Lunar Mission Profiles for Commercial Space Operations

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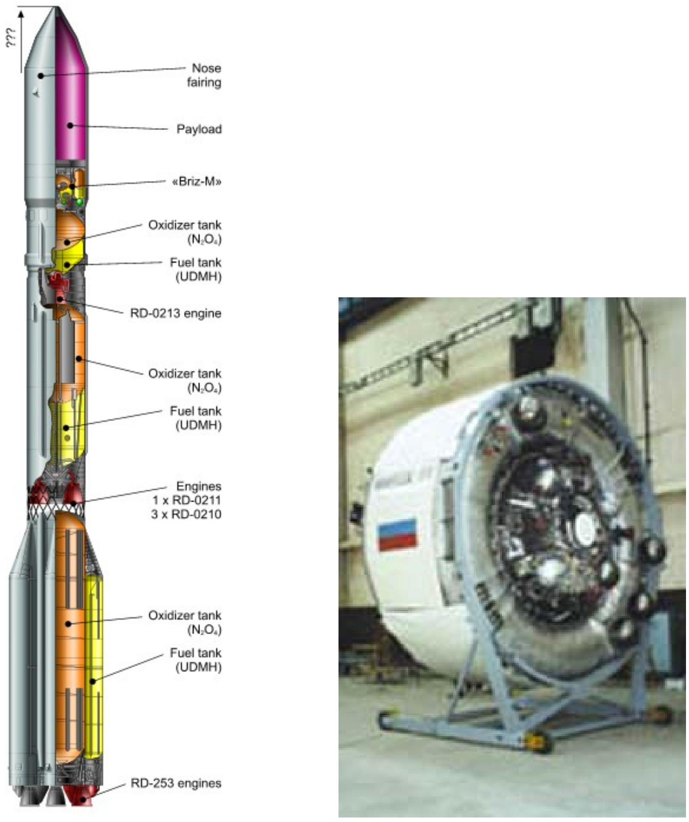
ABSTRACT

Three lunar mission profiles for manned commercial space operations utilizing existing and hypothetical hardware are analyzed: (1) direct insertion into a lunar transfer trajectory from a parking Earth orbit, similar to those used on Apollo missions; (2) insertion into a lunar transfer trajectory from a high elliptical parking orbit, similar to the elliptical phasing orbit profiles used on the Hughes satellite HGS-1 to alter its geo-transfer orbit to a geosynchronous orbit by propelling the satellite into a leading edge flyby of the Moon; and (3) direct ballistic insertion into a lunar transfer trajectory. Each mission profile has certain advantages and disadvantages in terms of energy use, length of mission, and safety considerations for manned operations. Our analysis indicates that all three types of missions can be accomplished using available hardware and operational techniques, and thus providing methods for commercial exploration and research in the Earth-Moon region.

1. INTRODUCTION

Despite the extensive use of commercial contractors since its inception, spaceflight has been controlled by national governments. However, much like in the world of atmospheric flight, there is a gap between what can be done by the public sector and what is done. Many propose that commercial interests can best fill this gap. Several companies have begun working on sub-orbital and low Earth orbit (LEO) missions, and one has even succeeded in putting a man in space [1]. We believe that in the very near future space tourism in low Earth orbit will be as commonplace as airline travel. There are even a few companies that have their sights set further than just LEO. These companies, like Excalibur-Almaz (E-A), see the Moon as a realistic goal for the near term future of space tourism.

This paper details the critical factors, constraints, capabilities, and risks of a commercially funded lunar flyby mission for one or more passengers. These proposed missions by E-A will use the pre-existing Russian four-stage Proton-M/KM configuration (Fig. 1. (a)) with the Briz-M upper stage (Fig. 1. (b)) [2]. This family of launchers has been in use by the Russians, and the Soviets before them, for more than forty years. It has a proven track record and long history of performance upon which we base our analysis. The only deviation from the baseline Proton-M considered in this paper is the presence of a second, hypothetically stripped-down, Briz-M upper stage to be attached to the regular Briz-M and payload stack. This modification is discussed in Section 2.2 of this paper.



