Conceptual Design and Analysis of a Small and Low-cost Launch Vehicle

AE8900 MS Special Problems Report
Space Systems Design Lab (SSDL)
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

Author
Kohei Taya

Advisor
Dr. John R. Olds
Space Systems Design Lab (SSDL)

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Acronyms and Symbols

A_{exit}	Exit Area (of Engine Nozzle)
Alt	Altitude
APAS	Aerodynamic Preliminary Analysis System
CCD	Central Composite Design
C_D	Drag Coefficient
C_L	Lift Coefficient
dia	Diameter
DOE	Design of Experiments
DSM	Design Structure Matrix
i	Inclination
Isp	Specific Impulse
KSC	Kennedy Space Center
LEO	Low Earth Orbit
LOX	Liquid Oxygen
NASA	National Aeronautics and Space Administration
O/F	Oxidizer to Fuel weight ratio
POST	Program To Optimize Simulated Trajectories
REDTOP	Rocket Engine Design Tool for Optimal Performance
RSM	Response Surface Method
$S_{fairing}$	Fairing Surface Area
sl	Sea Level
SLV	Small Launch Vehicle
Sref	Reference Wing Area (= Maximum Cross Section Area in this paper)
T/W	Thrust to Weight ratio
UDP	Unified Distributed Panel
vac	Vacuum
VAFB	Vandenberg Air Force Base
Wallops	Virginia Spaceport Authority, Wallops Flight Facility
$W_{fairing}$	Fairing Weight
W&S	Weight and Sizing
□	Angle of Attack
□	Coefficients of Response Surface Equation
□	Expansion ratio

1.0 Introduction

Small, mini, and micro-satellite technologies are leading to many innovative space applications. A primary obstacle to successful operational transition of these systems is the lack of affordable small launch capability. In addition, the broader space launch market in general demands lower launch costs. One of solution is Microcosm's *Sprite* launch system. This vehicle is planned to meet the need for low-cost, small-payload capability while verifying the technology for larger vehicles with much lower cost per pound[1]. In this project, we treat *Sprite* launch vehicle as an example of small and low-cost launch vehicle. The goal of project is to analyze its design concept, confirm performance, and refine its design.

The project consists of two parts. The first part is confirming part (Part I). Using disciplinary analysis tools, the performance of *Sprite* vehicle is simulated. In this part, mainly two disciplinary analyses are used, such as aerodynamics and trajectory. Aerodynamics is simulated by APAS (Aerodynamic Preliminary Analysis System), and trajectory is simulated by POST (Program to Optimize Simulated Trajectories). In addition, propulsion analysis using REDTOP (Rocket Engine Design Tool for Optimal Performance) is done by Chris Tanner, a student member of the Georgia Tech Space System Design Laboratory. Analyzing disciplinary details show the practicability of *Sprite* launch vehicle. Using data from these analyses, the performances of original design *Sprite* are estimated

The second part is design refining part (Part II). Based on Part I simulation, we find the room for improvement of *Sprite* vehicle. Adding weight and sizing disciplinary analysis, the vehicle is re-designed with optimal design techniques. Same analysis as Part I is done for new vehicle, and the performances of re-designed *Sprite* are estimated.

In the end of this project, we compare the performance of published data, simulated data of original design, and simulated data of refined design. This will be the result and the conclusion of this project.

2.0 Microcosm Launch Vehicles

In order to meet the increasing needs for responsive launch for various defense and other related programs, Microcosm has been developing the concept of operations for the *Scorpius* family of launch vehicles for over eleven years. The *Scorpius* family of pressure-fed launch vehicles shown in Figure 1 includes two suborbital vehicles that have been flown successfully and other orbital vehicles in development with capabilities ranging from 700 lb to 50,000 lb to Low Earth Orbit (LEO)[2]. The *Scorpius* program goal is to reduce the cost of launch by a factor of 5-10 below existing launch systems. *Scorpius* launchers are also designed for responsive launch operations.

Figure 1: Microcosm *Scorpius* Family On the left, are the SR-S and SR-XM suborbitals and the Sprite Small Launch Vehicle. The intermediate-sized vehicles in the center are Antares and Exodus. The Heavy Lift Space Freighter is on the right. (Source: James R. Wertz, Robert Conger, Jack Kulpa, "Responsive Launch with Scorpius of Low-Cost Expandable Launch Vehicle," Microcosm Inc, AIAA LA Section/SSTC 2003-500)

2.1 *Scorpius* Family

Two key features of the *Scorpius* family that have been a part of the design are dramatically lower cost than traditional vehicles and launch within 8 hours of demand. Microcosm has been working toward creating a responsive launch system for nearly a decade and has had to face many of the hurdles involved in their process. The small payload class member of the family workhorse, the *Sprite* SLV is expected to have the capability of 700 lb payload into LEO (100 nm circular orbit due east from the launch site) for $2.5 million. The other workhorse is a medium type lift vehicle. *Exodus* is expected to have the capability of 15,000 lb payload into LEO for $12.5 million. The *Sprite* and suborbital vehicles are expected to be the most used for truly responsive missions because of their low cost.

Also the *Scorpius* family of launch vehicles is designed to provide very low-cost access to space by using simple, modular design. All of the *Scorpius* vehicles share a number of features that significantly assist the responsive character and its low cost[3]:

(i) Assembled at or near the primary launch site
(ii) Assembled vertically on a reusable launch cradle on which they are also moved about the facility as needed
(iii) Short, fat design for rapid movement and handling
(iv) Transported vertically at the launch site on their cradles on rails or on a flatbed trailers
(v) No gantry or service tower needed for transportation or launch
(vi) Ground level servicing (vehicles are short enough that the avionics bay and payload compartment can be reached by a cherry picker if required)
(vii) All stages use environmentally friendly LOX/kerosene propellants

The kerosene that is used is Jet-A, available at essentially any airport worldwide. In the next section, more detail about *Sprite* launch vehicle, which is the object of this paper, is explained.

2.2 Sprite Launch Vehicle

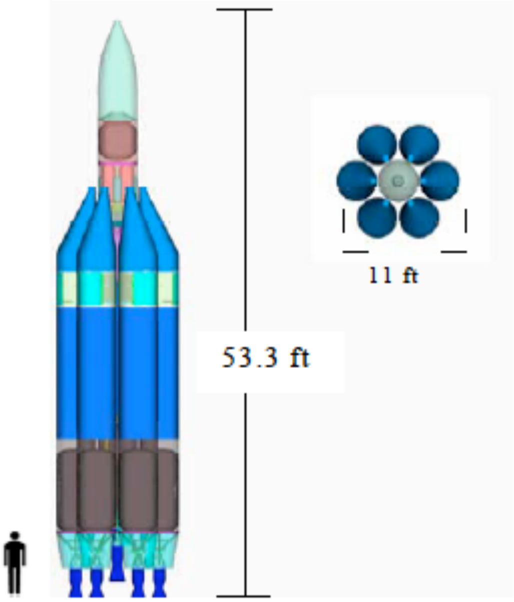


Figure 2: Sprite Configuration (Source: James R. Wertz, Robert Conger, Jack Kulpa, "Responsive Launch with Scorpius of Low-Cost Expandable Launch Vehicle," Microcosm Inc, AIAA LA Section/SSTC 2003-5001)

The three-stage *Sprite* SLV is the first orbital vehicle in the *Scorpius* family. The baseline configuration shown in Figure 2 is capable of carrying 700 lb to LEO (100 nm due east) or 330 lb to Sun synchronous orbit at 400 nm. *Sprite* uses seven common "pods" and a small upper stage. *Sprite* is a three-stage, pressure-fed rocket consisting of six external booster pods comprising the first stage, a center or sustainer second stage pod, and a third stage affixed to the top of the second stage. The first and second stages share the same components with the exception of a modified high-altitude nozzle in the second stage. This commonality reduces the number of unique parts on the vehicle which ultimately reduces cost and manufacturing time. The third stage is designed to meet mission requirements as either a small satellite launch system or long-range, tactical, sub-orbital rocket and includes provisions for a deorbit maneuver to avoid becoming orbital debris.[4]

Table.1: Sprite Launch Vehicle Physical Characteristics (Source: Yellow: Steven J. Isakowitz, Joshua B. Hopkins, Joseph P. Hopkins Jr.,"International Reference Guide to Space Launch System," AIAA, 2004, Green: James R. Wertz, Robert Conger, Jack Kulpa, "Responsive Launch with the Scorpius Family of Low-Cost Expendable Launch Vehicles," AIAA-LA Section/SSTC 2003-5001, Beige: REDTOP simulation result by Chris Tanner)

Payload volume		38"dia X 63" long	
Gross payload to 28.5deg 108nmi		700	lbm
Launch sites		KSC, Wallops or VAFB	
Stage 1/2/3 main propellant		Jet fuel and LOX	
Liftoff Configuration	Gross WT	83,643	lbm
	Dry WT	12,683	lbm
	Dimensions	53.3 ft X 11.2 ft dia.	

	Stage 1		Stage 2		Stage 3	
Gross Weight	68304	lbm	11549	lbm	3090	lbm
Empty Weight	10254	lbm	1851	lbm	578	lbm
Height	38.1	ft	33.2	ft	15.2	ft
Diameter	11.2	ft	3.5	ft	3.5	ft
Thrust	17129 x6	lbf (sl)	22700	lbf (vac)	2530	lbf (vac)
O/F Ratio	2.4	-	2.4	-	2.4	-
Chamber Press.	385	psi	385	psi	154	psi
Isp	285	sec (vac)	317	sec (vac)	330	sec (vac)
Expansion Ratio	6.56	-	30	-	80	-

Table 1 shows the physical characteristics of *Sprite* vehicle. The *Sprite* vehicle is approximately 53 feet in length and 11 feet wide at its base. Six 20-Klbf first stage engines provide 120,000 lbs of thrust while the second and third stages provide 20,000 lbs and 2,500 lbs of thrust respectively. The *Scorpius* launchers are pressure-fed liquid rockets with mostly carbon composite structures. Liquid oxygen and kerosene (Jet-A) were chosen as propellants because of their low toxicity, good performance, and low cost. Jet-A is readily available and LOX can be brought in or produced on site. Because the vehicle is pressure-fed, the tanks are robust enough to support themselves and can endure casual handling expected during the transportation and launch campaign without problems. The shorter, wider nature of the vehicle makes it stable while vertical, enabling easier movement of an integrated vehicle to the launch pad. The dry weight of the Sprite vehicle is comparable to a small bulldozer (about 10,000 lb) and can be easily towed by a standard truck tractor. All normal servicing of the vehicle on the pad is done at ground level thus eliminating the need for a gantry or tower.[5]

According to James V. Berry, the *Sprite* SLV addresses the need for small- and mini-payload capability with a price to orbit objective of "less than \$2.5 million (FY02\$) for 700 lb to LEO[6]." The minimum available payload volume is comparable to the Scout and Pegasus large fairing, i.e., 38-inch diameter by 63.25 inches long. The payload area, with provisions to deploy single or multiple payloads, can be accessed as needed with standard commercial equipment. The payload performance for different orbit inclinations is shown in Figure 3. Launch sites are depended on inclination (KSC for 28.5, Wallops for 51.6, and VAFB for 98.6)

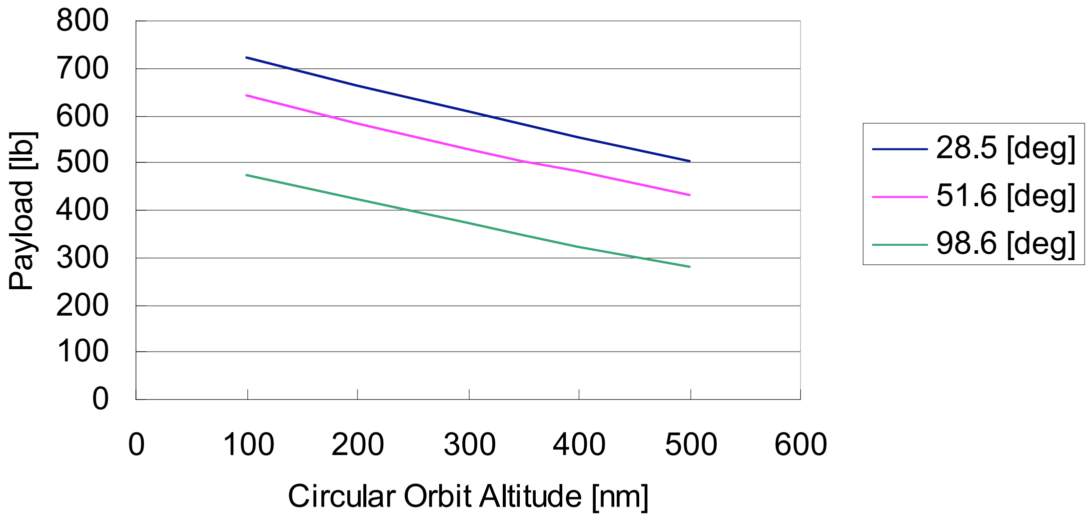


Figure 3: Sprite Payload Performance to Circular Orbit at Various Inclinations (Original data source: Robert E. Conger, James R. Wertz, Jack Kulpa,"The Scorpius Expendable Launch Vehicle Family and Status of the Sprite Mini-Lift," AIAA 2002-2004)

3.0 Approach

The focus of this project is the *Sprite* SLV as the example of small and low-cost vehicle. Here is one question about *Sprite* SLV. As shown in pervious section, *Sprite* vehicle has 120-Klbf (vacuum) total thrust in first stage. Compare to other small and low-cost vehicle, for example, Falcon I launch vehicle has only 85-Klbf (vacuum) thrust. However, *Falcon I* has the capability of 1472 lb payload into 108 nm LEO while *Sprite* has only about 700 lb capabilities into same orbit. Even though there are many differences such as shapes or mass ratio between *Sprite* and *Falcon I*, almost 700 lb payload difference seems too much. Thus, independently confirming the performance of *Sprite* is desired. Basically, the performance can be estimated by aerodynamics, propulsion and trajectory analysis. This is going to be the first part of the project (Part I).

Also one more question might occur after confirming the performance. Based on the confirming analysis, we might notice there is the room for improvement in the original design of *Sprite* SLV. If there is, refining design process is desired. Since *Sprite* SLV project is already started in Microcosm, minor change in engine parameters is going to be key of this part, but not major change in shapes, weight, or engine. Using same engine, but some changing in nozzle (thus Isp) can make the better performance of *Sprite* SLV. This is going to be the second part of the project (Part II)

4.0 Design Method

To analyze and confirm the original design or refined design, integrated design process is required. Several disciplinary design works are required for this type of system design, thus it is needed to integrate the results from each disciplinary. In this section, integration design technique is discussed first. Then we focus on three disciplinary codes, APAS, POST and REDTOP, which are used both Part I and Part II in this project. Then trade study about engine refining is discussed after confirming the performance of original design. Also additional weight and sizing calculation tool developed by Microsoft Excel spreadsheet is discussed in second half part of this section. In the end of this section, results of Part I and Part II are shown.

