SpaceWorks Engineering, Inc. (SEI)

Probabilistic Examination of Lunar Landers

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Overview of Content

Moonraker…

a new analysis model specifically tailored to the conceptual level design and evaluation of lunar ascent and descent systems.

Historical verification…

of the Moonraker model against an Apollo Lunar Excursion Module (LEM).

Acknowledge uncertainty…

in the performance modeling of future technologies, and effectively mitigate this uncertainty through probabilistic methods.

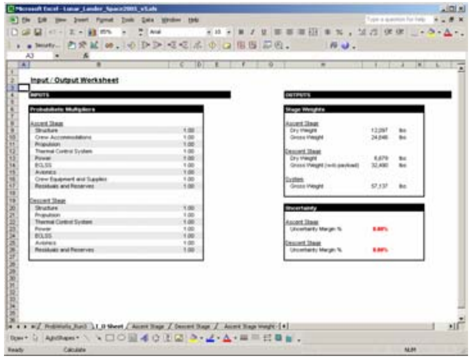
An all-new lunar lander…

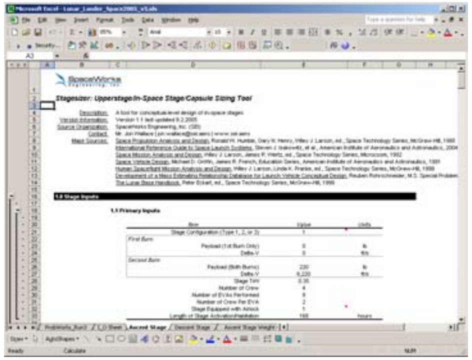
design developed probabilistically in Moonraker using a Monte Carlo simulation.

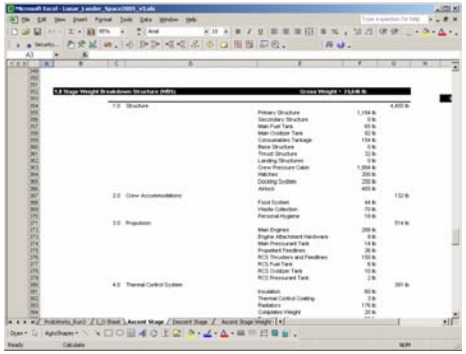
The *Moonraker* Tool

Moonraker Summary

- Lunar lander designs have historically come in a variety of shapes and sizes
- In order to perform conceptual design studies for a system that is characterized by such variability, the modeling approach must emphasize flexibility
- Moonraker Attributes:
  - designed for adaptability not only to a variety of stage configurations, but also to a range of main propellant combinations, crew sizes, delta-Vs, and other design variables
  - implemented in Microsoft Excel© to facilitate rapid execution and ease of output reporting
  - Over 200 input variables divided into Primary Inputs and Reference Sizing Inputs
  - Output includes a 3-level WBS for each vehicle stage, along with basic stage geometry (height, length/radius, surface areas)







Moonraker Inputs and Outputs: Primary Inputs

Primary Inputs

Input Variable	Description
Stage Configuration	Choices include: (1) inline, (2) torroidal tankage, (3) horizontal
Stage T/W	Thrust to weight ratio of the entire stage prior to any propulsive burns (i.e. Total Vacuum Thrust / System Gross Weight)
Number of Crew	Number of crew members inhabiting the system during the mission
Length of Stage Activation/Habitation	Length of time that crew and systems will be active on the stage
First Burn:	
Payload (1st burn only)	Portion of the payload that is released between 1st and 2nd propulsive burns
Delta-V	Total ideal delta-V imparted during the 1st burn
Second Burn:	
Payload (both burns)	Portion of the payload that is carried through both the 1st and 2nd propulsive burns
Delta-V	Total ideal delta-V imparted during the 2nd burn

