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PROJECT COLUMBIAD

Reestablishment of Human Presence on the Moon

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Abstract

In response to the Report of the Advisory Committee on the future of the U.S. Space Program and a request from NASA's Exploration Office, the MIT Hunsaker Aerospace Corporation (HAC) conducted a feasibility study, known as Project Columbiad, on reestablishing human presence on the Moon before the year 2000. The mission criteria established were to transport a four person crew to the lunar surface at any latitude and back to Earth with a 14-28 day stay on the lunar surface. Safety followed by cost of the Columbiad Mission were the top level priorities of HAC. The resulting design has a precursor mission that emplaces the required surface payloads before the piloted mission arrrives. Both the precursor and piloted missions require two National Launch System (NLS) launches. Both the precursor and piloted mission have an Earth orbit rendezvous (EOR) with a direct transit to the Moon post-EOR. The piloted mission returns to Earth via a direct transit. Included among the surface payloads preemplaced are a habitat, solar power plant (including fuel cells for the lunar night), lunar rover, and mechanisms used to cover the habitat with regolith (lunar soil) in order to protect the crew members from severe solar flare radiation.

Executive Summary

In 1990, the Report of the Advisory Committee on the future of the U.S. Space Program proposed a plan known as Mission from Planet Earth which included the establishment of a lunar exploration base. Under the direction of NASA's Exploration Office, the MIT Hunsaker Aerospace Corporation performed a feasibility study on the reestablishment of human presence on the Moon before the end of the decade. The project became known as Project Columbiad, named after the fictional cannon in Jules Verne's From the Earth to the Moon.

The primary objectives of Project Columbiad were to transport a four person crew to the lunar surface and back with a 28-day stay on the lunar surface. Project Columbiad was also designed to have the capacity to land at any latitude on the lunar surface and be able to abort at any time -- meaning within the next lunar launch window. Other goals of the mission were to provide the foundation for the aforementioned future lunar exploration base and in the meantime to provide an opportunity for preliminary lunar exploration and scientific research. Still other goals of a high profile mission such as this are to boost national confidence and at the same time to promote international cooperation.

Safety of the crew members was always the primary concern during the design of the mission. Redundancy standards for the mission were set at two levels for mission success and three levels for crew safety. High levels of subsystem reliability were achieved through the use of proven technologies. Results of the initial studies indicate an expected human survivability probability of 99.7%. It is expected that in the next design iteration of Project Columbiad, this probability will reach the targeted 99.9%. At this stage in the design the overall mission probability of success reached the targeted 95% probability.

Beyond safety, cost was the primary driver of the mission design. The final estimate for the complete first mission cost, including research, development, testing, and evaluation (RDT&E), was $12.8 billion -- a relatively low cost for a mission of this size. With the cost spread out over the remaining decade, the cost per year is within the scope of the NASA budget. The primary factor contributing to this low project cost is the use of already well-developed and tested technology.

In order to make many of the design choices, a trade study regarding Columbiad's trajectory was made. In the Apollo missions of twenty years ago, a lunar orbit trajectory was used in order to reduce the initial weight and, hence, cost of the missions. Given the constraints for Columbiad to land at any latitude and to stay on the Moon for 14-28 days, the lunar orbit trajectory has several complications due to the mission goal for abort at any time. For this reason, a direct transit from the Earth is a better choice and was selected for the Columbiad missions.

The second critical trade study that was conducted was the choice of launch vehicle. The National Launch System (NLS) was chosen first for its high reliability and second for its launch capacity. The NLS has a high expected reliability due to the large number of flight tests that have already occurred for much of its hardware. Despite the fact that the NLS does not match the Saturn V's launch capabilities, it will be the largest reasonable launch vehicle available by the end of the decade. Another reason to use the NLS instead of reviving the Saturn V or designing an entirely new launch vehicle is that the NLS can be used for other types of missions and would not be a launch vehicle built and designed solely for these lunar missions as the Saturn V was. These other markets for the NLS aid in bringing down the cost of the NLS vehicle and raising the reliability.