4.1 Design Structure Matrix

DSM (Design Structure Matrix) is the chart, which shows the relationship of each disciplinary analysis in whole conceptual design. We can easily identify the design process, especially feed-forward and feedback among several disciplinary analyses. Figure 4 shows DSM of *Sprite* SLV in part I. There is no feedback because all configurations of *Sprite* SLV are original one, and no change is allowed since this is confirming part. The first step is the aerodynamics analysis by APAS. The shape of *Sprite* vehicle is input. Output of aerodynamics disciplinary is lift coefficient, drag coefficient and pitching momentum coefficient, and these data become the input of trajectory analysis. With propulsion analysis data by REDTOP, POST simulates optimized trajectory for *Sprite* SLV. Then the performance data, which is maximum payload to specific orbit, will be given. In this project, we stop the simulation we get the performance data, but usually it will be continue to weight and sizing, cost or other disciplinary analysis.

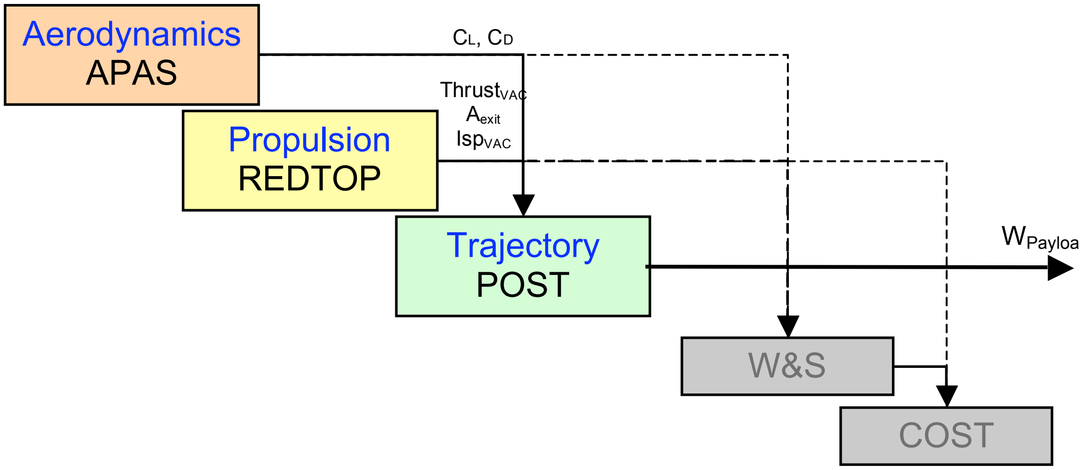


Figure 4: Design Structure Matrix of Part I Gray disciplinary and dotted lines are not simulated in this project

Figure 5 shows DSM for Part II. This part is refining part, thus there is a feed back between trajectory and propulsion. As mentioned before, changing in nozzle (expansion ratio) or Isp is occurred for better performance. The simulation looped among Propulsion, Trajectory, and Weight and Sizing calculation.

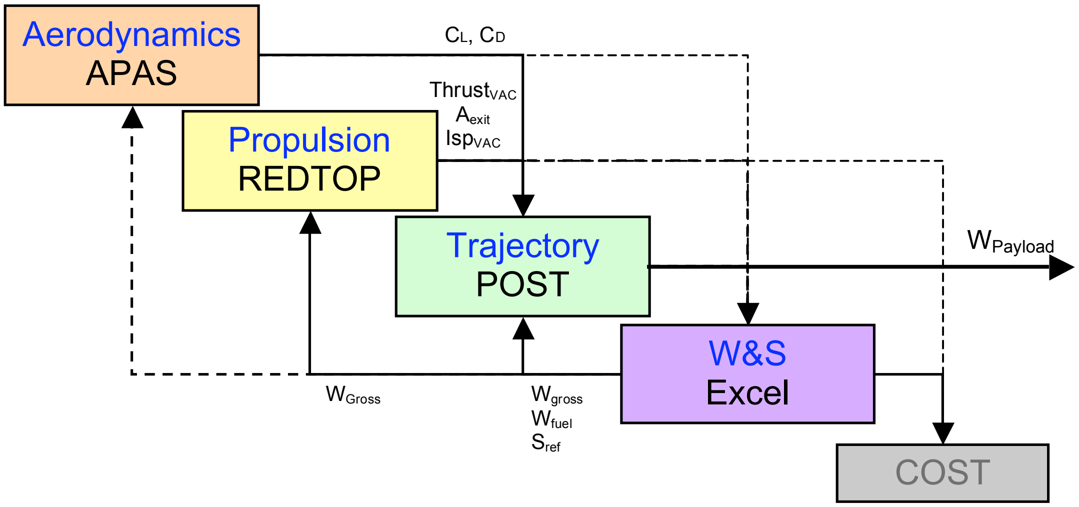


Figure 5: Design Structure Matrix of Part II Gray disciplinary and dotted lines are not simulated in this project

4.2 Aerodynamics Analysis

As shown in DSM, the first thing of design is aerodynamics analysis. In this project, APAS (Aerodynamic Preliminary Analysis System) program is used for aerodynamics analysis. The Aerodynamics Preliminary Analysis System was developed by the NASA Langley Research Center and the Rockwell International Corporation. APAS analysis can be done relatively quickly allowing multiple design iterations, and results are usually within twenty percent of actual values. Such results are good enough for conceptual design, and the speed with which they can be achieved allows designer to include aerodynamic calculations in Multi-Disciplinary Design Optimization loops. Based on the shapes or configuration of object, the program provides an efficient analysis for systematically performing various aerodynamic configuration tradeoff and evaluation studies[7].

4.2.1 APAS Inputs

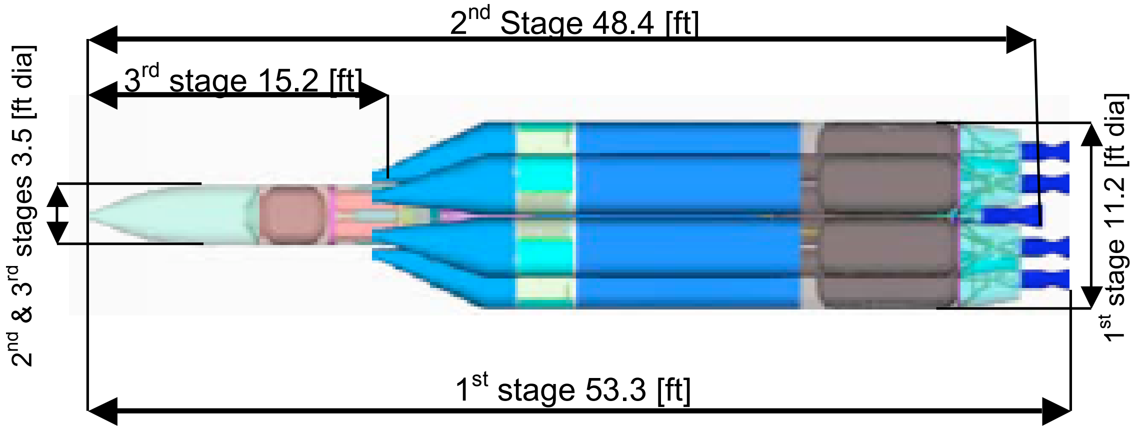


Figure 6: Sprite Configuration for Aerodynamics (Original Picture Source: James R. Wertz, Robert Conger, Jack Kulpa, "Responsive Launch with Scorpius of Low-Cost Expandable Launch Vehicle," Microcosm Inc, AIAA LA Section/SSTC 2003-5001)

Table 2: Sprite Configuration Data (Data Source: James R. Wertz, Robert Conger, Jack Kulpa, "Responsive Launch with the Scorpius Family of Low-Cost Expendable Launch Vehicles," AIAA-LA Section/SSTC 2003-5001)

	Stage 1		Stage 2		Stage 3	
Total Height	53.3	ft	48.4	ft	15.2	ft
Overall Diameter	11.2	ft	3.5	ft	3.5	ft

The Input of APAS is the shape or configuration of vehicle. Figure 6 and Table 2 shows the actual Sprite vehicle configuration. Based on these data, three-dimensional model geometry is built in APAS. Figure 7-9 shows actual input model in APAS for fist stage to third stage. Unfortunately, detail data of cone half-angles for the vehicle are not available, and these are estimations.

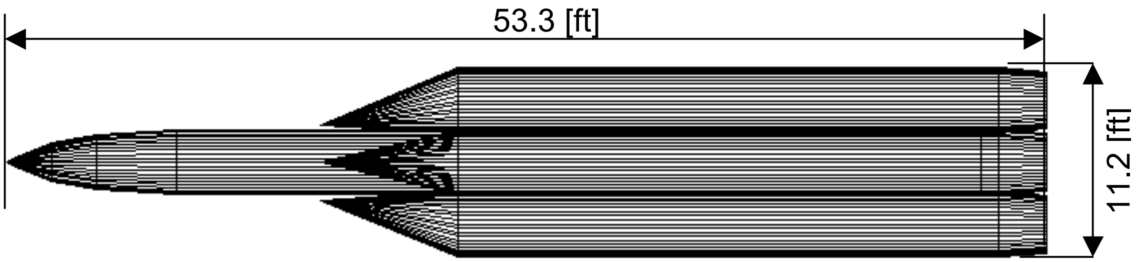


Figure 7: Sprite First Stage APAS Geometry

As illustrated in Figure 7 above, or other figures, the overall *Sprite* design is relatively short and squat, as are the other Scorpius launch vehicles. Thus the vehicle is expected to be stable while vertical, enabling easier movement of an integrated vehicle to the launch pad. Relatively smaller numbers of C_L (Lift Coefficient) and C_D (Drag Coefficient) are expected by APAS simulation compared to general "pencil looks" launch vehicles.

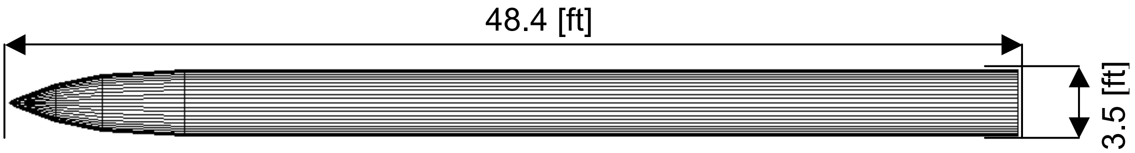


Figure 8: Sprite Second Stage APAS Geometry

Figure 8 shows the APAS input geometry of second stage. Different from the first stage, it looks like normal launch system – long and sharp. Since the length of second stage is not different from the first stage, higher numbers of C_L and C_D are expected by APAS simulation.

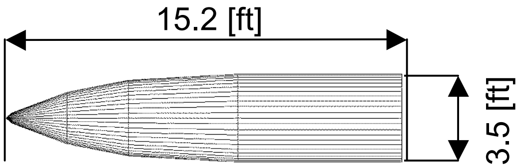


Figure 9: Sprite Third Stage APAS Geometry

Figure 9 are APAS input geometries of third stages. This is also looks like normal higher stage of launch system. *Sprite* is designed to have a similar payload fairing to the retired Scout G-1 launch vehicle.

4.2.2 APAS Run Conditions and Run Setup

The flight conditions of the ten HABP runs analyzed for each trial stage are shown in Table 3. “Tangent cone” and “Prandtl-Meyer” analyses methods are used for the body and shadowed regions. The base pressure is set to C_p=0. The Mach number range of 1.5-30 is considered to be the launch vehicle flight regime. This schedule is used for all 3 trials. Angles of Attack (□) from -15 to 30 degrees are analyzed.

Table 3: UDP Analysis Runs

Trials for 1-3 stages		
RUN	Mach	Altitude (ft)
1	1.5	20000
2	3	40000
3	4	60000
4	5	75000
5	7	100000
6	10	125000
7	15	150000
8	20	175000
9	25	200000
10	30	225000

4.2.3 APAS Results

Aerodynamics data (C_L vs. C_D plots) by APAS results are shown in Figure 10-12 for each stage. In these plots, Mach number 1.5, 7, 15 and upper are not shown here due to visibility. All detail data are available in Appendix A. As expected, the result of first stage has lower L/D compare to the result of second stage.

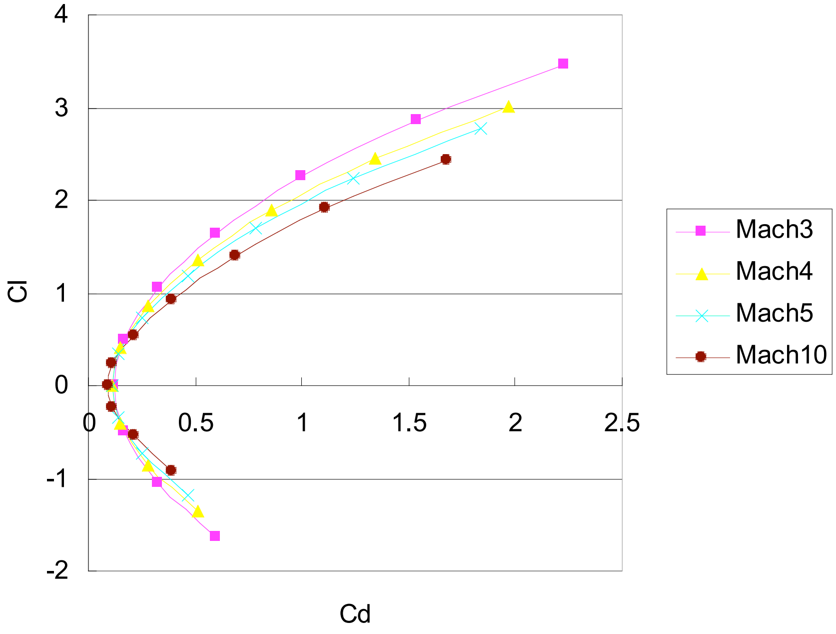


Figure 10: 1st stage C_L vs C_D (S_{ref} 64.7 [ft^2] Length 53.3[ft])

(Figure 11 and 12 on next page)

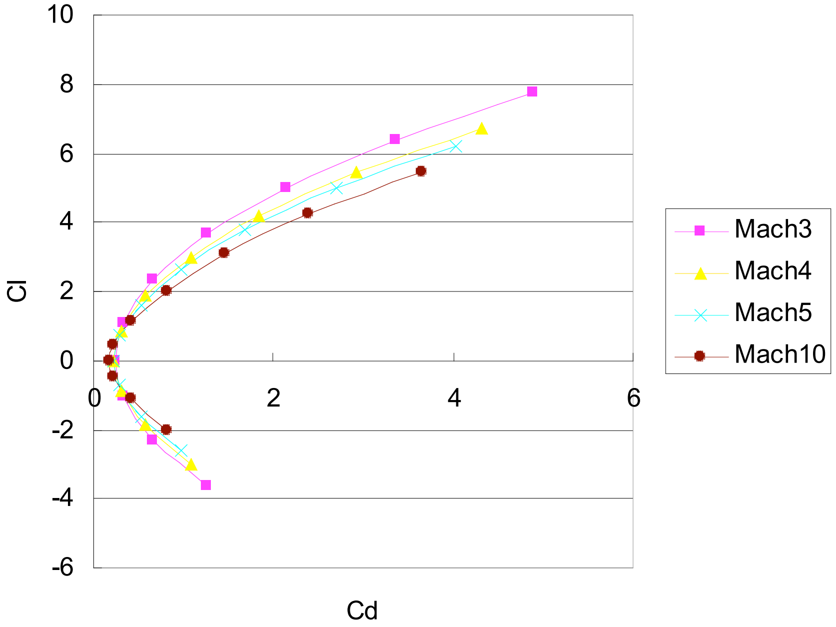


Figure 11: 2nd stage C_L vs C_D (S_{ref} 9.6 [ft^2] Length 48.4[ft])

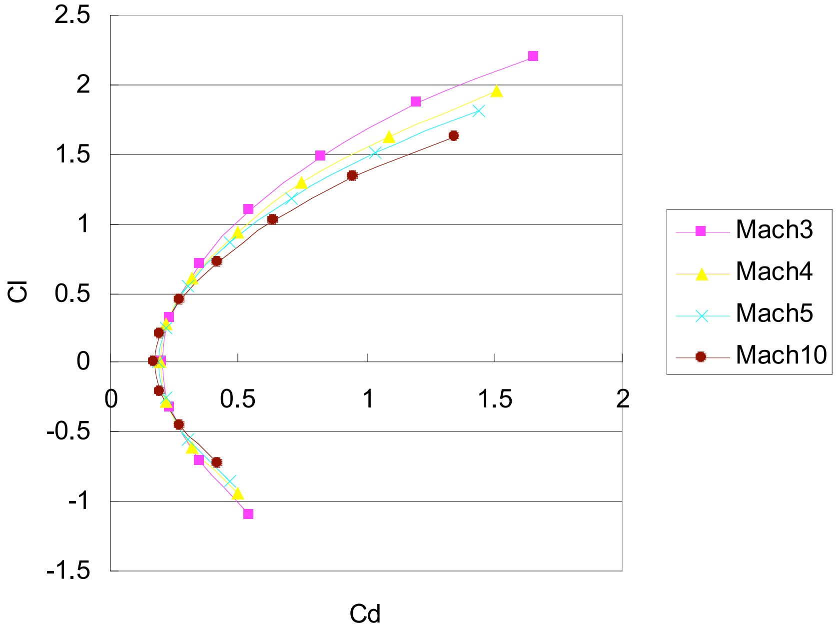


Figure 12: 3rd stage C_L vs C_D (S_{ref} 9.6 [ft^2] Length 15.2[ft])

4.3. Propulsion Analysis

This part is done by Chris Tanner, a student in the Georgia Tech Space System Design Laboratory, using REDTOP (Rocket Engine Design Tool for Optimal Performance) program. Only the input (Table 4) and output (Table 5) are shown in here.

