NASA Advanced Concepts Office, Earth-To-Orbit Team Design Process and Tools

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The Earth to Orbit (ETO) Team of the Advanced Concepts Office (ACO) at NASA Marshal Space Flight Center (MSFC) is considered the preeminent group to go to for pre-phase A and phase A concept definition. The ACO team has been at the forefront of a multitude of launch vehicle studies determining the future direction of the Agency as a whole due, in part, to their rapid turnaround time in analyzing concepts and their ability to cover broad trade spaces of vehicles in that limited timeframe. Each completed vehicle concept includes a full mass breakdown of each vehicle to tertiary subsystem components, along with a vehicle trajectory analysis to determine optimized payload delivery to specified orbital parameters, flight environments, and delta v capability. Additionally, a structural analysis of the vehicle based on material properties and geometries is performed as well as an analysis to determine the flight loads based on the trajectory outputs. As mentioned, the ACO Earth to Orbit Team prides themselves on their rapid turnaround time and often need to fulfill customer requests within limited schedule or little advanced notice. Due to working in this fast paced environment, the ETO team has developed some finely honed skills and methods to maximize the delivery capability to meet their customer needs. This paper will describe the interfaces between the 3 primary disciplines used in the design process; weights and sizing, trajectory, and structural analysis, as well as the approach each discipline employs to streamline their particular piece of the design process.

I. Introduction

The Earth to Orbit (ETO) Team from the Advanced Concepts Office (ACO) at Marshall Space Flight Center (MSFC) is the primary go-to group for preliminary design of launch vehicles within National Aeronautics and Space Administration (NASA) as a whole. They operate as the frontline for most vehicle architecture studies that are kicked off at an agency level and have been the performance assessment team for many high level studies. Some of the past studies include the complete trade space for all Exploration Systems Architecture Study (ESAS) vehicles as well as supplying vehicle performance data for the Augustine Report and leading the definition of the Ares V Heavy Lift Vehicle for Constellation. Within the last three years the team has analyzed over 2,500 launch vehicle concepts and pride themselves on the quick turnaround times required to meet customer requests, averaging 4 completed vehicle designs a day. The vehicle concept analyses that ACO produces are generally optimized to deliver the

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maximum payload capability to the desired orbit and are strictly performance driven. Within each study the vehicles that define the trade space are all designed to the same assumptions and reported to the customer in order for the concepts to be compared on equal footing. Presented here is the methodology that the ETO Team uses in order to maintain their edge in rapid response to customer requests.

II. Design Tools

The ETO Team is divided into three primary disciplines. Each discipline is responsible for one part of the vehicle design process and each has a specialized tool set to accomplish this: initial weights and sizing is performed in INTegrated Rocket Sizing (INTROS), trajectory analysis is run through Program to Optimize Simulated Trajectories (POST), structures and load analysis is done with Launch Vehicle Analysis (LVA). Both INTROS and LVA are software tools written and developed by the Advanced Concepts Office for the specific purpose of launch vehicle performance optimization. POST on the other hand is a Government off the Shelf (GOTS) program that has the versatility to support the optimization of maximizing or minimizing vehicle parameters.

A. INTROS

INTROS is an analytical tool that was developed at MSFC to establish launch vehicle designs and sizing. It is written in Visual Basic for Applications computer language and uses the Excel application for all input and output. Launch vehicle design and sizing are based on stage geometry and mass properties. Mass properties are established for selections from a large master list of launch vehicle systems, subsystems, propellants and fluids. Mass calculations are based on mass estimating relationships (MERs) that are automatically generated from a large database of MERs that is built into the program. Program mass calculation accuracy for existing and historical launch vehicles has been verified to be well within 5%.