The current design for the NLS allows only a 72-metric ton payload to a 200 km circular orbit. Therefore two additional Redesigned Solid Rocket Motors (RSRM) were added on to the baseline NLS for a total of four RSRMs. This NLS configuration allows the insertion of a 100,000-kg payload (including a 10% margin) into a 200-km apogee launch trajectory. With this launch capacity, a minimum of two launches is required for a single piloted mission and an additional two launches are required for a precursor mission. Therefore an Earth orbit rendezvous is necessitated.

A total of four NLS launches is required for a complete Columbiad mission. Each precursor and piloted mission launch has a payload mass of approximately 95,600 kg. The packaging of the two missions is shown in Figure 1. The first two launches in quick succession are for the precursor while the third and fourth launches for the piloted mission are launched only after the success of the precursor mission has been confirmed. All launches are scheduled from Kennedy Space Center, Launch Pads 39A and 39B.

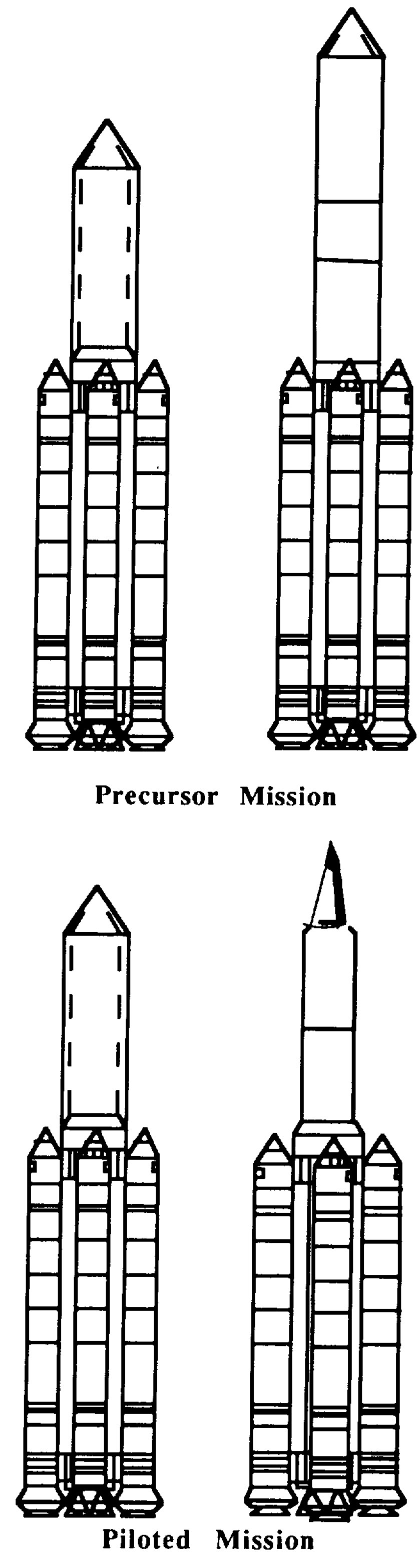

Fig. 1 NLS Launches for Columbiad

The precursor mission was designed to be as modular as possible with the piloted mission for cost considerations. Therefore, each precursor mission vehicle is composed of three propulsive elements (two are identical with the piloted mission stages) in addition to the surface payloads: Primary Trans-Lunar Injection (PTLI), Lunar Braking Module (LBM), and Payload Landing Module (PLM). Again, the PTLI is by itself on the first launch for the precursor mission (Launch 1) while the LBM, PLM, and surface payloads are on the second launch for the precursor mission (Launch 2). The surface payloads include a habitat (BioCan) and a payload bay for other equipment.