Table 4: Propulsion Data and REDTOP input (Data Source: Chris Tanner)

		Reference						**INPUT**		
Spec	Unit	**AIAA 2003-5001**			**Isakowitz**			**REDTOP**		
Stage	-	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Thrust	lbf (vac) *1	17330	22600	2530	20400	22700	2300	17129	22700	2530
O/F Ratio	-	2.4	2.4	1.0	2.4	2.4	2.4	2.4	2.4	2.4
Chamber Press.	psi *2	270	45	8	385	385	154	385	385	154
Isp	sec (vac)	281*3	297*3	319*3	277.5	309	323	285	317	330
Expansion Ratio	-	N/A	N/A	N/A	6.56	30	80	6.56	30	80
Oxidizer	-	LOX			LOX			LOX		
Fuel	-	kerosene (Jet-A)			kerosene (Jet-A)			kerosene (Jet-A)		

*1 All 1st stage thrusts are single pod, sea level

*2 Unit is not avaiable for Chamber Pressure in AIAA 2003-5001

*3 Values obtained in AIAA 2004-3358

Table 5: REDTOP output These values are going to be feed-forward to trajectory analysis by POST (Data Source: Chris Tanner)

REDTOP Output (feed-forward to POST)				
Spec	Unit	1st *	2nd	3rd
Exit area	ft^2	1.546	7.069	4.565
Thrust	lbf (vac)	20400	22700	2300
Isp	sec (vac)	285.05	317.267	330.06

*single pod

Table 4 shows propulsion data from two different references and actual input values used in propulsion analysis by REDTOP. Table 5 shows output values by REDTOP, and only the values, which are going to be feed-forward to trajectory analysis by POST, are shown here.

4.4 Trajectory Analysis (Part I)

The next disciplinary design analysis is trajectory analysis. In this project, POST (Program to Optimize Simulated Trajectories) program is used. POST is a generalized point mass, discrete parameter targeting and optimization program. POST provides the capability to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. POST has been used successfully to solve a wide variety of atmospheric ascent and reentry problems, as well as ex-atmospheric orbital transfer problems. The generality of the program is evidenced by its multiple phase simulation capability which features generalized planet and vehicle models. This flexible simulation capability is augmented by an efficient discrete parameter optimization capability that includes equality and inequality constraints. Data generated by APAS and REDTOP is the input of POST. Also other data, such as weight (usually this is a feed-back from weight and sizing analysis), launch site, or target orbit are used. Then POST estimates possible maximum payload for *Sprite* launch system.

4.4.1 POST inputs

The POST inputs, trajectory analysis inputs, are the feed-forward or –back from disciplinary analyses shown as DSM and other characteristic data of vehicle. By using POST, the maximum payload of *Sprite* SLV is estimated. Table 6 shows the calculation conditions. Inclination takes three patterns, 28.5, 51.6, and 98.6 degrees. Circular orbit altitude from 108 to 500 nm is analyzed. Launch sites are decided by target inclinations as shown as in Table 6. Also start up loss of 0.5% and fuel residual of 1% after burns out are set for calculation.

Table 6: Post calculation conditions

		Conditions			Unit
Target Orbit	Inclination	28.5	56.1	98.6	deg
	Altitude	108, 220, 300, 432, 500			nm
	Launch Site	KSC	Wallops	VAFB	-

In addition to the calculation conditions, *Sprite* SLV physical characteristics data shown in Table 7 are used in analysis. Fairing weight is not available in any pulished paper, so it is estimated as $W_{fairing} = S_{fairing}$ [ft^2] × 2 [lb/ ft^2] = 165 [lb]. These data are basically same values shown in Table 1 and Table 5. The actual POST input file is attached in the end of this paper (Appendix B).

Table 7: Sprite Physical Characteristics for POST (Original data source:Yellow: Steven J. Isakowitz, Joshua B. Hopkins, Joseph P. Hopkins Jr.,"International Reference Guide to Space Launch System," AIAA, 2004, Green: James R. Wertz, Robert Conger, Jack Kulpa, "Responsive Launch with the Scorpius Family of Low-Cost Expendable Launch Vehicles," AIAA-LA Section/SSTC 2003-5001, Beige: REDTOP simulation result by Chris Tanner)

Spec	Unit	1st *1	2nd	3rd
Total Height	ft	53.3	48.4	15.2
Reference Area	ft	67.35	9.62	9.62
Gross Weight *2	lbm	68304	11549	3090
Empty Weight	lbm	10254	1851	578
Exit area	ft^2	9.276	7.069	4.565
Thrust	lbf (vac)	122400	22700	2300
Isp	sec (vac)	285.05	317.267	330.06

*1 Total of 6 pods values

*2 Each Stage values (without Payload)

4.4.2 POST Results for Original Design (Single Burn)

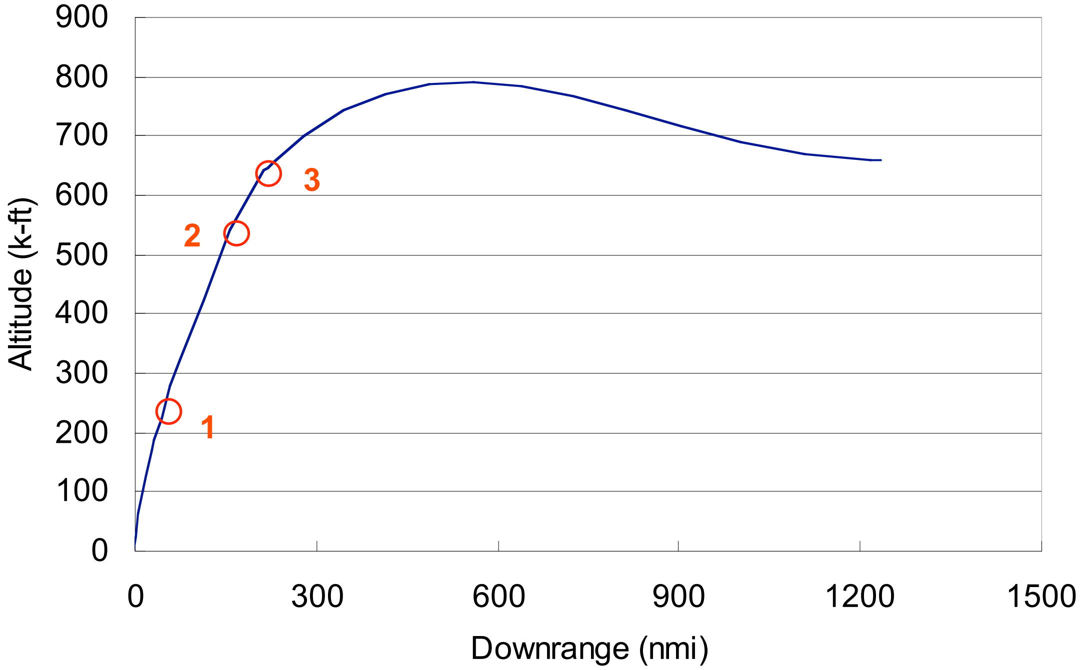


Figure 13: Altitude vs. Down Range (i=28.5 [deg] Alt=108 [nm], Single burn)

Figure 13 shows one of POST outputs, the trajectory of *Sprite* vehicle (Inclination = 28.5 [deg], Altitude = 108 [nm] Single burn case). X-axis represents downrange of vehicle in nautical miles, and Y-axis represents altitude of vehicle in kilo-feet. At point 1 on Figure 13, first stage burns out and jettison. Then fairing separate at point 2. Second stage burns out and jettison at point 3 on Figure 13. The vehicle reached to higher altitude than target altitude (108 nm = 657 k-ft), and then it descends into target altitude. Also Figure 14-16 are same case detail results from POST.

(Figure 14-16 on next page)

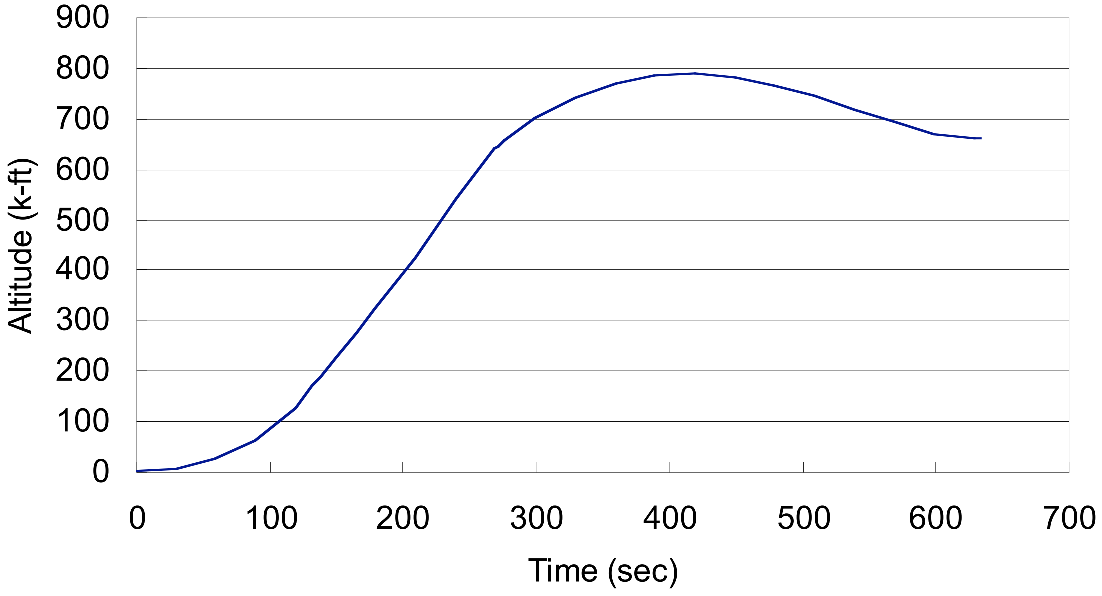


Figure 14: POST Output Altitude vs. Time (i=28.5 [deg] Alt=108 [nm], Single burn)

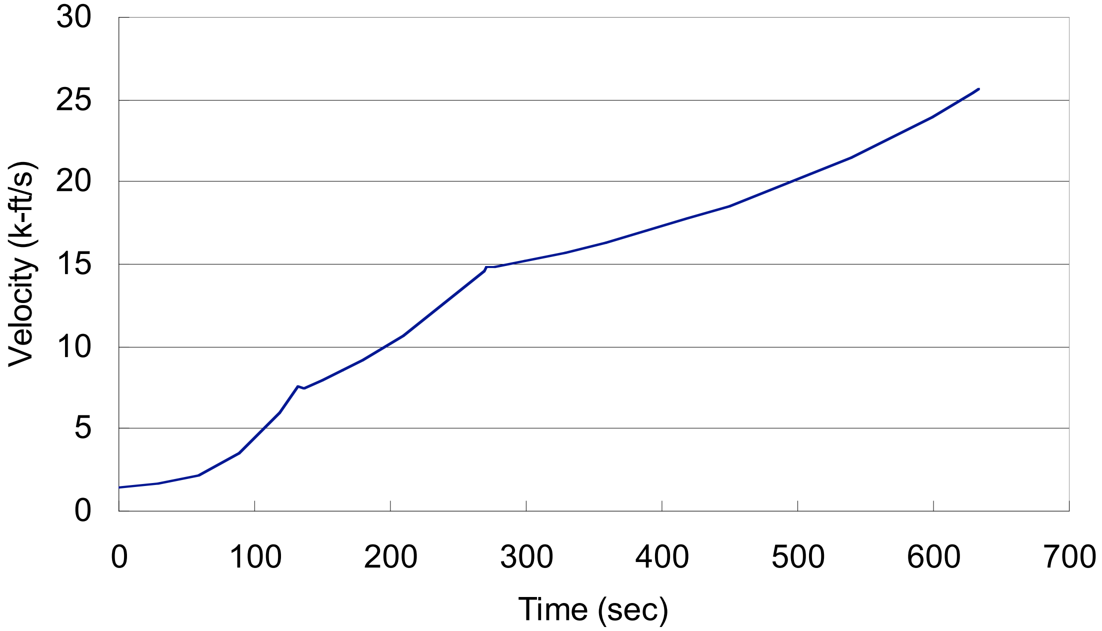


Figure 15: POST Output Velocity vs. Time (i=28.5 [deg] Alt=108 [nm], Single burn)

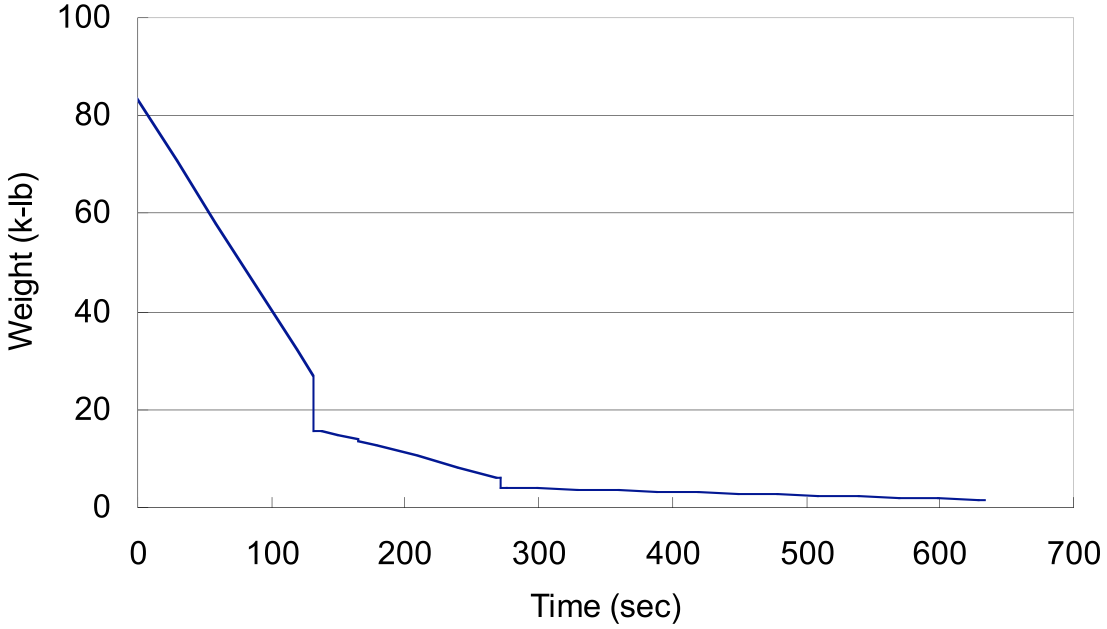


Figure 16: POST Output Weight vs. Time (i=28.5 [deg] Alt=108 [nm], Single burn)

Figure 14 shows vehicle altitude change by time. Figure 15 shows vehicle velocity change by time. From these two graphs, it is found that vehicle reaches target altitude before its velocity reaches required velocity for circularize. Thus, vehicle passes the target altitude once, and gets more velocity by thrusting. This phenomenon is only happen in 108 nm cases, which required high velocity for circularize but low altitude. Also Figure 15 shows separation points of each stage very well. Just before the jettison, vehicle uses almost all fuel and gets lighter, so the acceleration gets much better than start. But after the jettison points, acceleration gets worse because of changing to smaller engine (and starts again). Figure 16 shows vehicle weight change by time. Same as Figure 15, this plot also shows jettison points very well. Of course, the vehicle weight dramatically falls by separating burned out stages. Fuel consumption rate is known by Figure 16, too.

