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System Robustness Comparison of Advanced Space Launch Concepts

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ABSTRACT

This research proposes two methods to investigate the robustness differences between competing types of advanced space launch systems. These methods encompass two different phases of the advanced design process and are used to compare the relative advantages of two concepts in these phases.

The first is a Monte Carlo simulation during the conceptual phase of design, where mold lines can be changed to account for uncertainty in weight assumptions. This tests the vehicle weight growth for a fixed mission. Here, the all-rocket single stage to orbit (SSTO) shows a more narrow distribution of dry weight, suggesting higher concept robustness. A study of vehicle mass ratio and mixture ratio combinations for both vehicles show the relative location of the results.

The second phase represents the transition to detailed design. An optimization based on length determines the appropriate size for detailed design. This optimization takes into account uncertainties placed on both weight relationships and performance requirements.

Both of these analyses utilize Crystal Ball Pro® in conjunction with Microsoft Excel®. This gives the technique compatibility with commonly used computer platforms.

While the all-rocket SSTO does show an advantage in the area of system weight growth, several other factors are important in determining the viability of a reusable launch system, not the least of which is mission flexibility. Here the runway-operated RBCC SSTO has a distinct advantage.

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NOMENCLATURE

ACC	advanced carbon-carbon
c.g.	center of gravity
ESJ	ejector scramjet
LEO	low-earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MSE	mean square error
Mtr	transition Mach number
RBCC	rocket-based combined cycle
SSTO	single stage to orbit
T/W	thrust to weight ratio
TPS	thermal protection system
UHTC	ultra high temperature ceramic
VTO	vertical takeoff
WER	weight estimating relationship

INTRODUCTION

Background and Motivation

Stochastic design simulations give an entirely new aspect to conceptual design. By introducing uncertainty into the design process early in the design process, informed decisions can be made without requiring more accuracy than is possible from the conceptual designer.

This also brings the concept of quantifiable risk into the engineering arena in its earliest stages. Ideas that may seem appealing in a deterministic, point design environment might lose their luster when their sensitivity to assumptions is revealed. Alternatively, a concept decision that might seem less favorable might gain favor when it is found to have a low mission risk. By giving this new kind of information to the decision-maker, robustness simulations can improve the quality of decision making.

This technique is also valuable to potential investors or government backers of a space launch venture. Improving the information available to potential investors or government backers can not only help identify low-risk investments, but also weed out any seemingly benign concepts that have a propensity for weight growth. This helps the industry by limiting money spent on a project with little chance for success, and reduces the chance for public, and more importantly investor, disappointment.

The two concepts used in this study to test the techniques presented are a representative rocket powered Single Stage to Orbit vehicle (SSTO) (figure 1) and a representative rocket-based combined cycle (RBCC) powered SSTO vehicle (figure 2).

The first concept is a simple wing-body cylindrical propellant tank, oxidizer-aft SSTO vehicle. It features five high thrust-to-weight ratio liquid oxygen/ liquid hydrogen (LOX/LH2) rocket engines mounted in a cluster at the rear of the craft. The payload is carried centrally, near the vehicle center, giving it a small center of gravity (c.g.) travel between payload-in and payload-out conditions. Other design features include wingtip mounted fins for lower induced drag and greater control authority, cylindrical tanks with elliptical domes for low structural weight and a set of hydrogen powered turbofan landing engines for landing abort capability.

The second concept is an ejector scramjet (ESJ) concept from the Space Systems Design Laboratory at Georgia Tech called Hyperion. The ESJ RBCC engine has four operating cycles corresponding to different parts of its flight regime. The first mode is ejector. Here a rocket cluster inside the engine duct fires, having its thrust augmented by the entrainment of ambient air through the inlet and duct. From about Mach 2 to Mach 3, the vehicle gradually powers down its rocket engine and ramps up its ramjet fuel injectors. From Mach 3 to 6, the engine acts as a ramjet and here sees its highest efficiency. After Mach 6, the engine operates in scramjet mode until Mach 10, the transition Mach number (Mtr) for this particular concept. Past this Mach number, the front ducts close off and the ducted rockets fires to carry the craft the remainder of the way to orbit.

