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Probabilistic Examination of Lunar Landers

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SpaceWorks Engineering, Inc. (SEI) has developed a new analysis model specifically tailored to the conceptual level design and evaluation of lunar ascent and descent systems. Entitled Moonraker, the model includes over two hundred input variables that can be used to describe the entire system configuration, from subsystem components to high level mission assumptions. The weight estimation and sizing process is based on physical equations and a set of historical mass estimating relationships developed through extensive research. Moonraker's output consists of a three-level weight breakdown structure (WBS) for each vehicle stage that has been analyzed, as well as geometry information (surface area, volume). The result of a verification exercise of the Moonraker model against an Apollo Lunar Excursion Module (LEM) is addressed. Later, an examination of an all-new lunar lander design created in Moonraker and based on a relevant mission scenario is discussed. The design process outlined for this all-new concept acknowledges uncertainty in the performance modeling of future technologies, and seeks to effectively deal with this uncertainty through probabilistic methods.

Nomenclature

ETO = Earth-to-orbit
ft = foot
hr = hour
Isp = specific impulse
kW = kilowatt
lbs = pounds
LEM = Lunar Excursion Module
LK = Lunar Craft (translation from Russian)
LOI = lunar orbit insertion
MER = mass estimating relationship
N_2O_4 = nitrogen tetroxide
psia = pounds per square inch, absolute
s = second
SEI = SpaceWorks Engineering, Inc. (SEI)
TEI = trans-Earth injection
T/W = thrust-to-weight ratio
UDMH = unsymmetrical dimethylhydrazine
W = Watt
WBS = weight breakdown structure

I. Introduction

At the current stage of exploration system development, numerous architecture studies have either been conducted or are currently underway, each with the purpose of examining available design options and determining those that can provide maximum benefit to the program. SpaceWorks Engineering, Inc. (SEI) possesses recognized expertise in the creation and use of specialized conceptual level tools and processes suited to this type of assessment. In this paper, a means of modeling lunar lander concepts is discussed. The approach acknowledges

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uncertainty in the performance modeling of future technologies, and seeks to effectively deal with this uncertainty through probabilistic methods.

Historically, the lunar lander design space has included concepts with a wide variety of configurations. At a high level, a lander can be described by the number and function of its stages. For instance, the Apollo Lunar Excursion Module (LEM) is an example of a two stage system consisting of a descent stage and an ascent stage which also served as a surface habitat. Other proposed configurations have ranged from single stage systems in which one element performs descent, ascent, and habitation functions, to modular designs incorporating separate descent, ascent, crew transfer cabin, and crew surface habitat components. Still other designs may call for stages that possess expanded functionality including lunar orbit insertion (LOI) or trans-Earth injection (TEI) propulsive maneuvers.

In order to perform conceptual design studies for a system that is characterized by such variability, the modeling approach must emphasize flexibility. It is with this perspective that SEI introduces a newly developed lunar lander system sizing tool entitled Moonraker. This model was designed for adaptability not only to a variety of stage configurations, but also to a range of main propellant combinations, crew sizes, delta velocities (Delta-Vs), and other design variables.

The development of Moonraker coincided with several lunar architecture design studies at SEI which revealed the need for a flexible, rapidly executable conceptual lunar lander design tool. These characteristics become especially important when conducting a large number of trade studies or sensitivity analyses, or when carrying out a probabilistic design process involving thousands of executions.

The Moonraker model is described in greater detail in this paper, and the outcome of a verification exercise of the Moonraker model with an Apollo Lunar Excursion Module (LEM) is discussed. Finally, the capabilities of the model are demonstrated in the context of a probabilistic design study for a future crewed human lunar lander.

II. Moonraker Functionality

Moonraker is a weights and sizing tool implemented in Microsoft Excel© specifically for use in the conceptual design of lunar ascent and descent systems. Over two hundred input variables can be used to describe a system configuration, although a particular design may require only a subset of these. The weight estimation and sizing process is based on physical equations and a set of historical mass estimating relationships developed through extensive research.[1,2,3,4,5] The output of Moonraker consists of a three level weight breakdown structure (WBS) for each vehicle stage that has been analyzed.

The wide range of input variables in the model has been divided into Primary Inputs and Reference Sizing Inputs. Primary Inputs are those that relate directly to top level mission requirements, while Reference Sizing Inputs are typically subsystem sizing parameters. Table 1 below lists the Primary Input variables along with a description of each. Table 2 outlines the categories into which the Reference Sizing Inputs have been organized. Three screenshots of the Moonraker model are provided in Figure 1. From left to right they are: the inputs worksheet, the output WBS, and the probabilistic interface worksheet.

