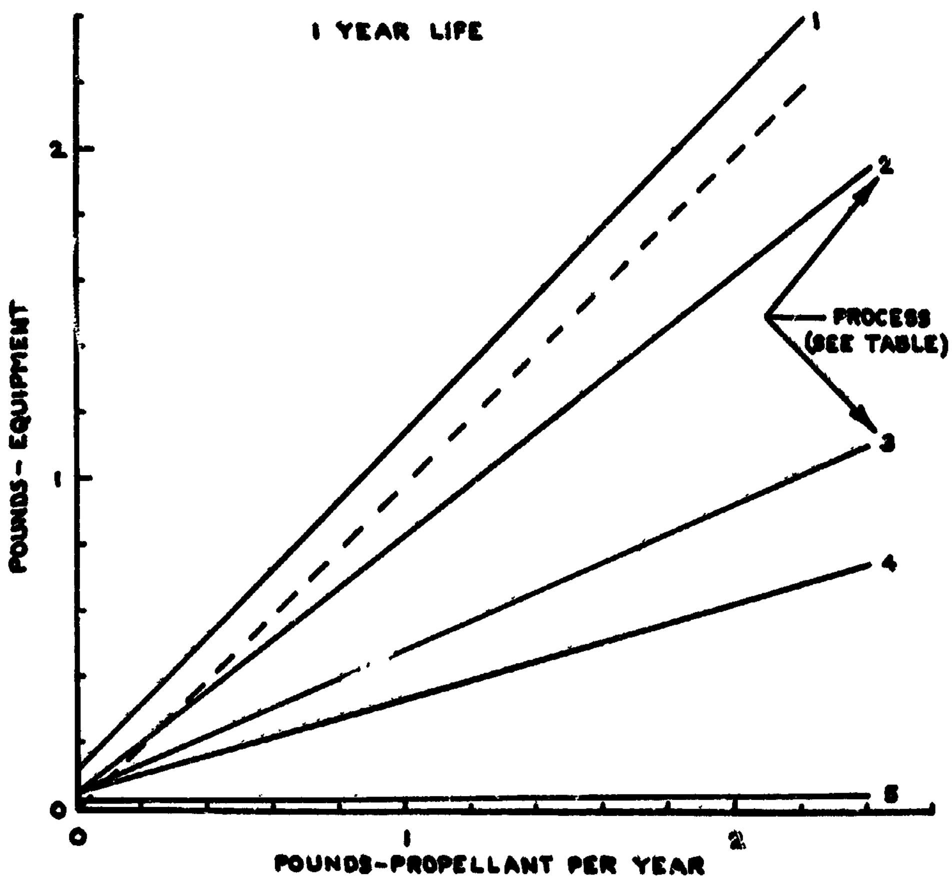

FIGURE 4.—Processing equipment weight against propellant weight for 1-year equipment life.

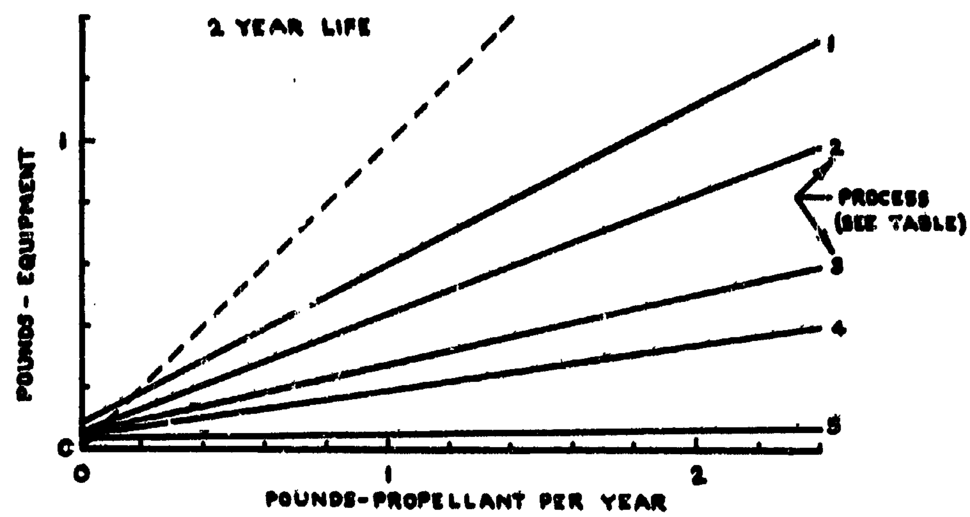

FIGURE 5.—Processing equipment weight against propellant weight for 2-year equipment life.