Moonraker Inputs and Outputs:
Primary Inputs

Reference Sizing Inputs

Category	Description of Contents
Structures	Configuration geometry definition; structural unit weights; tank unit weights; thrust structure definition; landing structure definition; ingress/egress structure definition; crew cabin definition
Crew Accommodations and Equipment	Define crew member weights; specify sizing parameters for food system, waste collection system, personal hygiene items, personal items, and additional supplies
Propulsion	Specify quantity and performance of main engine(s); specify quantity and performance of attitude control thrusters; define sizing parameters for pressurant gas system(s)
Thermal Control	Define coverage area for thermal insulation; specify insulation unit weight; define radiator and coldplate sizing parameters
Power	Describe baseline and peak power loads; specify system voltage; specify division of power system between stored and generated sources; define sizing parameters for stored and generated power sources
ECLSS	Define cabin atmosphere composition; provide sizing parameters for temperature and humidity control, atmosphere resupply, atmosphere revitalization, fire detection and suppression, and water recovery and management
Avionics	Define sizing parameters for guidance, navigation, and control systems; describe communications system; specify system redundancy
Residuals and Reserves	Specify residual and reserve main propellants as % of main propellant load
Propellant Boil-off	Define boil-off rate and applicability of boil-off to fuel and oxidizer
Consumables	Define consumption rates for food, water, and cabin atmosphere components; specify frequency of EVA activities

Moonraker: Historical Comparison

Historical Comparison: Moonraker Inputs

Primary Inputs

Input Variable	Apollo 12 LEM Historical Value
Ascent Stage	
Stage Configuration	In-line
Payload	75 lbs (lunar rock samples)
Delta-V	6,060 ft/s
Stage T/W	0.35
Number of Crew	2
Length of Stage Activation/Habitation	72 hours
Descent Stage	
Stage Configuration	In-line
Payload	Ascent Stage Weight
Delta-V	7,000 ft/s
Stage T/W	0.31
Number of Crew	0
Length of Stage Activation/Habitation	72 hours

Reference Sizing Inputs

Input Variable	Apollo 12 LEM Historical Value
Ascent Stage	
Primary Structure	Aluminum (7075)
EVA Pressure Suit Weight	180 lbs (each)
Fuel	UDMH
Oxidizer	N_2O_4
Engine Vacuum Isp	309.4 s
Battery Technology	Silver-Zinc
Crew Cabin Atmospheric Pressure	8 psia
Descent Stage	
Primary Structure	Aluminum (7075)
Fuel	UDMH and N2H4 (50-50 mixture)
Oxidizer	N_2O_4
Engine Vacuum Isp	301 s (approx. average)
Battery Technology	Silver-Zinc

Historical Comparison: Results

- Certain technologies have advanced dramatically since Apollo (computers, avionics, miniaturization of electromechanical devices, etc.)
- Some Moonraker inputs had to be set outside normal bounds to reflect Apollo technology performance

Comparison Results

Weight Line Item	Apollo 12 Historical Value	Moonraker Model Estimate	% Difference
Ascent Stage			
Inert Weight	4,780 lbs	4,860 lbs	+1.7%
Ascent Propellants	4,770 lbs	4,750 lbs	-0.4%
Stage Gross Weight	10,450 lbs	10,420 lbs	-0.3%
Descent Stage			
Inert Weight	4,395 lbs	4,340 lbs	-1.3%
Descent Propellants	17,250 lbs	16,995 lbs	-1.5%
Stage Gross Weight	22,055 lbs	22,620 lbs	+2.6%
Lander System			
Gross Weight	32,510 lbs	33,040 lbs	+1.6%

NOTE: Weight categories represent rolled up totals from Level-3 Weight Breakdown Statement (WBS)

A Probabilistic Design Process

Probabilistic Design Philosophy and Process

- What is meant by *uncertainty*?
  - The term is used here to refer to the inability of computational models to fully capture and predict the physical performance of a real world device or system
  - These models may overpredict or underpredict system performance

- The Objective of a Probabilistic Design Process:
  - Intended to mitigate future impacts of modeling uncertainty on system performance

- Description of Proposed Process:
  - Step 1: Derive input distributions to place on each of the lander stage dry weight line items
    - These distributions describe mathematically the likelihood of weight growth or reduction due to uncertainty for a particular weight component
    - Use triangular input distributions with high, low, and likeliest values based on either expert opinion, engineering analysis, or other means
  - Step 2: Employ a Monte Carlo simulation to sample randomly from the input distributions and produce output distributions
    - Moonraker is executed using randomly sampled uncertainty multipliers during each Monte Carlo trial
    - From the output distribution it is possible to obtain the mean weight growth due to uncertainty, or to determine the weight growth that corresponds to a desired certainty level
  - Step 3: Apply an uncertainty margin to baseline deterministic vehicle design (discussed later)