(a) (b)

Fig. 1. (a) Proton-M/KM and (b) Briz-M

The launcher payload principally consists of the Almaz command module and the service module (Fig. 2.). However, in this paper the combined command and service modules will simply be referred to as the Almaz, the spacecraft, or simply the craft. The limits of the craft's configuration constrain our problem. These constraints are explored in detail in Section 2.3 of this paper.

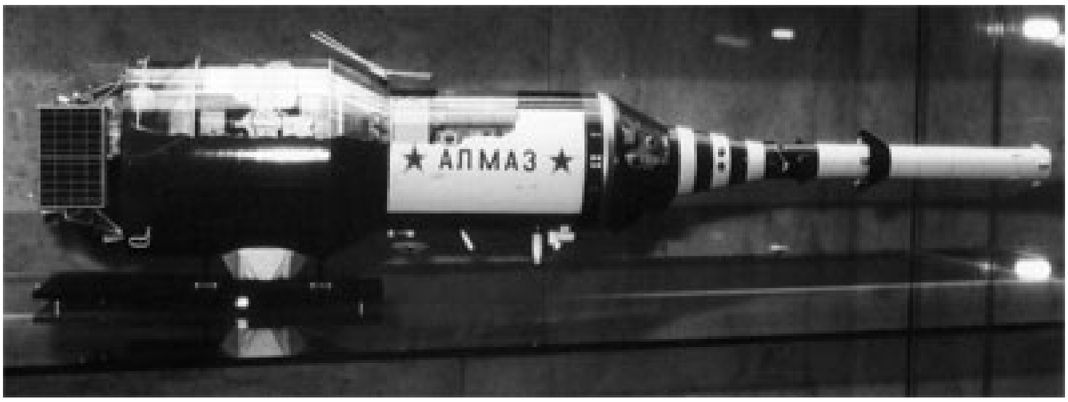


Fig. 2. Almaz command and service modules

With the constraints known from our launcher and craft configuration, specific mission plans emerge. The values of design parameters such as total payload mass, altitude of pericynthion, and total mission time become bounded since only a certain set can fall within the capabilities of the hardware. These are presented in Section 3. The combination of the launcher performance and the mission requirements are used to find the launch windows and their frequencies, as well as the occurrence and required velocity change for the trans-lunar injection (TLI). With this information, feasible missions can be planned.

These missions fall into one of three categories defined by when the TLI burn is performed. Type 1 missions are those that enter a low Earth parking orbit (LEO) for a given number of revolutions before enacting the burn. Type 2 missions are those that enter into a high Earth orbit (HEO) before injecting into lunar flyby. Type 3 missions are those that perform all burns, from launch to TLI, in quick succession for ballistic insertion (BI) to send the spacecraft flying by the Moon without ever entering into an Earth only orbit. Each of these mission profiles is further detailed and analyzed in Section 4.

Finally, the risks associated with spaceflight are many and critical. Among the basic spaceflight risks are micrometeorite strikes and cabin depressurization, radiation exposure, and muscle and bone atrophy. However, when performing a lunar flyby mission, an additional set of risks arise that become more acute the further the launch site is from the equator. These additional concerns are substantial with a Proton-M rocket launched from Baikonur into a high inclination orbit of 51.6 degrees. The risks associated with high inclination orbits derive mainly from the base orbit being increasingly out of plane with the Earth-Moon ecliptic. This will be discussed throughout the analysis section.

All figures in this paper are given principally in metric units with the exception of the Entry Interface (EI), which was defined by NASA during Apollo to occur at a geometric altitude of 400,000 ft. In some instances, imperial units will be given parenthetically for reference. Also, masses will usually be given in metric tonnes, defined to be 1000 kg. Hereafter the word metric will be dropped and the masses will only be referred to as tonnes.

2. FLIGHT CAPABILITIES AND ROCKET PERFORMANCE

A lunar flyby from the Earth's surface requires considerable expenditures of energy. The three existing launchers that are capable of accomplishing this task are the H-IIB rocket from JAXA, the Ariane V from ESA, and the Proton-M from Roscom [3]. Considerations of expense, thrust, and accessibility led Excalibur-Almaz to focus on the Proton-M configuration.

The Proton family of rockets has been in use since the early 1970s [2] and has flown in excess of 300 missions. The standard version of the Proton rocket is at present a three-stage launch vehicle with two possible upper stages, the Block-D or the more powerful Briz-M. The Briz-M upper stage consists of a main engine with a small primary fuel tank and a surrounding second larger toroidal fuel tank (Fig. 3.). We assume a hypothetically modified Briz-M stage of lower mass can also be attached to the Proton.