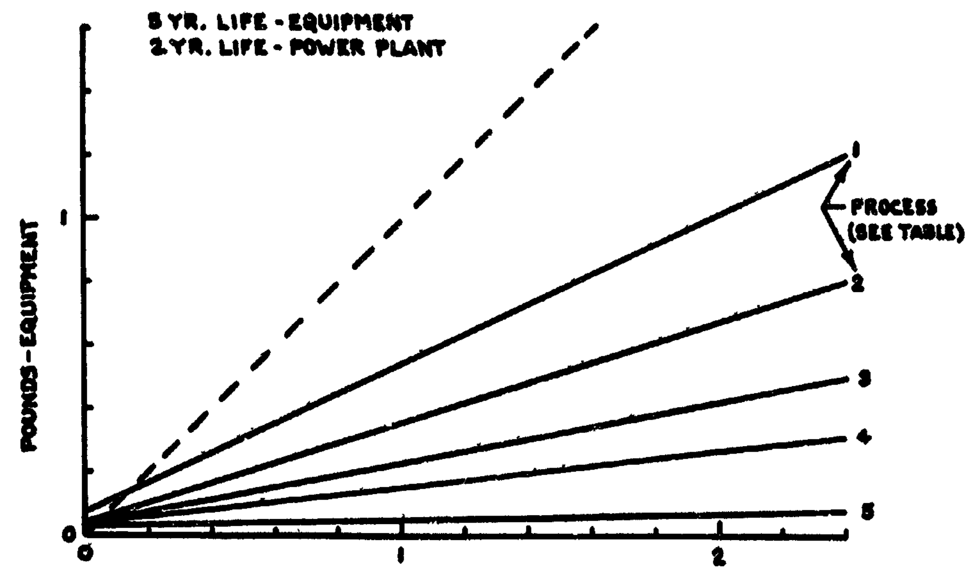

FIGURE 6.—Processing equipment weight against propellant weight for 5-year equipment life.

yet been included. Using figures 4 to 6, we get the equipment weights shown in table 7. The figures in parentheses under the column labeled "5-yr life" represent the number of Saturn V flights needed to deliver the equipment. In addition to the number needed for delivery of equipment, 4.6 Saturn V flights are needed per year to deliver payload from the Earth to the rendezvous point *R*.

Lunar supply is most beneficial to large-scale

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TABLE 4.—*Propellant Consumption for Different Versions of the Planetary Mission*

Version	Propulsion	Trip	Orbit	Consumption, klb				
				W_{PR6}	W_{PR5}	W_{PR4}	W_{PR1}	Total
1a	H_2-O_2 chemical	Slow	HO	143	207	309	21	740
1b			LO	143	520			
1c			EO	143	40	231	23	437
1d		Fast	HO	278	812	867	50	2008
1e			LO	985				
1f			EO	130	515	51	974	
2a	CH_4 nuclear	Slow	HO	171	330	500	42	1053
2b			EO	171	54	362	36	623
3a	He nuclear	Slow	HO	106	305	214	30	645
3b			EO	106	33	112	17	225
3c		Fast	HO	172	390	296	38	887
3d			EO	172	83	211	31	499
4a	H_2 nuclear	Slow	HO	72	97	63	3	256
4b			EO	72	16	47	3	
4c		Fast	HO	108	215	116	6	445
4d			LO	108	258			
4e			EO	108	41	50	5	204

TABLE 5.—*Equipment Weights Needed To Supply Planetary Mission Propellant*

Mission version	Propellant used, lb	Propellant process	Equipment weight per year, W_{PS}, lb [a]		
			1-yr life	2-yr life	5-yr life
1a	0.740×10⁶	1. Si reduction	0.90×10⁶ (31)	0.48×10⁶ (17)	0.44×10⁶ (15)
		2. 25 percent H_2O	.65	.34	.28
		3. 50 percent H_2O	.38	.22	.18
		4. 100 percent H_2O	.27	.16	.13 (4.5)
1c	.437	4. 100 percent H_2O	.17	.10	.08
1d	2.006	4. 100 percent H_2O	.63 (22)	.33 (12)	.27
1f	.974	4. 100 percent H_2O	.33	.18	.14
2a	1.053	5. Gas drill	.045 (1.6)	.030	.024
3a	.645	5. Gas drill	.037	.026 (1)	.022
3c	.877	5. Gas drill	.041	.029	.023

[a] Numbers shown in parentheses in selected cases give the number of Saturn V flights needed to move the indicated weight.

operations and in particular is not too favorable to the planetary mission when no lunar shuttle mission is flown. Therefore, combining the monthly lunar shuttle flight with a yearly planetary flight, the propellant consumption is given in table 8 by combining the totals from tables 4 and 6. The version 1a+1 shown in table 8 combines totals from mission version 1a from table 4 with totals in line 1 from table 6, etc. Again equipment weights are calculated with the aid of figures 4 to 6.

