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The Gryphon: A Flexible Lunar Lander Design to Support a Semi-Permanent Lunar Outpost

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A lunar lander is designed to provide safe, reliable, and continuous access to the lunar surface by the year 2020. The NASA Exploration System Architecture is used to initially define the concept of operations, architecture elements, and overall system requirements. The design evaluates revolutionary concepts and technologies to improve the performance and safety of the lunar lander while minimizing the associated cost using advanced systems engineering capabilities and multi-attribute decision making techniques. The final design is a flexible (crew and/or cargo) lander with a side-mounted minimum ascent stage and a separate stage to perform lunar orbit insertion.

Nomenclature

ACC = Affordability and Cost Criterion
AFM = Autonomous Flight Manager
AHP = Analytic Hierarchy Process
ALHAT = Autonomous Landing and Hazard Avoidance Technology
ATP = Authority to Proceed
AWRS = Advanced Air & Water Recovery System
CDR = Critical Design Review
CER = Cost Estimating Relationship
CEV = Crew Exploration Vehicle
CH_4 = Methane
DDT&E = Design, Development, Testing and Evaluation
DOI = Descent Orbit Insertion
DSM = Design Structure Matrix
ECLSS = Environmental Control & Life Support System
EDS = Earth Departure Stage
EFC = Extensibility and Flexibility Criterion
EMC = Environmental Monitoring & Control
EPC = Effectiveness and Performance Criterion
ESAS = Exploration Systems Architecture Study
FOM = Figure of Merit
GN&C = Guidance, Navigation and Control
GRC = Glenn Research Center
ISRU = In-Situ Resource Utilization
JPL = Jet Propulsion Laboratory
JSC = Johnson Space Center
LEM = Lunar Excursion Module
LEO = Low Earth Orbit
LH_2 = Liquid Hydrogen
LLO = Low Lunar Orbit
Log = Logistics Unit
LOI = Lunar Orbit Insertion

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LOX = Liquid Oxygen
LSAM = Lunar Surface Access Module
M&S = Modeling and Simulation
MMH = Monomethylhydrazine
MPU = Mini-Makeup Power Unit
N_2O_4 = Nitrogen Tetroxide
NAFCOM= NASA/Air Force Cost Model
OEC = Overall Evaluation Criterion
PDR = Preliminary Design Review
POST = Program to Optimize Simulated Trajectories
PRC = Programmatic Risk Criterion
QFD = Quality Function Deployment
RCS = Reaction Control System
SMC = Surface Mobility Carrier
SMSC = Safety and Mission Success Criterion
SPU = Standard Power Unit
SSR = System Requirements Review
STK = Satellite Tool Kit
T/W = Thrust to Weight Ratio
TRL = Technology Readiness Level

Introduction

ON January 14, 2004, the President's Vision for Space Exploration provided motivation for the United States to return to the moon by 2020 in preparation for an eventual manned mission to Mars. At the 1st Space Exploration Conference, a new architecture was unveiled based on the results of the Exploration Systems Architecture Study (ESAS) that utilized a 1.5 launch configuration with a separate cargo and crewed launch configuration.[0] The design reference mission was a 7-day sortie analogous to the Apollo surface missions. The point of departure Lunar Surface Access Module (LSAM) was similar to the two-stage Apollo Lunar Module where

Figure 1. ESAS Lunar Surface Access Module.[16]

Figure 2. Minimized Ascent Stage Configuration.[18]

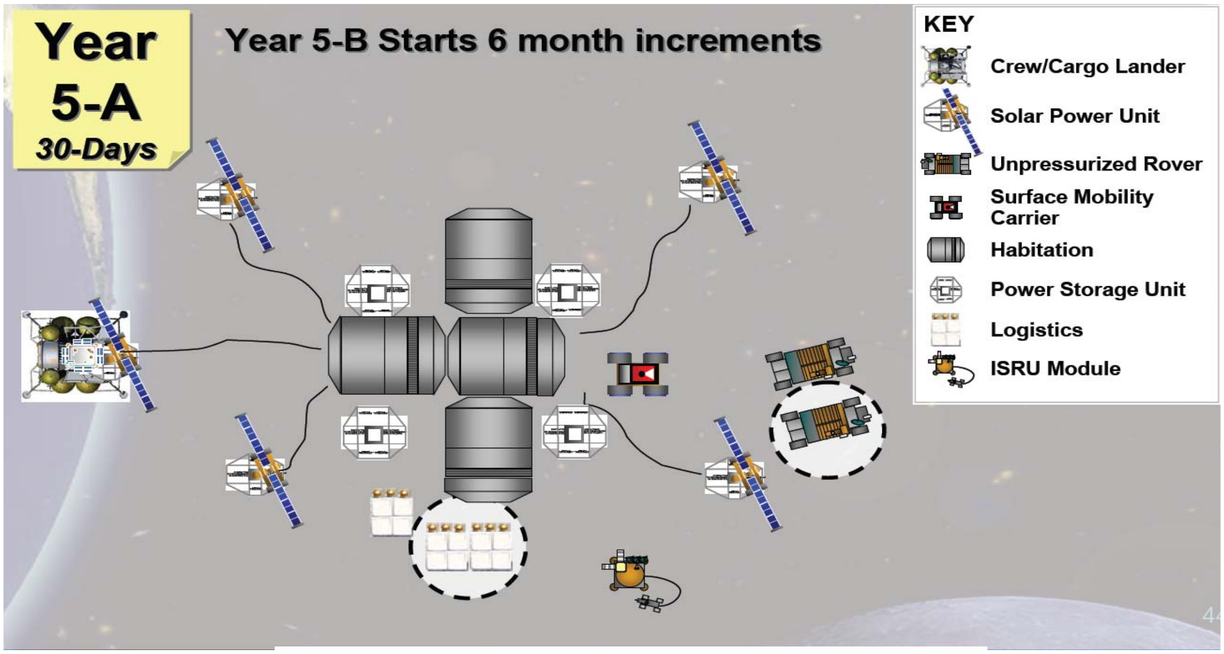


Figure 3. Lunar Outpost Architecture.[18]

a single crew volume was used for descent, surface habitation, operations, and ascent (Figure 1). In addition, ESAS defined a lunar outpost construction approach using three dedicated "cargo" flights, a fourth flight to preposition a backup LSAM, and a fifth flight to deliver the first crew. All following flights would be crew rotation flights.

At the 2nd Space Exploration Conference, NASA further refined the outpost mission and architecture – a lunar outpost at the south pole Shackleton Crater.[16] The reason for returning to the moon is to serve as a test bed for a future Mars outpost, therefore, the emphasis on the lunar program should be to establish a self-sufficient outpost on Mars where the crew would rotate on a 6 month schedule.

To support the outpost lunar architecture, NASA designed a minimized ascent stage, shown in Figure 2, based on the ESAS Configuration Concept 1 to separate the cargo/habitat/mobility units from the ascent stage. During initial outpost construction, four habitats would be delivered and then linked together to provide enough volume for the 6-month stay (figure 3). Additional flight would carry power units, rovers, and other initial hardware. Each of the flights would carry four support crew together with the cargo. Periodic resupply flights would carry logistics spares, science instruments, and crew for 6-month stays.

Based on NASA Level 0 Exploration Requirements and Level 1 Objectives,[24] "NASA shall separate crew from cargo for launches of exploration missions to the maximum extent practical." Because the baseline lander design mixed crew and cargo, a flexible lunar lander was designed (called the Gryphon) that can be configured to deliver cargo or crew or both.

Systems Engineering

In order to ensure that the Gryphon's design meets all of the requirements and is the best configuration for the Figures of Merit (FOM's) specified in ESAS, systems engineering analyses were performed. The FOM's analyzed Safety and Mission Success Criterion (SMSC), Effectiveness and Performance Criterion (EPC), Extensibility and Flexibility Criterion (EFC), Programmatic Risk Criterion (PRC), and Affordability and Cost Criterion (ACC).

Because of the limited resources available to evaluate the design, key trades were identified using Quality Function Deployment based on derived weights for the ESAS Figures of Merit using the Analytical Hierarchy Process (see Appendix A for the process, and Table 1 for the FOM weighting results).

FOM (Criterion)	Priority	Ranking
Safety and Mission Success	0.391	1
Effectiveness and Performance	0.274	2
Affordability and Cost	0.194	3
Programmatic Risk	0.096	4
Extensibility and Flexibility	0.046	5

Table 1. ESAS Figures of Merit.

Each of the key engineering characteristics were qualitatively assessed for their impact on the FOM's, and that score was multiplied by the weights to determine the highest priority trade studies (Table 2).

Ranking	Engineering Characteristic	Importance
1	Descent Propellant	425.66
2	Staging	408.02
3	Ascent Propellant	329.67
4	Descent Number of Engines	325.35
5	Trajectory	299.20
6	Ascent Number of Engines	297.84
7	Habitat Split	278.33
8	Lander Configuration	213.11

Table 2. Key Trade Areas.

Based on these key trade areas, architecture alternatives (Table 3- next page) were developed using a Morphological Matrix to determine the technologies, configuration, and analyses required for the definition of the Gryphon Lander concept. The yellow highlights in Table 3 reference the ESAS baseline lander, the red reference the selections for the present Gryphon lander as presented in the paper, and green are common to both designs.

