LAUNCH VEHICLE PERFORMANCE

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ABSTRACT

An analysis is made of launch vehicle size and staging requirements to conduct a manned lunar landing and return mission. Velocities required of rocket stages for each phase of the mission are determined and the total mission velocity established. Four types of lunar mission profiles are considered. These are direct launch, Earth orbit rendezvous, lunar orbit rendezvous, and lunar surface rendezvous. Spacecraft weights for each type of mission are assumed for the purpose of comparing launch vehicle needs. A rocket stage size equation is derived which permits a graphical analysis of total launch vehicle weight. Various propellants are considered for the stages used in different phases of the mission. Comparisons are made of the resulting vehicle sizes, numbers of vehicles required, use of propellants, and mission complexity.

INTRODUCTION

A vehicle to launch a manned spacecraft to land on the moon and return must be designed and sized to meet a variety of different requirements. Each rocket stage must be planned to use the most favorable propellants and to employ rocket engines of suitable thrust and control characteristics. The type of mission must be considered carefully in the sizing and staging of the vehicle. The lunar landing mission can be accomplished in a number of different ways. A direct launch to the moon, followed by a landing and return flight, is the simplest and most straightforward mission profile. Other methods for accomplishing this mission require some form of

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Presented at the ARS Lunar Missions Meeting, Cleveland, Ohio, July 17-19, 1962.

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assembly of portions of vehicles at an intermediate stage in the trip to the moon or during the return phase. This paper will derive some approximate vehicle sizes for four of the types of missions which are possible, indicate the number of vehicles needed, and show stage sizes and possible propellants for accomplishment of this mission. The author wishes to express his appreciation for the advice and assistance of Dr. A.B. Greenberg in the preparation of this paper.

In examining the launch vehicle requirements for a lunar landing mission, the first parameters to establish are the characteristics of the Earth-moon system in which the mission is to be accomplished. Fig. 1 shows the most important characteristics of this system for lunar mission vehicle performance. The physical dimensions and gravitational field of Earth establish the escape velocity from the surface and the circular satellite velocity at an altitude just above Earth's atmosphere. A rocket vehicle must be capable of propelling a spacecraft essentially to a velocity permitting escape from the Earth gravitational field. The trajectory followed by the spacecraft carries it to the vicinity of the moon. Upon reaching the vicinity of the moon, the spacecraft is attracted by the moon's gravitational field and would fall onto the surface of the moon if not retarded by rocket thrust. The velocity of impact would be close to the escape velocity from the surface of the moon, which is shown in Fig. 1. Also of interest is the satellite velocity close to the moon's surface. With these velocities, which are characteristic of the Earth-moon system, it is possible to construct a total velocity profile for this mission.

MISSION VELOCITY REQUIREMENTS

The lunar landing velocity profile is to be used for comparing the launch vehicles required for a number of different ways of accomplishing a lunar landing. Many features of these missions differ quite considerably; however, they have in common the same requirement for weight of the re-entering vehicle as it approaches Earth's atmosphere. Since this represents a common datum for all the different missions, it is convenient to construct a velocity profile for the mission considering re-entry into Earth's atmosphere as the velocity reference point, and each preceding phase of the mission then requires additional velocity from that datum. Table 1 shows this velocity profile with the reversed sequence of events. The lunar orbit and Earth orbit portions of the mission are not used in all of the different types of trajectories which will be considered. Table 1 shows a velocity of 3300 fps needed to depart from a lunar orbit for transfer to the vicinity of Earth. The velocity needed to achieve a lunar orbit from the lunar surface is 6700 fps which includes the gravity losses for the launch from the lunar surface. The lunar surface is therefore approximately 10,000 fps from the Earth return. Similarly, the velocity required to descend to the lunar surface from the lunar orbit is 6700 fps, so that the outbound lunar orbit is a total of 16,700 fps from Earth re-entry. An additional 3300 fps will provide the conditions for the Earth-moon transfer. In order to escape from Earth out of an orbit around Earth at 100 naut miles altitude, about 11,000-fps velocity is required. Thus, the Earth orbit is an additional 11,000 fps from the Earth re-entry. Finally, the launch phase through Earth's atmosphere into Earth orbit requires approximately 30,000 fps including gravity losses, so that at the launch point the total velocity requirement to leave the moon and then achieve the Earth re-entry condition is 61,000 fps. This, then, is the total velocity needed for this mission.