In order to point up the relative merits of

Table 6.—*Lunar Shuttle Propellant Consumption*

Mission version	Propulsion	Consumption, klb				
		W_{PR1}	W'_{PR1}	W'_{PR1}	Total	Total×12
1	H_2-O_2 chemical	6.5	20.4	20.9	47.8	574
2	CH_4 nuclear	7.1	25.3	31.4	63.8	765
3	He nuclear	5.3	13.6	10.6	29.5	354
4	H_2 nuclear	3.4	8.8	2.9	15.1	181

Table 7.—*Equipment Weights for Propellant Used by Lunar Shuttle*

Mission version	Propellant used per yr, lb	Propellant process	Equipment weight per yr, W'_{PS}, lb		
			1-yr life	2-yr life	5-yr life
1	0.574×10^6	1	0.71×10^6	0.38×10^6	0.34×10^6 ([a]8.7)
		2	.50	.27	.22 ([a]5.6)
		3	.30	.17	.16 ([a]4.1)
		4	.21	.12	.10 ([a]2.5)
2		5	.040	.027	.023 ([a].59)
3		5	.032	.024	.022
4		4	.020	.022	.021

[a] Number of Saturn V flights per year needed to deliver equipment.

selected mission-propellant manufacture combinations, the number of Saturn V flights required for the missions has been plotted in figure 7. The labels on the bars in figure 7 are explained below. The first number indicates the production process as given in table 3. The second number in a pair below indicates equipment life; for example, (4,5) connotes 5-year life for 100 percent H_2O propellant process.

Slow planetary:

- (0,–) Earth supply, LH_2, LOX chemical propulsion
- (1,1) Silicate reduction
- (4,5) Electrolysis of water, 100 percent water
- (5,2) Gas drill, helium nuclear propulsion

Fast planetary:

- (0,–) Earth supply, LH_2, LOX chemical propulsion
- (0,–) Earth supply, H_2, nuclear propulsion
- (4,1) Electrolysis of water, 100 percent water
- (4,2) Electrolysis of water, 100 percent water
- (5,2) Gas drill, helium nuclear

Lunar supply:

- (0,–) Earth supply, lunar lander, LH_2, LOX
- (0,–) Earth supply, lunar shuttle, LH_2, LOX
- (1,5) Silicate reduction
- (2,5) Electrolysis of water, 25 percent permafrost
- (3,5) Electrolysis of water, 50 percent permafrost
- (4,5) Electrolysis of water, 100 percent water
- (5,5) Methane, nuclear, gas drill

Lunar supply plus slow planetary:

TABLE 8.—*Total Propellant Consumption and Process Equipment Weight*

Mission versions	Propellant used, lb	Propellant process	Equipment weight per year, W_{P}, lb		
			1-yr life	2-yr life	5-yr life
1a+1	1.31×10⁶	1. Si reduction	1.5×10⁶	0.76×10⁶	0.70×10⁶
		2. 25 percent H_2O	1.1	.56	.46
		3. 50 percent H_2O	.64	.34	.29
		4. 100 percent H_2O	.43	.23	.19
1c+1	1.01	1. Si reduction	1.6	.60	.54
		2. 25 percent H_2O	.84	.43	.36
		3. 50 percent H_2O	.50	.28	.23
		4. 100 percent H_2O	.34	.19	.15
1d+1	2.58	1. Si reduction	3.0	1.5	1.4
		2. 25 percent H_2O	2.2	1.1	.92
		3. 50 percent H_2O	1.3	.67	.57
		4. 100 percent H_2O	.85	.45	.37
1f+1	1.55	1. Si reduction	1.75	.88	.80
		2. 25 percent H_2O	1.3	.66	.53
		3. 50 percent H_2O	.75	.40	.34
		4. 100 percent H_2O	.50	.27	.21
2a+2	1.82	5. Gas drill	.061	.038	.027
2b+2	1.39	5. Gas drill	.053	.035	.026
3a+3	1.0	5. Gas drill	.045	.030	.024
3b+3	.58	5. Gas drill	.037	.026	.022
3c+3	1.25	5. Gas drill	.050	.032	.025
3d+3	.85	5. Gas drill	.042	.028	.023
4a+4	.44 (ᵃ3.9)	4. 100 percent H_2O	1.36	.76	.60

ᵃ Water processed to get required H_2.