The piloted mission is composed of three propulsive elements in addition to the Crew Module: Primary Trans-Lunar Injection (PTLI) stage, Lunar Braking Module (LBM), and Earth Return Module (ERM). The PTLI is the only component on the first launch for the piloted mission (Launch 3) while the LBM, ERM, and CM are grouped together on the second launch for the piloted mission (Launch 4).

Before translunar injection the vehicle must be established in a circular LEO for rendezvous. The NLS vehicle does not perform the circularization burn into a 200-km altitude for any of the four launches. In the precursor mission, the PTLI performs a circularization burn, and then raises its altitude to 275 km at the desired trajectory window where it will await rendezvous with the surface payload in the second launch. For the surface payloads launch, it is the LBM that performs both the circularization burn and the burn to higher orbit. Once again, for the piloted mission, the PTLI performs the circularization burn and, then, raises its altitude to 275 km at the desired trajectory window where it will await rendezvous with the piloted launch. For the piloted launch, it is the LBM that performs both the circularization burn and the burn to higher orbit.

Table 1: Precursor Mission Profile

Event	Location	ΔV (m/s)
Circularization of Launch 1	200 km LEO	177
Launch 1 burn to higher LEO	200-275 km LEO	43
Circularization of Launch 2	200 km LEO	177
Launch 2 burn to higher LEO	200-275 km LEO	43
Earth Orbit Rendezvous	275 km LEO	60
Trans-Lunar Injection	LEO	2460
Trans-Lunar Injection	LEO	680
Midcourse Corrections	Midcourse	120
Lunar Braking into LLO	Prior to LLO	1060
Lunar Braking to Moon	LLO to Moon	1700
Hover and Land	Moon	500

Once the vehicles have completed rendezvous, the Trans-Lunar Injection is performed by two stages: the PTLI and the LBM. The PTLI separates from the remaining stages upon the completion of its burn. The LBM completes the burn and then performs midcourse corrections that are required during the three-day transit. Upon lunar arrival, the LBM inserts the vehicle into LLO, and then performs the major portion of the descent burn before it is staged and crashed safely away from the landing site. For the precursor mission, the PLM then performs the final descent and hover burn before landing and deploying the habitat. A brief mission profile along with propulsive requirements for each stage is featured in Table 1.

On the piloted mission, the ERM performs the final descent and hover burn before landing. After the 28-day lunar stay, the ERM launches the CM into LLO and then into the Earth transfer orbit. The ERM also performs any midcourse corrections. The ERM separates from the Crew Module (CM) just before reentry into the Earth's atmosphere, and then the CM proceeds to reenter the atmosphere safely. The piloted mission is completed when the CM lands at Edwards Air Force Base. A brief mission profile along with propulsive requirements for each stage is featured in Table 2. An outline of the trajectory that Columbiad vehicles will follow is shown in Figure 2.

Table 2 : Piloted Mission Profile

Event	Location	ΔV (m/s)
Circularization of Launch 3	200 km LEO	177
Launch 3 burn to higher LEO	200-275 km LEO	43
Circularization of Launch 4	200 km LEO	177
Launch 4 burn to higher LEO	200-275 km LEO	43
Earth Orbit Rendezvous	275 km LEO	60
Trans-Lunar Injection	LEO	2460
Trans-Lunar Injection	LEO	680
Midcourse Corrections	Midcourse	120
Lunar Braking into LLO	Prior to LLO	1060
Lunar Braking to Moon	LLO to Moon	1700
Hover	Moon	500
Lunar Launch	Moon to LLO	2200
Earth Return Injection	LLO	1060
Midcourse Corrections	Midcourse	120
Reentry	Earth's Atmosphere	100

In order to minimize the thermal stresses that the vehicle structures encounter during the mission, a decision was made to spin the transit vehicle at a rate of approximately once per hour. If a launch slippage occurs for either Launches 2 or 4, then the PTLI may initiate a spin while it waits in LEO. The PTLI would despin shortly before docking occured with Launch 2 or Launch 4.