Unless otherwise stated, a Proton or Proton-M will refer to the standard configuration with the three stages plus the Briz-M while "Proton-Heavy" refers to the launch vehicle with the dual Briz configuration. The term Briz or Briz-M will refer to the standard configuration, and the smaller hypothetical version will always utilize the term "mini." A standard Proton-M can launch approximately 6 tonnes into a lunar flyby trajectory. We assume the cargo mass can be increased with the addition of the mini-Briz.

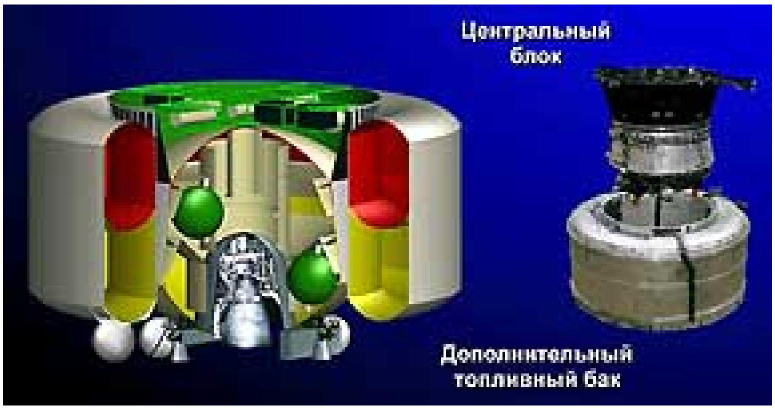


Fig. 3. Briz-M and fuel tanks

2.1 <u>Proton History and Capabilities</u>

While the Proton family has been in existence for more than four decades, the hardware and capabilities of the machine have improved with time. The Proton rocket itself has gone through a number of iterations, including the total number of stages. The largest and most advanced Proton rockets have included a fourth/upper stage which itself has evolved as technology has improved. Many of the early developments in the system were a result of the governmental applications of the Proton in its first thirty years of existence, while many of the more recent improvements have come from the fifteen years of commercial applications [2]. One such commercial improvement is the Briz-M upper stage, also known as the Breeze-M. An upgrade from the older Block-D upper stage, the Briz allows for heavier payloads to be put into orbit. The result of these changes is a launcher with the capability to put 21 tonnes into low Earth orbit (LEO). Since the mass of the Almaz capsule is less that 7 tonnes, a considerable percentage of the Briz-M's fuel remains for a TLI burn.

As a replacement to the Block-D upper stage, the Briz-M was designed to take up less volume than its predecessor while providing more thrust. A single Briz stage has been rated and published to put roughly 6 tonnes into a lunar flyby trajectory. This mass is on the low end of what is required for a crewed command and service module with supplies. In order to increase the available mass for the payload, we have utilized a hypothetical stripped-down Briz-M that can generate 0.5 km/s of delta-V. We have determined that the use of the dual Briz configuration, with the smaller engine burning first, can take a payload of 7 tonnes into a lunar free return trajectory.

Once in orbit, the standard Briz-M upper stage has a published battery life of 24 hours, which is the limiting factor in its life cycle. This works out well as a bound on the time spent in LEO or HEO since a lunar flyby mission takes approximately 6 days, and the life span of the Almaz capsule is roughly 7 days. At the end of any LEO or HEO portion of the flight, the Briz will again ignite and perform the TLI burn. The specific impulse and thrust of the Briz-M are different from those of the Apollo S-IVB yielding different burn times. While TLI burns of the S-IVB were roughly six minutes [4], those of the Briz-M will be between 10 and 13 minutes. The fact that the Briz burn will be twice as long as that of the S-IVB means it will be necessary to use more of the course correction fuel to keep the spacecraft and engine correctly oriented and that the variance from the norm of the engine firing will have a longer time to propagate causing a greater deviation in the trajectory.