A. Modeling and Simulation

In order to model these key trade areas, several analysis programs are linked together in a lander modeling and simulation. These programs pass inputs and outputs according to the Design Structure Matrix (DSM) shown in Figure 4.

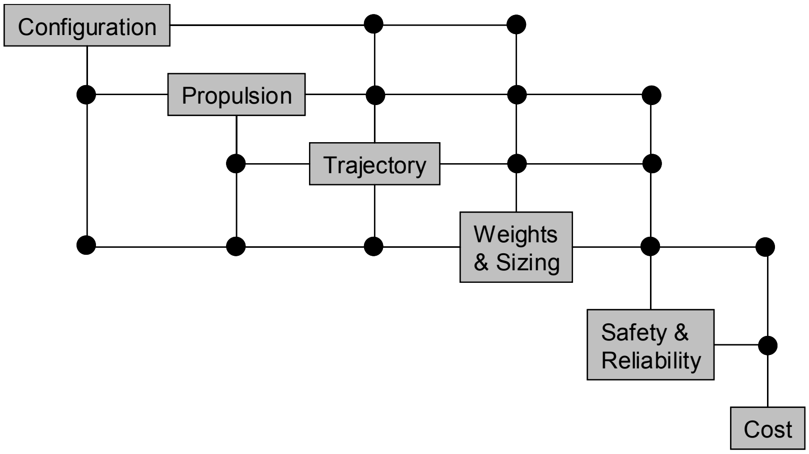


Figure 4. Gryphon DSM.

Characteristics	Alternatives				
	1	2	3	4	5
1 Structure/Configuration					
1.1 Landing Gear Configuration	3-Legged	4-Legged	5-Legged	6+Legged	
1.2 Landing Gear Feet	Conventional	Wheels	Crushable Material		
1.3 Lander Configuration	Horizontal Lander	Vertical Lander			
1.4 Habitat Split	Minimum Ascent	Apollo			
1.5 Ascent Material	Aluminum	Titanium	Composites		
1.6 Descent Material	Aluminum	Titanium	Composites		
1.7 Egress Method	Ladder	Elevator	Low To Ground	Modified Ladder	
1.8 Cargo Offload	Crane	Crushable Material	Elevator	Controlled Drop	Ramp
1.9 Habitat Thermal Control	MLI	Active Control			
1.10 Descent Blast Shield Material	Teflon Coating	Titanium Shield	Elastomeric Composite		
2 Human Factors					
2.1 ECLSS	Open	Closed	Hybrid		
2.2 Radiation Shielding	None	5 g/cm2 HDPE	Regolith Shield	Propellant Shield	Aluminum
3 Propulsion					
3.1 Descent					
3.1.1 Engine Feed Type	Pump Fed	Pressure Fed			
3.1.2 Propellant	Hydrogen/Oxygen	Methane/Oxygen	MMH/N_2O_4		
3.1.3 Number of Engines	1	2	3	4	
3.1.4 Expansion Ratio	40	75	120	150	
3.1.5 Tank Material	Aluminum	Titanium	Inconel 718 w/ Composite	Al-Li Alloy	Al-Li w/ Composite
3.1.6 Tank Shape	Spherical	Cylindrical	Toroidal	Conformal	
3.1.7 Tank Insulation	None	MLI	Cryogenic Cooler		
3.2 Ascent					
3.2.1 Engine Feed Type	Pump Fed	Pressure Fed			
3.2.2 Propellant	Hydrogen/Oxygen	Methane/Oxygen	MMH/N_2O_4		
3.2.3 Number of Engines	1	2			
3.2.4 Expansion Ratio	40	75	120	150	
3.2.5 Tank Material	Aluminum	Titanium	Inconel 718 w/ Composite	Al-Li Alloy	Al-Li w/ Composite
3.2.6 Tank Shape	Spherical	Cylindrical	Toroidal	Conformal	
3.2.7 Tank Insulation	None	MLI	Cryogenic Cooler		
3.3 Reaction Control System					
3.3.1 Engine Feed Type	Pump Fed	Pressure Fed			
3.3.2 Propellant	Hydrogen/Oxygen	Methane/Oxygen	MMH/N_2O_4		
3.3.3 Expansion Ratio	40	75	120	150	
3.3.4 Tank Material	Aluminum	Titanium	Inconel 718 w/ Composite	Al-Li Alloy	Al-Li w/ Composite
3.3.5 Tank Shape	Spherical	Cylindrical	Toroidal	Conformal	
3.3.6 Tank Insulation	None	MLI	Cryogenic Cooler		
3.3.7 Tank Setup	Independent	Tap-Off from Ascent			
4 Power					
4.1 Storage	Batteries	Fuel Cells	Batteries and Fuel Cells		
4.2 Powerplant Location	Ascent Stage	Descent Stage	Mobile Power Platforms	Hybrid	
4.3 Generation Method	Solar	Chemical			
5 Guidance, Navigation & Control					
5.1 Stability and Control	Reaction Wheels	RCS	Control Moment Gyros		
5.2 Navigation	DSN Tracking	Lunar Orbital Satellites	Optical		
5.3 Communication	S-Band	Ka-Band	Ku-Band	X-Band	C-Band
5.4 Approach Optics	Windows	Synthetic	Hybrid		
6 Mission					
6.1 Staging	Single Stage	Two Stage	Three Stage (Braking)	Three Stage (Droptanks)	
6.2 Trajectory	Direct w/ SM Burn	ESAS	Optimized ESAS	Hyperbolic to Parking	
6.3 Cargo Location	Below Ascent Stage	Even with Ascent Stage	Above Ascent Stage		

Table 3. Morphological Matrix.

For configuration, Pro/ENGINEER, a solid modeling program developed by PTC, was used. REDTOP-2, developed by SpaceWorks Engineering Inc, was used for propulsion design and performance. A response surface was created from the data output from REDTOP-2, allowing rapid exploration of the design space. The trajectory analysis is divided into three sections: in-space trajectory, descent/ascent trajectory, and trajectory visualization. Copernicus v.1.0, developed at the University of Texas at Austin and NASA Johnson Space Center (JSC), and Program to Optimize Simulated Trajectories (POST), developed by NASA, were used for in-space and atmospheric trajectory optimization. Satellite Tool Kit (STK) was developed by Analytical Graphics, Inc. and was used for concept of operations visualization. ROSETTA is an Excel based tool that uses mass estimating relationships that were developed at Georgia Tech and modified for this analysis based on the ESAS lander detailed mass statements and performance; this tool was used for weights and sizing. The NASA/Air Force Cost Model (NAFCOM) that uses cost estimating relationships (CERs) parameters developed from historical data was used for development and production costs.

B. Problem Definition

The overall goal of this study is to design a lander to provide routine and safe access to the moon by 2020. The Gryphon must fit within NASA's current space exploration architecture, integrating with the launch vehicles, Earth Departure Stage (EDS), and Crew Exploration Vehicle (CEV) elements specified in ESAS. The planned outpost is to be occupied for 10 years. Several key parameters and constraints of this architecture are listed in Table 4.

In order to develop routine access to the moon, an outpost facility is necessary. Shackleton Crater at the south pole of the moon was chosen as the location of this outpost due to its potential sources of water and nearly continuous sunlight. In addition, less ΔV is required to reach the poles when compared to other sites on the moon, and polar locations provide more opportunities to return to Earth.[0]

Architecture Parameters	Value
Ares V Launch Vehicle	
LEO Delivery Capability	125 mT
Payload Fairing Length	12.0 m
Payload Fairing Diameter	8.3 m
Earth Departure Stage	
Crew Lander Capability	45.9 mT
Cargo Lander Capability	54.6 mT
Outpost Requirements	
Number of Crew	4
Continuous Stay Time per Crew	180 days

Table 4. Architecture Parameters.

The LSAM specified in ESAS has the capability to deliver both crewed and cargo missions to the surface. However, any crewed mission must take a full ascent stage/habitat module, reducing the available cargo mass. The sortie version of the LSAM is capable of carrying a maximum of 2.29 mT of cargo to the surface, and the cargo mission is capable of carrying 20.90 mT of cargo to the surface.[0] This is not enough capability to keep up with the required 5.18 mT of consumables required for a 180 day stay of four crew members. Therefore, each mission must be accompanied by a separate cargo mission in order to fulfill the requirements.

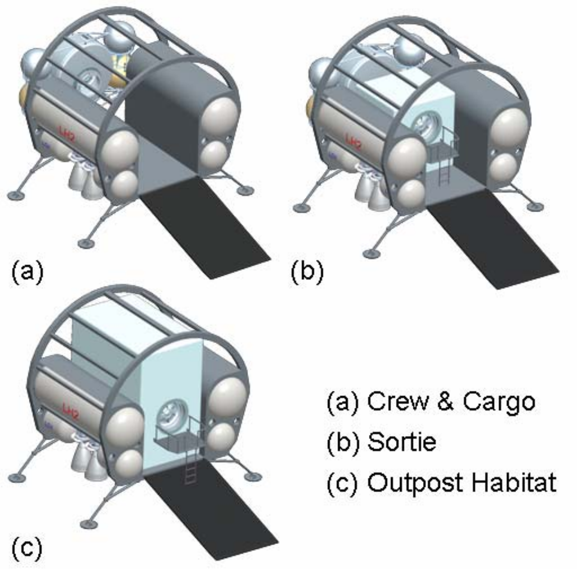


Figure 4. Flexible Lander Available Configurations.