To equalize the payload weights of the launches, the TLI burn was split between two stages. The four launch weights were roughly equalized by allocating approximately 85% (ΔV = 2460 m/s) of the TLI burn to the Primary TLI stage. This left a ΔV = 680 m/s to be included in the next stage.

A separate stage was not designed for this small ΔV. Instead, the propellant was included in the following stage, the LBM.

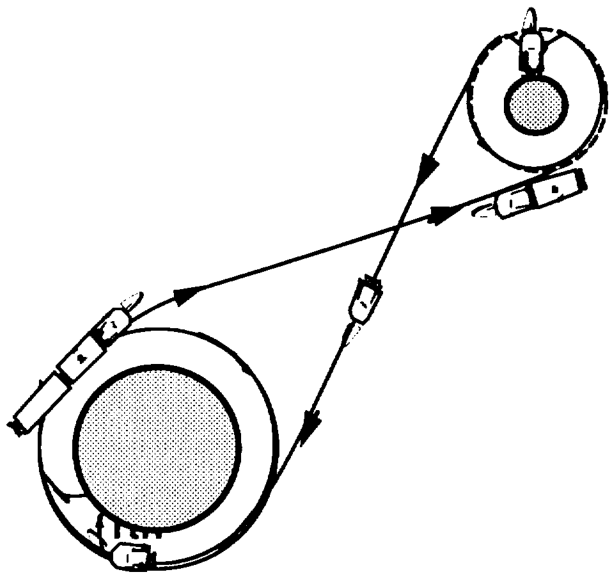

Fig. 2 Columbiad Mission Trajectory

To reduce the height of the vehicle landing on the surface of the Moon, a decision was made to stage just prior to the hover and landing phase of the lunar descent. Therefore, for both missions, the LBM is staged after completing the major portion of the descent. The ERM and PLM are both equipped with landing gear and propulsion systems to conduct the final descent phase. This is a significant aid as it reduces the height of the landing vehicle by 12-13 m.

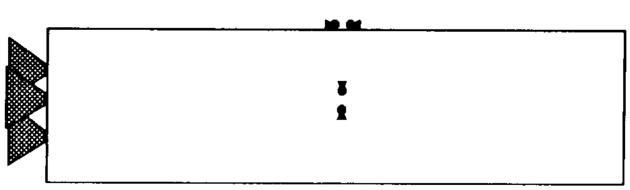

Fig. 3 Primary Trans-Lunar Injection Stage

The PTLI stage, shown in Figure 3, has five RL10 engines and performs four burns. The first PTLI burn circularizes the PTLI's Earth Orbit at 200 km. The second burn is the initial burn to transfer to a higher orbit, and the third burn completes the higher orbit transfer at 275 km. The fourth burn is the only burn occuring when the PTLI is attached to the other stages. When this burn is complete the PTLI has expended its fuel and is staged off.

The dry mass budget for this stage is 11,587 kg and the wet mass budget is 94,825 kg. Since the PTLI must remain in orbit about the Earth for up to 40 days, independently of the rest of the vehicle, it has its own power; Guidance, Navigation, and Control (GNC); and Command, Communications, and Control (C^3) systems on board. Included among its apparatus is a low gain antenna for communication with Earth and a Reaction Control System (RCS) for stationkeeping.

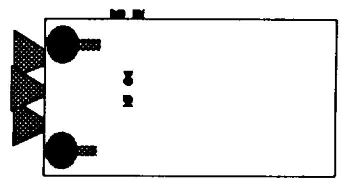

Fig. 4 Lunar Braking Module

The LBM, shown in Figure 4, has three RL10 engines and performs six burns plus midcourse corrections. The first LBM burn circularizes the veicle's Earth Orbit at 200 km. The second burn is the initial burn to transfer to a higher orbit and the third burn completes the higher orbit transfer at 275 km, where docking with the PTLI occurs. The fourth burn is the Secondary Trans-Lunar Injection burn that occurs just after the PTLI stage is staged off. The fifth burn brakes the module into LLO, and the sixth and final burn completes most of the lunar descent burn before it is staged.