SPACECRAFT WEIGHTS

The next factor that must be considered in determining the size and design of the launch vehicle is the weight of spacecraft required to accomplish the mission. Table 2 shows assumptions for the spacecraft size which will be used here for the purpose of determining launch vehicle size. These particular numbers do not represent any firm design, but they permit a compatible comparison between the various mission alternatives which can be considered. In Table 2, the top line indicates the weight of spacecraft which re-enters the atmosphere upon completion of the mission. Notice that for the four types of missions to be considered, the re-entry weight is 10,000 lb for each. The four missions that will be considered in this comparison are also indicated in Table 2. The first one is the direct mission, which is characterized by a launch from Earth's surface, a transfer to the vicinity of the moon, direct descent to the lunar surface, and direct launch from the lunar surface to transfer to the vicinity of Earth and re-entry into the atmosphere. In this case, the intermediate orbit velocities are not necessary in considering the mission. The weight for departure from the lunar surface is indicated at 16,000 lb. This includes an additional 6000 lb above the re-entry weight which is comprised of communications, guidance, power supply, attitude control, maneuvering, midcourse velocity correction equipment, and life support expendables. The weight of spacecraft which originally left the vicinity of the Earth is indicated at 18,000 lb. The difference between this figure and the 16,000 lb for departure from the lunar surface is 2000 lb of life support expendables used during the course of the transfer.

The next mission to be considered in Table 2 is an Earth orbit rendezvous mission. Here, the spacecraft weight upon re-entry into the atmosphere is the same as for the direct mission. The weight for departure from the lunar surface is also the same, and likewise, the weight upon entry into the Earth-moon transfer for this Earth orbit rendezvous mission, the spacecraft weight profile, is the same as the direct mission. However, the launch vehicle stages that are associated with the mission are quite different in that assembly in Earth orbit is required in order to build the vehicle up to a size capable of directing the loaded stages to the vicinity of the moon. Thus, the spacecraft weight is only a small fraction of the total weight that must be directed to the vicinity of the moon.

The next mission that will be considered is the lunar orbit rendezvous mission. Here, the weight of spacecraft which departs from the lunar orbit for return to Earth is the same as that departing the lunar surface in the previous two missions. However, this 16,000-lb weight is not carried to the lunar surface in the lunar orbit rendezvous mission. Rather, a considerably smaller spacecraft is used for descent to the lunar surface from the lunar orbit. The total spacecraft weight that enters the lunar orbit is 21,000 lb, as shown in Table 2. Of this, 16,000 lb is the spacecraft that will be used for returning to the vicinity of Earth and 5000 lb is the spacecraft that will be used for descending to the lunar surface. The weight of spacecraft needed to enter the Earth-moon transfer on the outbound trip is 2000 lb heavier than the arriving spacecraft, as in the previous examples, the difference in weight, once again, being accounted for by life support expendables. In this mission, the weight of spacecraft which departs Earth's surface is therefore 23,000 lb.

For the lunar surface rendezvous mission, the spacecraft weight history is the same as for the direct mission. The difference between the lunar surface rendezvous mission and the direct mission is that, upon landing on the lunar surface, the landing vehicle does not have aboard the propellants needed to return. Therefore, although the spacecraft weight is the same as for the direct mission, the weight landed on the moon for each launch is considerably less as will be shown in later calculations of vehicle size.

STAGE WEIGHT-VELOCITY EQUATION

With the velocity profiles for the four mission types established and the weight of spacecraft assumed, it is possible to determine the size of rockets needed to accomplish this mission for various propellant combinations and vehicle weight factors. In deriving the vehicle sizing equations, the basic rocket equation is used. The parameters that are considered are the specific impulse of the rocket stage, the amount of fuel in the rocket stage, the empty weight, and the payload weight. For the purposes of developing launch vehicle sizes for the entire lunar landing mission, an equation will be developed which applies to each stage individually. A graphical procedure will be used to combine several stages into a complete vehicle.