Table 8 shows POST trajectory analysis results. Maximum payloads for specific altitudes and inclinations are shown.

Table 8: Single Burn Trajectory Analysis Result

	Inclination [deg]		
Altitude [nm]	28.5	51.6	98.6
108	886	825	657
220	850	795	621
300	715	686	518
432	496	459	351
500	364	334	215

*Values in [lb]

Figure 17-19 show performance of published data and simulated data. The simulated data marks better performance in lower altitude, but it drops in higher altitude. In contrast, the published data draws gentle decline curve. The difference is probably burn times. The simulation uses single burn for the upper stage trajectory. The published data does not mention about burn times, but usually two-burn shows slower decline like the published performance data of *Sprite* vehicle. Thus, using same condition showed in section 4.4.1, the two-burn simulation is analyzed in next section.

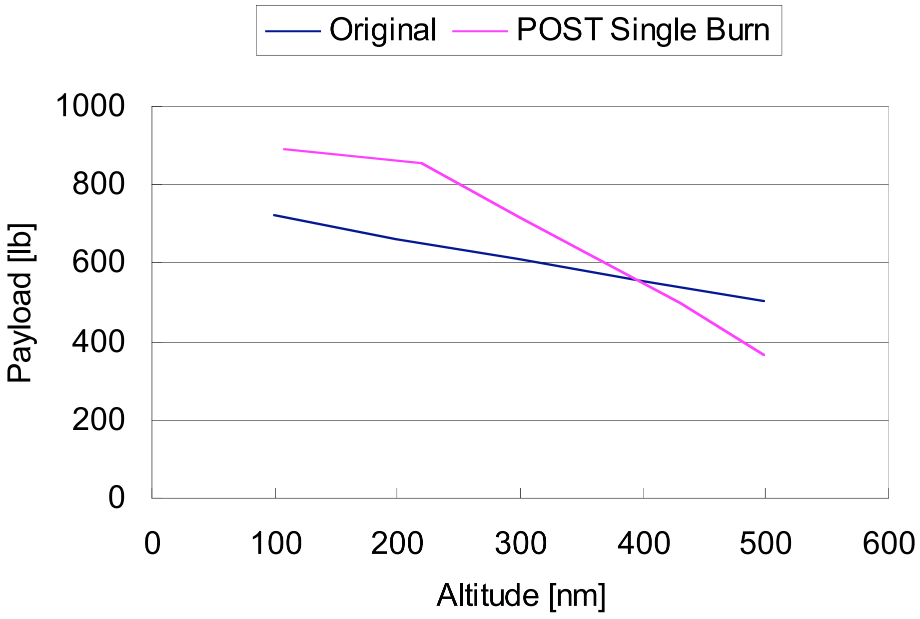


Figure 17: Performance of Published and Simulated (Single burn, i = 28.5)

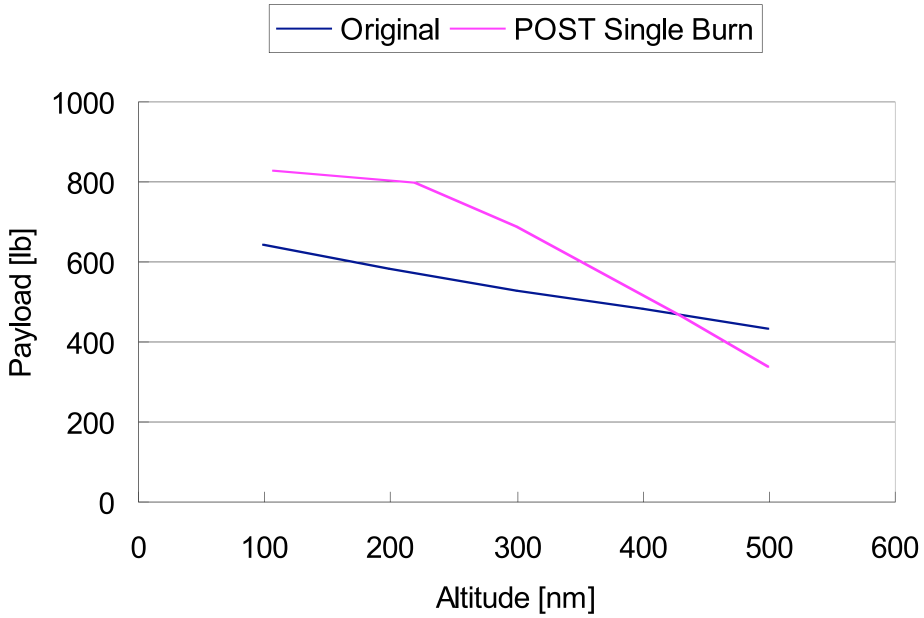


Figure 18: Performance of Published and Simulated (Single burn, i = 51.6)

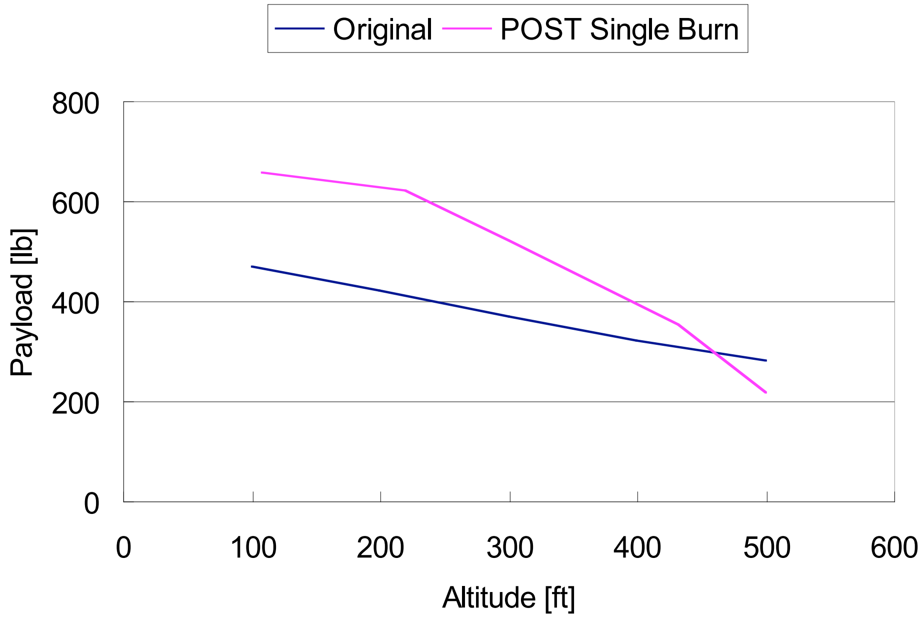


Figure 19: Performance of Published and Simulated (Single burn, i = 98.6)

4.4.3 POST Result for Original Design (Two-Burn)

As discussed in former section, two-burn simulation was assessed. Two burns techniques usually increase maximum payload, and show better performance in higher altitude than single burn. In *Atlas* launch system case, for example, in a single burn mission, t he payload is injected directly into a transfer or circular orbit. In a two-burn mission, the first burn injects the payload into a parking orbit followed by a coast period. The second engine burn places the vehicle in the desired orbit, followed by separation of the payload. The POST input file has minor change about two-burn. The same simulation conditions shown in Table 6 and same characteristics shown in Table 7 are used.

Figure 20-23 show example trajectory analysis results of two burns upper stage case. These figures are correspondence to Figure 16-19 of single burns. Compare to single stage case, vehicle reached to the target orbit very smoothly. Figure 22 and 23 shows it is actually two-burn upper stage. In third stage, the acceleration is stopped when vehicle stop the first burning. It started the engine again to circularize when it reached to the target altitude.

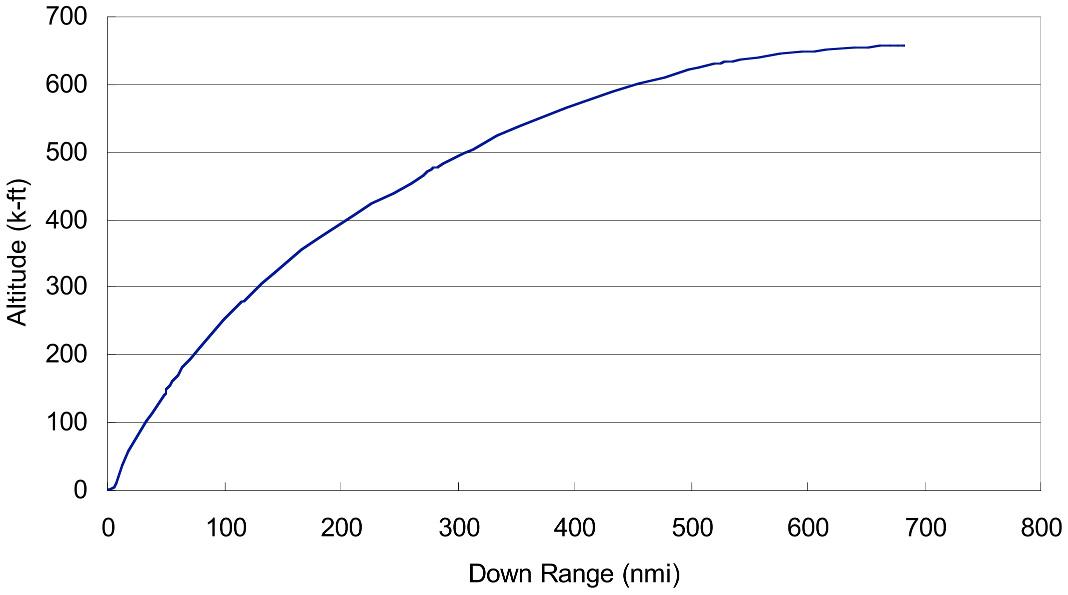


Figure 20: Altitude vs. Down Range (i=28.5 [deg] Alt=108 [nm], Two-burn)

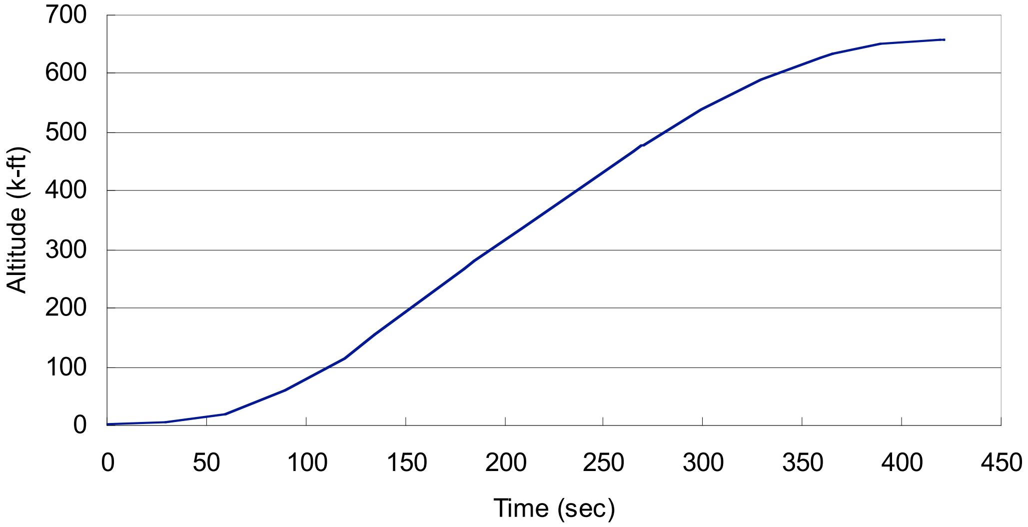


Figure 21: POST Output Altitude vs. Time (i=28.5 [deg] Alt=108 [nm], Two-burn)

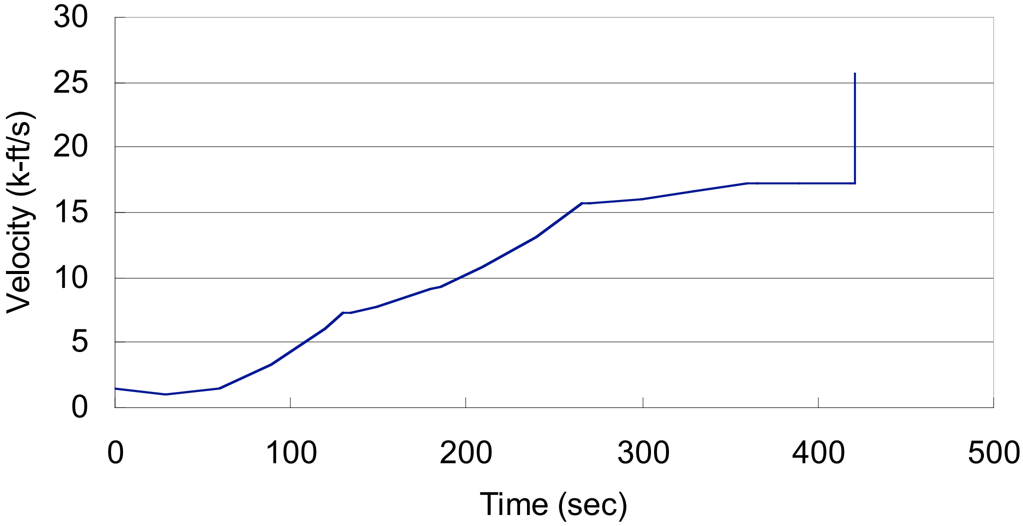


Figure 22: POST Output Weight vs. Time (i=28.5 [deg] Alt=108 [nm], Two-burn)

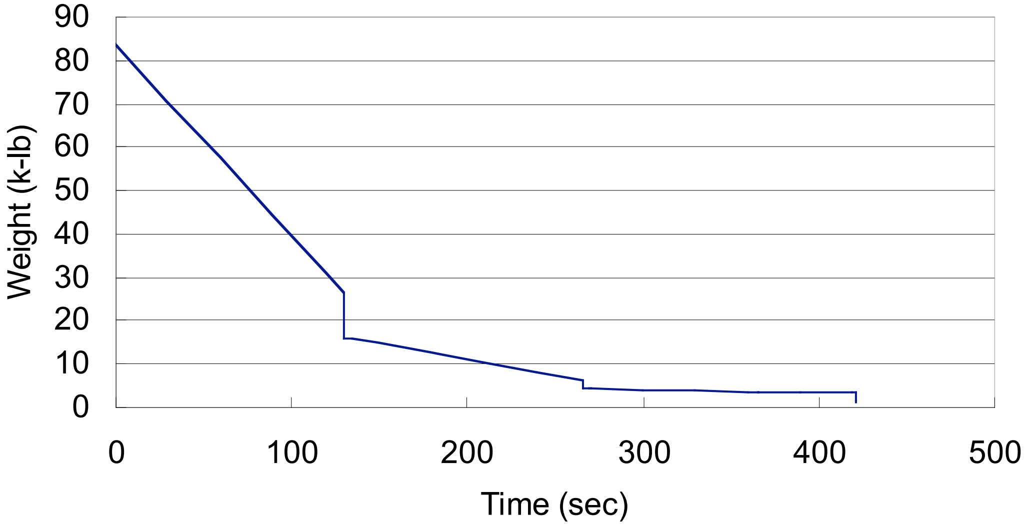


Figure 23: POST Output Weight vs. Time (i=28.5 [deg] Alt=108 [nm], Two-burn)

Table 9 shows POST trajectory analysis results. Two burn case maximum payloads for specific altitudes and inclinations are shown.