The dry mass budget for this stage is 6,731 kg and the wet mass budget is 62,285 kg. The LBM does not have its own power source. Either the ERM or the PLM provides the necessary power for it during its burns.

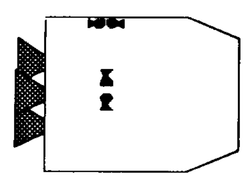

Fig. 5 Earth Return Module

The ERM, shown in Figure 5, utilizes three RL10 engines to perform three burns plus midcourse corrections. The first ERM burn is extremely critical because it prevents the CM from crashing into the lunar surface after the LBM has initiated the descent to the lunar surface. The second burn is the launch from the lunar surface into LLO and the third burn injects the vehicle into an Earth return trajectory.

The dry mass budget for the ERM is 5,553 kg, including 500 kg for landing legs that are jettisoned off after lunar launch. Within the stage, an additional payload weight of 3000 kg to the lunar surface can be stowed. This weight is twice the minimum necessary to resupply the habitat for future piloted missions. Therefore the total wet weight budget is 26,210 kg. The ERM has an RCS for both rendezvous and midcourse correction burns. It also contains a high gain antenna so that the crew can communicate with Earth in the vicinity of the Moon. The ERM supplies power to both the LBM and the CM in addition to itself.

Fig. 6 Crew Module

The crew module, shown in Figure 6, is designed as a biconic reentry vehicle with a maximum lift to drag ratio of 1.1. The lift to drag ratio allows for reentry maneuvering and extends the downrange and cross range distances of the vehicle. The vehicle safely houses the four crew members for the transit to the Moon and back to Earth, including the reentry phase. The budgeted mass of the CM is 6330 kg which includes the 730 kg heat shield.

Table 3: Piloted Mission Mass Summary

Stage	ΔVtotal (m/s)	Wet Mass (kg)	Length (m)
PTLI	2680	94,825	15.96
LBM	3780	62,285	12.7
ERM	3880	22,710	9.97
Piloted Payload to Moon		3500	(in ERM)
Crew Module		6330	7.69
Nose Cone (Launch 3)		820	5
Total Mass		190,470	

Total Length
Total Mass for Launch 3 (PTLI stage) - 94,825 kg
20.96 m
Total Mass for Launch 4 (Piloted launch)- 95,645 kg
27.66 m (plus 2.7 m)

The total height allowance for an NLS payload is 35 m including a nose cone. The height of Launch 4 is less than the total height of the LBM, ERM, and CM because the LBM stage is recessed into the launch vehicle by 2.7 m. This height adjustment is not needed for Launch 4; however, it is needed for Launch 2, and in the interests of modularity, the height adjustment occurs on both Launches 2 and 4. There was no need to recess the PTLI stage for launches 1 and 3.

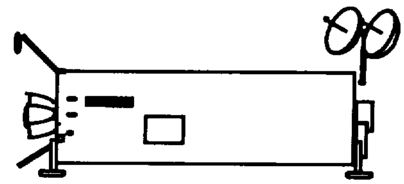

Fig. 7 Payload Landing Module and BioCan

The PLM, shown in Figure 7, has three RL10 engines and performs only one burn. The PLM burn is extremely critical in that it prevents the surface payloads from crashing into the lunar surface after the LBM has initiated the descent to the lunar surface. The PLM is also involved with the deployment of the surface payloads.

The dry mass budget for this stage is 2,743 kg. This dry mass budget does not include the weight of the landing legs. The landing legs are part of the surface payloads budget of 26,500 kg. The propellant mass is 3,582 kg although a greater amount of LOX and LH2 are stored in the propellant tanks because the tanks share the space with the lunar base fuel cell system. The total wet weight budget of the PLM is 6,325 kg. With the fixed propellant mass, the total wet weight budget of the combined PLM and surface payloads is 32,825 kg.