Eq. 1 shows the theoretical vacuum velocity increment of a rocket stage as a function of the propulsion and weight parameters that determine it:

$$V = g\, I_{sp} \ln \frac{W_f + \delta W_c + W_p}{\delta W_c + W_p} \qquad [1]$$

where
- V = velocity gain capability of stage with W_f lb of propellant remaining, fps
- W_f = remaining propellant, lb
- W_c = propellant capacity of stage, lb
- W_p = payload weight of stage which may include other fueled upper stages, lb
- W_{bo} = stage burnout weight, lb
- I_{sp} = specific impulse of propulsion system, sec
- g = acceleration of gravity at Earth surface, 32.2 fps^2
- δ = structural factor $\cong W_{bo}/W_c$

Solving for W_f:

$$W_f = (\delta W_c + W_p)\,(e^{V/g\, I_{sp}} - 1) \qquad [2]$$

when $W_f = W_c$

$$W_c = (\delta W_c + W_p)\,(e^{V_c/g\, I_{sp}} - 1) \qquad [3]$$

where V_c = maximum velocity gain capability of stage, fps.
Solving for W_c:

$$W_c = W_p \frac{e^{V_c/g\, I_{sp}} - 1}{1 - \delta\,(e^{V_c/g\, I_{sp}} - 1)} \qquad [4]$$

Letting W_v be the weight of a stage and its payload at any time during stage burning

$$W_v = W_f + \delta\, W_c + W_p \qquad [5]$$

Substituting Eqs. 2 and 4 into Eq. 5:

$$\frac{W_v}{W_p} = \frac{e^{V/g\, I_{sp}}}{1 - \delta\left[e^{V_c/g\, I_{sp}} - 1\right]} \qquad [6]$$

Eq. 6 gives an expression that shows the ratio of the total vehicle weight to stage payload weight as a function of the structure factor, the specific impulse of the stage, the maximum velocity that the stage can achieve, and the velocity that the stage has achieved at any given expenditure of available propellants. Eq. 6 is shown plotted in Fig. 2 for three different values of stage specific impulse. In all cases, a value of structure factor of one tenth is used as typical of rocket stages of this type. The actual value of structure factor will depend on the propellants used, the size of the stage, and the stage design. However, for the purposes of comparison of vehicle sizes for different missions, a single value of structure factor appears to be adequate. A specific impulse of 264 sec is typical of solid rockets. The curve for I_{sp} of 310 is typical of liquid oxygen/kerosene first stages and storable propellant upper stages. The curve for I_{sp} of 425 is typical of oxygen/hydrogen upper stages. The curves in Fig. 2 are plotted on a semi-log scale so that Eq. 6 plots as a straight line. Each line represents a weight/velocity history for a stage with a $V_c/g\ I_{sp}$ value as labeled. Intermediate values of $V_c/g\ I_{sp}$ would plot as straight lines parallel to those shown. It should be noted that the parameter $V_c/g\ I_{sp}$ is a measure of the velocity capability of a given stage. Thus, each line in Fig. 2 terminates at the velocity increment corresponding to total propellant utilization. Plotting Eq. 6 in this way makes it possible to construct an approximate graphical weight/velocity history for a multistage vehicle using the curves of Fig. 2. The velocities used in Eq. 6 and Fig. 2 are theoretical vacuum velocities. The mission velocity requirements of Table 1 include trajectory losses and are therefore compatible with Fig. 2.

MISSION WEIGHT-VELOCITY HISTORIES

An example of a weight-velocity mission history constructed by this technique is shown in Fig. 3. In this figure the vehicle weight is plotted as a function of the velocity expended during the course of a direct lunar mission. The history is constructed in a sequence opposite to that of the actual mission, and, accordingly, starts with the return payload of 16,000 lb at a mission velocity of zero. The initial portion of the weight history is horizontal, and corresponds to the empty weight of the last stage. The weight and mission velocity then increase simultaneously, reflecting the lunar launch maneuver of 10,000 fps. The weight-velocity history then repeats this cycle for each previous stage in the mission. In this calculation, as in all the missions analyzed in this paper, the lunar landing and launch stages are assumed to utilize storable propellants. Therefore, the left two burning periods shown on Fig. 3 correspond to storable propellants with a specific impulse of 310 sec. The break in the line at 10,000 fps indicates that one stage was used for descent to the lunar surface and that another stage was used for ascent from the surface and escape from the moon's gravitational field. The stage that was used to depart from Earth's orbit for a transfer to the moon is an oxygen/hydrogen stage. For the purposes of this analysis, it is assumed that staging of the launch vehicle will be conducted in Earth orbit. Although this procedure is not necessary for accomplishment of this mission, it provides an additional safety factor to permit the crew to return to Earth safely if all aspects of the ascent of the launch vehicle are not satisfactory. The next portion of the curve shows the weight history for an oxygen/hydrogen upper stage that propels the vehicle from the conditions of the first-stage burnout into Earth orbit. For the first stage, two types are shown: an oxygen/kerosene first stage and a solid propellant first stage. The primary difference between these two types of first stages is the total weight required. The oxygen/kerosene first stage requires a total weight of approximately 9.5×10^6 lb for the overall vehicle at launch, whereas the solid first stage requires about a 12.5×10^6 lb vehicle. This difference in vehicle weight is typical of the comparison between liquid oxygen/kerosene first stages and solid propellant first stages. Vehicle size alone is not necessarily a governing factor, and a propellant selection for a first stage should also consider such factors as cost, reliability, logistics, and operating characteristics.