The capability, however, still must exist for both an outpost buildup and 7-day sortie.[0] While the ESAS LSAM meets the requirements for a sortie mission, it is not flexible enough to perform crew exchange missions and cargo delivery missions. To perform these missions with one lander design, a flexible lander is naturally advantageous. The Gryphon was therefore designed to perform all of these missions using a flexible platform (similar to the use of a flat-bed truck) with a common descent stage and interchangeable ascent stage and/or cargo components. The Gryphon lander showing all three configurations is presented in Figure 4.

Technical Analysis

A. Outpost Buildup Manifest

The outpost buildup strategy is a main architecture driver which will determine the capability requirements of the Gryphon. Two strategies are available for outpost buildup: link together several small habitat modules baselined in the current outpost architecture, or use one large, monolithic habitat (which would require a redesigned lander concept like Gryphon). In order to determine the best solution for outpost buildup, the two options were evaluated against the FOM's.

The four separate small habitat modules will have to be moved around on the lunar surface and connected in order to meet the volume requirements for a 180-day stay. Four separate Environmental Control and Life Support Systems (ECLSS) or one centralized ECLSS would have to be implemented. Furthermore, four separate habitat modules would complicate any Integrated System Health Management (ISHM) System. The complex nature of the ECLSS, ISHM system, and all of the linkages between the habitats will result in an increased probability of loss of crew or mission due to the increased likelihood of failure of one of the components.

The separate habitats would have to arrive on multiple missions. Since only two missions are allowed per year, this would increase the schedule risk and delay cargo delivery to surface. Additionally, the effectiveness and performance of the mission would be negatively impacted due to the delay in the availability of a fully functioning

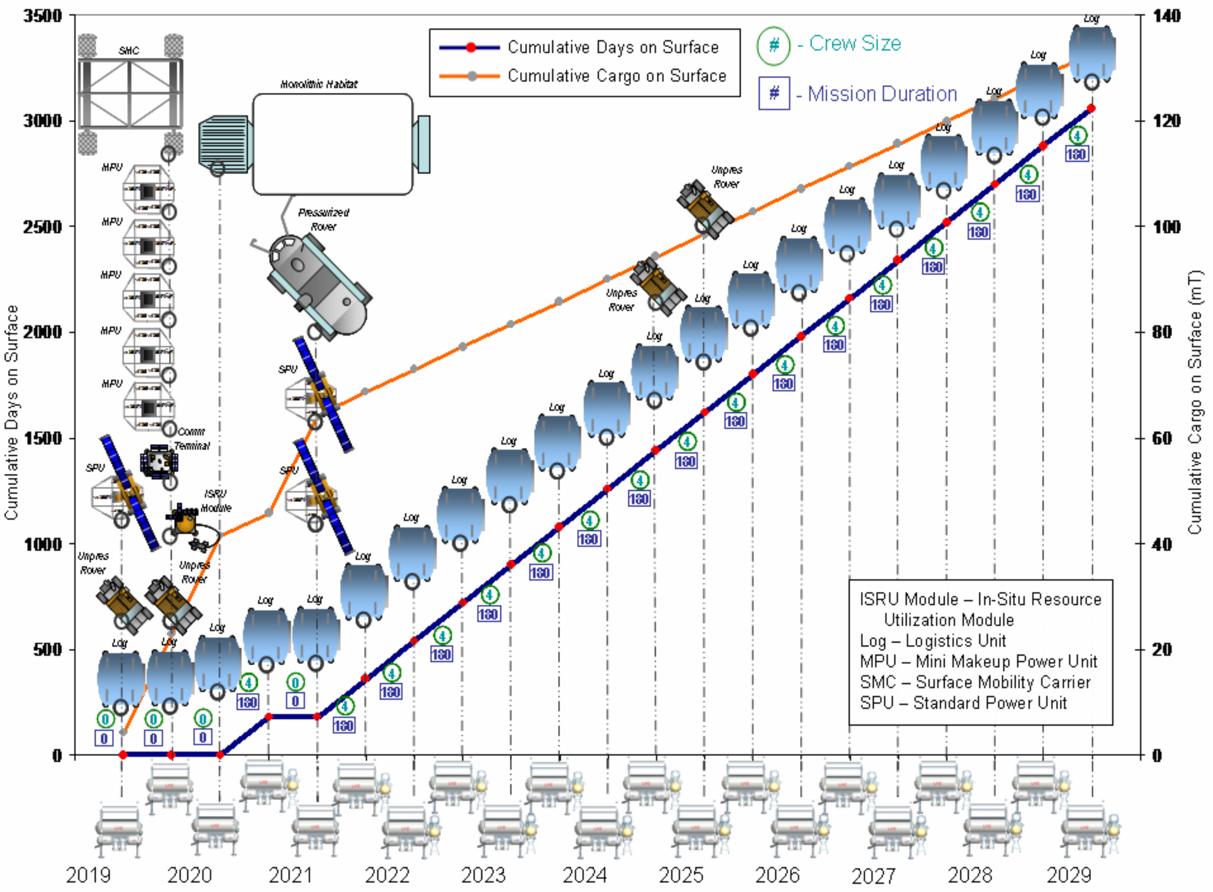


Figure 5. Manifesting Breakdown Using a Monolithic Habitat.

habitat resulting in decreased usable surface crew-hours.

The Mars Design Reference Mission uses a single habitat for living/storage space.[0] With the increased time between potential launch opportunities, waiting to send multiple small habitat modules would greatly increase the schedule duration. Furthermore, designing a descent stage that is capable of delivering a monolithic habitat or supporting a sortie mission, as proposed in this study, greatly increases lunar mission flexibility.

The technology development risk and initial cost risk for a monolithic habitat may be greater, but the political risk, schedule risk, and long-term cost risk will be lower than the multi-habitat strategy. For political risk, the sooner humans are on the lunar surface the better. A monolithic habitat will allow for a 180-day stay after only three previous missions, while at least four missions would be required to deliver the four separate small habitat modules with at least one additional sortie mission to move and connect the modules. The initial cost for development of a single monolithic habitat versus multiple small habitat modules would be greater, but this is outweighed by the costs associated with moving and connecting the smaller habitat modules, as well as facilities and operations costs for maintaining the more complicated multi-habitat system.

The single monolithic habitat strategy was chosen for its superior compliance with the Figures of Merit. With this strategy, a manifesting tool was used to map out the delivery of key outpost elements and consumables including: standard power units (SPU), mini make-up power units (MPU), unpressurized and pressurized rovers, logistics units (Log), in-situ resource utilization (ISRU) modules, a communication terminal, the monolithic habitat, and a surface mobility carrier (SMC). This manifest, shown in Figure 5, places a payload delivery requirement of 18.63 mT for the cargo mission and 10.37 mT per year to maintain a crew of four astronauts.

The habitat volume requirements for a given mission duration for a 180-day stay is 67.28 m^3.[20] The resupply mass of 5.18 mT is based on the average consumable masses for a four-person crew staying 180 days, and assumes 90% reuse of atmosphere and water.[0] The descent stage is capable of carrying 4.27 mT of cargo on a crewed mission, so extra consumables are brought early in the manifest on cargo dedicated launches to ensure that there is some margin between the consumables available and those required. At the end of outpost habitation, 3.24 mT of consumables remain, and this margin could instead be used to bring another SPU, ISRU module, or other science equipment at some point in the manifest. Sufficient power units are brought early in the manifest to allow habitat operation by the fourth mission. The manifest takes into account degradation of the SPU's with time and allows for redundancy of one SPU. The last power units are delivered on the last cargo dedicated flight to delay these degradation losses. This manifest is optimized to maximize the crewed time at the outpost, allowing 3,060 crew-days on the surface and delivering over 132.72 mT to the outpost.

B. Concept of Operations / Trajectory Analysis

Based on the ESAS Architecture and the current lunar architecture, the lander is required to perform the Lunar Orbit Insertion (LOI) burn with the CEV attached[13,18] to ensure anytime return capability and reduce the ΔV associated with plane change maneuvers. An example of this trajectory is shown in Figure 6. The first burn puts the Gryphon and CEV into an elliptical orbit around the moon from its hyperbolic entry orbit. The second performs the plane change (while the velocity is low), and the third burn inserts the lander and CEV into a Low Lunar Orbit (LLO) of 100 km altitude.

The 3-burn trajectory optimization was performed allowing the altitude and true anomaly of the intermediate burn to be varied, and the objective function is based on ΔV (to minimize propellant) and time of flight (to minimize consumable mass).

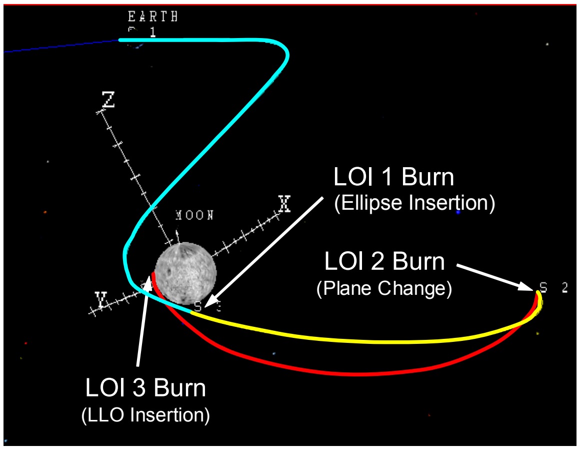


Figure 6. Three-Burn LOI Sequence.