Probabilistic Design of a Crewed Lunar Lander

- Moonraker was used to develop an all-new crewed lunar lander in a probabilistic fashion

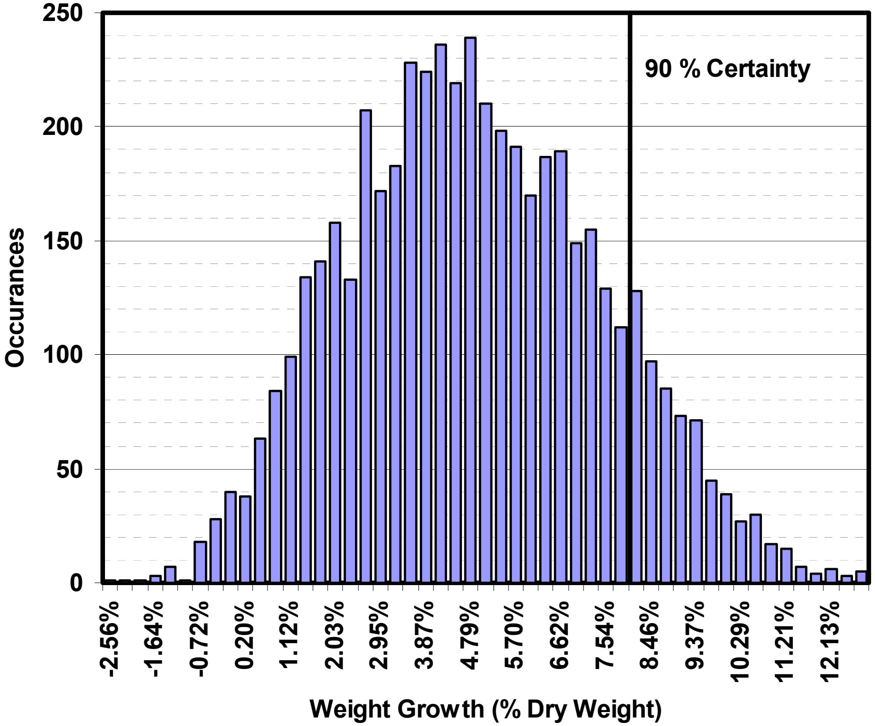
- The all-new lander was subject to the following mission requirements:
  - Crew Size: 4
  - Surface Stay Time: 6 days
  - Landing Site: Equatorial
  - Stage Configuration: Two Stage
  - Propellant Combination: Liquid Oxygen / Liquid Methane

- Input Distributions on Potential Weight Growth Due to Uncertainty:

Dry Weight Line Item	Likeliest Value	Low Value	High Value
Ascent Stage			
Structure	0%	-5%	+30%
Crew Accommodations	0%	-5%	+30%
Propulsion	0%	-5%	+20%
Thermal Control System	0%	-5%	+20%
Power	0%	-10%	+20%
ECLSS	0%	-5%	+30%
Avionics	0%	-15%	+10%
Crew Equipment and Supplies	0%	-5%	+30%
Descent Stage			
Structure	0%	-5%	+30%
Propulsion	0%	-5%	+20%
Thermal Control System	0%	-5%	+20%
Power	0%	-5%	+20%
ECLSS	0%	-5%	+30%
Avionics	0%	-15%	+10%