Table 9: Two-Burn Trajectory Analysis Results

	Inclination [deg]		
Altitude [nm]	28.5	51.6	98.6
108	943	834	667
220	867	797	622
300	786	725	557
432	675	636	481
500	636	597	448

*Values in [lb]

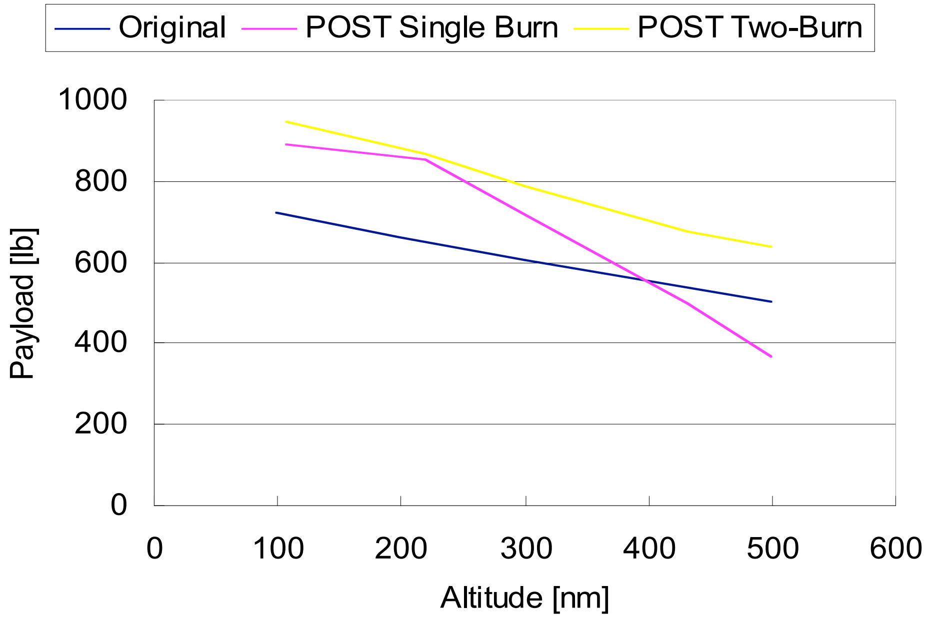


Figure 24: Performance of Published, Single Burn, and Two-Burn (i = 28.5)

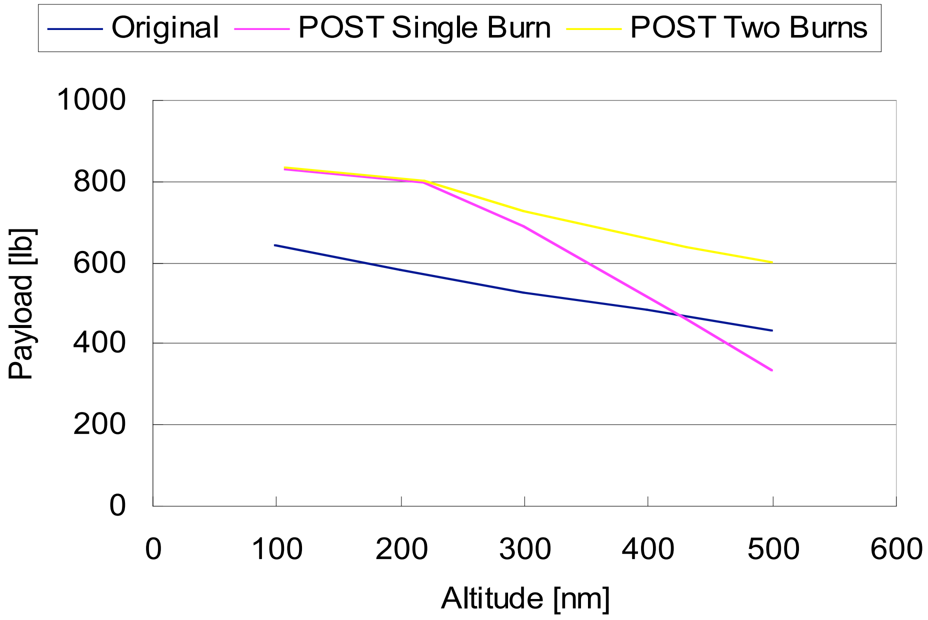


Figure 25: Performance of Published, Single Burn, and Two-Burn (i = 51.6)

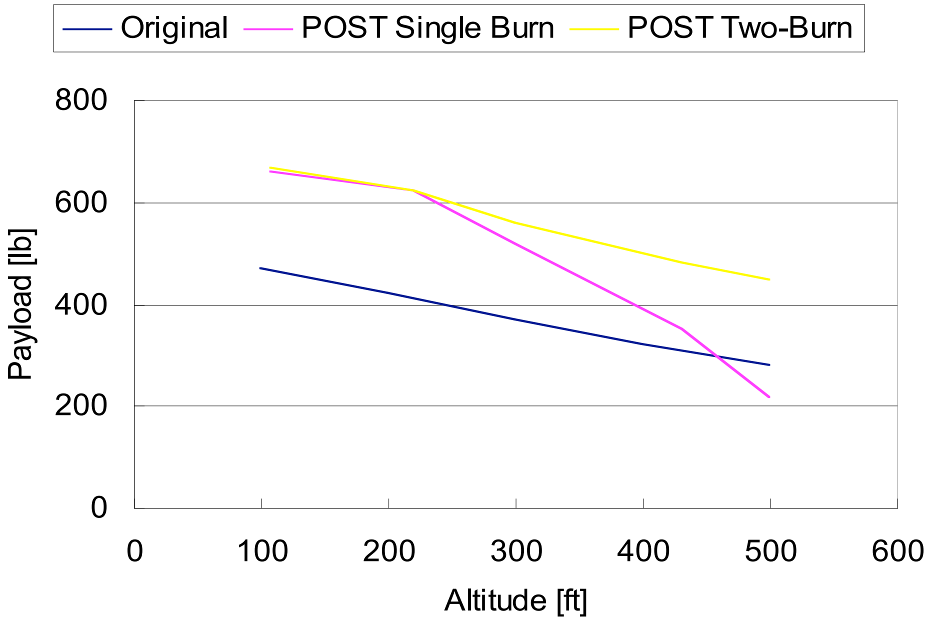
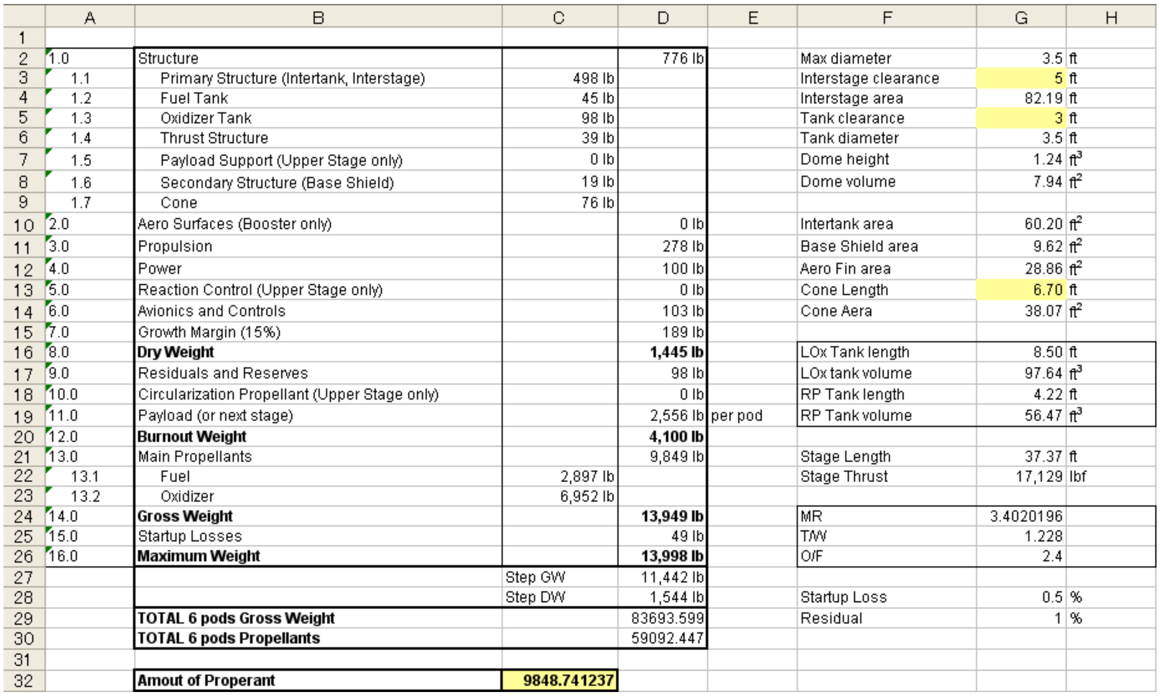


Figure 26: Performance of Published, Single Burn, and Two-Burn (i = 98.6)

Figure 24-26 shows performance comparison of published data, single burn simulated data, and two-burn simulated data. For all points, two-burn simulated data superior to others. Also the curvature of two-burn is similar to published curve. It can conclude that *Sprite* SLV's published data is two-burn on the upper stage.

4.5 Weight and Sizing Analysis

Before design refining analysis, new disciplinary tool is required. As DSM shown in Figure 5, weight and sizing (W&S) analysis is used in Part II of this project. This new tool is made by Microsoft Excel, and based on same type tool made by Janssen Pimentel, a former student in the Georgia Tech Space System Design Laboratory. Inputs are *Sprite*'s dimensions, payload weight, and engine data. Figure 27 displays weight calculation of first stage in this Excel spreadsheet tool.



	A	B	C	D	E	F	G	H
1								
2	1.0	Structure		776 lb		Max diameter	3.5	ft
3	1.1	Primary Structure (Intertank, Interstage)	498 lb			Interstage clearance	5	ft
4	1.2	Fuel Tank	45 lb			Interstage area	82.19	ft
5	1.3	Oxidizer Tank	98 lb			Tank clearance	3	ft
6	1.4	Thrust Structure	39 lb			Tank diameter	3.5	ft
7	1.5	Payload Support (Upper Stage only)	0 lb			Dome height	1.24	ft^3
8	1.6	Secondary Structure (Base Shield)	19 lb			Dome volume	7.94	ft^2
9	1.7	Cone	76 lb					
10	2.0	Aero Surfaces (Booster only)		0 lb		Intertank area	60.20	ft^2
11	3.0	Propulsion		278 lb		Base Shield area	9.62	ft^2
12	4.0	Power		100 lb		Aero Fin area	28.86	ft^2
13	5.0	Reaction Control (Upper Stage only)		0 lb		Cone Length	6.70	ft
14	6.0	Avionics and Controls		103 lb		Cone Aera	38.07	ft^2
15	7.0	Growth Margin (15%)		189 lb				
16	8.0	**Dry Weight**		**1,445 lb**		LOx Tank length	8.50	ft
17	9.0	Residuals and Reserves		98 lb		LOx tank volume	97.64	ft^3
18	10.0	Circularization Propellant (Upper Stage only)		0 lb		RP Tank length	4.22	ft
19	11.0	Payload (or next stage)		2,556 lb	per pod	RP Tank volume	56.47	ft^3
20	12.0	**Burnout Weight**		**4,100 lb**				
21	13.0	Main Propellants		9,849 lb		Stage Length	37.37	ft
22	13.1	Fuel	2,897 lb			Stage Thrust	17,129	lbf
23	13.2	Oxidizer	6,952 lb					
24	14.0	**Gross Weight**		**13,949 lb**		MR	3.4020196	
25	15.0	Startup Losses		49 lb		T/W	1.228	
26	16.0	**Maximum Weight**		**13,998 lb**		O/F	2.4	
27			Step GW	11,442 lb				
28			Step DW	1,544 lb		Startup Loss	0.5	%
29		**TOTAL 6 pods Gross Weight**		83693.599		Residual	1	%
30		**TOTAL 6 pods Propellants**		59092.447				
31								
32		**Amout of Properant**	**9848.741237**					

Figure 27: Weight and Sizing Analysis Spreadsheet (First stage breakdown)

Since engine parameter changing is occur in Part II, engine weight equation is key of this spread sheet. The equation used in this tool is

$$W_{engine} = \frac{mdot(h_c - h_e)}{k} \qquad (1)$$

where W_{engine}: Engine weight, mdot: Mass flow rate, h_c,h_e: Combustor/Exhaust plane flow enthalpy, and k: Weight relation coefficient. This equation and value of k is determined by D. W. Way (AIAA 99-2353)[8]. In *Sprite* SLV case, k=520 [BTU/s/lbf] is used.

4.6 Trade Study

From this section, second part of the project begins. For refining design, minor change of engine is decided. First of all, visualization of trade study is required. Table 10 shows available design space of expansion ratio. Based on these upper and lower boundaries, Design of Experiments (DOE) between expansion ratio and maximum payload is generated. Third stage engine is eliminated from trade study. Third stage almost always burns in vacuum environment, thus no change is expected on third stage. Using Response Surface Methods, model is generated so that it can used to determine optimum values and for sensitivity studies and design space visualization.

Expansion Ratio : _			
	baseline	Lower Bound	Upper Bound
1st stage	6.56	6	18
2nd stage	30	25	45

Table 10: Upper and Lower Boundaries of Expansion Ratio

4.6.1 Design of Experiments and Response Surface Methods

Design of experiments (DOE) is a systematic, rigorous approach to engineering problem-solving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible, and supportable engineering conclusions[9]. In this project Central Composite Design (CCD) Type of DOE is used (Figure 28). Error can be lager than full factorial design, but it reduces the number of test points. Test points are set as Table 11.