Table 1. Moonraker Primary Input Variables

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

Table 2. Moonraker 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 enables analysis of certain interactions between the crew and subsystems. For example, selecting fuel cells using hydrogen and oxygen reactants gives the user the option of allowing some or all of the water produced from this device to augment the crew water supply. These capabilities, along with the inclusion of numerous input parameters enable this new model to capture a wide range of design variations while providing the user with rapid conceptual level results.

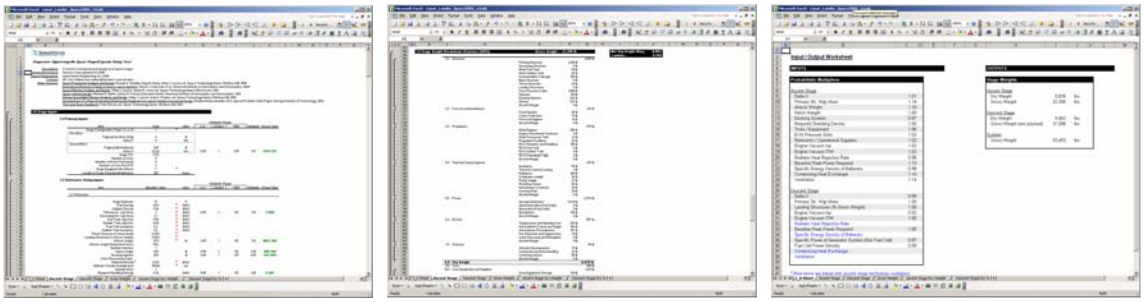

Figure 1. Screenshots of Moonraker Implementation in Microsoft Excel©

III. Moonraker Verification by Historical Comparison

It is essential to verify a computational model against an established data point before using it to design future systems. In the case of the Moonraker model, options for selecting a historical point of comparison are limited.

The Lunar Excursion Module (LEM) was designed and built by the Grumman Aircraft Corporation in the late 1960's and to this day remains the only vehicle to successfully transport humans to and from the surface of another extraterrestrial body. The LEM underwent various modifications over the course of seven attempted lunar landing missions flown during the Apollo program, but in large part the LEM used on Apollo 17 was the same as the LEM on Apollo 11.

The Soviet Union's lunar craft (LK) is the only example other than the Apollo LEM of a lunar lander that was designed, built, and actually flown in space.[6] However, in terms of selecting a verification case for SEI's Moonraker model it proved too difficult to acquire a reliable breakdown of subsystem weights for the LK. Weight and performance data for the LEM, on the other hand, is comparatively easy to come by and therefore it was deemed the most appropriate verification case. In particular, it was decided to compare Moonraker's output for an Apollo-like lander to actual data from the Apollo 12 LEM.

The data in Table 3 was collected for the purpose of performing a verification of the Moonraker tool in the context of the Apollo 12 LEM. Selected variables from the Reference Sizing Inputs section are shown in Table 4.

Table 3. Apollo 12 Primary Inputs for Moonraker Verification[7,8,9]

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

Table 4. Selected Apollo 12 Reference Sizing Inputs for Moonraker Verification[7,8,9,10]

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

Given the above input variables, Moonraker was able to estimate the weight breakdown of the Apollo 12 LEM quite closely. Table 5 shows the item by item comparison of the model results versus the historical values. Matching historical values from a mission conducted over 30 years ago presented some challenges. Certain technologies have advanced dramatically since Apollo, especially in the area of computing. Input variables for sizing avionics and communications equipment had to be adjusted to degress recent technology improvements.

Table 5. Comparison of Apollo 12 Historical Data with Moonraker Model Estimates[7,8,9]

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%

IV. Probabilistic Design Process

A renewed focus has been placed on manned exploration beyond low Earth orbit, and with it has emerged a set of challenges for the aerospace community. We have been asked to achieve an affordable and sustainable exploration program while still utilizing advanced technologies and systems. The ultimate success of The Vision for Space Exploration depends in part on our ability to identify and manage uncertainty.

Before proceeding with a description of the lander sizing analysis, it is reasonable to take a look at what is meant by the term uncertainty. While the word may take on various definitions depending on the context in which it's used, for the purposes of this paper uncertainty is taken to mean modeling uncertainty. In particular, we refer to the inability of computational models to fully capture and predict the physical performance of a real world device or system.