B. LVA

LVA is a standalone application written at MSFC in Visual Basic that provides extremely fast launch vehicle loads, structural design and analysis. It is important to note this program does not use weight estimating or scaling routines – it supplies detailed analysis by using time proven engineering methods based on material properties, load factors, aerodynamic loads, stress, elastic stability, deflection, etc. For the fastest turnaround, the program is designed to work with the absolute minimum of input data. The output data is purposely limited to the least possible quantity to prevent the analyst from having to dig through a large amount of data for the necessary information. The max q and max g values are run as the maximum loads for the class of vehicle. Loads are run as a single combined worst case. Structural analysis is run to within 5%-10% of closing, the results are these values.

C. POST

POST is a FORTRAN 77 based legacy code developed by NASA Langley for detailed trajectory simulations. From the POST user's manual, Volume II:

> 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 exo-atmospheric orbital transfer problems. The generality of the program is evidenced by its N-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.

III. Design Process

The process used for the preliminary performance and sizing of launch vehicle concepts is shown in Figure 1.

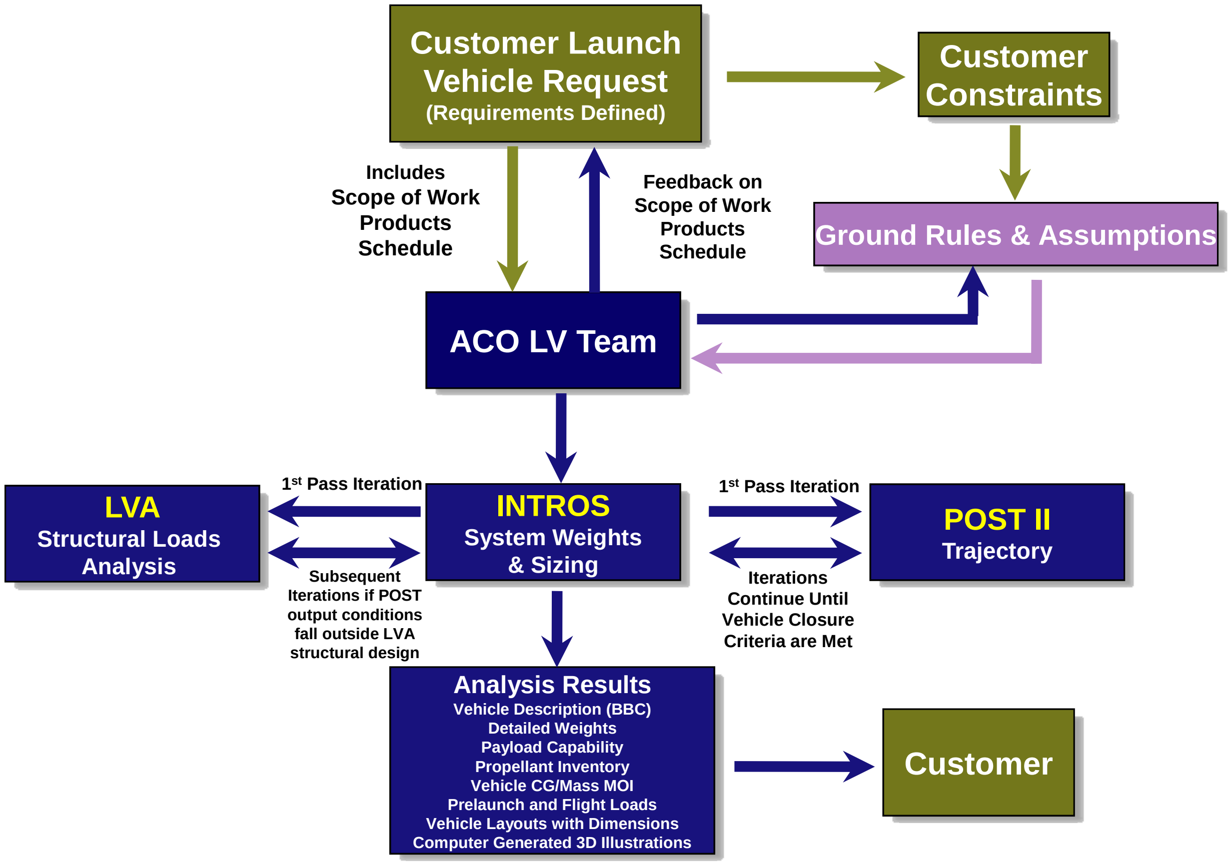

Figure 1. ETO Team Design Process Flow Chart.