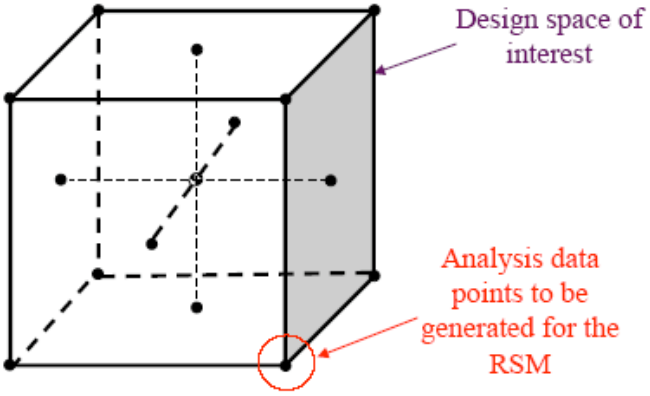


Figure 28: Central Composite Design (Three Parameter Case)

Table 11: Central Composite Design Setting

k = 2		
No	x1	x2
1	-1	-1
2	1	-1
3	-1	1
4	1	1
5	-_	0
6	_	0
7	0	- _
8	0	_
9	0	0

* _ = 1.414 for 2 parameters

Response Surface Method (RSM) is a technique for building and optimizing empirical models of continuous functions. RSM approximates the underlying dependence of output responses to input parameters with an empirical polynomial relationship based on a given set of data (DOE). Advantage of using RSM is that simplified equation representing a complex system. Initially, the dependent parameter is assumed to be a second-order equation, base on a Taylor series approximation, of the form:

$$\mathrm{Re}\,sponse = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + error \qquad (2)$$

where *Response* is the dependent parameter (response) of interest

□$_i$ are regression coefficients for the first order terms

□$_{ii}$ are coefficients for the pure quadratic terms

□$_{ij}$ the coefficients for the cross-product terms

x_i, x_j are the independent variables

error is the error associated with neglecting higher order effects

$$Payload = \beta_0 + \beta_1 \varepsilon_1 + \beta_2 \varepsilon_2 + \beta_3 \varepsilon_1^2 + \beta_4 \varepsilon_2^2 + \beta_5 \varepsilon_1 \varepsilon_2 \qquad (3)$$

Equation (3) shows the response surface (payload) of this part (Part II). To determine these coefficients in equation, DOE of Part II are generated. Responded payload is calculated by APAS, REDTOP, POST and W&S spreadsheets for each expansion ratio in CCD. Simulation includes the loop calculation as shown in DSM (Figure 5). At least five time iterations are simulated for each. In addition, T/W ratio and O/F ratio are fixed. These simulation results are shown in DOE (Table 12).

Table 12: Design of Experiments

No	CCD Sets		Parameters		Response
	x1	x2	1	2	Payload
1	-1	-1	6.0	25.0	1030
2	1	-1	18.0	25.0	471
3	-1	1	6.0	45.0	1060
4	1	1	18.0	45.0	481
5	-√2	0	20.5	35.0	883
6	√2	0	3.5	35.0	373
7	0	-√2	12.0	49.1	784
8	0	√2	12.0	20.9	829
9	0	0	12.0	35.0	911

From the DOE, the coefficients in equation (3) are solved. To get the equation, JMP, the statistical data handling program, is used in this project. Equation (4) shows the result of JMP calculation. The calculation error is one digit in second order error. This is not small, but acceptable in this case.

$$Payload = 265.2777 + 51.2330\varepsilon_1 + 31.3098\varepsilon_2 - 3.6266\varepsilon_1^2 - 0.4145\varepsilon_2^2 - 0.0833\varepsilon_1\varepsilon_2 \qquad (4)$$

4.6.2 Optimized Values by Response Surface Method

In last section, RSM is defined for *Sprite* Refining. Figure 29 shows visualized response surface from equation (4). Top of hill, where is the maximum payload point, is in our ranges ($6<\varepsilon_1<18$, $25<\varepsilon_2<45$). This means optimal values of expansion ratios are in range. By calculation, maximum value of equation (4) is 1016.1 [lb] when $\varepsilon_1=6.63662$, $\varepsilon_2=37.1015$. Table 13 shows comparison of payload. Refined *Sprite* SLV has better performance than original. Also it shows both payload from RSM equation, and simulated payload with $\varepsilon_1=6.63662$ and $\varepsilon_2=37.1015$.

(Figure 29 and Table 13 are shown in next page)

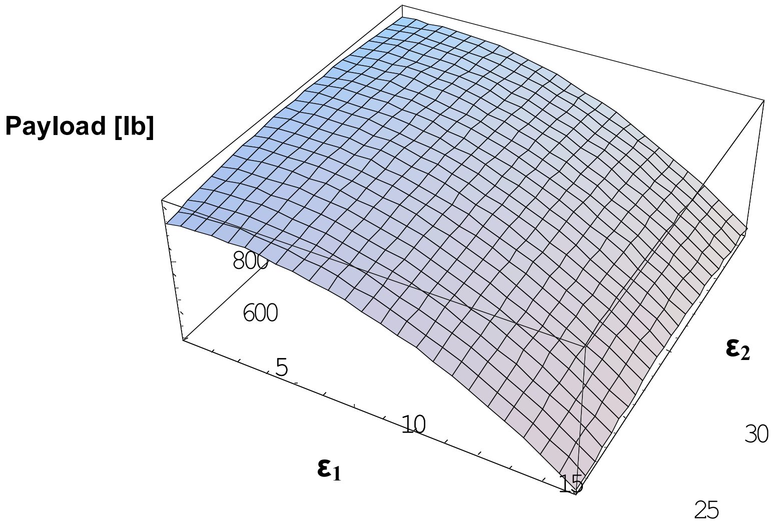


Figure 29: Response Surface

Table 13: Refined *Sprite* vs. Original *Sprite*

Case i=28.5 alt=108[nm]				
	Original (Published)	Part I	Part II	
			RSM Cal.	Simulate
—1	6.56	6.56	6.64	6.64
—2	30	30	37	37
Payload [lb]	700	943	1016	1003

Maximum Payloads between RSM calculation and Actual simulation are slightly different. This is happened because of error in RSM. RSM is very useful Technique for system designing, but it assumes response surface has quadratic form in this case. This makes some error in calculation, thus the expansion ratios we have might not be the best answer. Hopefully, the values are not so far from central point (middle values point) so that error might be small as ignorable. Also the payload of simulated value in Part II is larger than Part I. This means the expansion ratios are may not the best but these values actually makes improvement. From this reason, we take these expansion ratios for refined design vehicle. From next section, refined vehicle analysis is started with these new values.

4.7 Refined Vehicle Analysis

In this section, performance of refined *Sprite* SLV is simulated with new expansion ratios. Due to changing of expansion ratios and other values, Table 14 shows new inputs values for simulation. New *Sprite* SLV has smaller first and second stages. Simulation methods are basically same as Part I, so analysis details are omission. Same conditions are used for all calculations.

Table 14: Refined *Sprite* Data

Spec	Unit	1st *1	2nd	3rd
Total Height	ft	52.8	47.9	15.2
Reference Area	ft	67.35	9.62	9.62
Gross Weight *2	lbm	68165	11249	3090
Empty Weight *2	lbm	10310	1854	578
Exit area	ft^2	9.378	8.65	4.565
Thrust	lbf (vac)	122400	22700	2300
Isp	sec (vac)	285.38	320.67	330.06

*1 Total of 6 pods values

*2 Each Stage values (without Payload)

Table 15 shows simulation results of New *Sprite* SLV. In this section, only this table shows the simulation results. Basically, table shows the better performance of refined design vehicle. The performance comparison graphs are shown in next section with comments. Trajectory detail graphs are omission here. Since there is not so much big difference in Input data, trajectory is almost same as Figure 20-23.

Table 15: Refined Vehicle Analysis Results

	Inclination [deg]		
Altitude [nm]	28.5	51.6	98.6
108	1003	834	661
220	878	794	630
300	825	749	596
432	711	668	512
500	657	629	481

*Values in [lb]

5.0 Performance Comparison

All simulations and calculations are completed. Performance of Published Data, Simulated Data of Original Design (two burns case), and Simulated Data of Refined Design are gathered. Then performance comparison of all three models with comments is here. Let's start from i=28.5 case in Figure 30.

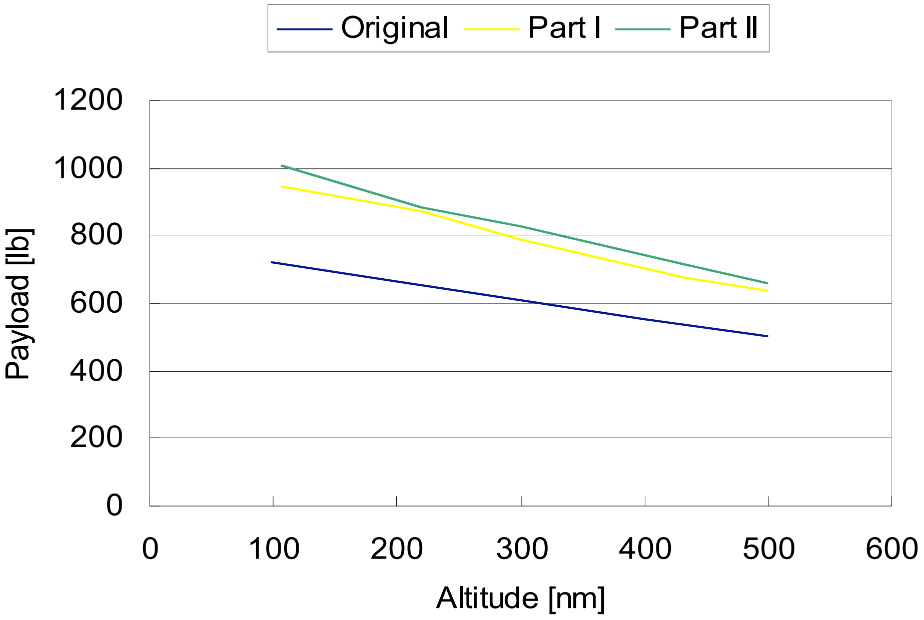


Figure 30: Performance Comparison (i=28.5)

Figure 30 shows the maximum payload of these three designs. It shows the refined design vehicle has the slightly better performance than Part I design (Original, simulated). It means the improvement of *Sprite* SLV is succeeded. Basically all curves shows almost same grade of declines. Figure 31 and 32 shows same performance comparison graphs, but inclinations are 51.6 [deg] and 98.9 [deg]. These also show better performance of Part II analyses. In Figure 31, Part I analysis shows minute better performance than Part II analysis at around 200 [nm]. It should be lower, but it is possible there is an error because of some noise. At the other altitude, it shows better performance, thus it can be neglected.

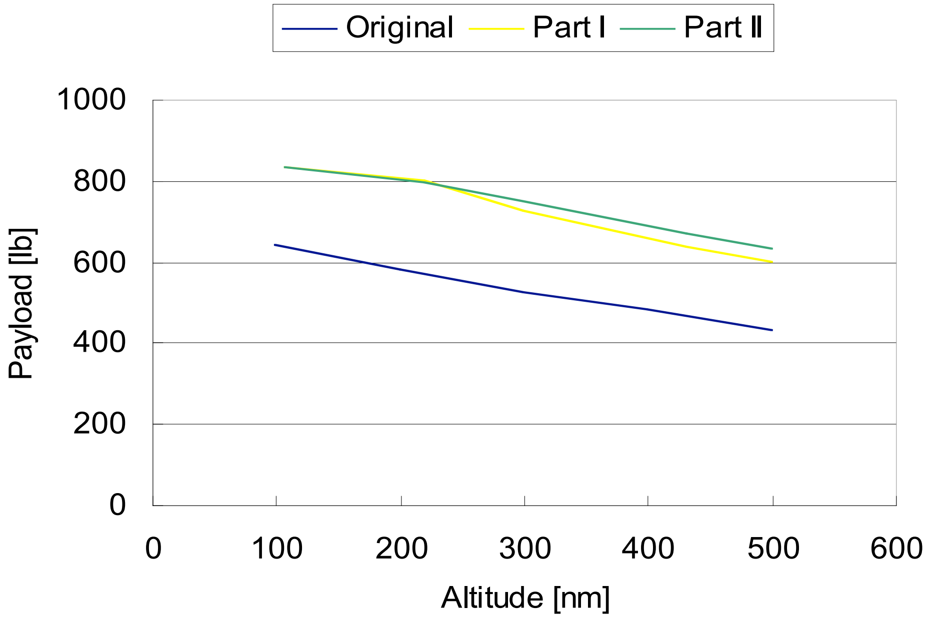


Figure 31: Performance Comparison (i=51.6)

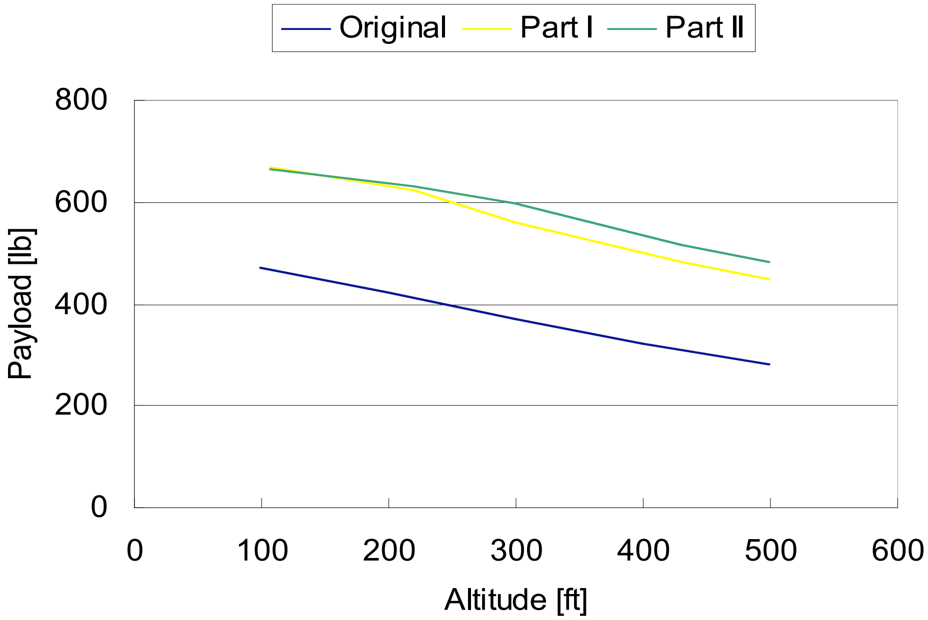


Figure 32: Performance Comparison (i=98.6)

6.0 Conclusions

All simulations and calculations are done. Figure 33 shows the maximum payload of all three data. From these results, we can conclude that the project is success.