Also, the ΔV magnitude is dependent upon the Earth-Moon geometry at the time of arrival. The moon's inclination changes on an 18 year cycle between 28.7° and 18.1°.[0] A launch from Kennedy Space Center in Florida will put the EDS and the Gryphon in a 28.5° LEO orbit. Therefore, the larger lunar orbit inclination is easier to access because it has less plane change to perform. During the 10 years that the Gryphon will be operating, the lunar orbit reaches its maximum inclination, but not its minimum. Therefore, the lander does not need to be sized for the worst case inclination change, as it was in ESAS.[0] At the end of the 10-year operations period, the inclination reaches a minimum of 24.4°.

In order to reach Shackleton crater in the 10 years of operations, the total LOI ΔV will be less than 918 m/s. In order to determine what percentage of the lunar surface can be reached with this ΔV, a grid of the surface was run, and the results are shown in Figure 7. The ESAS sites of interest are identified on this figure as the numbered locations, and Site 1 is the outpost site.[0] This ΔV gives a surface coverage of over 77%, and only one ESAS site is not within the capability. However, this site can be reached with up to three days of loiter in LLO.

The ESAS LSAM was sized for global access at the worst Earth-Moon alignment. This worst alignment occurs in December 2034, and the LSAM is capable of 1,390 m/s, which far exceeds the requirements of the outpost mission.

Descent Trajectory. Two different types of descent trajectories were examined to fulfill mission requirements.

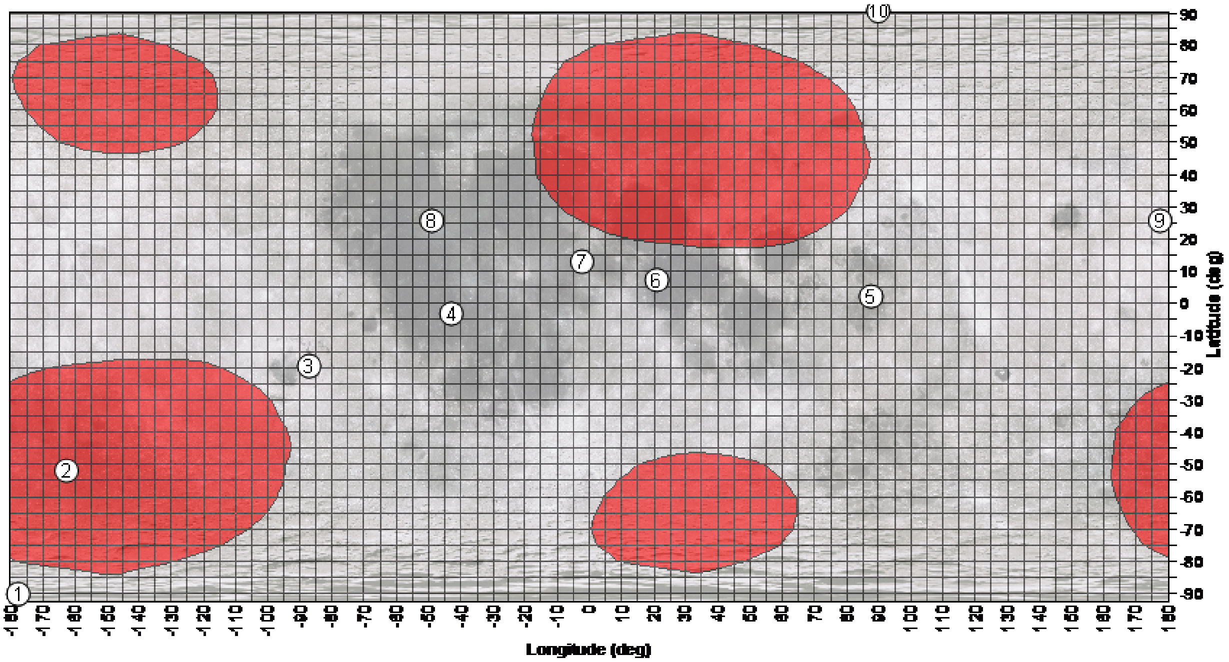


Figure 7. The Gryphon's Global Access Capability with ESAS Sites of Interest Identified.

The first case follows an unconstrained ΔV optimized trajectory used for an automated (cargo) mission, while the second simulation incorporates an approach glideslope to accommodate sensor and pilot visibility envelopes during crewed missions. The nominal glideslope angle of 45^o was selected for ΔV optimization. This selection represents a compromise between lower, pilot-optimal angles and higher angles which are more fuel efficient. Shackleton Crater (89.9^o S, 0.0^0 E) is the nominal landing and launch site for the descent and ascent trajectories.

The descent trajectory is initiated with the Descent Orbit Insertion (DOI) burn, placing the lander on a Hohmann transfer ellipse to 15.24 km above the lunar surface, where powered descent initiation (PDI) occurs. At PDI, the four descent stage engines ignite approximately 188 km up-range of the nominal touchdown point. The base descent trajectory follows a POST-optimized trajectory to a point 30 m above the lunar surface. At this point (known as "low gate"),[0] the vehicle has zero forward velocity and a sink rate of 1.0 m/s. The vehicle pitch attitude is now fixed at 90° from the horizontal in preparation for landing, which are maintained until touchdown. The initial thrust-to-weight ratio was optimized to be 0.365 with the total mission performance shown in Table 5 where redesignation to 100 m and piloted flight allowances are added to the optimized performance.

Item	Value	Source
DOI ΔV [m/s]	19	Analytic calculation
Optimized & Constrained Nominal ΔV [m/s]	1958	POST II Simulation
LZ Redesignation & Dispersion ΔV [m/s]		
dispersion	35	Assumed
manual low redesignation	85	Apollo heritage
manual high redesignation	20	Apollo heritage
subtotal (redesignation & dispersion)	140	
Total Descent ΔV [m/s]	2117	

Table 5. Descent ΔV, m/s.

The constrained approach follows identical event sequencing until approximately 10 km above the lunar surface at glideslope interface. Pitch and throttle authority are passed to a generalized acceleration steering algorithm which is used to bring the horizon-relative flight-path angle of the vehicle to 45° for 100 seconds. Then, attitude and throttle control are returned to the optimization and targeting algorithms. The vehicle de-rotates to a pitch attitude of 90° and targets the same low gate conditions as the unconstrained trajectory. The unconstrained trajectory reduced delta-V by 112 m/s; however, the constrained case for astronaut visibility was retained as the baseline.

Ascent Trajectory. At launch, the nominal ascent trajectory completes a 6 second vertical rise to allow for clearance of terrain obstacles. Pitch authority is then passed to the optimizer and the vehicle begins a single axis rotation to gain horizontal velocity. The ascent engine completes its burn when the vehicle reaches the desired target orbit of 15.24 x 75 km.

The optimized initial thrust-to-weight-ratio was 0.45 with an optimized ΔV of 1,823 m/s and a total mission ΔV of 1,849 m/s.

Visualization. STK was used to provide visualization of the resulting trajectories from the Copernicus and POST outputs in the J2000 coordinate frame.

C. Staging

Staging considerations for this project are limited to after the EDS is jettisoned. The options are a one- and two-stages, with the one-stage variant performing the LLO insertion, descent (including the deorbit portion), and ascent burns, while the two-stage option differs only in that the ascent phase is performed by a separate vehicle. Two innovative options explored for this report involve a separate LLO insertion stage; these stages will be designated as 2L when added to the standard one-stage variant and 3L when added to the standard two-stage variant. The various staging options are shown in Figure 8.

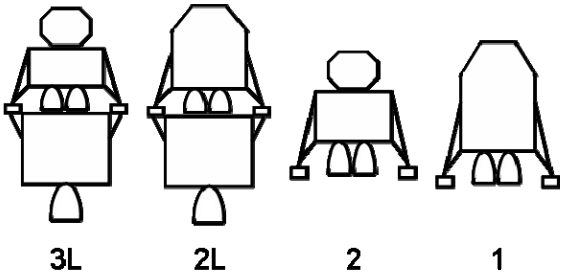


Figure 8. Gryphon Staging Options.

Evaluating the staging types against the FOM's, the 3L option emerged as the best overall. Having the lowest gross mass leads to having the highest cargo capability, a key metric within the Effectiveness/Performance category. And while adding stages usually decreases reliability, the LOI stage counteracts this by removing the need to reignite the engines (which the descent stage would have had to do). The 3L variant also ranks high in terms of Affordability and Extensibility, as is illustrated in Table 6.

	Option	SMSC	EPC	EFC	PRC	ACC	Overall
Staging Option	1-Stage	2	4	3	1	3	4
	2-Stage	4	2	3	1	1	2
	2L	1	3	1	3	4	3
	3L	**3**	**1**	**1**	**3**	**2**	**1**

Table 6. Staging Options Compared to FOM's.