Recognizing that models may overpredict or underpredict system performance, it is prudent to employ measures during the early phases of design that tend to mitigate future impacts of this uncertainty on system performance. The approach recommended here is to establish an uncertainty margin that can absorb potential weight growth due to modeling uncertainty in much the same way as the traditional manager's reserve margin addresses growth due to programmatic changes. It is generally accepted in the aerospace industry to establish a manager's reserve amount based on prior relevant program experience. In this paper we propose a stochastic approach to developing an appropriate uncertainty margin.

The first step in this probabilistic sizing process was to 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. Probability distributions can be expressed in a number of ways, however for the analysis discussed in this paper we will focus on the triangular input distribution. A triangular distribution is defined by a low value, a high value, and a likeliest value as illustrated in Figure 2. The low, high, and likeliest values may be established by engineering analysis, expert opinion, or by referring to historical trends.

Once the desired input distributions were established, a Monte Carlo simulation was used to sample from the input distributions and produce output distributions. Specifically, for each trial of the Monte Carlo a random value was sampled from each of the triangular input distributions, the Moonraker model was executed with these uncertainty multipliers applied to their respective weight components, and the magnitude of the weight growth due to uncertainty was recorded for each stage. The aggregate of these dry weight growth magnitudes was used to produce the desired output distributions. 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. Figure 3 is a diagram of this process.

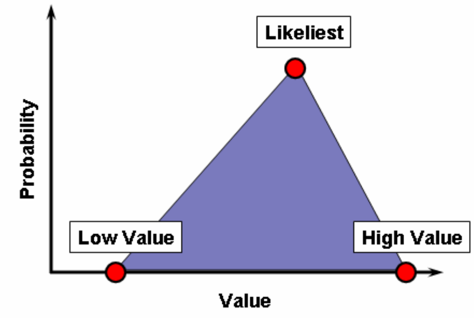

Figure 2. Triangular Probability Distribution

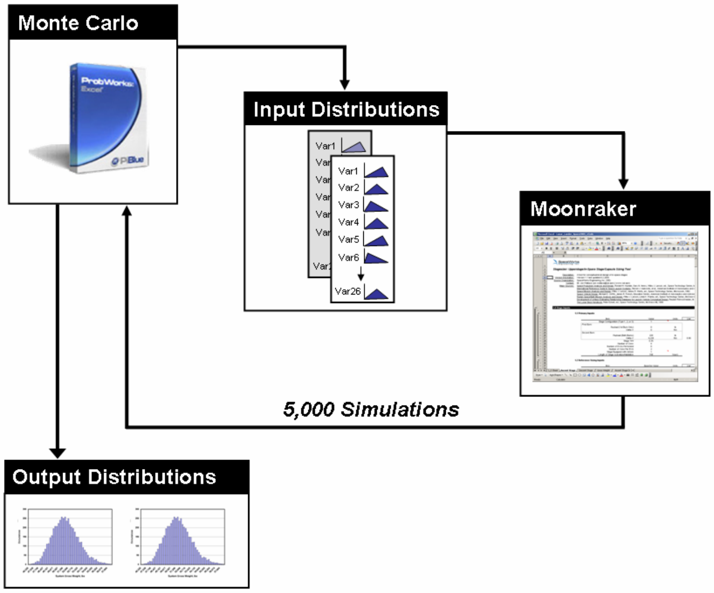

Figure 3. Probabilistic Design Process Diagram

V. Probabilistic Design of a Crewed Lunar Lander

The Moonraker tool and the probabilistic design process described above were used to design a future lander system capable of carrying humans to and from the lunar surface. A set of mission requirements relevant to current industry and government studies was established to begin the design process. In particular, the mission calls for four crew members to spend six days on the lunar surface at a landing site near the equator. The lander itself is a two stage system with both stages utilizing a liquid oxygen and liquid methane propellant combination. The crew will live and work in a pressurized cabin that is part of the ascent stage, and a lightweight inflatable airlock will be used for EVA egress and ingress.

In order to conduct the probabilistic sizing process, it was first necessary to define input distributions for the system dry weight line items. A rigorous approach to this process would require building input distributions up from the component level. However, the example procedure described in this paper was simplified by defining input distributions for 14 level-1 weight items in Moonraker rather than the complete set of over 200 design variables. A summary of these weight items and associated input distributions for the future lunar lander is provided in Table 6.