The PLM, also shown in Figure 7, has an RCS for both rendezvous and midcourse correction burns. It also has a high gain antenna in order that the crew can communicate with Earth while on the Moon. The PLM is responsible for providing power to itself and to the LBM during transit to the Moon in addition to its power duties on the surface. A self-deploying power system was designed for the power requirements of the habitat during the "hibernation state" (the period between the PLM touchdown and arrival of the crew). 2.5 kW of continuous usable power is supplied by two 10 m^2 arrays that partially track the sun and are deployed from an external surface of the PLM.

The surface payloads, shown in Figures 10 to 13, are either packed into the payload bay located just on top of the PLM, or they are packed into the habitat (BioCan) which is located above the payload bay. The payload bay has a large door on the side so that the crew members can access the packaged payloads. The payload bay is also connected to the habitat's emergency exit/entry airlock. The pathway for this airlock is only clear after the payload bay has been emptied out. The primary airlock is unobstructed on the opposite end of the BioCan.

One of the primary requirements for the lunar habitat is to provide protection against radiation from solar flares. For extended operations on the lunar surface, precautions are mandatory. In particular, Project Columbiad's 5-year campaign plan overlaps with the period 1999 to 2004 which is predicted to be a peak period in the solar flare cycle. Thus solar flare protection of the habitat is given a high priority in the surface operation requirements of the piloted mission. For Project Columbiad applications, a 25 Radiation Exposure Man (REM) *maximum* was set for the entire mission duration (36 earth-days). For almost all of the solar flares that will occur, the radiation dosage is much lower than the 25 REM with the amount of protection that the BioCan provides.

Columbiad's stategy for solar flare protection is to cover the habitat with regolith, the lunar soil. A depth of 50 cm is needed to provide the desired level of protection. This operation is performed by a regolith collecting machine that brushes the dirt from the lunar surface and dumps it into a dump-bucket attachment on the rover. The rover, in turn, pours the regolith onto a drivable conveyer, which dumps it to different heights on the side and top of the habitat. A regolith support structure is also designed to hold the regolith on a 45 ^{o} incline along the sides of the habitat (see Figure 8).