D. Propulsion Systems

Various propellant type and propulsion cycle combinations were evaluated to determine which would best meet the FOM's. The ESAS option was treated as the baseline in both the descent and ascent stage cases. For the descent stage, only a pump-fed cycle was considered since pressure-fed engines would result in overly massive propellant tanks, while in the case of the ascent stage, both cycle options were feasible. The four fuel and oxidizer combinations considered for the descent stage were liquid oxygen/liquid hydrogen (LOX/LH_2), the ESAS selection), liquid oxygen/methane (LOX/CH_4), monomethylhydrazine/dinotrogen tetroxide (MMH/N_2O_4), and Apollo's Aerozine 50/N_2O_4. The ascent stage analyses included these four propellants with pressure-fed engines in addition to considering LOX/LH_2 and LOX/CH_4 with pump-fed engines (ESAS used pressure-fed LOX/CH_4).

The pressure-fed MMH/N_2O_4 ascent propulsion system (Isp = 310 s) performed well in all the FOM categories, particularly with Affordability and Programmatic Risk. Since hypergolic propellants have a long history of space application, this experience leads to much lower technology development and schedule risk. For the descent stage, the pump-fed LOX/LH_2 propulsion system (Isp = 451 s) best satisfied the FOM's. One attractive feature is the fact that this system can be extended to a Mars mission, as oxygen can be extracted from the planet's atmosphere. The results of these trade studies are presented in the first two sections of Table 7.

Another propulsion trade considered was the number of engines on the ascent and descent stages. For the ascent

	Option	SMSC	EPC	EFC	PRC	ACC	Overall
Ascent Engine Type	Pressure-Fed LOX/CH4 (ESAS)	1	5	2	3	5	3
	Pressure-Fed LOX/LH2	5	6	2	3	6	5
	Pressure-Fed MMH/N2O4	**4**	**3**	**5**	**1**	**1**	**1**
	Pressure-Fed Aerozine 50/N2O4	6	4	5	1	2	2
	Pump-Fed LOX/CH4	2	1	1	5	3	4
	Pump-Fed LOX/LH_2	3	2	2	6	4	6
Descent Engine Type	**Pump-Fed LOX/LH2**	**2**	**1**	**1**	**3**	**4**	**1**
	Pump-Fed LOX/CH4	1	2	1	3	3	3
	Pump-Fed MMH/N2O4	3	3	3	1	1	2
	Pump-Fed Aerozine 50/N2O4	4	4	3	1	2	4
# Ascent Engines	**1 Ascent Engine**	**2**	**1**	**1**	**1**	**1**	**1**
	2 Ascent Engine	1	2	1	2	2	2
# Descent Engines	1 Descent Engine	4	1	4	1	1	4
	2 Descent Engines	3	2	3	2	2	3
	3 Descent Engines	2	3	2	3	3	2
	4 Descent Engines	**1**	**4**	**1**	**3**	**4**	**1**

Table 7. Propulsion System Options Compared to FOM's.

stage, 1- and 2-engine options were evaluated with the 2-engine version sized for 1 engine-out capability. The descent engine options ranged from 1 to 4, with 1 engine-out capability for the 2- to 3-engine options and 2 engine-out capability for the 4-engine option. The ascent and descent stage propulsion system results are shown in the last two sections of Table 7.

The 1-engine ascent stage option outperformed the 2-engine variant in four of the five FOM categories. In addition, if the 2-engine variant experiences an engine out, the ascent stage would undergo large moments, making it extremely difficult to control. For the descent stage, the 4-engine configuration proved to be the overall best selection. Unlike the 2-engine ascent stage, if the 4-engine descent stage experienced an engine out, it could maintain stability by cutting the engine across from it, running on the two remaining diagonal engines.

E. Vehicle Subsystems

Table 8 summarizes non-critical subsystems and their components. These characteristics were not selected as key trade areas during the systems engineering analysis and were therefore assigned the baseline (ESAS LSAM) configurations.

Subsystem	Component	Comment
Power	Batteries for Primary Power	4 rechargeable Li-ion batteries
	PEM Fuel Cells	
	Hydrogen Accumulator Tanks and Distribution System	
	Oxygen Accumulator Tanks and Distribution System	
	Remote Power Control Units	Distibute power to subsystems
	Wiring Harness	3 primary 28 VDC buses
Structure	Pressure Vessel Structure	Aluminum
	Unpressurized Structure	Graphite epoxy composite (on descent stage)
	Windows	Double paned fused silica
	Tank Support Structure	
Protection	Insulation	MLI blankets, active control
Control	Engine Gimbals	Pitch & roll axis gimbals, EMA actuated
	EMA Controllers	
Avionics	Stability and Control	RCS
	Navigation	DSN Tracking
	Communication	S-Band
	Approach Optics	Windows and synthetic
Environment	Environment Control and Life Support Systems	90% closed loop, 10% open loop
	Radiation Shielding	5 g/cm^2 HDPE

Table 8. Gryphon Subsystem Breakdown.

Technology Assessment

In order for Gryphon to be possible, several technology advancements are first required. These include advancements in areas such as protection, propulsion, power, thermal controls, avionics and software, ECLSS, crew support and accommodations, mechanisms.[0] From these areas, the design team identified several enabling and enhancing technologies, detailed in Table 9. It is assumed that all technologies should be developed to a Technology Readiness Level (TRL) of 6 or better by the Preliminary Design Review (PDR) of the corresponding component.

The Lunar surface is covered with 1 to 10 cm of extremely fine lunar dust. The effects of long-term exposure to lunar regolith are still unknown, but there are concerns that it could lead to mechanical failures or health problems. The Dust Management Project, centered at Glenn Research Center (GRC), is focused on developing dust mitigation technologies such as dust tolerant airlocks and EVA suits.[0] Additionally, a Lunar Dust Workshop was help in early 2007 at NASA Ames to discuss effects of lunar regolith and potential mitigation technologies.[0] The current TRL of these technologies is 3-5.

According to ESAS,[0] fuel cells will usually provide more power for less total mass for sortie missions than other power sources. Additionally, fuel cells allow for increased mission flexibility because of their general independence from the environment. Fuel cells do not require sunlight, as they combine hydrogen and oxygen to produce electricity and drinkable water. Fuel cells are currently used on the space shuttle, but more advanced versions would have to be created to meet the requirements for the various planned lunar missions. In the past, improvements have been made to the efficiency and longevity of fuel cells by modifying the platinum catalyst that covers the electrodes where the reaction takes place.[0] The current TRL for fuel cells is 5.The ESAS architecture also calls for advanced ISHM,[0] which can be defined as "the processes, techniques, and technologies used to design, analyze, build, verify, and operate a system to prevent faults and/or minimize their effects.[0]" The system integrates human actions with automated responses to different situations and monitors the effects of those actions,[0] and is critical to the functionality and affordability of the lunar sortie and outpost missions. The current TRL for ISHM is 5-6.

Advances in autonomous precision landing and Guidance, Navigation and Control (GN&C) will also be required for the Gryphon to be successful. Because the lunar outpost will be gradually built up over time through a number of outpost missions and cargo drops, both piloted and autonomous, advances in avionics must occur for these landings to be precise, such that the deliveries are made at the proper location. Draper Laboratory and NASA are currently developing the Autonomous Landing and Hazard Avoidance Technology (ALHAT) system to be used on the next-generation lunar lander. From Draper Laboratory, the "technology development to mature the Autonomous Flight Manager (AFM) to TRL 6 will continue as part of the ALHAT program.[0]" Having verified the technology in a relevant environment, a TRL of 5 is assigned.

One of the most critical components of the next-generation lunar lander will be the ECLSS. The ECLSS functions to create a habitable environment for the astronauts to survive in. Although these have been in use since the early days of space exploration, research is needed to reduce the mass and volume of these systems, all while increasing their reliability. One of the main functions of the ECLSS is atmospheric management, which concerns removing impurities in the atmosphere, supplying and storing the various gases, and recycling the resources or using in situ resources as a means to save mass. JSC is currently heading up research on improvements in these systems,[0] along with many of the other NASA locations, and a TRL of 4 is given.

The ECLSS also serves to monitor and control the environment. Using advanced Environmental Monitoring and Control (EMC), the efficiency of the ECLSS will be increased, as well as being able to sense any environmental hazards that may pose a threat, such as a leak, in order for the safe environment to be maintained. The Jet Propulsion Laboratory's (JPL's) Office of Biological and Physical Research is currently researching improvements in EMC,[0] so a TRL of 7 is assigned to advanced EMC.

A final critical function of the ECLSS is to recover the water and air that is used in the environment, as this correlates to a large mass and volume savings. Advanced Air and Water Recovery Systems (AWRS) use biological, physical, and mechanical methods to recycle the air and water that are used to support the environment of the habitat. Improvements in these systems will contribute to large savings in the mass and volume needed for re-supply, allowing these savings to be used elsewhere for other cargo, in addition to being more efficient and requiring less power.[0] A 90-day ground demonstration of advanced AWRS has been completed, so a TRL of 6 has been assigned.