Table 6. Input Distributions for Modeling Uncertainty in System Dry Weight Line Items

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%

Once the set of input distributions was completed, the Moonraker model was executed automatically using a Monte Carlo simulator in Microsoft Excel. The ProbWorks Monte Carlo add-in, available from Pi Blue Software, Inc., was used to produce three output distributions based on 5,000 simulations in the Moonraker model. These output distributions included dry weight growth magnitude for both the ascent and descent stages. The runtime for 5,000 simulations on a 3.6GHz PC running Windows XP was approximately 20 minutes.

In order to interpret the output distribution results, it is useful to calculate several parameters that describe the distribution. Here we have chosen to report the mean value, the standard deviation, and a certainty value for each output distribution. In the context of this design process, the mean value represents the average weight growth magnitude that occurred over the course of 5,000 simulations. Standard deviation is a familiar statistical parameter that describes the relative tightness or spread of a distribution. Approximately 68% of the data points in a distribution lie within one standard deviation of the mean value. The certainty value is a way of describing a point on the output distribution from which a certain percentage of the total points lie either above or below. In this analysis, the 90% certainty value is defined as the dry weight growth magnitude that 90% of the total results fall below.

Figure 4 presents the output distribution of dry weight growth magnitude as a percentage of the stage dry weight for the ascent stage of the lander. Table 7 lists the corresponding mean, standard deviation, and 90% certainty value. Figure 5 and Table 8 show similar results for the distribution of weight growth margin on the descent stage.

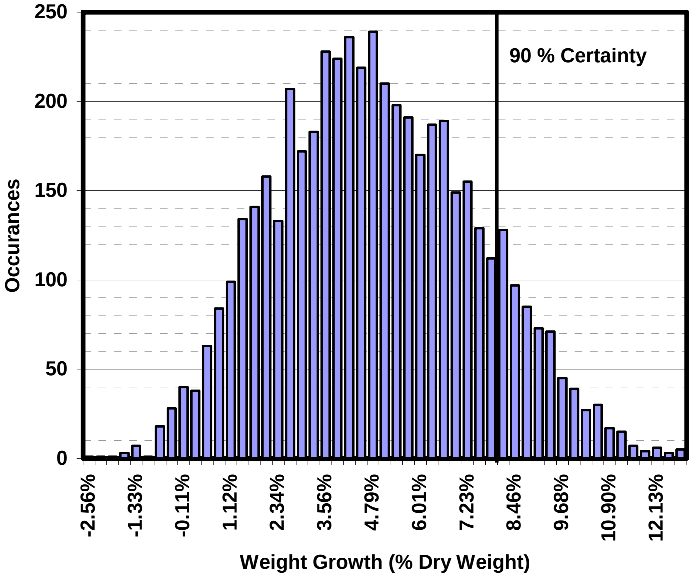

Figure 4. Ascent Stage Dry Weight Growth Due to Uncertainty as a Percentage of the Stage Dry Weight

Table 7. Ascent Stage Dry Weight Growth Output Distribution Parameters

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

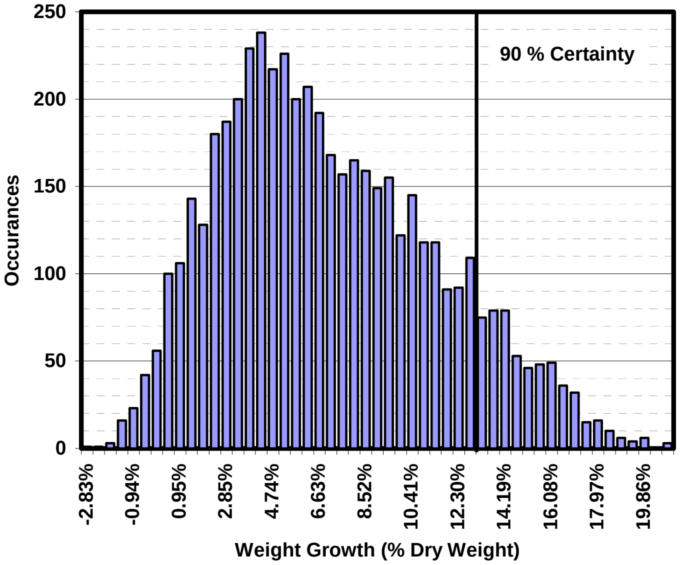

Figure 5. Descent Stage Dry Weight Growth Due to Uncertainty as a Percentage of the Stage Dry Weight

Table 8. Descent Stage Dry Weight Growth Output Distribution Parameters

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

After the output distributions had been obtained the next step was to select an appropriate level of stage dry weight growth potential to be used in the design of both the ascent and descent stages. Here we chose the 90% certainty values from the ascent and descent stage output distributions in the interest of maintaining a conservative approach. Referring to Tables 7 and 8 we have a 90% certainty value of 8.22% for the ascent stage and a value of 13.15% for the descent stage. The means of incorporating dry weight growth due to uncertainty in the lander design was to establish an uncertainty margin line item in the weight statement for both vehicle stages.