The next mission that will be considered is the Earth orbit rendezvous mission, which is shown in Fig. 4. Here, the final three stages of the vehicle are identical to those for the direct mission. The take-off from the lunar surface, landing on the lunar surface, and departure from Earth orbit to transfer to the moon are conducted with essentially the same equipment shown for the direct mission. In Earth orbit, Fig. 4 indicates two possibilities for assembly of vehicles. The lower curve indicates the weight-velocity profile for a launch vehicle which can place sufficient weight into an Earth orbit to permit accomplishment of this mission with assembly of two units. This means that two launches would be required for each mission accomplished. The upper curves show the size of a smaller vehicle which could accomplish this mission by the assembly of three units in Earth orbit. The size of the launch vehicle is traded off here against the increased complexity of assembling three rather than two units in orbit. Analysis of this trade-off is complex and must take into consideration many operating factors in addition to vehicle size.

The next mission, shown in Fig. 5, is a lunar orbit rendezvous. Here, the velocity-weight profile starts with entry into the moon-Earth transfer and shows the weight profile with a history for departure from a lunar orbit to that condition. The left hand curve, which remains constant in weight at just over 23,000 lb from 3300 fps to 16,700 fps, indicates that this weight remains in lunar orbit during the excursion of the smaller vehicle to the lunar surface. The right hand curve, with a changed scale, indicates the weight history of the excursion to the lunar surface. The 5000-lb vehicle shown here departs from the lunar orbit, lands on the surface, and returns to lunar orbit with a single propulsion unit. A total weight of 26,800 lb in lunar orbit is required to accomplish the landing and take-off maneuver for the 5000-lb spacecraft. This 26,800 lb therefore, must be added to the 23,200 lb in lunar orbit required for the return vehicle in order to determine the amount of total weight which must be placed in lunar orbit for accomplishment of this mission. This is shown at the 16,700-fps point of entry into lunar orbit. 3300 fps of additional storable propellant velocity must be obtained for entering the lunar orbit from the Earth-moon transfer. The velocity from Earth orbit to transfer and then through the launch phase is accomplished with oxygen/hydrogen upper stages and a liquid oxygen/kerosene first stage. If a solid first stage had been used on this vehicle, the weight comparison for vehicle size would be analogous to that of a direct mission. The weight of vehicle required for this mission is shown to be about 3.9×10^6 lb.

The final mission is that of lunar surface rendezvous, as illustrated in Fig. 6. Here, the mission starts with the vehicle re-entering Earth's atmosphere from the moon-Earth transfer, and the first portion of the weight-velocity profile shows the ascent from the lunar surface by means of storable propellants. At 10,000-fps velocity the spacecraft is at rest on the lunar surface. The drop in the profile indicates that the vehicle was originally out of propellants when it landed on the lunar surface, and the difference between the 16,000-lb weight at landing and the 52,700-lb weight required for return must be made up from propellants landed with other vehicles. In order to accomplish this propellant transfer all with one size landing vehicle, a total of four launches per mission are required. The landing on the lunar surface is accomplished by a storable propellant stage, preceded by two oxygen/hydrogen stages and an oxygen/kerosene first stage.