For all studies the process begins with drafting a Ground Rules and Assumptions (GR&A) document. The GR&A document is designed to capture the customer requirements as well as present the justifications for all assumptions the ETO Team makes. Once the team and customer reach consensus on the GR&A and everyone signs off on the document the ETO Team begins their work. The first step is building a vehicle model in INTROS. With the geometry defined and the necessary subsystems selected, a mass statement is created; this is sent to the trajectory analyst. With the INTROS output and the conditions described in the GR&A the trajectory analyst can build the input files for POST. The trajectory is optimized within the given constraints and the delivered payload to orbit is found along with the flight load environment the vehicle experiences on ascent. These trajectory outputs are sent back to INTROS so the vehicle can be resized with the new payload value. The weights and sizing analyst then sends the vehicle geometry, material properties, and the load environment from the trajectory run to LVA. The structural analyst evaluates the load conditions and the vehicle geometry, and returns the new structural mass properties to the INTROS analyst, based on material properties and the design necessary to maintain structural integrity during flight. INTROS is updated with the new structural mass values and predicts a new payload value, and a new mass statement is sent to POST.

This is where the iterative part of the process begins. If the loads environment has not significantly changed from the previous trajectory run after the next POST run, then the current structural masses do not need updating, so the LVA updated step is considered complete and iteration will only occur between POST and INTROS. The iterative process continues until the payload estimate from INTROS is within an acceptable closure criterion of the optimized payload found by POST. Once this criterion is reached the vehicle is considered closed and optimized. The final step of the process is detailing the vehicle results for the customer. The INTROS analyst is responsible for compiling all the vehicle data and creating what is called a vehicle baseball card. Details on what a typical baseball card given to the customer are presented later in the final products section. If there is any additional analysis that is requested outside the scope of what the ETO Team performs, for example cost or reliability, the team provides an output data set for those analysis groups.

A. Ground Rules and Assumptions (GR&A)

Typical of most GR&A, the purpose is to capture and quantify all assumptions that could drive the maturation or down selection of a design. It also provides the basis of knowledge that all concepts are comparable to each other and any vehicle specific accommodations in the design process are documented. Each of the three design disciplines has its own section within the document to define how they will approach their area of expertise and what general inputs they will use in their modeling tools. For weights and sizing these inputs include mass margin justifications, fluid densities, ullage definitions, and propellant allocations. Structural definitions include factors of safety, application of load conditions, propellant tank pressures, and material properties. The trajectory specific inputs define many of the event based criteria used in building the trajectory model along with the upper bounds for the acceleration and dynamic pressure limits. Additional trajectory inputs established are the gravity model, atmospheric flight conditions, monthly variations or mean annual temperatures and winds, and launch location.

The GR&A document also contains general information that is important to all three disciplines which often overlaps with customer driven requirements. The customer may provide items such as vehicle configurations to be analyzed, the engines and engine parameters that they want used in the vehicle study, the final orbit or destination that the maximum payload will be delivered to, and finally the definition of what that payload is. In fact the payload section is often further subdivided into how payload is defined as well as shroud related topics such as payload density and volume as well as shroud drop criteria.

B. Weights and Sizing

Although the ETO team as a whole develops and analyzes a launch vehicle concept from different perspectives (i.e., mass properties, structures and trajectory), the INTROS analyst is ultimately responsible for formally initiating and finalizing the analysis team process. The INTROS analyst first establishes a baseline vehicle concept within the defined GR&A document scope and insures that the GR&A are maintained as the concept iterates and evolves. Upon completion the analyst then creates a vehicle summary sheet to describe overall performance, capability, mass estimates, and geometry. As the team's process integrator, the INTROS analyst is also primarily responsible for managing all vehicle configurations such that organization and traceability within the team are maintained.