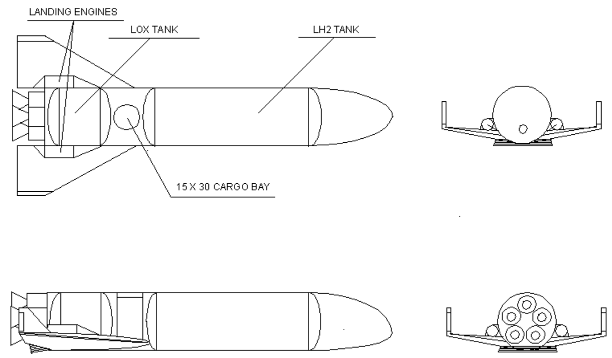

Figure 1 - All Rocket SSTO Concept

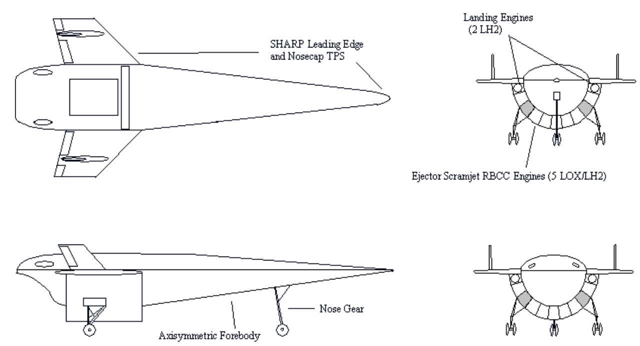

Figure 2 - RBCC SSTO Concept

Neither of these concepts employ launch assist and both land on a runway. However, due to the lower gross weight of the RBCC engine concept and larger wings required for its more flattened trajectory, the representative RBCC vehicle is able to launch horizontally from a runway where the all-rocket SSTO requires a prepared pad and vertical launch. Other than these differences, both vehicles perform the same mission, 20 klbs. to low-earth orbit (LEO), then a powered landing.

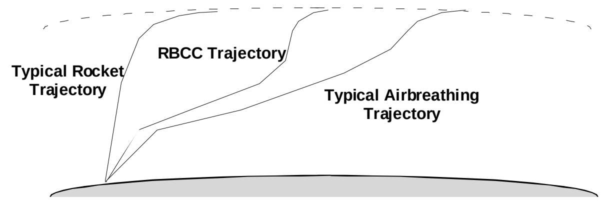

Figure 3 - Comparison of Trajectories

Recently, RBCC space launch vehicles have been touted as promising higher system robustness due to their lower fuel mass fractions.

Alternatively, the all-rocket SSTO has a higher thrust-to-weight (T/W) engine than the RBCC SSTO (reference 7). This means that dry weight gains realized by the RBCC's higher efficiency engine could be offset by its engine weight. In addition to this, rocket concepts typically have a higher propellant bulk density and simpler shape, meaning higher volumetric efficiency. All of these advantages have the potential to translate into enhanced system robustness.

Since both of these are valid arguments for either RBCC or all-rocket SSTO's, debate should benefit from a quantitative analysis of system robustness for these representative vehicles.

Simulation Method

Monte Carlo simulation is an accurate, if not computationally efficient, way to include uncertainty in the design process. It involves randomly choosing values for variables designated as uncertain then performing a function evaluation several thousand times with the random factors until an acceptable distribution is generated.

Once this distribution is obtained, it can be used in any number of ways. It becomes an output like any other result of an objective function call and can be manipulated through chosen design variables using any one of many optimization techniques and multiple simulations.

When combined with optimization techniques, this method can modify systems so that they are insensitive to the effects of uncertainties. In the first phase of the study, it is used for a fixed set of design variables to determine the variance of the response. The second uses a design variable, vehicle length, to minimize the effect of uncertainties on dry weight margin. This is an excellent example of bringing optimization into the uncertain design process.