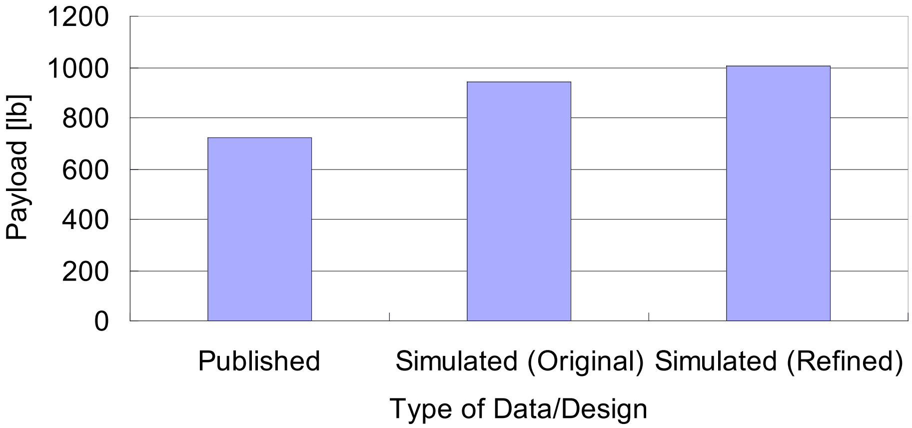


Figure 33: Payload of all three data (i=28.5[deg], alt=108[nm])

The simulated data of original design is better than published data. As expected in the approach of the project (see 3.0 Approach), the *Sprite* SLV has better performance, which corresponds to the engine sizes. Upper stage burns time (single burn or two burns) is unknown when the project starts. These data are not published so far. However, it is able to conclude that *Sprite* SLV uses two burns upper stage from the simulation results in this project*.

The refining part is also success. As mentioned before, the expansion ratios are calculated by RSM equation with some error. Thus, it might not be the optimal values for *Sprite* vehicle. However, the simulation results show better performance enough. That is the reason we can say this is success.

*According to Microcosm engineer, it is actually two burns upper stage.

7.0 Reference

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[8] Way, D. W., Olds, J. R., "SCORES: Web-Based Rocket Propulsion Analysis Tool for Space Transportation System Design," AIAA 99-2353, 1999.

[9] Michelle R. Kirby, “The “How To” Guide for Response Surface Methodology,” Georgia Institute of Technology Aerospace Systems Design Laboratory, 2003

Appendix A: APAS Analysis Data

Frist Stage Data (Sref = 67.34 [ft^2], Length=53.3 [ft])

Run 1						Run 5					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
1.5	-15	0	-3.2498	1.0949	9.4049	7	-15	0	-1.0239	0.4192	2.7784
1.5	-10	0	-2.1633	0.582	6.15	7	-10	0	-0.6129	0.2297	1.5928
1.5	-5	0	-1.0647	0.2793	3.018	7	-5	0	-0.274	0.1321	0.6899
1.5	0	0	0	0.1812	0	7	0	0	0	0.1053	0
1.5	5	0	1.0647	0.2793	-3.018	7	5	0	0.274	0.1321	-0.6899
1.5	10	0	2.1633	0.582	-6.15	7	10	0	0.6129	0.2297	-1.5928
1.5	15	0	3.2498	1.0949	-9.4049	7	15	0	1.0239	0.4192	-2.7784
1.5	20	0	4.3843	1.8423	-13.019	7	20	0	1.5049	0.7217	-4.2848
1.5	25	0	5.4524	2.8166	-16.783	7	25	0	2.0293	1.1546	-6.0943
1.5	30	0	6.371	3.9681	-20.573	7	30	0	2.5627	1.7264	-8.1683
Run 2						Run 6					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
3	-15	0	-1.6413	0.5956	4.631	10	-15	0	-0.9212	0.3934	2.4725
3	-10	0	-1.0576	0.3242	2.9126	10	-10	0	-0.53	0.2106	1.3447
3	-5	0	-0.5034	0.1713	1.3731	10	-5	0	-0.2271	0.1153	0.5475
3	0	0	0	0.1247	0	10	0	0	0	0.0937	0
3	5	0	0.5034	0.1713	-1.3731	10	5	0	0.2271	0.1153	-0.5475
3	10	0	1.0576	0.3242	-2.9126	10	10	0	0.53	0.2106	-1.3447
3	15	0	1.6413	0.5956	-4.631	10	15	0	0.9212	0.3934	-2.4725
3	20	0	2.2514	0.9966	-6.5604	10	20	0	1.3903	0.6878	-3.9444
3	25	0	2.8651	1.5391	-8.7052	10	25	0	1.9084	1.1126	-5.735
3	30	0	3.4548	2.2288	-11.054	10	30	0	2.4391	1.6751	-7.7976
Run 3						Run 7					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
4	-15	0	-1.3491	0.5092	3.7534	15	-15	0	-0.8634	0.3609	2.2847
4	-10	0	-0.8524	0.2792	2.3037	15	-10	0	-0.4794	0.1899	1.1865
4	-5	0	-0.3988	0.1527	1.0626	15	-5	0	-0.1936	0.1097	0.4468
4	0	0	0	0.1152	0	15	0	0	0	0.0888	0
4	5	0	0.3988	0.1527	-1.0626	15	5	0	0.1936	0.1097	-0.4468
4	10	0	0.8524	0.2792	-2.3037	15	10	0	0.4794	0.1899	-1.1865
4	15	0	1.3491	0.5092	-3.7534	15	15	0	0.8634	0.3609	-2.2847
4	20	0	1.8874	0.858	-5.447	15	20	0	1.3234	0.666	-3.7445
4	25	0	2.4492	1.3414	-7.3986	15	25	0	1.8358	1.0959	-5.5317
4	30	0	3.0025	1.966	-9.5787	15	30	0	2.3638	1.6586	-7.5947
Run 4						Run 8					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
5	-15	0	-1.1877	0.4631	3.2683	20	-15	0	-0.8418	0.3577	2.2208
5	-10	0	-0.7365	0.2549	1.9594	20	-10	0	-0.4579	0.1918	1.1257
5	-5	0	-0.3393	0.1429	0.8851	20	-5	0	-0.1781	0.1129	0.402
5	0	0	0	0.1103	0	20	0	0	0	0.0928	0
5	5	0	0.3393	0.1429	-0.8851	20	5	0	0.1781	0.1129	-0.402
5	10	0	0.7365	0.2549	-1.9594	20	10	0	0.4579	0.1918	-1.1257
5	15	0	1.1877	0.4631	-3.2683	20	15	0	0.8418	0.3577	-2.2208
5	20	0	1.6949	0.7869	-4.8592	20	20	0	1.3093	0.6358	-3.6723
5	25	0	2.2351	1.2423	-6.7282	20	25	0	1.8298	1.0441	-5.4469
5	30	0	2.7755	1.8377	-8.8437	20	30	0	2.3438	1.631	-7.5049

Frist Stage Data (Sref = 67.34 [ft^2], Length=53.3 [ft])

Run 9						Run 10					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
25	-15	0	-0.8294	0.3653	2.1924	30	-15	0	-0.8208	0.3808	2.1806
25	-10	0	-0.4467	0.1988	1.0976	30	-10	0	-0.4395	0.2124	1.0843
25	-5	0	-0.1696	0.1203	0.3791	30	-5	0	-0.1641	0.1329	0.3666
25	0	0	0	0.1003	0	30	0	0	0	0.113	0
25	5	0	0.1696	0.1203	-0.3791	30	5	0	0.1641	0.1329	-0.3666
25	10	0	0.4467	0.1988	-1.0976	30	10	0	0.4395	0.2124	-1.0843
25	15	0	0.8294	0.3653	-2.1924	30	15	0	0.8208	0.3808	-2.1806
25	20	0	1.2957	0.6437	-3.6443	30	20	0	1.2855	0.6606	-3.6345
25	25	0	1.8154	1.0518	-5.4199	30	25	0	1.8038	1.0696	-5.4126
25	30	0	2.3508	1.5994	-7.4706	30	30	0	2.3379	1.6176	-7.4662

Second Stage Data (Sref = 9.62 [ft^2], Length=48.4 [ft])

Run 1						Run 4					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
1.5	-15	0	-7.2636	2.3285	52.69	5	-15	0	-2.615	0.9742	17.833
1.5	-10	0	-4.7541	1.1915	33.978	5	-10	0	-1.5995	0.5224	10.504
1.5	-5	0	-2.26	0.5369	16.151	5	-5	0	-0.7184	0.2838	4.5924
1.5	0	0	0	0.3294	0	5	0	0	0	0.2162	0
1.5	5	0	2.26	0.5369	-16.151	5	5	0	0.7184	0.2838	-4.5924
1.5	10	0	4.7541	1.1915	-33.978	5	10	0	1.5995	0.5224	-10.504
1.5	15	0	7.2636	2.3285	-52.69	5	15	0	2.615	0.9742	-17.833
1.5	20	0	9.8283	3.9945	-73.248	5	20	0	3.7574	1.6867	-26.781
1.5	25	0	12.19	6.1383	-94.357	5	25	0	4.9757	2.696	-37.339
1.5	30	0	14.323	8.7628	-116.19	5	30	0	6.1995	4.0219	-49.329
Run 2						Run 5					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
3	-15	0	-3.6448	1.261	25.663	7	-15	0	-2.241	0.8772	14.998
3	-10	0	-2.3189	0.6655	15.926	7	-10	0	-1.3199	0.4653	8.3943
3	-5	0	-1.0753	0.3355	7.2923	7	-5	0	-0.5747	0.2553	3.4921
3	0	0	0	0.2369	0	7	0	0	0	0.2009	0
3	5	0	1.0753	0.3355	-7.2923	7	5	0	0.5747	0.2553	-3.4921
3	10	0	2.3189	0.6655	-15.926	7	10	0	1.3199	0.4653	-8.3943
3	15	0	3.6448	1.261	-25.663	7	15	0	2.241	0.8772	-14.998
3	20	0	5.0199	2.149	-36.543	7	20	0	3.3246	1.542	-23.47
3	25	0	6.401	3.3558	-48.648	7	25	0	4.5091	2.5001	-33.702
3	30	0	7.7309	4.8921	-61.928	7	30	0	5.7186	3.7735	-45.474
Run 3						Run 6					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
4	-15	0	-2.9823	1.0747	20.63	10	-15	0	-2.0084	0.8153	13.22
4	-10	0	-1.8602	0.5729	12.472	10	-10	0	-1.1331	0.4228	6.9567
4	-5	0	-0.8492	0.3015	5.5828	10	-5	0	-0.4714	0.2219	2.6819
4	0	0	0	0.2228	0	10	0	0	0	0.1743	0
4	5	0	0.8492	0.3015	-5.5828	10	5	0	0.4714	0.2219	-2.6819
4	10	0	1.8602	0.5729	-12.472	10	10	0	1.1331	0.4228	-6.9567
4	15	0	2.9823	1.0747	-20.63	10	15	0	2.0084	0.8153	-13.22
4	20	0	4.1946	1.8441	-30.159	10	20	0	3.0666	1.459	-21.502
4	25	0	5.4607	2.9166	-41.18	10	25	0	4.2383	2.4005	-31.642
4	30	0	6.7123	4.3087	-53.525	10	30	0	5.4408	3.6558	-43.361

Second Stage Data (Sref = 9.62 [ft^2], Length=48.4 [ft])

Run 7						Run 9					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
15	-15	0	-1.8751	0.7472	12.123	25	-15	0	-1.7898	0.7784	11.582
15	-10	0	-1.0139	0.3892	6.0259	25	-10	0	-0.9371	0.4215	5.5058
15	-5	0	-0.3943	0.2227	2.0954	25	-5	0	-0.3391	0.2586	1.6969
15	0	0	0	0.181	0	25	0	0	0	0.2185	0
15	5	0	0.3943	0.2227	-2.0954	25	5	0	0.3391	0.2586	-1.6969
15	10	0	1.0139	0.3892	-6.0259	25	10	0	0.9371	0.4215	-5.5058
15	15	0	1.8751	0.7472	-12.123	25	15	0	1.7898	0.7784	-11.582
15	20	0	2.9149	1.4141	-20.355	25	20	0	2.8432	1.3865	-19.774
15	25	0	4.0772	2.3624	-30.487	25	25	0	4.0209	2.2879	-29.847
15	30	0	5.2768	3.6145	-42.215	25	30	0	5.2363	3.5056	-41.509

Run 8						Run 10					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
20	-15	0	-1.8196	0.7537	11.744	30	-15	0	-1.7691	0.8219	11.52
20	-10	0	-0.9636	0.3986	5.6689	30	-10	0	-0.9201	0.4594	5.4323
20	-5	0	-0.3589	0.2346	1.8324	30	-5	0	-0.3265	0.2937	1.6244
20	0	0	0	0.1946	0	30	0	0	0	0.2539	0
20	5	0	0.3589	0.2346	-1.8324	30	5	0	0.3265	0.2937	-1.6244
20	10	0	0.9636	0.3986	-5.6689	30	10	0	0.9201	0.4594	-5.4323
20	15	0	1.8196	0.7537	-11.744	30	15	0	1.7691	0.8219	-11.52
20	20	0	2.8757	1.3611	-19.929	30	20	0	2.8186	1.4343	-19.729
20	25	0	4.0556	2.2628	-29.992	30	25	0	3.9922	2.3382	-29.82
20	30	0	5.2262	3.5675	-41.713	30	30	0	5.204	3.5569	-41.502

Third Stage Data (Sref=9.62 [ft^2], Length=15.2 [ft])

Run 1						Run 3					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
1.5	-15	0	-1.9899	0.866	4.6853	4	-15	0	-0.944	0.4949	2.0372
1.5	-10	0	-1.2799	0.5286	2.9559	4	-10	0	-0.6059	0.3206	1.2483
1.5	-5	0	-0.5821	0.3391	1.3366	4	-5	0	-0.2814	0.2215	0.5574
1.5	0	0	0	0.2776	0	4	0	0	0	0.1909	0
1.5	5	0	0.5821	0.3391	-1.3366	4	5	0	0.2814	0.2215	-0.5574
1.5	10	0	1.2799	0.5286	-2.9559	4	10	0	0.6059	0.3206	-1.2483
1.5	15	0	1.9899	0.866	-4.6853	4	15	0	0.944	0.4949	-2.0372
1.5	20	0	2.6994	1.3516	-6.5564	4	20	0	1.2913	0.7502	-2.9375
1.5	25	0	3.3336	1.9618	-8.4656	4	25	0	1.631	1.0892	-3.9495
1.5	30	0	3.9031	2.7019	-10.445	4	30	0	1.9484	1.5125	-5.0606

Run 2						Run 4					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
3	-15	0	-1.0967	0.5436	2.4403	5	-15	0	-0.8609	0.4691	1.8159
3	-10	0	-0.7073	0.3477	1.5168	5	-10	0	-0.549	0.3066	1.0961
3	-5	0	-0.3277	0.2365	0.6819	5	-5	0	-0.2547	0.2145	0.4853
3	0	0	0	0.2016	0	5	0	0	0	0.186	0
3	5	0	0.3277	0.2365	-0.6819	5	5	0	0.2547	0.2145	-0.4853
3	10	0	0.7073	0.3477	-1.5168	5	10	0	0.549	0.3066	-1.0961
3	15	0	1.0967	0.5436	-2.4403	5	15	0	0.8609	0.4691	-1.8159
3	20	0	1.488	0.8272	-3.4585	5	20	0	1.1879	0.7108	-2.6629
3	25	0	1.8624	1.2009	-4.5701	5	25	0	1.5122	1.0344	-3.6314
3	30	0	2.2047	1.661	-5.7677	5	30	0	1.8185	1.4397	-4.7077

Third Stage Data (Sref=9.62 [ft^2], Length=15.2 [ft])