The INTROS analyst first establishes a baseline launch vehicle concept by implementing all GR&A's starting with system level attributes such as stage configuration, crew and/or cargo payload(s), and reusability. Stage configurations can include strap-on boosters for additional liftoff thrust, for example, and typically anywhere from two to four stages in either serial or clustered configurations. Likewise, payload configurations can also be rather unique so vehicle mass estimates can therefore vary substantially depending on whether the payload consists of crew and/or cargo. Requirements such as reusability, mission duration, and payload capability must be defined upfront as these potential attributes very much impact mass estimates depending on the size of the vehicle; otherwise, performance impacts can be tracked to show a range of payload capability, for example.

Following overall system configuration definition, propulsion system and stage component geometries are defined to help establish propellant load requirements as well as the vehicle's outer mold line, two essential inputs required for POST. Standard propulsion system inputs include ullage fraction, propellant type, mixture ratio, tank pressure, and engine performance parameters and geometries (if known), some of which are also used by LVA to assist in further refining component structural masses. Stage dry component geometries including, but not limited to, forward and aft skirts, compartments, interstages, and intertanks, are normally defined using standard clearances suggested within ACO unless the GR&A document notes otherwise such as restrictions due to assembly building height. The payload shroud is typically determined from a joint effort between INTROS and LVA where payload density and optimal shape are some of the main inputs. As the vehicle analysis iterates, the component geometries are adjusted with respect to mixture ratio until a particular payload capability requirement is met, unless geometric restrictions prohibit component adjustments.

With all stage structures and the main propulsion system defined, other subsystems are selected from an Architectural Breakdown Structure (ABS), a large list of subsystems which are a result of many years of NASA experience and knowledge in successfully designing complex launch vehicles. Each subsystem selected generates a specific mass estimate from a unique Mass Estimating Relationship (MER) embedded within INTROS.

At the conclusion of working down through the ABS, a subsystem mass properties list is created summing all internal dry structures, propellant and residual masses internal subsystem component masses, and the payload. The list allows for a Mass Growth Allowance (MGA) to be assumed since it is likely that the vehicle concept being analyzed has not fully come to fruition. All important masses are then compiled and a simplified image of the vehicle is drawn to create a vehicle summary sheet that officially serves as the standard customer deliverable.

An additional task performed by the INTROS analyst is that of error checking. The INTROS analyst reviews the LVA drawings to insure the correct geometry is being used by the LVA analyst. In addition, the LVA mass numbers are also reviewed for any out of family values for vehicle components. This part of the review process relies heavily on the experience level of the INTROS analyst. POST results are also checked with ideal rocket equation calculations that have been setup within INTROS. These calculations not only check the POST results but also provide the INTROS analyst with the necessary information to pin point any discrepancy. The INTROS analyst is then able to guide the POST analyst to a specific event in the POST deck that has a potential error. This set of checks and balances has allowed the Launch Vehicle Team to minimize total simulation time while providing high confidence in the final products provided to the customer.

C. Trajectory

With the completion of the GR&A document the trajectory analyst has a good starting point on how the input deck should be setup. The input deck is the term used to describe the input files needed to perform a trajectory analysis and is so named from historical precedent of using punch cards. A deck of punch cards would be required to make a trajectory run. The GR&A document contains the configurations to be analyzed and the initial conditions the vehicle will experience on the pad. Knowing these things the analyst can begin filling out the trajectory template that the ETO team uses. Since the template is meant to be useful across multiple vehicle configurations the events are generic and are common among all launch vehicles. Table 1 lists the event number and corresponding vehicle action.