The uncertainty margin appears in the weight statement alongside the traditional manager's reserve margin. To obtain the weight to be used as uncertainty margin, the sum of the preceding dry weight line items was multiplied by the 90% certainty dry weight growth value discussed in the previous paragraph. It was decided for this analysis that the traditional manager's reserve would be set at a fixed value of 15% of the stage dry weight for both the ascent and descent stages, and that the manager's reserve would be applied to all dry weight items inclusive of the uncertainty margin.

In summary, we have described an approach to quantifying the potential dry weight growth in a lunar lander due to modeling uncertainty, and also outlined a means of integrating an uncertainty margin into the design process. At this point we are ready to present the results of a lunar lander sizing exercise using the probabilistically derived uncertainty margin. Table 9 below contains the level-1 weight breakdown structure (WBS) for the ascent stage of our example lunar lander system. Probabilistic results are presented side-by-side with deterministic results obtained by setting the uncertainty margin to 0%. Similar results for the descent stage are listed in Table 10. Note that in Table 10, the weight of the ascent stage is considered to be the payload of the descent stage.

Table 9. Comparison of Deterministic and Probabilistic Ascent Stage Weight Breakdown Structures (WBS) For Example Lunar Lander Design.

	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

Table 10. Comparison of Deterministic and Probabilistic Descent Stage Weight Breakdown Structures (WBS) For Example Lunar Lander Design.

	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

VI. Discussion of Probabilistic Design Results

The results of this design exercise suggest that, given the uncertainty in system performance modeling is similar to that described by the input distributions in Table 6, ignoring the potential impact of this uncertainty could jeopardize the fulfillment of mission requirements. In other words, as Table 10 shows, there is a difference of more than 5,000 lbs between the gross mass of the probabilistic and deterministic lander systems. 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 of over two and a half tons on the lander 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. Neither of these scenarios is likely to benefit the schedule, cost, or effectiveness of the architecture.

Of course, by designing for the 90% certainty value of the uncertainty margin we have taken a conservative approach. Nine out of ten Monte Carlo simulations actually resulted in a smaller uncertainty margin. Therefore, if this conceptual lander design were to progress through detailed design an on to production, it is likely that the actual sum of weight increases attributable to modeling uncertainty would be less than the uncertainty margin weight carried throughout the design. Any margin weight remaining after the production lander has been built can be converted at that point to useful payload. Perhaps the crew will be able to bring additional equipment to the surface or deploy a broader array of scientific equipment.

VII. Conclusions

SpaceWorks Engineering, Inc. (SEI) has developed a new conceptual level lunar lander weights and sizing model. Entitled Moonraker, this tool is capable of modeling a wide variety of lander configurations, technology assumptions, and mission scenarios. The usefulness of the model is enhanced by its rapid execution time and ease with which it can be incorporated into a probabilistic design process.

A verification of Moonraker results based on the Apollo 12 LEM was discussed. The purpose of the verification case was to establish confidence in the model’s conceptual level predictions. Given mission and technology assumptions appropriate for the historical vehicle, Moonraker was able to match actual system and subsystem weights to a reasonable degree of accuracy.

Finally, a design exercise was conducted using Moonraker to model a future crewed lunar lander. The mission for the two stage, methane fueled lander was similar to current studies by industry and government organizations.

The design exercise was conducted probabilistically, including placing uncertainty distributions on each dry weight line item and performing 5,000 simulations using a Monte Carlo method. The outcome of the Monte Carlo simulations was an increased understanding of the impact of modeling uncertainty on the weight of a lunar lander system. This knowledge was applied to the design process through the implementation of an uncertainty margin intended to mitigate the risk associated with potential future weight growth.

The lander system can be one of the biggest drivers when sizing a lunar architecture because its mass is typically pushed through most of the mission's propulsive maneuvers. For this reason, quantifying and addressing the uncertainty in the design of the lander system is especially important.

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