All-new Lunar Lander:
Ascent Stage Results

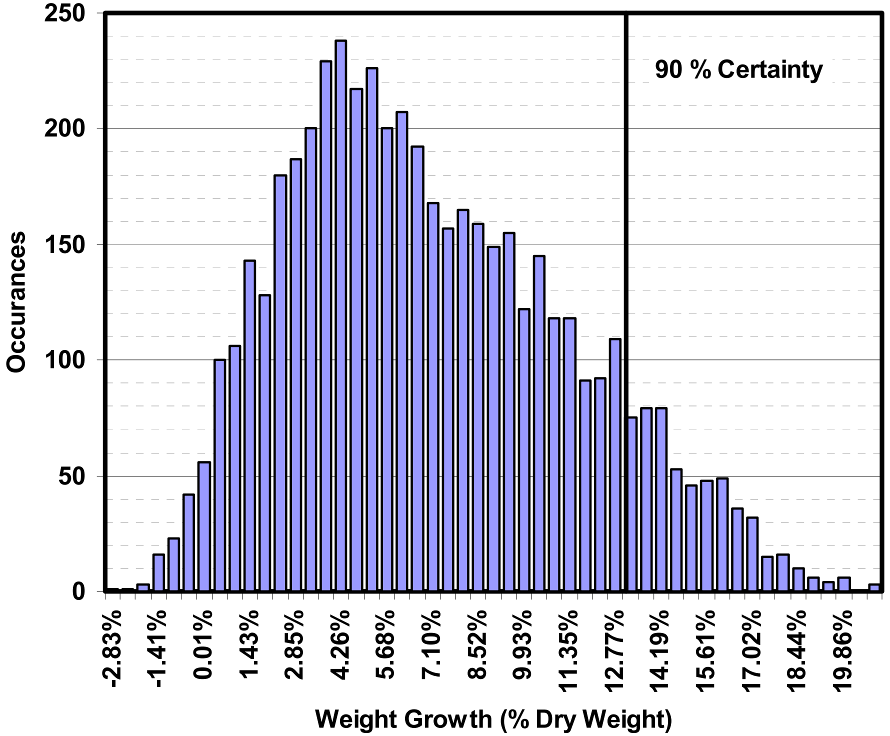
Ascent Stage Dry Weight Growth Due to Uncertainty as a Percentage of the Stage Dry Weight



Parameter	Value
Mean	4.72%
Standard Deviation	2.58 percentage points
90% Certainty Value	8.22%

All-new Lunar Lander: Descent Stage Results

Descent Stage Dry Weight Growth Due to Uncertainty as a Percentage of the Stage Dry Weight



Parameter	Value
Mean	6.80%
Standard Deviation	4.38 percentage points
90% Certainty Value	13.15%

The Concept of an Uncertainty Margin

- Terminology: “Manager’s Reserve” and “Uncertainty Margin”
  - Manager’s Reserve: The principle of margin is that while design requirements may change, subsystem design goals may not be met, or new subsystems may become required items, the manager must still ensure that the vehicle can perform the mission. As system weight increases due to these factors, margin weight is withdrawn from the margin reserve. A fixed manager’s reserve margin of 15% was placed on the dry weight of the all-new lunar lander.
  - Uncertainty Margin: For this analysis the term uncertainty refers specifically to modeling uncertainty, with other types of unpredictable weight growth captured by the weight margin. The uncertainty margin in this analysis was based on the 90% certainty weight growth for each stage and was calculated as follows:

WBS Item 1	Weight
WBS Item 2	Weight
…	…
WBS Item N	Weight
Uncertainty Margin	$\Sigma_{1\text{-}N}$Weight x 90% Certainty Weight Growth
Manager’s Reserve	$[\Sigma_{1\text{-}N}$Weight + Uncertainty Margin$]$ x 15%
Dry Weight	$\Sigma_{1\text{-}N}$Weight + Uncertainty Margin + Manager’s Reserve

All-new Lunar Lander:
Weight Breakdown Structure (WBS) Results

Ascent Stage

	WBS Item	Deterministic Weight	Probabilistic Weight
1.0	Structure	4,455 lb	4,496 lb
2.0	Crew Accommodations	132 lb	132 lb
3.0	Propulsion	514 lb	542 lb
4.0	Thermal Control System	381 lb	383 lb
5.0	Power	2,465 lb	2,465 lb
6.0	ECLSS	532 lb	532 lb
7.0	Avionics	114 lb	114 lb
8.0	Crew Equipment and Supplies	1,926 lb	1,926 lb
9.0	Uncertainty Margin	0 lb	870 lb
10.0	Manager’s Reserve	1,578 lb	1,719 lb
11.0	**Dry Weight**	**12,097 lb**	**13,178 lb**
12.0	Crew	880 lb	880 lb
13.0	Residuals and Reserves	295 lb	317 lb
14.0	Propellant Boil-off	50 lb	53 lb
15.0	Consumables	1,001 lb	1,004 lb
16.0	Payload (both burns)	220 lb	220 lb
17.0	RCS Propellants	282 lb	303 lb
18.0	Burnout Weight	14,825 lb	15,956 lb
19.0	Main Propellants	9,822 lb	10,572 lb
20.0	**Gross Weight**	**24,646 lb**	**26,528 lb**
21.0	Stage Weight (w/o payload)	24,426 lb	26,308 lb