Table 1. POST Trajectory Template

Event	Vehicle Action
1	Vehicle on Launch Pad / initial conditions
5	Acceleration check, T/W > 1.0, release hold down
10	Tower clear, first pitch over event
20	Initiate gravity turn
30-35	Throttle events to limit dynamic pressure
50	Booster jettison
60	Core jettison
65	Upper stage ignition
70	Shroud jettison
110-170	Optimizing steering profile
900	Main engine cutoff criteria
1000	Final orbital condition

Using the template as described above the trajectory analyst can create most launch vehicle concepts that ACO is requested to analyze. The template is also flexible enough in structure to enable the addition of other events of similar type when the need arises, which is quite often in pre-phase A conceptual analysis. As an example, if a 3 stage vehicle is being considered the analyst will add events 80 and 85 for the second stage shutdown/jettison and third stage ignition respectively. Also if the time based spacing for the optimized steering profile is longer than the burn time of the stages of the vehicle some steering events can be removed so the entire optimized profile is only events 110 through 150. The flexibility and modular approach to the trajectory setup means that only minor changes need to be made from one trajectory input file to another. This increases the capability the analyst has to optimize several vehicle designs in a day and makes the hand-off of trajectory files between any two analysts as seamless as possible.

With the structure of the trajectory file built the analyst then takes the INTROS mass properties sheet and inputs the vehicle data into the trajectory file. The analyst inputs generic stage weights of total propellant available to burn and the jettison or burnout mass of each stage. The amount of propellant available to burn for each stage is only the propellant value that adds to the vehicles ideal velocity. Propellant values of RCS thrusters, OMS devices, or any other maneuvering propulsion elements are not included since they do not contribute significantly to the ideal velocity of ascent. Likewise, tank bias, reserve, and residuals are not included in the available propellant value; these are considered as part of the burnout or jettison mass of the stage.

The trajectory analyst also needs to modify the engine data specific to each vehicle. This will involve possibly changing out the thrust trace table for any solid motor that will be strapped on or changing the liquid engine inputs. The INTROS data sheet provides the thrust level, engine isp, and exit area which are the primary inputs used to establish the engines in POST. Sometimes additional engine data related to throttle levels is needed if the vehicle will violate a maximum dynamic pressure or acceleration limit, as described in the GR&A.

The INTROS datasheet also includes reference areas that need to be updated to accurately model the aerodynamics of the vehicle. Due to the varying range of vehicle concepts that ACO analyzes there are often vehicles with different stage diameters as well as concepts with multiple solid motors strapped on to the vehicle core stage. To accurately model these changes new reference areas are calculated and scaled to the ETO team's existing aerodynamic data. Since the ETO team does not have the capability or the design time to create new aerodynamics for every vehicle concept the ETO team uses a generic vehicle model and scale based on reference area.

With the INTROS datasheet inputs incorporated into the trajectory deck the analyst can begin to form a preliminary steering profile for the vehicle as well as the initial payload estimate. The array of these values is known as the u-vector. The steering part of the u-vector corresponds to the pitch rates the trajectory code will optimize to reach the final orbital parameters. The analyst is looking for a starting profile that is a gentle sweep in attitude without violating the maximum and minimum altitude constraints and does not complete the trajectory with any negative mass. Also, there should be no dramatic changes in rate that may exceed what the vehicle control system is capable of handling.

Once this starting u-vector is defined POST can typically perturb the components of the u-vector in order to find the optimal values that will result in the trajectory meeting all boundary conditions. If POST does not successfully reach an optimal solution the analyst needs to determine which of the initial u-vector values limited the optimization and change it manually. Optimization is considered to have occurred when all the variables in the u-vector have reached a maximum or minimum value that any further change in their value will mean that the optimized variable of the trajectory, typically payload, does not change within the bounds of a set error value. When this occurs POST will stop running and create an output file with the final optimized u-vector results.