These four mission types are compared in Fig. 7. It is apparent that the launch vehicle required for the direct ascent type of mission is considerably larger than that required for any of the rendezvous methods. The lunar orbit rendezvous and lunar surface rendezvous vehicles are almost the same in size. The Earth orbit rendezvous vehicle for a two-launch rendezvous is intermediate between the lunar rendezvous and direct ascent types of missions, whereas the Earth orbit rendezvous vehicle for a three-launch mission would be almost identical to that for the lunar orbit rendezvous and lunar surface rendezvous. Based on the assumptions of this analysis any of the rendezvous methods could use a vehicle in the vicinity of $3x10^6$ to $4x10^6$ lb weight. Actual vehicle gross weights for such missions depend upon real spacecraft weights and the performance margins required for rendezvous maneuvers, hovering to land and conservatism for crew safety. These factors have been neglected in this analysis so the vehicle sizes shown are an absolute minimum for the spacecraft weights assumed. However, the comparison between the mission types gives an indication of the advantages in vehicle size of using rendezvous.

Launch vehicle gross weight is an important factor in determination of vehicle development costs, launch costs, operating procedures, and availability schedules. Some characteristics of the vehicle increase in size virtually proportionally to vehicle gross weight. These include engine thrust, structural weight, pressurization systems, propellants, propellant storage equipment, and ground handling equipment. Other parts of the vehicle are virtually unaffected by size. These include guidance, telemetry, power supplies, controls, and checkout equipment. A detailed analysis is required to determine the relative costs, schedules, and reliability of vehicles of different sizes.

A complete comparison of these mission alternatives must consider many factors in addition to launch vehicle size. The direct mission is simplest in operation and requires the largest launch vehicle. The Earth orbit rendezvous missions can use smaller launch vehicles at the expense of increased complexity in orbital operations. This type of operation places a particularly severe burden on launch facilities and procedures since several vehicles must be readied for launching almost simultaneously. A two-launch rendezvous requires a launch vehicle of intermediate size, whereas a three-launch rendezvous needs a smaller vehicle but makes the rendezvous operation more complex. The lunar orbit rendezvous uses only one of the smaller vehicles but requires a rather intricate rendezvous in lunar orbit. The lunar surface rendezvous can use the smaller vehicle but requires four launches for each mission and a refueling on the lunar surface. Table 3 summarizes the primary characteristics of these missions and the required launch vehicles.

Several conclusions can be drawn from this analysis:

1. The rendezvous method of accomplishing the lunar mission requires vehicles approximately half the size of that required for the direct mission. The choice of which type of rendezvous to use need not be made in order to initiate development of the launch vehicle, since the same design and staging arrangement will be suitable for lunar orbit rendezvous, lunar surface rendezvous, and three-launch Earth orbit rendezvous.

2. The choice of a first stage between oxygen/kerosene and solid propellants is not clearly indicated by vehicle size. A solid propellant first stage causes the launch vehicle to be heavier in weight, but many other factors must be considered before determining which is the most favorable first stage.

3. The use of storable propellants for all velocity increments accomplished after entering the Earth-moon transfer offers operational advantages without exorbitant increase in launch vehicle size.

4. Analysis of launch vehicle size, staging, and propellant selection does not provide a clear basis for selecting the most favorable means of accomplishing a lunar mission, and many other details and factors associated with the spacecraft operation, launch operations, and economics must be considered in selection of a preferred mission mode.

Table 1 Mission velocity requirements

Mission phase	Velocity increment between phases, ft/sec	Cumulative mission velocity, ft/sec
Earth re-entry		0
	3,300	
Lunar orbit (return)		3,300
	10,000[a]	
Lunar surface		10,000
	6,700[a]	
Lunar orbit (outbound)		16,700
	3,300	
Earth-moon transfer		20,000
	11,000	
Earth orbit		31,000
	30,000[b]	
Launch		61,000

[a]Including correction for gravity loss

[b]Including corrections for gravity loss, drag and Earth rotation

Table 2 Spacecraft weight comparison

Mission phase	Spacecraft weights* (lb)			
	Direct	Lunar orbit Rendezvous	Earth orbit Rendezvous	Lunar surface Rendezvous
Re-enter atmosphere	10,000	10,000	10,000	10,000
Depart lunar orbit		16,000		
Depart lunar surface	16,000	5,000	16,000	
Enter lunar orbit		21,000		
Enter Earth moon transfer	18,000	23,000	18,000	18,000
Enter Earth orbit			18,000	
Depart Earth surface	18,000	23,000	18,000	18,000

*Weights shown include expendables but exclude propulsion systems and propellants