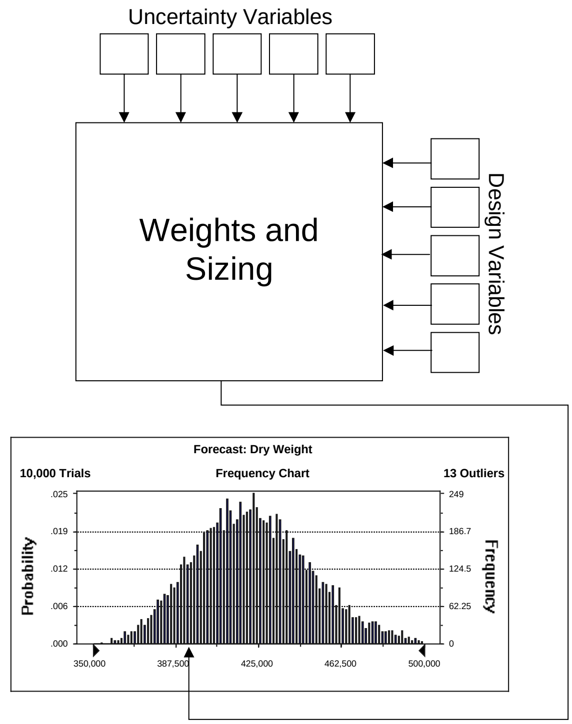

Figure 4 – Illustration of Monte Carlo Method

CONCEPTUAL DESIGN SIMULATION

Methodology

The goal of this phase of the study is to determine if there is any inherent robustness advantages to either all-rocket or RBCC SSTO vehicles during conceptual design and to validate the resizing Monte Carlo algorithm. To do this, trajectory information for a single-valued baseline is inserted into a weights and sizing module that has several weight estimating relationships (WER's) that determine the size and weight of various subsystems. This model combines them to determine the dimensions of a vehicle to perform the mission required by the trajectory data.

The sizing module for both cases is a photographically scaling set of WER's that alter the length of the vehicle to match a required mass ratio. With increasing length, in most size ranges, the available ratio of fuel mass to vehicle mass will increase (figure 5). The model utilizes this effect by increasing or decreasing the modeled length of the vehicle until the mass ratio of the scaled vehicle equals the required mass ratio determined by the trajectory analysis.

To study the effect of uncertainty on the dry weight distribution, uncertainty distributions are applied to the WER's and a Monte Carlo simulation is run for a constant mass ratio and mixture ratio. The outputs of the analysis (dry weight) are therefore available in probability distribution form for analysis.

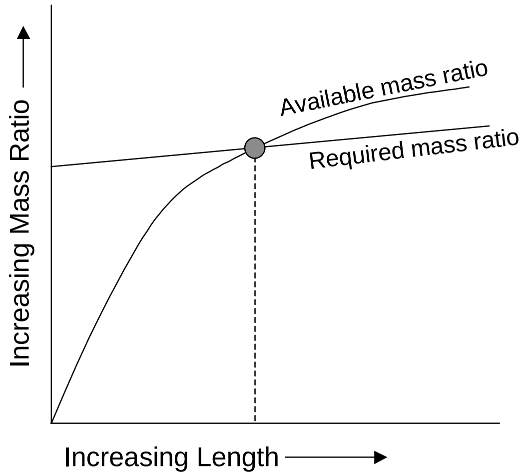

Figure 5 – Photographic Scaling for Weights and Sizing

The two comparison concepts are identical in weight uncertainty assumptions where appropriate. Some areas where assumptions differ are in the main engine, body flap (Hyperion has no body flap), landing/takeoff gear and nosecone/wing leading edge thermal protection system (TPS). In this area, Hyperion uses ultra high temperature ceramic (UHTC, reference 6) due to the sharper edges on the fuselage and wing. These edges enable Hyperion to have a high dynamic pressure trajectory without excessive drag losses. The all-rocket SSTO vehicle uses advanced carbon-carbon composite (ACC). This is more useful in blunt body applications. There are other differences that are important but are not uncertainty assumptions.

The first of these is the airframe shape. Hyperion is a semi-conical lifting body with a high fineness ratio and a long slender cone in the forward section of the vehicle (figure 2). The all-rocket SSTO vehicle considered has a mostly cylindrical shape, with a drooped nose at the front for hypersonic stability. These divergent shapes necessitate different structural concepts for the two vehicles. Hyperion, to better fit into its lifting body shape, has non-integral propellant tanks. In addition to this, the forward main hydrogen tank is built with 'double-bubble' construction technique. This robs Hyperion of some packaging efficiency, but it hopefully will give the tank a similar unit weight to the mostly cylindrical tank of the all-rocket SSTO vehicle.

The all-rocket SSTO vehicle (figure 1) has an integral tank structure. This eliminates the need for an aeroshell, providing great weight savings. It also provides high packaging efficiency. Both of these factors help minimize the effects of weight growth, a paramount issue in SSTO concepts. They do not, however, directly relate to the assumptions for the Monte Carlo simulation, yet they do affect the response of the model to uncertainty.

<u>Results</u>

Tables 1 and 2 show results of the simulation described above for the all-rocket and RBCC SSTO vehicles. The distributions for dry and gross weight show a clear robustness advantage for the all-rocket SSTO.