2.2 <u>Dual Briz Engine Configuration</u>

Augmenting the upper stage with the mini-Briz increases the launch weight but also provides additional fuel and reduces the total fuel expenditure of the main Briz-M to reach either type of

Earth orbit. The launch profile has been analyzed to determine if there is enough fuel left in the Briz-M to propel 7 tonnes to a lunar flyby. Knowing the masses of fuel and structure for the two Briz engines and the 7 tonnes for the payload, we determined the maximum delta-V of the combined system as well as the required amount of fuel to accomplish the mission. The difference in these two values was the total fuel available to take the entire stack, the two engines and the payload, from its position at stage 3 burn out to LEO.

Assuming that both engines burn the entirety of their fuel stores, the total delta-V that the engines can produce is 4.1 km/s, of which 3.6 km/s is the Briz-M and 0.5 km/s is assumed for the mini-Briz-M. Since the required delta-V for lunar flyby is roughly 3.15 km/s, there is enough fuel between the two Briz engines for a delta-V of 0.9 km/s to take the stack from third stage burnout to low Earth orbit and still have enough fuel for TLI. An analysis of the launch of the Proton rocket's first three stages launching a dual Briz M fourth stage plus 7000 kg Almaz payload.

From this analysis, we found that the "Proton-Heavy" has the following post-stage 3 burnout characteristics: an inclination of 51.6 degrees, downrange distance of roughly 1800 km, altitude of roughly 200 km, and velocity of 7.2 km/s. At a parking orbit of 277.8 km (150 nm) the orbital velocity is 7.74 km/s. Further analysis indicated that a finite burn of approximately 0.8 km/s can take the stack from stage 3 burn out to LEO. Thus, the smaller Briz-M engine will burn its total fuel weight and achieve 0.5 km/s of delta-V, leaving roughly 0.3 km/s delta V for the main Briz-M. This will leave 3.3 km/s of delta-V in the Briz-M for the TLI burn, which requires a maximum of 3.15 km/s. This indicates that the dual Briz configuration has the capability of placing 7 tonnes of payload into lunar flyby with a 0.15 km/s delta-V safety margin. These findings are summarized in Table 1 below.

Table 1: Dual Briz-M Configuration

Required Delta-V		Available Delta-V	
To LEO	0.80 km/s	Mini-Briz	0.50 km/s
For TLI	3.15 km/s	Briz-M	3.60 km/s
Total	3.95 km/s	Total	4.10 km/s

3. MISSION DESIGNS AND REQUIREMENTS

The use of the "Proton-Heavy" with the Almaz dictates the maximum mass and flight time and aids in finalizing items including course correction fuel mass, consumables, and structure break down. All of these items also determine how many passengers a mission can accommodate within the time constraints. Further, Briz-M battery life and capsule habitability help to determine different mission parameters such as length of parking orbit and TLI burn options.

Another parameter that controls time in LEO or HEO and time of TLI, is the value of the TLI burn delta-V. As the fuel available sets the upper bound for affecting a delta-V, mission planners can solve for the lowest delta-V value that will return the crew in the time allotted for a given trajectory. As with any free return trajectory, excepting a few minor course corrections, everything about a mission is set by time, value, and position of the TLI burn. These values are themselves partially set by launch time and any parking orbit length. Thus, the entire mission design with existing hardware can be seen as tuning the coupled inputs of launch time, parking orbit length, and delta-V value. The problem outputs then are the requirements of returning to Earth within a certain time, at a certain EI angle, and landing near the launch site.

3.1 Launch, Parking Orbits, and Delta-V

The time of launch determines where the line of apogee vector points in space in the Earth's equatorial plane. However, parking orbit time has an important and multi-faceted role. First and foremost, the time in parking orbit must be spent ensuring that all the systems are working correctly, especially the Briz engine. Because there are only small thrusters for course corrections, the Briz must burn on time and as accurately as possible to ensure that the mission trajectory is optimal. This is even more important for an out-of-plane mission as the craft trajectory is very sensitive to the change of plane caused by the Moon. Apollo missions spent at least one and a quarter orbits in LEO before proceeding to the Moon, and this is a good lower limit for time in LEO or HEO.