Table 3 Mission vehicle requirements

Mission type	Vehicle gross weight, lb (O_2/kerosene first stage unless noted)	Number of launch vehicles per mission
Direct	9.49×10^6	1
	12.09×10^6 (solid first stage)	1
Earth orbit rendezvous	4.76×10^6	2
	3.17×10^6	3
Lunar orbit rendezvous	3.92×10^6	1
Lunar surface rendezvous	3.45×10^6	4

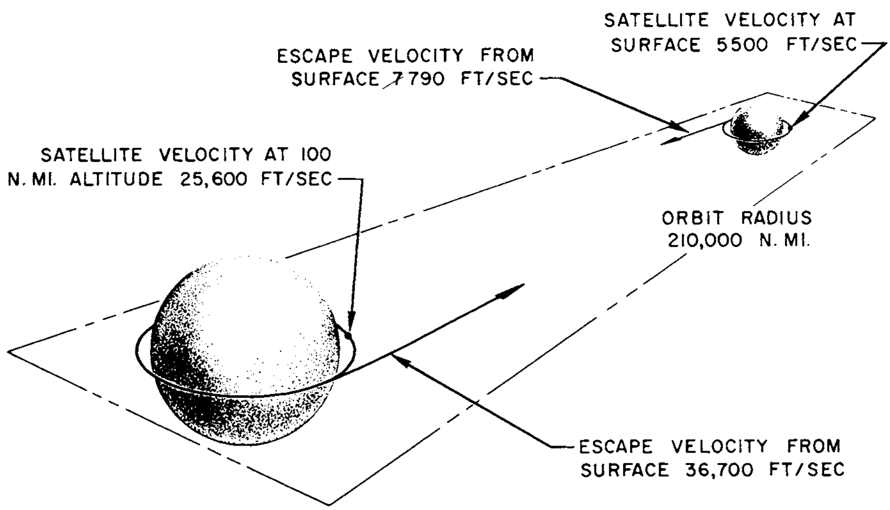

Fig. 1 Earth-moon system characteristics

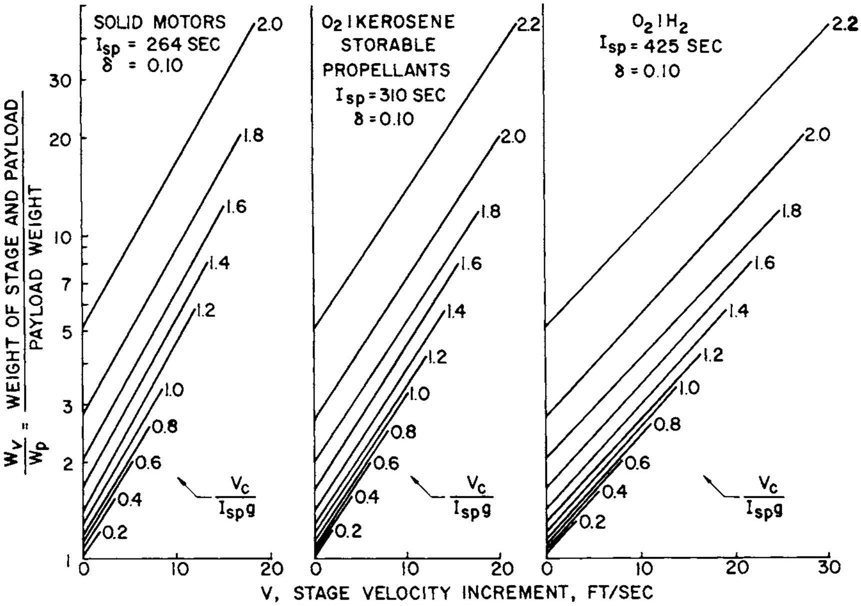

Fig. 2 Weight-velocity profiles for rocket stages

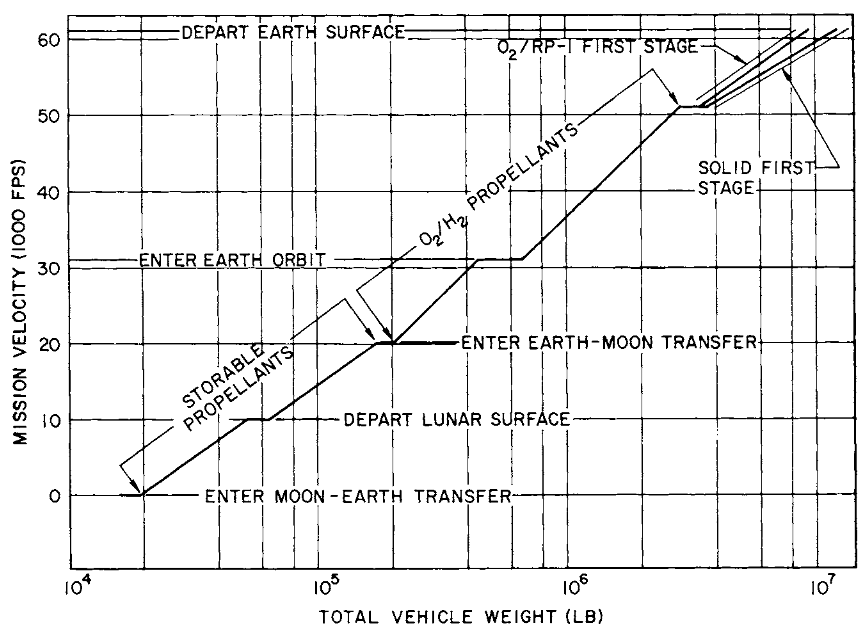

Fig. 3 Weight-velocity profile - direct lunar mission

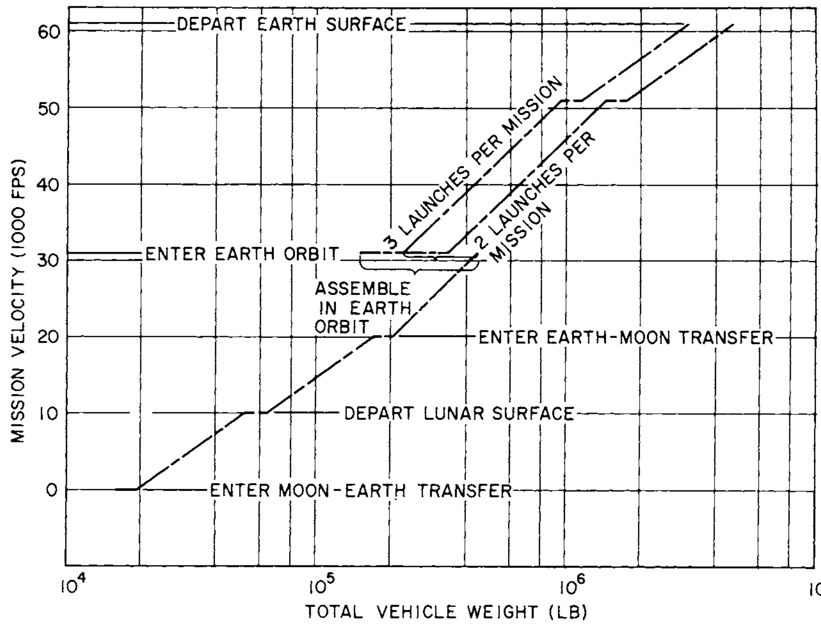