Table 1 – Hyperion Uncertainty Results

	Mean	**Standard Dev.**
Dry Weight	218,700 lbs.	11,650 lbs.
Gross Weight	1,278,100 lbs.	62,600 lbs.
Land./TO Gear	37,385 lbs.	1,830 lbs.

Table 2 – All-Rocket SSTO Uncertainty Results

	Mean	**Standard Dev.**
Dry Weight	126,200 lbs.	8,075 lbs.
Gross Weight	1,251,350 lbs.	69,350 lbs.
Land./TO Gear	4,350 lbs.	240 lbs.

While the lower mass ratio does appear to reduce the variance of the response in this test, there are many other factors to consider. Bulk density, here evidenced in terms of mixture ratio, also plays a large role. The higher density of the all-rocket system certainly lowers the dry weight standard deviation. It should be noted that Hyperion suffers not only from a higher bulk density, but a packaging concept that is very sensitive to weight growth. The last lines of both tables 1 and 2 show the largest difference between the two vehicles in their weight breakdowns. Because Hyperion takes its own gear with it on liftoff, this gear must support the weight of the fully loaded vehicle. The all-rocket SSTO vehicle gear must only support the weight of the empty vehicle on landing. This is a major area for weight growth in Hyperion and is at the same time its greatest operational advantage.

The confidence percentiles for both vehicles in dry weight can be seen in figures 6 and 7 below. Since this is a "lower is better" situation, the probabilities of the plots below increase from left to right with increasing confidence in their answers.

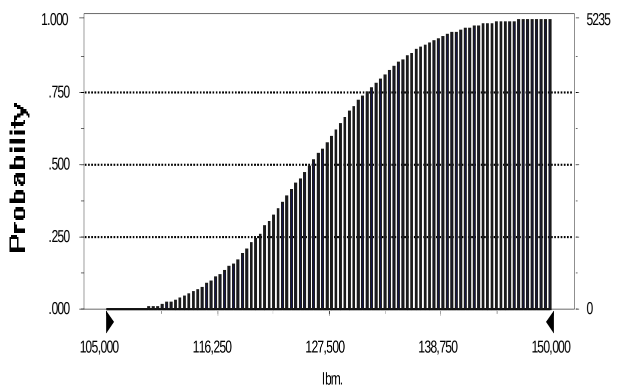

Figure 6 – All Rocket SSTO Dry Weight Cumulative

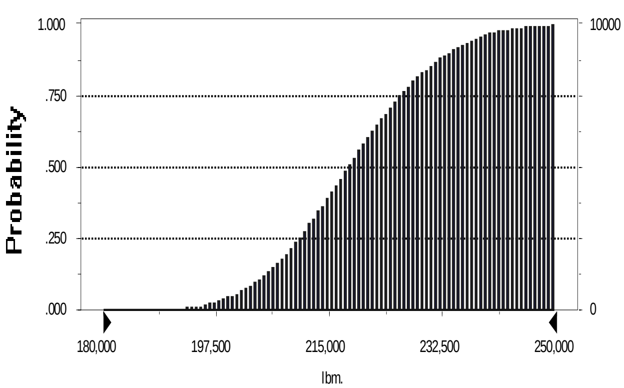

Figure 7 – Hyperion Dry Weight Cumulative

The final explanation of these results is that the RBCC SSTO vehicle is an inherently more versatile machine. The fact that it can take off and land on a runway means that any airport with a hydrogen and oxygen supply could support the space launch of such a vehicle. This statement restricts the size of the craft to that of a large subsonic transport, such as a Boeing 747-400 (231 ft. in length, reference 13). While this may not improve its commercial satellite profitability, its military and emergency deployment capability exceeds that of an all-rocket SSTO.

To better demonstrate the relative differences in standard deviation of the two concepts, the sensitivity in figure 8 shows the mass ratio and mixture ratio combination required to give Hyperion the same dry weight standard deviation as the all-rocket SSTO vehicle. Any combination along the frontier shown will have the same standard deviation and any values below will have less standard deviation.