Currently, several spacecraft operate using in-space staging of propulsion units, including upper stages on launch vehicles and solid kick motors.[0,0] However, this particular configuration has never been used before. Therefore, some ground and flight testing of this configuration is necessary to ensure reliable staging of the LOI stage. The current TRL for this technology is 8.

The four descent stage engines will be similar to the RL-10 engine, which was designed by Pratt and Whitney in the 1950's and has since been used extensively. The RL-10 was the first LOX/LH_2 rocket used in space, and the descent stage engines will also be LOX/LH_2. Due to the extensive experience with the RL-10 engine, the TRL for

Category	Description	Current TRL
Protection	Dust and contaminant mitigation	3-5
Power	Surface system fuel cells	5
Avionics	Advanced Integrated System Health Management (ISHM)	5-6
Avionics	Autonomous precision landing and Guidance, Navigation & Control (GN&C)	5
ECLSS	Atmospheric management	4
ECLSS	Advanced environmental monitoring and control	7
ECLSS	Advanced air and water recovery systems	6
Propulsion	Ascent Propulsion System	7
Propulsion	Descent Propulsion System	8
Propulsion	Staging	8

Table 9. Enabling Technology Overview.

the descent engines is 8. The single ascent stage engine will be similar to the Aestus storable propellant engine. Aestus uses pressure fed N_2O_4/MMH propulsion system and is currently used on the second stage of the Ariane 5. The storable properties of the propellant will allow the ascent stage to sit on the lunar surface for the 180 days of the outpost missions, and the pressure fed system is more reliable than a pump fed system. The TRL for the ascent engine is 7.

Gryphon Configuration

The Gryphon's configuration was selected by analyzing the options in Table 3 under the Configuration and Habitat Split categories using both AHP and an overall evaluation criterion (OEC) to compare them to the FOM's. This analysis is shown in more detail in Appendix B.

A comparison of size and mass between the Gryphon and ESAS is shown in Figure 9. The integrated Gryphon concept is sized to the same gross mass as the ESAS lander. Because of the minimized ascent stage, the payload with the crew rotation (crew exchange payload) for an outpost is greater because the large habitat is not required for the mission but is required for the crewed ESAS lander. The payload mission capability is slightly less because the split lander requires a hatch between the ascent stage and the habitat. The cargo mission capability is less than the ESAS capability but there are no details in the ESAS report to make a rationale argument; however, it should be noted that the Gryphon lander is sized for the increased cargo capability (engines, landing gear, etc.). A mass breakdown of the Gryphon is presented in Table 10.

The Gryphon has approximately the same gross mass as the ESAS lander and fits within the same payload fairing, but offers significant advantages in several categories. Gryphon's cargo bay is 71% closer to the lunar surface, allowing easy egress and access to the ascent stage and delivered cargo. The ESAS lander does have slightly better payload capability during either a sortie mission or a cargo dedicated mission (2% and 11% respectively), but after the monolithic habitat has been delivered, the majority of the missions during the campaign will be crew exchange missions. The Gryphon is capable of delivering over 86% more cargo during a crew exchange mission, which is critical in maintaining the necessary consumables level throughout the 10-year stay. Due to this increased capability, the Gryphon manifest only requires three cargo-dedicated launches to support 3,060 days on the lunar surface. In contrast, the ESAS manifest requires four dedicated cargo launches to supply the necessary equipment and consumables and only supports crew on the surface for 2,709 days. Even with this extra

CREW LANDER

DESCENT STAGE MASS	
1.0 Structure	2,123
2.0 Protection	68
3.0 Propulsion	2,215
4.0 Power	392
5.0 Controls	72
6.0 Avionics	81
7.0 Environment	815
8.0 Other	884
9.0 Growth	1,330
DRY MASS	**7,980**
10.0 Non-Cargo	1,337
11.0 Cargo	4,268
INERT MASS	**13,585**
12.0 Non-Propellant	-
13.0 Propellant	11,959
GROSS MASS	**25,543**

ASCENT STAGE MASS	
1.0 Structure	491
2.0 Protection	50
3.0 Propulsion	276
4.0 Power	476
5.0 Controls	84
6.0 Avionics	259
7.0 Environment	53
8.0 Other	382
9.0 Growth	464
DRY MASS	**2,536**
10.0 Non-Cargo	593
11.0 Cargo*	100
INERT MASS	**3,229**
12.0 Non-Propellant	6
13.0 Propellant	3,085
GROSS MASS	**6,320**

* Cargo is Returned from Lunar Surface

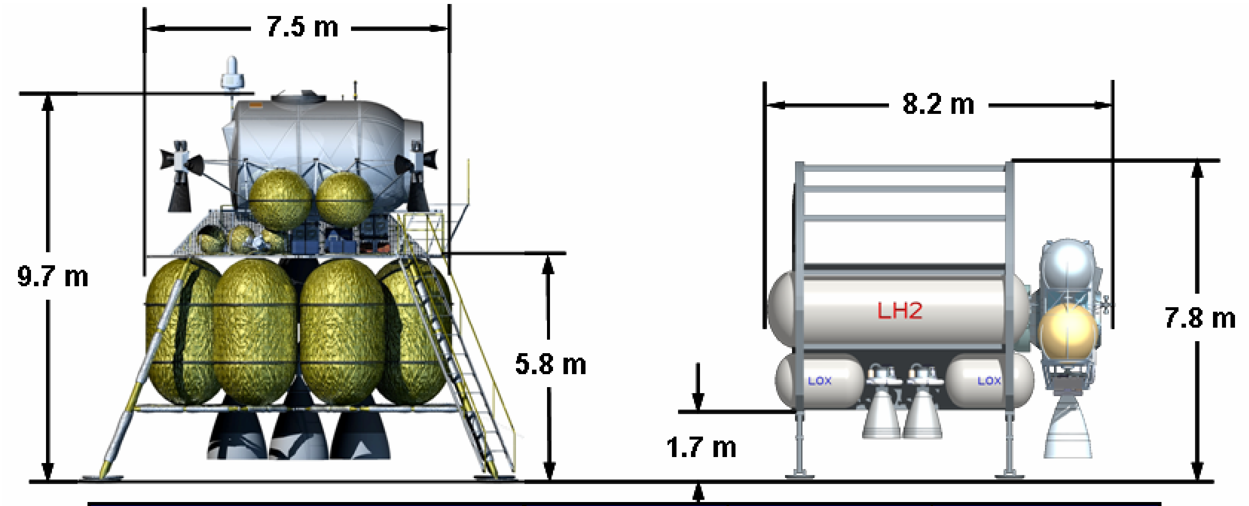
CARGO LANDER

DESCENT STAGE MASS	
1.0 Structure	1,826
2.0 Protection	73
3.0 Propulsion	2,215
4.0 Power	228
5.0 Controls	77
6.0 Avionics	80
7.0 Environment	243
8.0 Other	708
9.0 Growth	1,090
DRY MASS	**6,539**
10.0 Non-Cargo	1,961
11.0 Cargo	18,634
INERT MASS	**27,134**
12.0 Non-Propellant	-
13.0 Propellant	16,366
GROSS MASS	**43,501**

TOTAL LANDER MASS	**31,863**

Table 10. Gryphon Mass Breakdown (Crew and Cargo Configurations).

cargo dedicated launch, the final mission stay times have also been reduced (from 180 to 123 days) to maintain sufficient consumables near the end of the campaign. Ultimately, the ESAS manifest results in 13% less days on the surface and 8% less cargo delivered.



Characteristic	ESAS LSAM	Gryphon Lander	Percent Difference from ESAS
Gross Mass, mT	45.9	45.9	0.0%
Landed Mass, Crewed, mT	20.3	16.8	-17.2%
Cargo Height, m	5.8	1.7	-70.7%
Crew Exchange Payload Capability, mT	2.29	4.27	86.5%
Sortie Mission Payload Capability, mT	2.29	2.24	-2.2%
Cargo Mission Payload Capability, mT	20.9	18.63	-10.9%
Campaign Days on Surface	2709	3060	13.0%
Total Campaign Cargo Delivered, mT	122.6	132.7	8.2%

Figure 9. Comparison of ESAS LSAM and Gryphon Lander.

Cost & Schedule

In order to ensure that the Gryphon is a viable option for NASA's lunar exploration program, a cost and schedule analysis must be performed. These must show that the Gryphon conforms to the available NASA budget and deadlines.

A. Cost Analysis

NAFCOM was utilized for the cost analysis aspect of this project. NAFCOM incorporates data from the Resource Data Storage and Retrieval (REDSTAR) library, which allows the user to perform parametric CER estimates. Our cost analysis incorporated specific analogy CERs based upon the subsystem masses for the LOI, descent, and ascent stages by comparing each subsystem to a predetermined similar historical system. Various filters were used that further refined the analysis based upon the selected subsystem choices to account for varying complexities among the subsystems when they were compared to their historical counterpart.

The cost analysis comprised of the total cost of the subsystems, system integration, and vehicle level integration for the descent, ascent, and LOI stage. The subsystems that make up the descent stage analysis included thermal control, structures and mechanisms, main propulsion system (less engines), GN&C, engines, electrical power and distribution, and command, control, and data handling. The analysis of the ascent stage included the above subsystems and also incorporated a number of different subsystems to include a reaction control subsystem (RCS), ECLSS, crew accommodations, and avionics. The LOI stage comprised only of the main propulsion system (less engines), engines, avionics, and structure subsystems do to its unique mission.