There are two other factors that control the upper limit and the actual time to leave the parking orbit. The first of these upper limits for missions utilizing the parking orbit is set by the competing goals of giving the passenger as much time in Earth orbit while ensuring that the total Mission Elapsed Time (MET) is within the safety margins of the capsule habitability limit. The Briz-M upper stage engine's 24 hours of battery life also sets a hard upper limit. With a lifetime of 7 days for the spacecraft and a general round trip time of approximately 6 days, there is roughly 1 day for the parking orbit. Assuming the upper stage and the payload orbit the Earth every 90 minutes, this translates to between 10 and 15 orbits. As there will be no orbiting of the Earth after the TLI burn, this is the total time the passengers will have to view the planet as well as to adjust to weightlessness before the journey to the Moon.

With upper and lower limits on the orbit time set, the final requirement on the line of apogee sets the specific time for beginning the TLI burn. The line of apogee must be above or below the Moon's equator for missions when the Moon is above or below the Earth's equator, respectively. Once the total number of parking orbits has been reached, the craft must then continue along the trajectory until it is at such a point that the post-TLI burn apogee vector is in the correct position. For example, for a mission where the craft must fly above the Moon's equator, it will be necessary for the craft to be on the opposite side of the Earth from the Moon as it descends from the north to the south, then continue heading slightly further south in the orbit until such time as its antipode is above the Moon's orbit.

Once the orbit phase has been completed, the TLI burn will commence. The range of acceptable TLI delta-V is relatively small for each of the Type 1 and 2 missions given these machines. The higher the delta-V, the closer to the Moon the craft can pass, and the sooner it will return to the Earth. For a Type 1 mission, the delta-V to escape LEO is roughly 3.15 km/s, while for a Type 2 mission, since the craft is already moved from LEO to HEO, the delta-V is about 0.7 km/s. A higher delta-V value from a given orbital altitude will necessitate a closer lunar flyby but return the crew to the Earth sooner while a lower delta-V will allow the crew more time in space but increase the pericynthion altitude. Since the launch date, parking orbit time, and delta-V value are coupled, changing one will affect the others. Once a mission is planned, all three values must be reset if there is the desire to decrease the altitude of the lunar flyby, or to return sooner, or to alter the launch date.

3.2 Lunar Flyby and Return to Earth

If we view the launch date, time of TLI and its delta-V value as the independent variables that control the mission, then the pericynthion, EI flight path angle, and landing site act as dependent variables to the mission designers. Along with how it affects travel time and plane change, the designer uses the pericynthion to control the passenger's lunar flyby altitude. Control of the flight path angle at EI and the landing site, however, are required for a safe mission.

The two most important aspects of the pericynthion are altitude and lighting conditions. The closer to the Moon the craft can fly, the more spectacular and discernable the lunar surface will be. Being able to reach an altitude close enough to see Apollo landing sites, for example, might help set the desired flyby altitude. Secondly, the flyby should occur in such a manner as to maximize the illuminated portion of the Moon; some passengers may want to see as much of the near side as possible while others may wish to see a fully illuminated "dark side."

Unlike the pericynthion, the entry interface (EI) and landing site are requirements set by the realities of physics and E-A resources. Returning from the Moon, the spacecraft will be flying at roughly 11 km/s as it reaches Earth; the rapid increase in the atmospheric density places very tight restrictions on how the craft enters and lands. With the Apollo flights, the EI was defined by NASA to be 400,000 ft above sea level at which point the angle of the craft's flight must be -6 ± 1 degrees to the Earth's surface for a safe reentry. Reentry at a more negative (steeper) angle may cause the craft to burn up while a shallower angle may cause the craft to skip off of the Earth's atmosphere.

The flight path corridor constraints mean that the window through which the craft can reach EI is directly related to the location and size of the landing site. Unfortunately, because of limited manpower and resources available to a commercial interest like E-A, and the limited amount of consumables that can be carried aboard the craft, the landing site must be small and close to the launch site.

The values for the time and position of the craft at TLI burnout can be back-propagated, given that a Baikonur launched mission must return to Kazakhstan within roughly 7 days and pass through EI in a 2 degree corridor. This TLI burnout conditions can in turn be used to find the time in parking orbit and the corresponding launch date. We have employed this inverse approach, as well as the forward problem approach of choosing launch, LEO, and TLI characteristics and iterating until a realistic and acceptable mission is achieved.