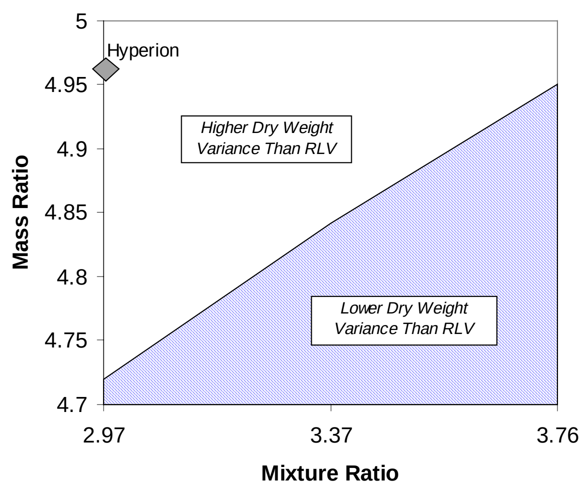

Figure 8 – Hyperion Variance Comparison

Conversely, the mixture and mass ratio combinations required to give the all-rocket SSTO vehicle the same standard deviation as Hyperion are shown in figure 9. Just like the previous figure, anything above the line has a higher dry weight standard deviation than Hyperion, anything below the frontier is lower.

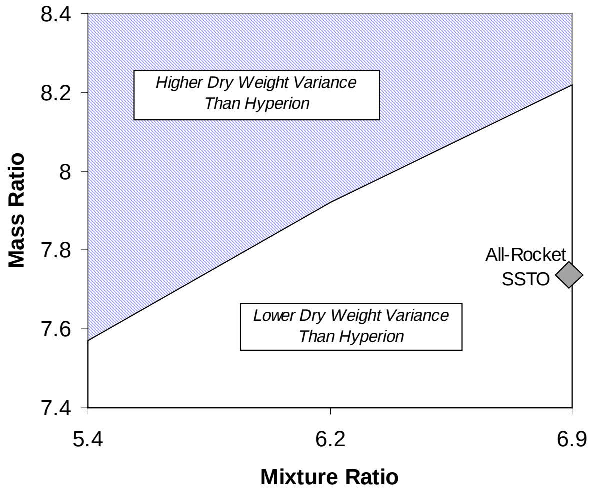

Figure 9 – All Rocket SSTO Variance Comparison

Here you can see that the differences in robustness are not insurmountable for either concept, and several realistic trajectory combinations could shift the relative advantages of either. These figures give a good idea of the multidimensional aspect of the problem. In this case, a great many factors were found to be of importance to the final response, not just engine performance. This indicates a need for this type of simultaneous modeling of factors.

The other goal in this phase was to determine the feasibility of this method in a true conceptual launch vehicle application. Here, the method seems quite useful, even if used in a multidisciplinary environment. A single execution took approximately ten minutes on a Pentium II 333Mhz equipped personal computer. The analysis is quick enough that it could be used in conjunction with other stochastic analyses in an overall design framework that includes uncertainty.

PRELIMINARY DESIGN SIMULATION

Methodology

This technique would more accurately be described as pre-preliminary design. In it, criteria placed on the output distributions of multiple Monte Carlo simulations determines the fixed length through optimization. This is the point from which preliminary and detailed design should commence.

To accomplish this, a different sizing technique from the one described in the previous section is employed. In this case, the effect of lowering available mass ratio by decreasing the dry weight margin is used (figure 10). Again, available and required mass ratios are matched keeping the same vehicle length but changing the dry weight margin to compensate for unexpected weight growth.

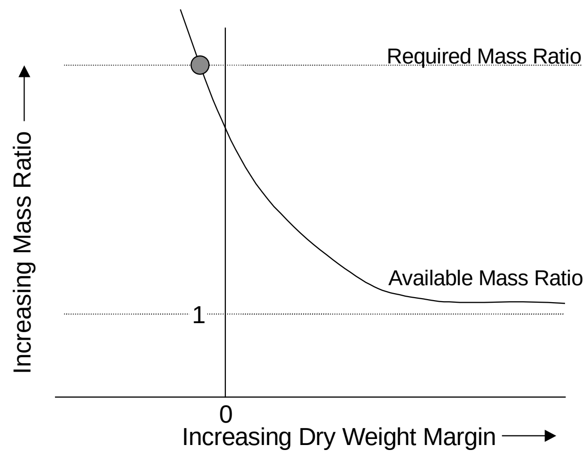

Figure 10 – Dry Weight Margin Sizing Method

For each set of randomly selected WER's and trajectory data, the model finds the dry weight margin that satisfies the random trajectory parameters. This process is then repeated several thousand times in Monte Carlo simulations. The distribution of dry weight margin that results can be shifted using the vehicle length as a design variable and then repeating the Monte Carlo process. In this case, the distribution is shifted until only one percent of the results are below a fifteen percent dry weight margin. Using this as a constraint, the optimizer minimizes the objective function that is the size of the vehicle. See figure 11.