(0,–) Earth supply, lunar lander, LH_2, LOX
(0,–) Earth supply, lunar shuttle, LH_2, LOX
(3,5) LH, LOX 50 percent permafrost, shuttle, libration rendezvous
(3,5) LH, LOX 50 percent permafrost, shuttle, eccentric rendezvous
(1,5) LH, LOX silicate reduction, shuttle, eccentric rendezvous
(1,5) LH, LOX silicate reduction, shuttle, eccentric rendezvous
(2,5) Methane, nuclear, libration rendezvous
(4,5) H_2 nuclear, 100 percent water, libration rendezvous

It can be seen that some lunar propellant schemes compare favorably with a direct Earth supply, and some unfavorably. If a nuclear propulsion system using liquid hydrogen as a propellant is developed, no advantage can be seen for lunar propellant, at least for a one-shot planetary mission similar to that which has been considered here. If the planetary craft is recoverable and can be resupplied with resources from the destination planet, the situation may reverse itself (see ref. 2). The most favorable cases using helium or methane should be compared to an Earth-based nuclear system using hydrogen as a propellant inasmuch as the technology is the same. Here, as can be seen from figure 7, the comparison is slightly favorable to the lunar source of propellant for the fast planetary mission.

For the lunar supply mission and the combined lunar supply and slow planetary missions, the comparison is much more favorable to the lunar propellant schemes. This is due to the use of much of the propellant at the Moon

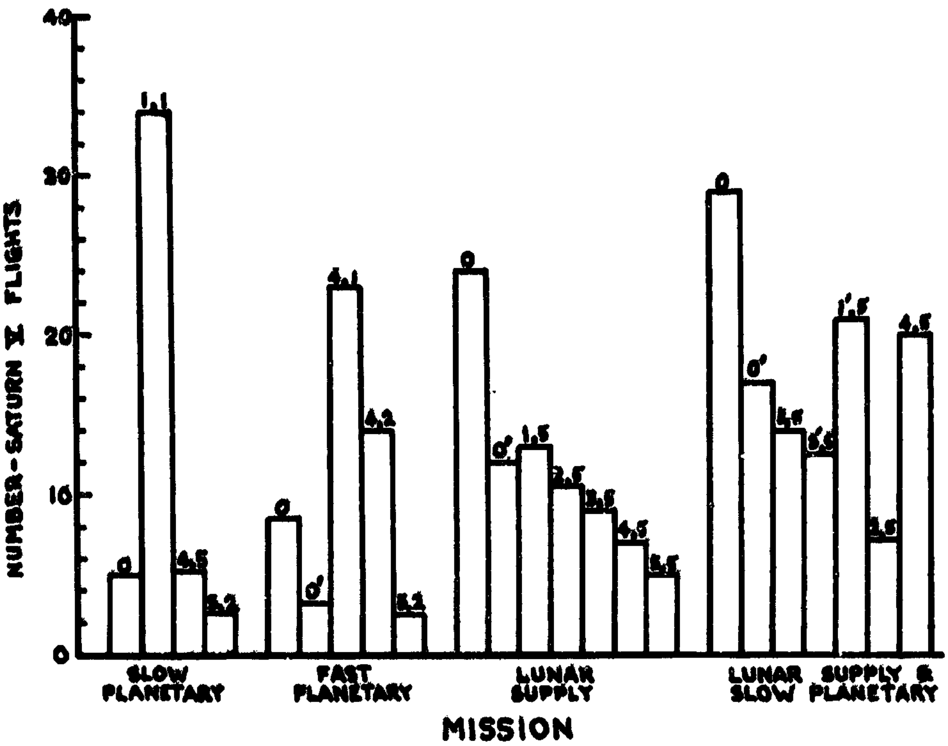

FIGURE 7.—Chart of Saturn V launches required.

and the resulting savings over transporting propellant from the Earth.

In conclusion, we return to the position stated in the introduction; namely, that too many uncertainties exist to decide at this time for or against the use of lunar resources for propellants. However, there are promising situations that could evolve as shown by the preceding analysis. Future planning for lunar exploration and exploitation should keep these situations in mind.

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