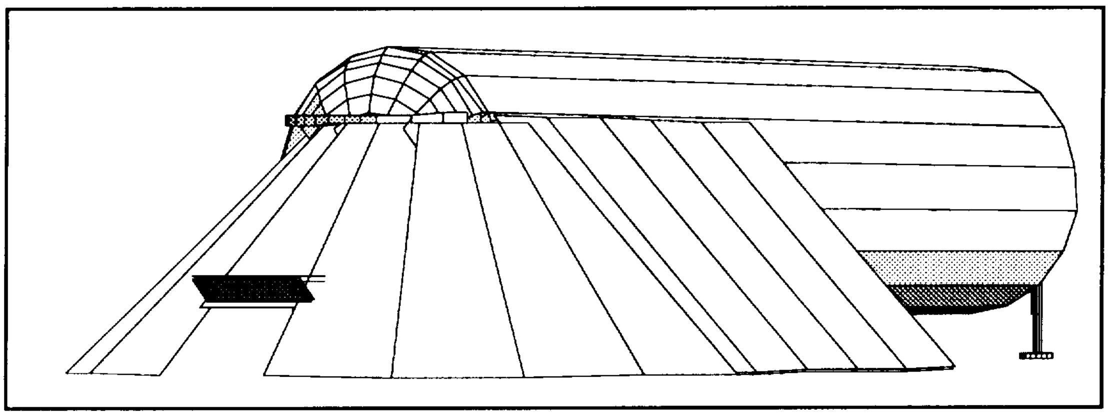

Fig. 8 Habitat with Regolith Support Structure

The habitat, shown in Figure 8, is the lunar home for four astronauts. It is a 10-m long and 6-m diameter double-walled cylinder. The external skin is integrated with the external structure of the PLM. The internal cylinder, made of composite material, is separated by a thin layer of sealed vacuum from the external cylinder and is pressurized with 5 psi of breathable atmosphere. The internal space is arranged to optimize the layout of all subsystems based on their predicted need and frequency of use. A 2-m by 1-m airlock door on one end of the habitat provides the primary access to the habitat. In case of an emergency, a secondary airlock that opens into the cargo bay from the crew quarters can be used. The total estimated mass of the habitat is less than 10,000 kg.

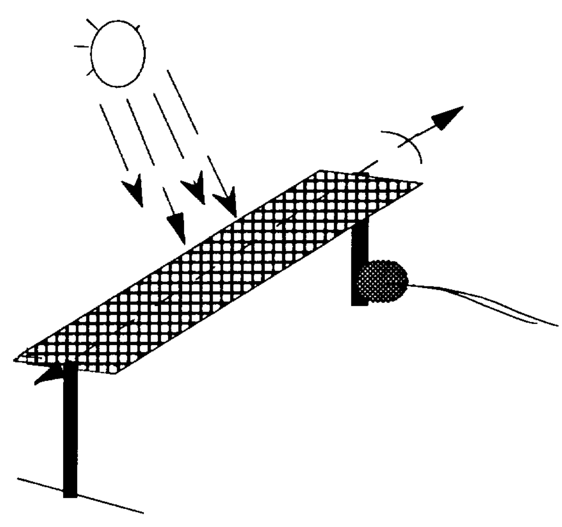

Fig. 9 Solar Lunar Power Plant

A solar power plant, shown in Figure 9, is designed to meet the power requirements of running all the base operations. A 250 m^2 photovoltaic array provides 35 kW of continuous daytime usable power during the lunar day. The rest of the power goes into charging up alkaline fuel cells system for 35 kW of night power. The fuel for the fuel cells is stored along with the propellant for the PLM. The total mass of the power system hardware is approximately 1000 kg. All fuel cells and other power conditioning hardware are located inside the PLM and the cargo bay.

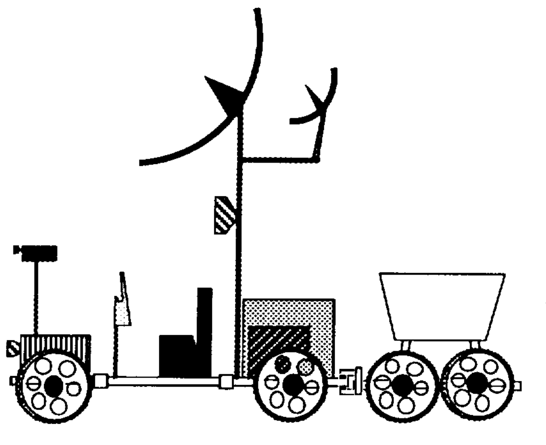

Fig. 10 Lunar Rover

The Rover, shown in Figure 10, is the surface transportation vehicle, capable of ferrying 1500 kg of payload. It is a six-wheel drive, four-wheel steered vehicle. The fully deployed rover is 5 m long and 2.5 m wide. The height of the vehicle is 2.5 m, including the height of its fully deployed high gain antenna. The vehicle is battery powered for a 120-km nominal mission range at an maximum velocity of 20 km/hour. To ensure the walk-back capability of the astronauts, all missions are limited to within a 50-km radius of the habitat. The maximum mission duration is 8 hours. The vehicle is unpressurized, but the astronauts can hook up their EVA suits to the Portable Life Support System (PLSS) packs onboard the rover. The astronauts' PLSS backpacks are held in reserve for off-the-vehicle activities and for emergency procedures. Essentially, the rover is the workhorse for all surface operations. The regolith collector and the conveyer both require the rover for their operation.