4. ANALYSIS AND RESULTS

The three mission types analyzed were designed using a combination of the two-body problem (2BP) and the restricted three-body problem (R3BP). The 2BP was used to develop a Hohmann transfer with an apogee beyond the orbit of the moon as an initial guess for the parameters for the TLI. This flight plan was designed to lead the Moon by a certain amount of time such that the spacecraft came to be dominated by the influence of the lunar gravity before it reached its apogee. After the burn was executed, the rest of the analysis performed operated under the R3BP. Because the mass of the spacecraft is so much less than that of both the Earth and the Moon (weight ratios of roughly $1x10^{-24}$ and $1x10^{-22}$ respectively), this approach is both acceptable and is the standard model used in the analysis and planning of trajectories in an Earth-Moon-Spacecraft system [2].

In determining the required fuel expenditures for each mission type, it was necessary to work through the three Briz-M engine burns required to achieve the desired delta-V. Regardless of the mission type, the engine burns must increase the apogee of its orbit to 400,000 km to achieve a lunar flyby with free return.

4.1 <u>Low Earth Orbit Mission</u>

For the low Earth orbit Type 1 missions, a balance must be found between the life span of the Briz with Almaz capsules and the desire of the passenger to view the Earth. As previously mentioned, this mission type is the safest from an operational perspective. After achieving low Earth orbit, there will be time to perform a full systems-check and for the passengers to view the Earth. If something was affected by launch, mission planners can determine if the component(s) can either be fixed or replaced, or whether or not the mission must be reevaluated given the parameters. However, if some part of the craft is damaged to the point that the ground crew feels it would be beyond the safety envelope to continue the mission, there would be ample fuel to de-orbit the Almaz and bring the crew home safely.

What the LEO mission gains in crew options and safety in one area, it loses in another. Between the small but finite atmospheric drag in LEO, the flattening effect of the Earth's oblateness, and other factors, the Almaz-Briz stack will be slightly out of its expected position. As with satellites and the International Space Station, it could be necessary to perform station-keeping burns to ensure that the Almaz remains in the correct position. This will use up a portion of the course correction fuel that is also needed for the finite (non-impulsive) TLI burn to aim the engine, as well as for actual course corrections. It may seem that if course corrections are already needed that using fuel on station-keeping would be a waste, but even for a burn from the correct position and with the correct velocity vector, a burn of 10,000 ft/s for the Apollo S-IVB required precision of less than 0.1ft/s [4]. Thus, there is some balance between minimizing the fuel used in station-keeping and fuel needed for post-TLI corrections.

Further, it will be necessary to burn some extra Briz-M fuel to put the spacecraft into LEO then break it back out during TLI. How much this is will depend on the altitude of the LEO and desired proximity to the Moon. Here again there must be a balance between safety and LEO flexibility within the performance constraints of the Proton. Missions of this type require the mini-Briz to burn all its fuel, along with roughly 20% of the Briz fuel burning to reach LEO. After 10-15 orbits (approximately one day) with minor station-keeping, the TLI burn will occur lasting 10 minutes and changing the magnitude of the velocity by approximately 3.15 km/s. We have analyzed and planned out missions with pericynthions ranging from 200 km to 2000 km, and returning to the Earth in between 5 days 19 hours after TLI and 6 days 1 hr after TLI, respectively.

4.2 <u>High Earth Orbit Mission</u>

High Earth orbit missions provide some of the benefits of the LEO mission while reducing some of the waste; however, additional disadvantages arise along with those advantages. In the Type 2 mission, there is still time spent close to the Earth to allow for some of the same viewing options as with the Type 1 missions, while having more safety features than the ballistic insertion method.

With the HEO mission, it is possible to spend some time in LEO, burn to a higher orbit, and then after an additional pass of the perigee, burn again for TLI. Here, though, we look at a mission where less than two orbits are spent in LEO before firing out to the elliptical orbit. In this case, just as in the LEO mission, the mini-Briz will burn its full complement of fuel, stage, and then the Briz will perform the additional burn to place itself and the Almaz into Earth orbit. If the mission designers elect to go with a LEO portion for this mission, the fuel waste is as above, however, if they elect to go directly into HEO, some of that fuel waste is lessened.