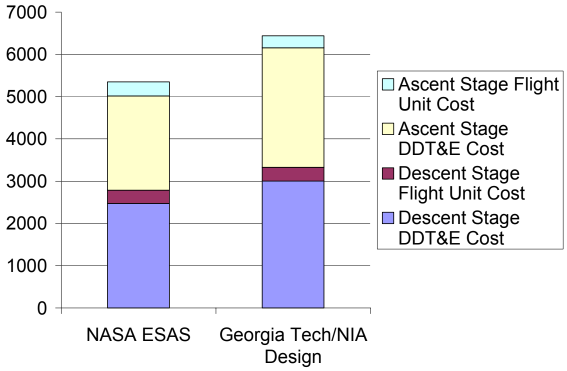


Figure 10. Lunar Lander Cost Comparison (M$ FY06).

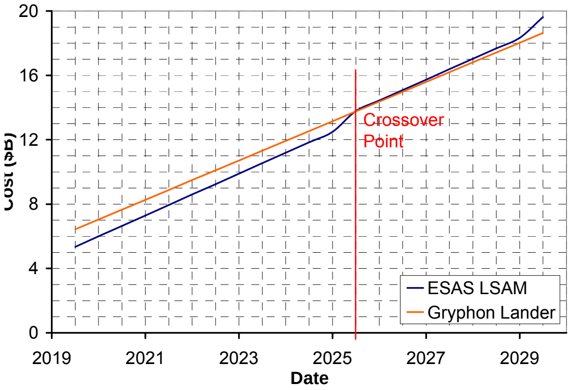


Figure 11. Life-Cycle Cost Comparison Between the Gryphon and LSAM.

In addition to the subsystem costs for each stage, various system integration costs were also addressed by NAFCOM. These costs included Integration, Assembly, and Checkout, System Test Operations, Ground Support Equipment, System Engineering and Integration, Program Management, and Launch and Orbital Operations Support. These costs, in addition to the vehicle level integration costs and the subsystem costs, comprise the total vehicle costs. Table 11 depicts the breakdown of total costs for the descent, ascent, and LOI stages by the above three categories and provides the total cost for each stage.

Upon completing the cost analysis using NAFCOM, the generated data for the descent and ascent stages was compared to the costs, also computed by NAFCOM, of NASA's ESAS LSAM. The cost comparison utilized the total Design, Development, Test and Evaluation (DDT&E) costs and the total flight unit costs of each of the separate designs.

Figure 10 depicts the costs for each design in each of these two categories. As can be seen by the data, our system's descent and ascent stage DDT&E costs exceed NASA's LSAM DDT&E costs by approximately 24%. The flight unit cost of the Gryphon is approximately 6% less than the LSAM unit cost. Because the LSAM cannot perform the missions that the Gryphon can perform, however, the LSAM would cost more throughout the entire lunar campaign to accumulate the same number of crew days, as shown in Figure 11. The crossover point where, although the LSAM has a higher initial cost, the Gryphon surpasses the LSAM is in 2025. The difference at the end of the two campaigns is $988 M.

B. Schedule Analysis

The project schedule for the design and fabrication of the lander and its associated support systems has been benchmarked with several control gates. These gates ensure equitable attention and effort are expended on each phase of the project. The four primary control gates are:

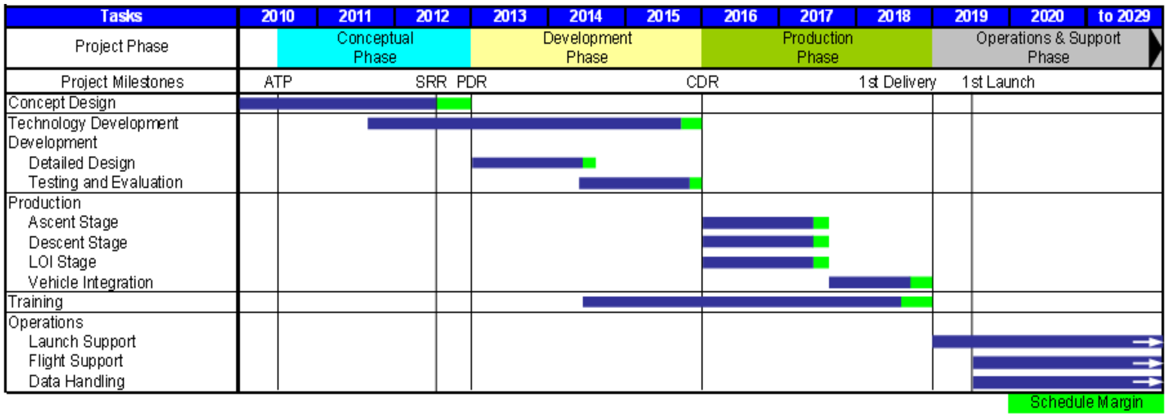


Figure 12 Gryphon Project Schedule.

1. Authority to Proceed (ATP): initializes the conceptual design of the vehicle.
2. Systems Requirements Review (SRR): ensures that the system requirements have been properly identified and that mutual understanding exists between contractor and customer.
3. Preliminary Design Review (PDR): confirms that the preliminary design meets the specified requirements.
4. Critical Design Review (CDR): evaluates the completeness of the design before beginning production.

The current schedule sequencing shown in Figure 12 is timed to support the Vision for Space Exploration with the ATP in mid-to-late 2010. The conceptual design phase extends through the end of 2012 at the PDR. Detailed design and development will proceed over the next three years ending at the CDR in 2015. Prototype production extends over the next three years finishing in time for the first delivery in early 2019. Operations support for the lander and associated support systems will extend throughout the duration lunar exploration program.

Conclusions

With NASA's goal for the future of placing an outpost on Mars, placing one on the moon is a necessary first step. Learning to live on an alien body for extended periods of time is a key to the future success of NASA's manned space exploration program. The Gryphon is designed to be a flexible, horizontal lander capable of the various missions a lunar campaign would have: sortie missions, cargo missions, and outpost crew exchange missions.

Finally, the Gryphon lander satisfies several of the ESAS FOM's better than the LSAM. The Gryphon's lower cargo bay will increase safety and mission success by allowing easy access and egress. Additionally, operations cost of a lander closer to the lunar surface would be lower. Gryphon delivers more cargo to the lunar surface, permits more usable surface crew-hours, and allows for easy cargo-offload: all important aspects of the lander's effectiveness/performance. Gryphon's flexible descent stage allows for increased lunar flexibility, as it is capable of crew exchange, sortie, and dedicated cargo missions. Although the development costs of the Gryphon lander are greater, the ESAS lander would cost one billion dollars more to perform the same campaign because of increased per unit costs and the need for an additional two cargo missions during the 10 year campaign.

Education and Public Outreach

The design team went to Tabb Middle School and provided an interactive presentation to 7 science classes of 6th grade students and an after-school science club meeting. The event took place from 7:45 am - 12:45 pm and later from 2 - 3 pm on May 11, 2007.

The presentation outlined the reasons for returning to the moon, the ESAS Figures of Merit which help mold the objectives and requirements of the ESAS architecture (the baseline for this project), and an overview of the team's revolutionary design. A question and answer session followed the presentation to clear up all the nagging questions of the inquisitive students.

The final event was a competitive trivia game in which the students were divided into teams and their attention and comprehension was put to the test. The winning team took home NASA temporary tattoos, while each participating student was awarded a NASA sticker, a moon lithograph, and an increased understanding of NASA's plan to return to the moon. In order to continue the education process, the team provided each teacher with a teacher's guide on earth and space sciences.

Later in the afternoon, the team presented a modified version of their RASC-AL presentation to the after-school science club. These students were provided a more detailed explanation of all the work carried out by the NIA team, including an introduction to the methodologies of aerospace systems engineering. The NIA team would like to extend a special thank you to Pat Wilhite of Tab Middle School who helped make the public outreach a great success.

In order for a mission like this to work, the young people must be involved. They will be the astronauts inhabiting the moon and building the spacecraft. Therefore, an exciting education and public outreach campaign was included with this design to get the students of today interested in the missions of tomorrow.

Appendix

A. Systems Engineering

In order to ensure that the Gryphon's design meets all of the requirements and is the best configuration for the Figures of Merit (FOM's) specified in ESAS, systems engineering analyses were performed.

Because of the limited resources available to evaluate the design, key trade areas must be identified for trade. This reduction was performed using a Quality Function Deployment (QFD)

Architecture alternatives are then developed through the use of a Morphological Matrix and compared to the FOM's using a Quality Function Deployment (QFD). Based upon the sensitivity of the FOM's for each subsystem, ten key trade areas are identified which must be evaluated using a modeling and simulation (M&S) environment.