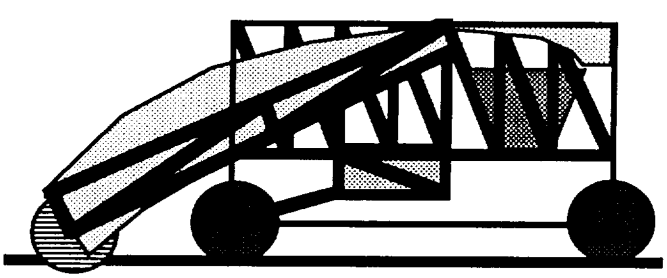

Fig. 11 Regolith Collector

The regolith collector is quite similar in operation to a street sweeper. Loose lunar soil is swept up by a brush at a nominal rate of 0.05 m^3 per minute. The regolith particles slide up a shroud and collect in a 1 m^3 hopper. After every twenty minutes of soil collecting, the hopper dumps the collected regolith into a dump-bucket attached to the rover. The armature arm can be raised to lift the brush above 50-cm obstacles in the collector's way. The drive mechanism of the wheels can be preprogrammed and/or operated remotely within line of sight. The regolith collector runs on 7.5 kW of power, stored on board in Sodium-Sulfide cells. Maximum operating time of the machine, limited by the total stored power, is 8 hours. The cells require 12 hours to charge up to the maximum power levels.

The Lunar conveyor, shown in Figure 12, is a multipurpose conveyer system. The main use of the conveyer is to transport loose regolith to any height on the regolith support structure. The expandable design consists of four segments, each 4 m long for a total length of 16 m. The belt width is 1 m. The entire system sits on 16 wire-mesh wheels and can be driven around as an articulated, 4-wheel-drive vehicle. The power required to run the conveyer is 5 kW. This determines a maximum feed rate of 0.28m^3 of regolith over a 16.00 m distance in one minute. Each connection point is a pin which gives the conveyor the flexibility to deliver its payload up inclines and over obstacles. With torsional clamps, the joints can be made rigid to allow for transport over trenches.

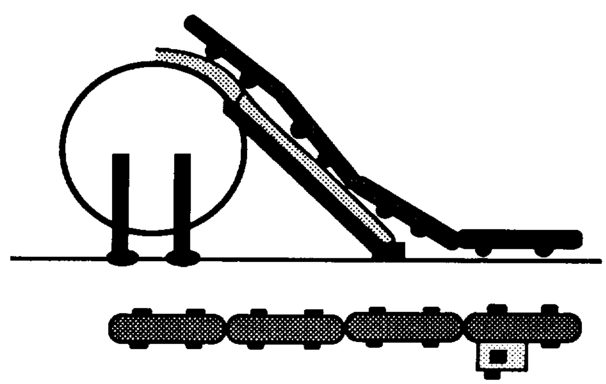

Fig. 12 Regolith Conveyor on top of Regolith Support Structure

Table 3: Precursor Mass Summary

Stage	ΔVtotal (m/s)	Wet Mass (kg)	Length (m)
PTLI	2680	94,825	15.96
LBM	3780	62,285	12.7
PLM	500	6325	6.77
Surface Payloads		26500	12.5
Nose Cone (Launches 1, 2)		820	5
Total Mass		190,755	

		Total Length
Total Mass for Launch 1 (PTLI stage)	94,825 kg	20.96 m
Total Mass for Launch 2 (Piloted launch)	95,930 kg	34.27 m (plus 2.7 m)

The total height allowance for an NLS payload is 35 m including a nose cone. The height of Launch 2 is less that the total height of the LBM, PLM, and the surface payloads because the LBM stage is recessed into the launch vehicle by 2.7 m. This height adjustment brings the total height of the launch within the 35 m limit.