Regardless of whether or not the LEO portion is utilized, the spacecraft can spend several orbits around the Earth checking systems to ensure a safe lunar flyby. If this scan is done during an LEO portion the mission can proceed as above, but if the check-out occurs during the time in the higher Earth orbit, additional considerations must be taken into account. The most important of these, which will provide an upper limit on the apogee of the high Earth orbit, is the fuel needed to return to the Earth. A large percentage of the Briz-M fuel will be needed to put the Almaz into an elliptical orbit, and after a point, there will be enough left to fly by the Moon but not enough to bring the perigee in such that it reenters the Earth's atmosphere at the correct angle and land within the recovery zone. Hitting the correct recovery zone from the high Earth orbit will provide an additional constraint on the mission.

As there are many radii of apogee that leave plenty of fuel in the Briz tanks for an abort, this mission profile remains safer and somewhat less wasteful than the LEO mission. Further, the required delta-V to break out of the HEO is closer to 0.7 km/s instead of the 3.15 km/s of the LEO. Because the burn magnitude is less, the time of the burn will also be less; these two combine to reduce the chance for the errors in the burns and increase the acceptable deviation from the planned delta-V, provided that the mission planners correct the burn characteristics once the Briz-Almaz stack has entered HEO. This will reduce the required fuel for course corrections, which in turn improves the safety of the overall mission.

The Type 2 mission necessitates the mini-Briz to burn all its fuel, along with roughly 20% of the Briz fuel burning to reach LEO or about 70% of its fuel for a direct high Earth orbit insertion. After approximately 10 hours, with minor station-keeping, the two minute TLI burn will occur and change the magnitude of the velocity by approximately 0.7 km/s for an apogee on the order of 50,000 km. Once again, we have analyzed and planned out missions with pericynthions ranging from 200 km to 2000 km, and returning to the Earth in between 5 days 19 hours after TLI, and 6 days 1 hr after TLI, respectively.

4.3 Ballistic Insertion Mission

Of the three types of missions, the Ballistic insertion method provides the fewest unknowns for the mission planner, has the least fuel waste up to TLI, but also has the smallest margin for error. By minimizing the time spent in the Earth's atmosphere as well as the time that the planet's oblateness changes the orbit, the high thrust of the four stages completely dominates the mission through TLI. Further, as there is no time spent in Earth orbit, the list of input parameters that must be matched to reach the correct pericynthion are entry interface and landing conditions.

The primary issue with the ballistic insertion is the reduced time available for a post-launch systems check. During the pre-launch procedures, all the systems are given a thorough evaluation, including the two Briz engines. The safety of the mission can be increased by bringing additional course correction fuel along with the rest of the Almaz since the ballistic insertion method does not experience the waste associated with entering into and breaking out of Earth orbits. The fuel that would be kept in the Briz engine to make all the necessary energy changes can now be used for course correction fuel.

Further, with the engines in working order, the mission planners will know more precisely where the Almaz-Briz stack will be when the mini-Briz engine is exhausted so that they can plan the next burn more accurately. This is important because with the TLI burn being almost indistinguishable from the launch sequence, the deviations from the burn norm will be played out over a much longer time span and delta-V. This is another area where the additional course correction fuel available for this mission will be necessary.

Because the mission will have no time spent in orbit, the planning of the missions becomes more straightforward, though not necessarily easier. Without the time in LEO as a parameter, and with the value of the delta-V somewhat more hard coded once the Almaz is built and physically sitting on top of the Proton, the launch occasion will be the only parameter that is necessary. As such, missions will be more clear-cut to plan.

As with the other mission types, the mini-Briz will burn all of its fuel. However, with this profile, the Briz-M will also burn its full complement of fuel. This reduces the amount of fuel spent on course correction during orbits but means additional fuel will be spent to keep the engines properly positioned during the Briz-M burn. As with the other missions, pericynthions of 200 km to 2000 km can be achieved yielding mission times of between 5 days 19 hours and 6 days 1 hour. However, unlike the other two mission types, this is the total mission time, thus one day's less cargo, consumables, and life support are needed.

5. CONCLUSIONS

Commercial lunar ventures are not only now feasible, we believe they are inevitable especially considering the availability of existing launch vehicles that include the Proton. Using the dual Briz upper stage configuration, three types of lunar flyby missions were explored in this paper. Each mission type had its advantages and disadvantages including additional LEO time, launch flexibility, fuel usage, and margins of safety. However, we found that all three missions types were workable and could be executed within a few years using the Proton system.

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