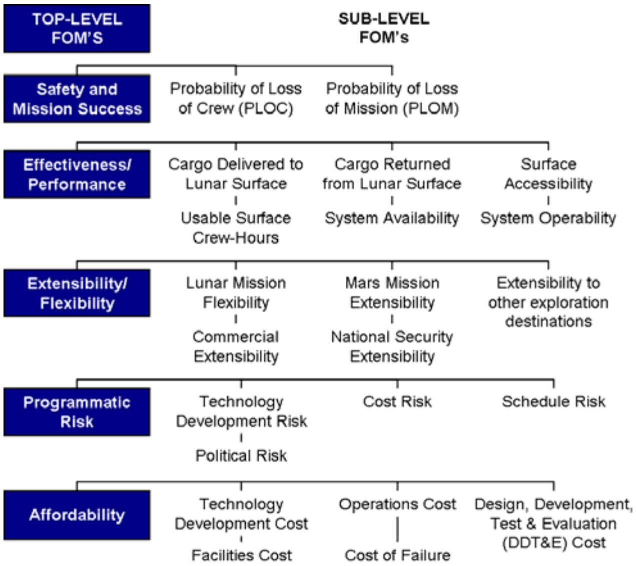


Figure A1: ESAS Figures of Merit.

Architecture Alternatives

A morphological matrix, or matrix of alternatives, is a tool that is used to decompose a vehicle's functions and characteristics into different options. It is useful in generating and identifying feasible alternatives that could be used in all areas of the design. The morphological matrix for the Gryphon is shown in Table 3. The vehicle's engineering characteristics are listed on the vertical axis, while possible alternatives are presented on the horizontal axis, with a maximum of five alternatives for each characteristic. The alternatives highlighted in yellow are those that correspond to the baseline design for the Gryphon, or the ESAS LSAM.

From the morphological matrix, a total of 6.55×10^{21} possible combinations of the lander design were identified. A number of these combinations can be discarded due to certain alternatives being incompatible with other alternatives, such as a pump-fed hypergolic engine, or being dependent on another characteristic, such as how communication and navigation are highly related (i.e. navigating using lunar orbiters would limit the communications system to bands that are compatible with the orbiters). However, even after ignoring the incompatible and dependent alternatives, there are still an extremely high number of possible combinations left, such that it would be impossible to evaluate each one. Thus, in order to efficiently and effectively evaluate the best alternatives, the FOM's are ranked to determine their relative importance, the key trade areas are identified based on these rankings, and the key trades are performed, and this process identifies the best designs.

Evaluation Criteria

In order to evaluate each alternative based on the same set of criteria, the five top-level FOM's from ESAS were used. These FOM's, along with the sublevel FOM's, are shown in Figure A1.[21]

So as to compare the alternatives effectively, the relative importance of each of these FOM's must be understood. Analytic Hierarchy Process (AHP) was used to rank each top-level FOM, developing a relative weighting for each. The weightings developed for the ESAS FOM's are shown in Table A1, with the higher priority ratings representing more important FOM's. From this, it can be seen that the most critical criterion, by far, was Safety and Mission Success Criterion (SMSC), followed by Effectiveness and Performance Criterion (EPC), then Affordability and Cost Criterion (ACC), and finally Programmatic Risk Criterion (PRC), and Extensibility and Flexibility Criterion (EFC).

Table A1: FOM Weighting Based on AHP.

FOM (Criterion)	Priority	Ranking
Safety and Mission Success	0.391	1
Effectiveness and Performance	0.274	2
Affordability and Cost	0.194	3
Programmatic Risk	0.096	4
Extensibility and Flexibility	0.046	5

Identification of Key Trade Areas

The key trade areas were then identified using these FOM priorities and a QFD. The QFD maped the second-level FOM's to the engineering characteristics identified in the morphological matrix, with the ultimate objective of identifying the critical areas of the design that should be evaluated further. This was accomplished by determining if any correlation existed between each engineering characteristic and the second-level FOM's, and if so, either a 1, for a low correlation, 3, for a medium correlation, or 9, for a strong correlation, were assigned. A non-linear scale was used so that the characteristics with strong correlations would have a higher chance of standing out from the others. Once all of these values were assigned, the values were multiplied by the corresponding FOM's relative importance, and the sum of these for each column were determined to give the importance of each engineering characteristic. The eight columns with the greatest values represented the top eight, or key, trade areas that were focused on in the technical analysis of the design, and these are shown in Table A2. The engineering characteristics that are not determined to be key trades are kept the same as the baseline design, the ESAS LSAM, as these do not affect the FOM's as much as the key trade areas do.

Table A2: Top Eight Key Trade Areas.

Ranking	Engineering Characteristic	Importance
1	Descent Propellant	425.66
2	Staging	408.02
3	Ascent Propellant	329.67
4	Descent Number of Engines	325.35
5	Trajectory	299.20
6	Ascent Number of Engines	297.84
7	Habitat Split	278.33
8	Lander Configuration	213.11

B. Configuration Selection

Several different configuration options were considered for the design of the Gryphon. From the morphological matrix presented earlier, a number of critical options were identified for the design. The first of these options was the physical setup of the lander, which was to either have a horizontal (wider than it is tall) or vertical (taller than it is wide) lander. Another configuration option identified concerned which type of habitat split to use. The first alternative was to use an Apollo-type habitat split, where the entire habitat is located in the ascent stage. This has the advantage of being a simple and proven concept, but does not allow the habitat to be left on the lunar surface, decreasing the potential performance of the ascent stage. The other alternative was to use a minimum ascent habitat split, with either a pressurized or unpressurized ascent stage. For this concept, the habitat is separate from the ascent stage. This is beneficial in that it allows more mass to be left on the surface, such that the ascent stage can be lighter since it does not have to lift as much, but also makes the system more complicated. The minimal ascent stage also facilitates the flexible lander concept, which uses interchangeable parts to accommodate different missions. After identifying these critical configuration options, five different configurations were decided on to examine further. These five configurations are presented below in Table B1.

Table B1: Final Five Configurations Analyzed.

Number	Name	Description
1	Design 1	Vertical, unpressurized minimal ascent
2	Design 2	Vertical, pressurized minimal ascent
3	Design 3	Horizontal, unpressurized minimal ascent
4	Design 4	Horizontal, pressurized minimal ascent
5	Design 5	Vertical, pressurized Apollo

In order to evaluate these five configurations and identify the best overall design, a method to rank the designs all on the same scale needed to be implemented. Two methods were decided on to accomplish this. The first was AHP, which had already been applied earlier when determining the rankings of the FOM's. Additionally, an Overall Evaluation Criterion (OEC) was used to validate the results from AHP. The OEC is a similar method of ranking alternatives, but instead of ranking them based on overall weightings like in AHP, the alternatives are ranked based on the ratio of each design's benefits to costs[0] The benefits for the Gryphon, or metrics that were desired to be maximized, were SMSC, EPC and EFC, while the costs, or the metrics that were sought to be minimized, were PRC and ACC. The coefficients in the function, shown below in Equation B1, were determined using the priorities from AHP and normalizing them for both the benefits and the costs, such that the sum of the coefficients in the numerator and denominator both add up to one.

$$\mathrm{OEC} = \frac{\mathrm{Benefits}}{\mathrm{Costs}} = \frac{0.550(\mathrm{SMSC}) + 0.386(\mathrm{EPC}) + 0.064(\mathrm{EFC})}{0.330(\mathrm{PRC}) + 0.670(\mathrm{ACC})} \tag{1}$$

In order to begin the AHP and OEC, the five configurations were evaluated against the FOM's, using all sixteen sub-level FOM's and their 55 proxy parameters, to determine initial values for each designs' top-level FOM importance. With these values, AHP was performed on each top-level FOM with respect to the five configurations to determine priority vectors for each FOM for all five configurations. For AHP, these priority vectors for each configuration were multiplied by the corresponding FOM priority vectors to obtain the overall priority vector, with the largest number representing the best design. These overall priority vectors are presented below in Table B2, where the highlighted cells indicating the best in that specific category, indicating Design 4 as the best option.

Table B2: Weighted Priority Vectors for Five Configurations Analyzed.

	SMSC	EPC	EFC	PRC	ACC	Priority Vector	Ranking
Design 1	0.0403	0.0184	0.0018	0.0045	0.0216	0.0866	4
Design 2	0.0156	0.0691	0.0121	0.0239	0.0078	0.1286	3
Design 3	0.0311	0.0184	0.0018	0.0045	0.0216	0.0775	5
Design 4	**0.2266**	**0.1573**	**0.0231**	0.0239	**0.0714**	**0.5022**	**1**
Design 5	0.0772	0.0113	0.0066	**0.0388**	**0.0714**	0.2052	2

Next, an OEC was used to validate the results from AHP. Using the priority vectors obtained for each of the five configurations with respect to the five top-level FOM's, the OEC function value for each configuration was calculated, as shown below in Table B3. The highlighted values are the best values for the individual categories, or the maximum values for the benefits and overall ranking, and the minimum values for the costs. The results from OEC match those from AHP, indicating the best overall design as the horizontal, pressurized minimal ascent lander.

Table B3: OEC Rankings for Five Configurations Analyzed.

Design Option	SMSC	EPC	EFC	PRC	ACC	OEC Value	Ranking
Design 1	0.103	0.067	0.040	0.953	0.888	0.094	4
Design 2	0.040	0.252	0.267	0.750	0.960	0.153	3
Design 3	0.080	0.067	0.040	0.953	0.888	0.079	5
Design 4	**0.580**	**0.573**	**0.507**	0.750	**0.632**	**0.854**	**1**
Design 5	0.197	0.041	0.145	**0.595**	**0.632**	0.216	2

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