Fig. 4 Weight-velocity profile - earth orbit rendezvous

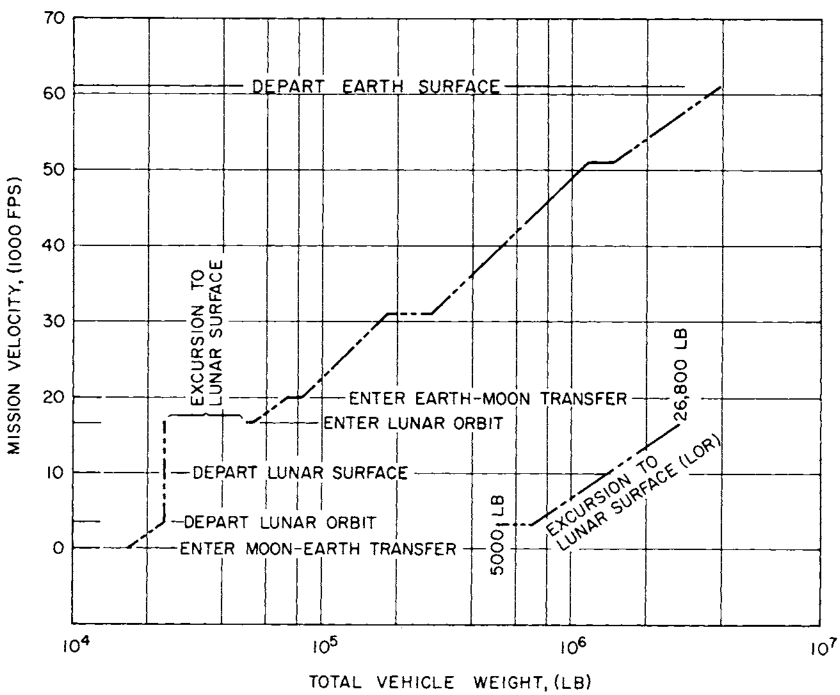

Fig. 5 Weight-velocity profile - lunar orbit rendezvous

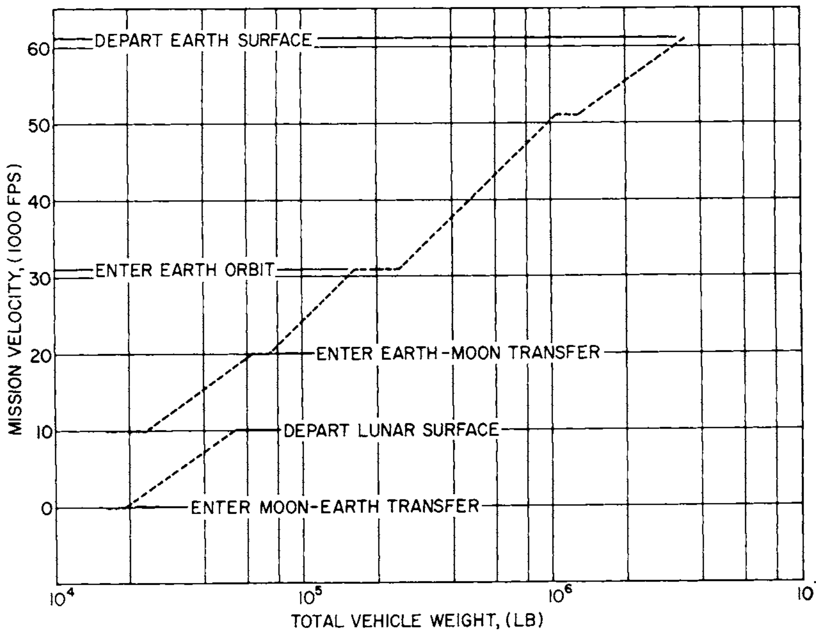

Fig. 6 Weight-velocity profile - lunar surface rendezvous

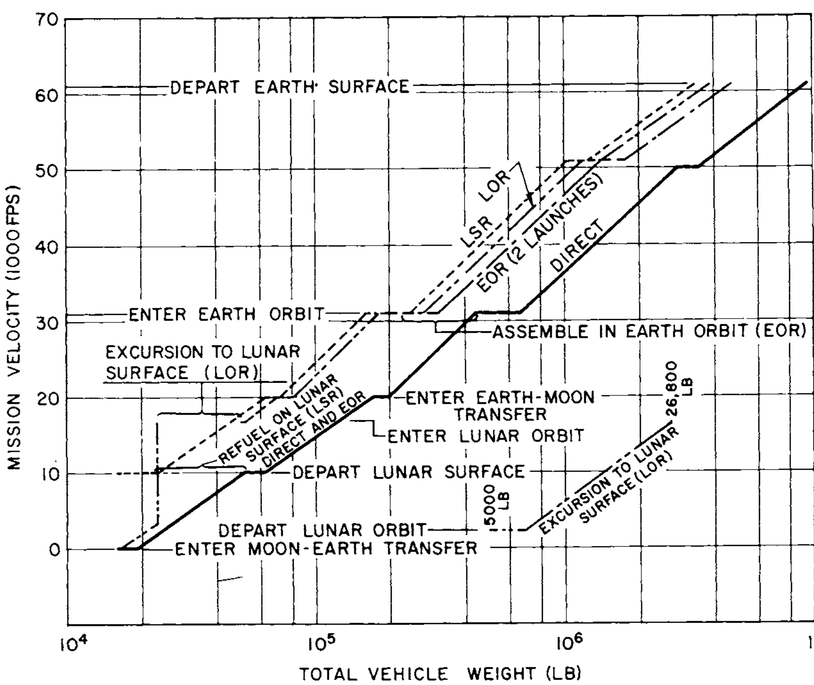

Fig. 7 Weight-velocity profiles - comparison of mission plans