Descent Stage

	WBS Item	Deterministic Weight	Probabilistic Weight
1.0	Structure	3,023 lb	3,209 lb
2.0	Crew Accommodations	0 lb	0 lb
3.0	Propulsion	997 lb	1,081 lb
4.0	Thermal Control System	349 lb	352 lb
5.0	Power	1,065 lb	1,065 lb
6.0	ECLSS	261 lb	261 lb
7.0	Avionics	114 lb	114 lb
8.0	Crew Equipment and Supplies	0 lb	0 lb
9.0	Uncertainty Margin	0 lb	800 lb
10.0	Manager’s Reserve	871 lb	1,032 lb
11.0	**Dry Weight**	**6,679 lb**	**7,912 lb**
12.0	Crew	0 lb	0 lb
13.0	Residuals and Reserves	722 lb	793 lb
14.0	Propellant Boil-off	122 lb	134 lb
15.0	Consumables	251 lb	260 lb
16.0	Payload (both burns)	24,646 lb	26,528 lb
17.0	RCS Propellants	653 lb	718 lb
18.0	Burnout Weight	33,072 lb	36,345 lb
19.0	Main Propellants	24,064 lb	26,446 lb
20.0	**Gross Weight**	**57,137 lb**	**62,791 lb**
21.0	Stage Weight (w/o payload)	32,490 lb	36,262 lb

NOTE: Component categories represent rolled up totals from Level-3 Weight Breakdown Statement (WBS)

All-new Lunar Lander: Discussion of Results

- There is a difference of more than 5,000 lbs between the gross mass of the probabilistic and deterministic lander systems
- By designing for the 90% certainty value of the uncertainty margin we have taken a conservative approach
  - By definition, nine out of ten Monte Carlo simulations actually resulted in a smaller uncertainty margin
  - Using this approach we are likely to carry more uncertainty margin than will ultimately be needed
  - Any margin weight remaining after the production lander has been built can be converted at that point to useful payload

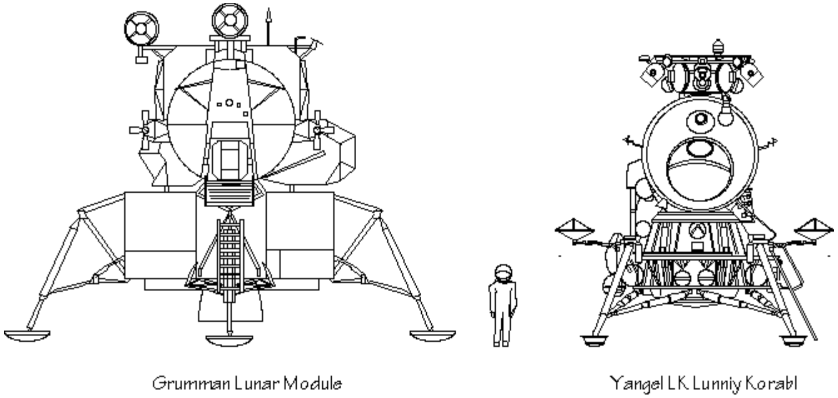
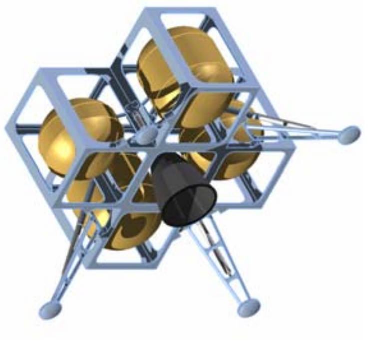


Image Credit: Mark Wade, Encyclopedia Astronautica



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Conclusions

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- Ignoring the potential impact of modeling uncertainty could jeopardize the future fulfillment of mission requirements
- Given that the lander is often one of the biggest drivers in the design of a complete lunar exploration architecture, the effects of an unaccounted for growth on this particular stage may cascade back through the sizing of several other in-space or Earth-to-orbit (ETO) stages
  - Alternatively, designers may be forced to offset the weight growth on the lander by reducing its capabilities
- Quantifying and addressing the uncertainty in modeling the performance of a future lunar lander system is especially important

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