Run 5						Run 8					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
7	-15	0	-0.7761	0.4437	1.5906	20	-15	0	-0.6802	0.4247	1.3338
7	-10	0	-0.4885	0.2863	0.9324	20	-10	0	-0.4126	0.2827	0.7272
7	-5	0	-0.2272	0.1934	0.4042	20	-5	0	-0.1852	0.2054	0.29
7	0	0	0	0.167	0	20	0	0	0	0.1819	0
7	5	0	0.2272	0.1934	-0.4042	20	5	0	0.1852	0.2054	-0.29
7	10	0	0.4885	0.2863	-0.9324	20	10	0	0.4126	0.2827	-0.7272
7	15	0	0.7761	0.4437	-1.5906	20	15	0	0.6802	0.4247	-1.3338
7	20	0	1.0849	0.6754	-2.3931	20	20	0	0.9769	0.6409	-2.1051
7	25	0	1.3972	0.9859	-3.3293	20	25	0	1.2833	0.9363	-3.0226
7	30	0	1.6958	1.3772	-4.3832	20	30	0	1.5798	1.3123	-4.0625
Run 6						Run 9					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
10	-15	0	-0.7272	0.4183	1.4448	25	-15	0	-0.6715	0.4406	1.3248
10	-10	0	-0.4507	0.2725	0.8217	25	-10	0	-0.4057	0.2986	0.7175
10	-5	0	-0.2069	0.1923	0.3476	25	-5	0	-0.1809	0.222	0.2821
10	0	0	0	0.1677	0	25	0	0	0	0.1984	0
10	5	0	0.2069	0.1923	-0.3476	25	5	0	0.1809	0.222	-0.2821
10	10	0	0.4507	0.2725	-0.8217	25	10	0	0.4057	0.2986	-0.7175
10	15	0	0.7272	0.4183	-1.4448	25	15	0	0.6715	0.4406	-1.3248
10	20	0	1.0282	0.642	-2.225	25	20	0	0.9667	0.6566	-2.0973
10	25	0	1.3334	0.9519	-3.1516	25	25	0	1.272	0.9513	-3.0163
10	30	0	1.6254	1.3429	-4.201	25	30	0	1.5678	1.3261	-4.0576
Run 7						Run 10					
mach	alpha	beta	cl	cd	cm	mach	alpha	beta	cl	cd	cm
15	-15	0	-0.6943	0.4165	1.3618	30	-15	0	-0.6648	0.464	1.326
15	-10	0	-0.4243	0.2737	0.7528	30	-10	0	-0.4008	0.3201	0.7162
15	-5	0	-0.1922	0.1959	0.3073	30	-5	0	-0.178	0.2425	0.2794
15	0	0	0	0.1722	0	30	0	0	0	0.2186	0
15	5	0	0.1922	0.1959	-0.3073	30	5	0	0.178	0.2425	-0.2794
15	10	0	0.4243	0.2737	-0.7528	30	10	0	0.4008	0.3201	-0.7162
15	15	0	0.6943	0.4165	-1.3618	30	15	0	0.6648	0.464	-1.326
15	20	0	0.9925	0.6337	-2.1336	30	20	0	0.9582	0.6808	-2.1015
15	25	0	1.2999	0.9305	-3.051	30	25	0	1.2616	0.9757	-3.0235
15	30	0	1.597	1.3082	-4.0904	30	30	0	1.5557	1.35	-4.0678

Appendix B: POST sample input file

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c   Simple 3-D POST trajectory to simulated a rubberized
c   Atlas III-like TSTO ELV.
c
c   Modified for Microcosm Sprite (3 Stages) by Kohei Taya
c   108 nm altitude from KSC
c
c   written by: John R. Olds (Georgia Tech)
c               December, 1999
c cccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c     *** set up optimization inputs ***
c
l$search
   ioflag  = 0,                  / english input, english output units
   opt     = 1,                  / optimizer should maximize
c  opt     = 0,                  / target only
   maxitr  = 30,
   ipro    = -1,                 / print only the final, optimized trajectory
c
c    *** optimization variable ***
c
   optvar  = 6hweight,           / maximize the final weight (payload)
   optph   = 1000,               / optimize at the end of booster stage
c
c    *** constraint variables ***
c
     ndepv   = 6,
     depvr   = 'gdalt','gammai','inc','veli','xmax2','xmax6', /names of dependent variables
     depval  = 656640.0, 0.0, 28.5,25540.42841,50.0,1500.0,   /target values
     deptl   = 100.0,0.05,0.1,10.0,1.0,1.0,                  /targeting criteria(allowable errors)
     depph   = 1000,1000,1000,1000,800,800,
c
c    *** simulation control variables (u's) ***
c
   nindv   = 18,
   tabl    = 6*'pitt',5*'pitt',5*'pitt',
   tably   = 3,4,5,6,7,8,1,2,3,4,5,1,2,3,4,5,
   indvr   = 'tabl1','tabl2','tabl3','tabl4','tabl5','tabl6','tabl7','tabl8','tabl9',
    'tabl10','tabl11','tabl12','tabl13','tabl14','tabl15','tabl16','wstpd4','azl',
   indph   = 6*1,5*500,5*800,1,1,
c
c    *** initial guesses for u's ***
c

 u=  -10,-20,-30,-40,-50,-60,-70,-80,-80,-80,-80,-80,-80,-80,-80,-80,700,90,

c cccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c  Projected Gradient Options
c  (comment out this block if using npsol)
c
   srchm   = 5,                  / use accelerated projected gradient
   idepvr  = 0,  0,  0,  0, 1, 1,
c  modew   = 0,                  / use manual weighting for u's
c  wvu     = 1e-3,2*2e-2,3e2,5*2e-01,1e-02,
   pert    = 18*1e-5,
c  coneps  = 89.99,0,0,0,0,0,       / tighten optimality criteria
   pctcc   = .5,                 / limit maximum change in u's for targeting
   npad(1) = 0,                  / ignore requirements on pert precision
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
```

```
c  NPSOL Options
c  (comment out this block if using projected gradient)
c
c   srchm   = 6,                    / use npsol
c   depvub  = 6.080e5,   0,   10000,   0,
c   depvlb  = 6.080e5,   0,       0,   0,
c   deptl   = 100,    .005,       2,   1,
c   indpub  = 1000,0,0,0,0,0,0,
c   indplb  = 0,-70,-90,-90,-90,-100,-150,
c   wopt    = 100,
c   wvnlc   = 10000,1,10,
c   wvu     = 100,20,100,100,100,100,100,
c   isens   = 3,                  /  automatic pert control from npsol
c   isens   = 1,                  /  user selected central differences
c   pert    = 1e-6,6*1e-7,
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
 $
c    *** trajectory simulation inputs ***
c
l$gendat
   title=0h*Scorpius Sprite*,
   event   = 1,
   fesn    = 1000,           / final event number
   npc(1)  = 3,              / Keplerian conic calculation flag
   npc(2)  = 1,              / fourth order runge-kutta
   dt      = 1,              / integration step size
   lref    = 53.3,           / body length
   pinc    = 30,             / print interval
   prnc    = 0,
c    *** initial conditions ***
   npc(3)  = 4,              / earth relative velocity components
c    azl     = 90,           / rotate L coordinates so that Z points due east
   npc(4)  = 2,              / geocentric position components
   gdalt   = 20,             / initial altitude - feet
   gdlat   = 28.4583,        / Kennedy Space Center
   long    = 279.4728,
   npc(5)  = 5,              / 1976 standard atmosphere
   npc(7)  = 1,              / limit accelaration using etal
   asmax   = 6.4,            / asmax is the maximum number of g's allowed
   npc(8)  = 2,              / cl and cd aero inputs
   sref    = 67.34,          / aero reference data is max cross sectional area (guess)
   npc(9)  = 1,              / use thrusting engines (rather than delta V's)
   npc(12) = 1,              / calculate downrange and crossrange distances
   npc(15) = 1,              / calculate heating using Chapman's equation
   npc(16) = 1,              / use spherical planet for gravity model
   npc(21) = 1,              / calculate prop brun
   npc(25) = 2,              / calculate velocity losses
   npc(27) = 1,              / integrate to find prop flow rates
   npc(30) = 3,              / use enhanced weight model (steps)
c
c   *** enhanced weight model - 4 steps , 3 engines
c
  ispv  =  285.05, 317.27, 330.06, / engine 1, engine 2, engine 3 (All LOX/Kerosene)
  iengmf=     1,     0,    0, / which engines are on and what type
  ienga =     1,     1,    1, / use engine throttle to limit acceleration
  iwdf  =     2,     2,    2, / type of flowrate calculation (isp table or const).
  iwpf  =     1,     1,    1, / include 3 engines in flowrate calculations
  nengl = 1,                 / lowest number of all engines
  nengh = 3,                  / highest number of all engines (= total number of engine)
  nstpl = 1,                 / lowest number of all steps
  nstph = 4,                 / highest number of all steps (= total number of step)
  wstpd(1)= 67962.48,        / Step 1 Gross Weight (0.5% Startup losses)
  wstpd(2)= 11549,           / Step 2 Gross Weight
  wstpd(3)= 3090,            / Step 3 Gross Weight
```

```
c
   menstp   = 1,2,3,           / map each engine to a specific step
   mentnk   = 1,2,3,           / map each engine to a specific tank
   istepf   = 1,1,1,1,         / include all steps in calculation of dry weight
c
c
c    *** guidance inputs ***
c
   iguid(1)  = 1,0,
   iguid(4)  = 2,   / inertial Euler angles with table look up
c
   monx      = 'dynp', 'alpha', 'heatrt', 'asmg',  'gdalt', 'qalpha',/ monitor variables
   maxtim    = 1600,        /max time of flight
   altmax    = 10000000,    /max alt
   altmin    = -100,        /min alt
c
c
c    *** print block ***
c
   prnt(97)= 'wprus1','wprus2','wprus3',
           'wpru1','wpru2','wpru3',
           'thr1','thr2','thr3',
           'isp1','isp2','isp3',
           'dynpdt',
           'xmin1','xmax1',
           'xmin2','xmax2',
           'xmin3','xmax3',
           'xmin4','xmax4',
           'xmin5','xmax5',
           'xmin6','xmax6',
           'netisp',
           'timrf1','timrf2','timrf3',
           'videal',
           'pstop',
  $
l$tblmlt tvc1m = 1.0,
  $
c
c    *** inertial pitch angle table includes vertical rise segment ***
c
l$tab
  table= 'pitt',1,'time',8,1,1,1,
  0,    0,
  5,    0,   / Forced to be vertical for 5 seconds
  15,   0,
  30,   0,
  60,   0,
  90,   0,
  120,  0,
  180,  0,
  $
c
c    *** include APAS aerodynamic coefficients table for 1st stage ***
c
*include '/ssdldsk/ae6322a/Kohei_Taya/POST/1ststage.aero'
l$tab
c
c    *** Thrust at liftoff ***
c
   table = 5htvc1t,0,122400, /Vacuum thrust of 6 engines (1st stage)
  $
l$tab
c
c    *** exit area for engine 1 (ft^2) ***
c
   table = 4hae1t,0,9.276,
   endphs = 1,
  $
```

```
l$gendat
c
c     *** enent 110 ***
c
c     *** 1st stage burns out ***
c     *** prop weight accounts for 1% residuals at separation ***
c
  event    = 110, critr='wprus1', value = 57131.4, /usuable prop used on 1st stage
  wsjtd(1) = 10834.5,  /dry weight and prop residuals of 1st stage
  iengmf   = 0, 0, 0,
  nengl    = 2,
  nstpl    = 2,
  endphs   = 1,
  $
l$gendat
c
c     *** event 500 ***
c
c     *** coast for 5 seconds then start 2nd stage engine ***
c
  event    = 500, critr = 5htdurp, value = 5,
  iengmf   = 0, 1, 0,
c
c     *** turn on timer for second pitch table ***
c
  dtimr(1) = 1,
  sref  = 9.62,  / aero reference data is max cross sectional area
  $
l$tblmlt tvc2m = 1.0,
 $
c
c     *** include APAS aerodynamic coefficients table for 2nd stage ***
c
*include '/ssdldsk/ae6322a/Kohei_Taya/POST/2ndstage.aero'
c
c     *** start new pitch angle steering table ***
c
l$tab
  table=4hpitt,1,6htimrf1,8,1,1,1,
  0,    0,
  10,   0,
  60,   0,
  90,  0,
  120,  0,
  150,  0,
  180,  0,
  210,  0,
  $
l$tab
c
c     *** 2nd stage engine ***
c
  table = 5htvc2t,0,22700,  /vacuum thrust of 2nd stage engine
  $
l$tab
c
c     *** exit area for 2nd stage engine ***
c
  table = 4hae2t,0,7.069,
  endphs = 1,
  $
l$gendat
c
c     *** event 600 ***
c
c     *** Fairing Separation at dynp=1.0 psf w=165 lbs ***
c
  event=600,1,critr=4hdynp,value=0.5, /separation by dynp=0.5 psf
```

```
  mdl=3, /Event will only be initiated if derivative of dynp is negative
  wsjtd(3) = 165,
  endphs = 1,
  $
l$gendat
c
c    *** 2nd stage burns out ***
c    *** prop weight accounts for 1% residuals at separation ***
c
  event    = 700,0, critr='wprus2', value = 9601.02, /usuable prop used on 2nd stage
  mdl = 1,  /Event will only be initiated if derivative of wprus2 is positive (default)
  wsjtd(2) = 1947.98, /dry weight and prop residuals of 2nd stage (the fairing has already been released)
  iengmf   = 0, 0, 0,
  nengl    = 3,
  nstpl    = 3,
  endphs   = 1,
  $
l$gendat
c
c    *** coast for 5 seconds then start 3rd stage engine ***
c
  event    = 800, critr = 5htdurp, value = 5,
  iengmf   = 0, 0, 1,
c
c    *** turn on timer for third pitch table ***
c
  dtimr(2)    = 1,
  sref  = 9.62,  / aero reference data is max cross sectional area
  $
l$tblmlt tvc3m = 1.0,
 $
c
c    *** include APAS aerodynamic coefficients table for 3rd stage ***
c
*include '/ssdldsk/ae6322a/Kohei_Taya/POST/3rdstage.aero'
c
c    *** start new pitch angle steering table ***
c
l$tab
  table=4hpitt,1,6htimrf2,5,1,1,1,
  0,    0,
  50,   0,
  100,  0,
  200,  0,
  500,  0,
  $
l$tab
c
c    *** 3rd stage engine ***
c
  table = 5htvc3t,0,2300,  /vacuum thrust of 3rd stage engine
  $
l$tab
c
c    *** exit area for 3rd stage engine ***
c
  table = 4hae3t,0,4.565,
  endphs = 1,
  $
l$gendat
c
c    *** 3rd stage burns out when all prop are used ***
c
  event    = 900, critr='wprus3', value = 2486.88, /usable prop used on 3rd stage
  wsjtd(3) = 413, /dry weight of 3rd stage (the fairing has already been released)
  iengmf   = 0,0,0,
  pinc     = 1,
c
```

```
c     *** begin to fly zero angle of attack for minimum drag ***
c
  iguid(1) = 0,0,0,
  iguid(3) = 1,
  alppc(1) = 0,
  nstpl    = 4,
  nstph    = 4,
  endphs   = 1,
  $
l$gendat
c
c     *** this is the final event ***
c
  event   = 1000,critr=5htdurp,value=0.0,
  endphs  = 1,
  endjob  = 1,
  endprb  = 1,
  $
```