This process gives an idea of the weight growth that will take place during preliminary and detailed design while preserving the fifteen percent weight growth margin for construction related weight growth. Of course, the technique is flexible so that any desired outcome of weight margin could be used. This use of WER uncertainty differs from a simple dry weight margin in that it takes into account the weight growth characteristics of the vehicle to determine the appropriate length of the final product. This flexibility means that a project can be engineered to have a specific and acceptable failure rate. Overall this method should enhance the robustness of the project to unexpected weight growth without over-compensating and hurting economic and performance projections.

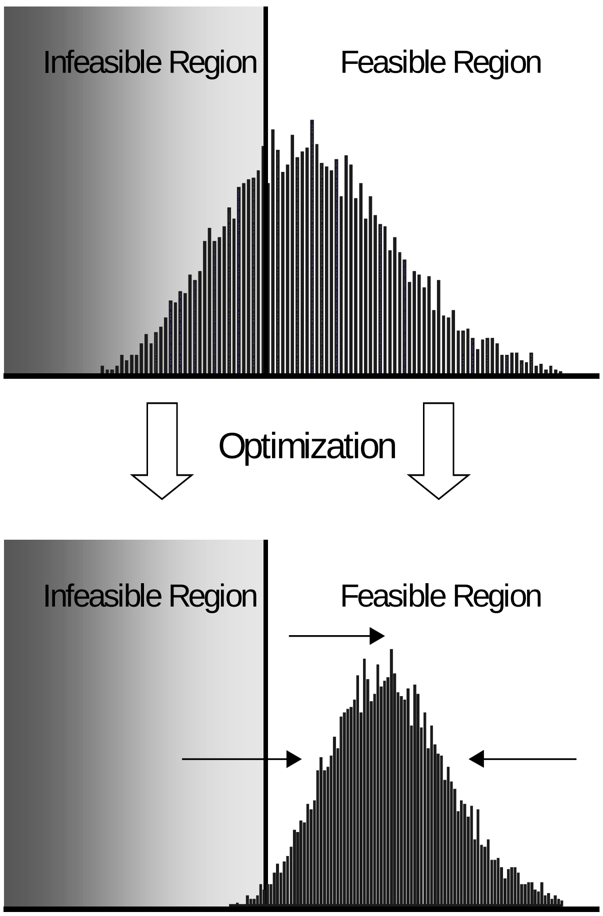

Figure 11 – Optimization with Uncertainty

Results

Table 3 below shows the length results for both concepts in this test. These again show and advantage to the all-rocket SSTO in the "safe size" required for the vehicle designs to have a good chance of meeting their mission requirements.

Table 3 – Optimization Results for Preliminary Design

	All-rocket SSTO	Hyperion
Length	148 ft.	255 ft.
Margin Average	26%	28%
Margin Std. Dev.	4.5%	6.1%

Again, the simulation shows that this particular all-rocket SSTO is a safer proposition than Hyperion from the perspective of weight growth. Figure 12 below shows the disadvantage of high variance in this particular decision making process. The dry weight margin distribution of Hyperion indicates that it requires a higher average margin in order to meet the statistical requirements of the test. In other words, to be sure that the vehicle will meet its mission requirements, a higher "overshoot" on average dry weight margin is required for Hyperion.

The results above clearly show how a propensity for weight growth can translate to program risk.

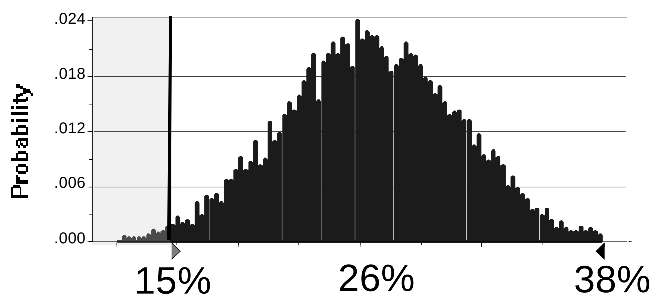

Figure 12 – All-Rocket SSTO Dry Margin Distribution

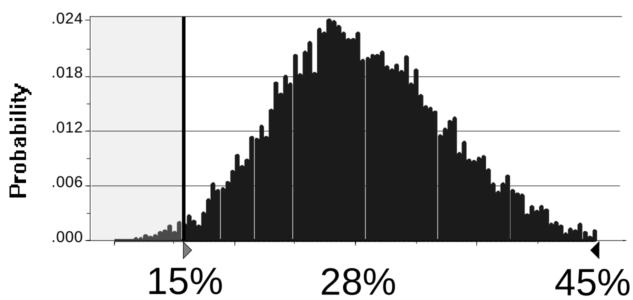

Figure 13 – Hyperion SSTO Dry Margin Distribution

From the perspective of verification of the technique, valuable information was also gathered. The typical time to optimize was approximately four hours again on a Pentium II 333Mhz equipped personal computer. Also, if there were not enough runs conducted in the Monte Carlo simulation the distributions sent to the optimizer was very noisy. This limited the ability of the process to find an optimum. Several test runs were conducted in this case to find the typical number of runs required (in this case 8000-9000) to obtain a mean square error (MSE) of the response that was of a lower order than the accuracy required for the optimum value. This is important, as if the number of executions in each Monte Carlo was too low, noise would cause the optimizer to wander indefinitely without getting close to the minimum or required values.

CONCLUSIONS

1. Two new methods for determining the uncertainty of space launch concepts were presented. Along with them, two examples were given for the use of these methods. Useful information about the robustness of the concepts was extracted and the methods were tested in practical application.

2. The burden of overly precise WER's was removed using these techniques, provided they can be interfaced with other stochastic methods. This lowers the chances of promising too much on a launch system project, enhancing the credibility of the conceptual design results.

3. During the verification of these techniques, the all-rocket SSTO vehicle was shown to have a clear advantage in not only the area of absolute dry weight, but also in variance. This holds true only for the payload range studied here (20 klbs.) and to this particular orbit (LEO). It is also not a statement about any single feature of either vehicle. There are many items on both vehicles aside from their engine differences that contributed to this result. Therefore, extrapolating these results to other vehicles with similar engine concepts but differing layouts and structural concepts would be unwarranted.

4. Another item that must be considered when comparing the two concepts shown here is the fact that the capabilities, and therefore the mission performed, are not exactly equal. The key difference is that the all-rocket SSTO lifts off vertically while the RBCC vehicle takes off horizontally from a runway. This gives Hyperion the ability to operate any place there is an adequate propellant supply, maintenance facility and runway. A vertical takeoff (VTO) rocket would require a specifically designed reinforced launch pad to handle the extreme environment created by the engines at takeoff. This runway capability of Hyperion adds flexibility lacking in the all-rocket SSTO that is of interest to a multitude of operators.

FUTURE WORK

Some future work to continue this research includes the following:

1. The investigators will attempt integration of this stochastic method for weights and sizing analysis with other conceptual launch vehicle analyses. Because many of the other analyses involved with conceptual launch vehicle design are more computationally intensive, this may require an approximate method such as response surface modeling or linearization of the response to directly calculate expected value and variance for an assumed normal distribution. This could very well resemble the techniques in reference 3.

2. Additional simulations will also be run on modified versions of Hyperion. Hyperion is currently being modified by the Space Systems Design Lab (SSDL) at the Georgia Institute of Technology to include improved packaging efficiency and integral forward and aft hydrogen tanks. This should address some of the weight growth evidenced in the current study by this RBCC concept.

3. Other areas of the design space for both concepts will be investigated. This should give a better idea

of the relative advantages of each concept, if they exist. It should also indicate whether any regions of the design space have a robustness advantage by the merits of payload or mission.

ACKNOWLEDGEMENTS

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Appendix A - Additional Tables

Table of launch vehicle parameters using standard 15% dry weight margin

	Hyperion	All-Rocket SSTO
Dry Weight	132,139 lbs.	109,175 lbs.
Gross Weight	828,675 lbs.	1,102,700 lbs.
Mass Ratio	5.025	7.552
Mixture Ratio	2.95	6.90
Length	181 ft.	124 ft.

Table of common uncertainty group assumptions

Category	High	Low
Fluid Contingencies	+10%	-10%
Tankage	+20%	-10%
Wing/Tails	+10%	-10%
Structure	+20%	-10%
Thermal Protection	+30%	-10%
Internal Systems	+10%	-10%
Auxiliary Propulsion Isp	+20%	-20%