The post processing of the trajectory results consists of a closed case summary, a blank sample summary is provided in Figure 2. The summary is broken down in to flight events and lists the times and states of other select variables at those times. The closed case summary is one of the methods used to error check in the design process. The closed case summary lists the total delta-v values as well as the accelerations at each of the staging, and possibly throttling, events during flight. These values can be cross checked with the INTROS values that are expected to occur at these events. As long as these values match within a few percent no errors are considered to have been made. There are some instances where the closed case summary does not provide enough detail of the trajectory, in this case a comma delimited file can also be supplied that has a complete listing of vehicle variables for every time step as set by the analyst.

Closed Case Summary to 100x100 nmi @28.5°

Liftoff to SRM staging
GLOW = lbs
T/W at RSRB ignition =
Stage 1 throttle @ liftoff =
Maximum T/W during RSRM burn =

Max Q
Maximum Q = psf

RSRB jettison
Time of RSRB jettison = sec
dVideal @ jettison = ft/s
T/W after RSRB jettison =
Stage 1 throttle @ stg+ =
Stage 1 propellant remaining after RSRB jettison = lbm
Maximum T/W during stage 1 burn =

Core jettison
Time of jettison = sec
dVideal @ jettison = ft/s

Stage 2 ignition (Stg2 only)
Time of stage 1 jettison = sec
dVideal @ jettison = ft/s
T/W after stage 1 jettison =
Stage 2 throttle @ stg+ =
Maximum T/W during stage 2 burn =

Shroud/LAS jettison
Time of jettison = sec
dVideal @ jettison = ft/s

At EDS MECO / Orbital Insertion
Time to MECO = sec
MECO altitude = ft
Perigee alt = nmi
Apogee alt = nmi
Inclination = °
dVideal @ MECO = ft/s
Injected mass = lb

Figure 2. Trajectory Closed Case Summary.

This closed case summary is also where the loads the vehicle will experience in flight are captured. The summary provides the maximum dynamic pressure, undispersed, as well as the accelerations each stage will undergo on ascent. Again more detailed data can be provided in the comma delimited file indicating pressures and accelerations for the entire trajectory timeline if necessary. The case summary is then sent back to the INTROS analyst for error check, for vehicle resizing, and possibly an update to the structural masses. When the INTROS analyst completes the resizing and the trajectory analyst receives the next iteration for the vehicle the process starts over again.

D. Structural Analysis

From the various design constraints provided by INTROS (inline or sidemount vehicle, booster type, stiffened or monocoque, multi-stage, part length and radius, etc.) and the loads drivers provided by POST (max g, max q, angle-of-attack, etc.), LVA conducts a structural design and analysis and provides a report for the INTROS analyst.

The design constraints are compiled into an input text file with the nosecone of the vehicle described first, then each subsequent part described in order from top to bottom (fore to aft) of the vehicle. The loads drivers are also captured in this input file along with the various structural design options designated in the GR&A. Once this text input file is submitted for processing, several actions occur in the software. First, the text description is translated in a dimensioned vehicle layout drawing, Figure 3. This layout drawing is useful in checking that the input data was entered correctly and that the vehicle description has no logical flaws, such as an intertank providing too little room for the tank domes. This layout drawing is also provided back to the INTROS analyst to make sure the design data provided by INTROS was interpreted correctly. Next, the loads drivers are applied to the vehicle layout to provide prelaunch, launch, and flight loads using aerodynamic and loads analysis codes. The results are provided in a graphical format for both error checking and presentation purposes, Figure 4. Once the dimensioned drawing and loads graph are reviewed, the structural analysis can be performed. Since compression loads are important design loads for launch vehicle structural analysis, the weight of one part is dependent on the weight of the part above it. Also, the bending moment on a part will depend on the weight of part on both its top and the bottom (fore and aft). Therefore, the weights of the various vehicle structural parts have to be iterated with the loads and weights being updated on each pass. LVA iterates to a hundredth of a pound. The time from the text input file submittal to the calculation of the loads is a few tenths of a second, with each structural analysis pass taking one to three seconds. It usually takes 2 to 7 iterations to come up with the final structural weights.

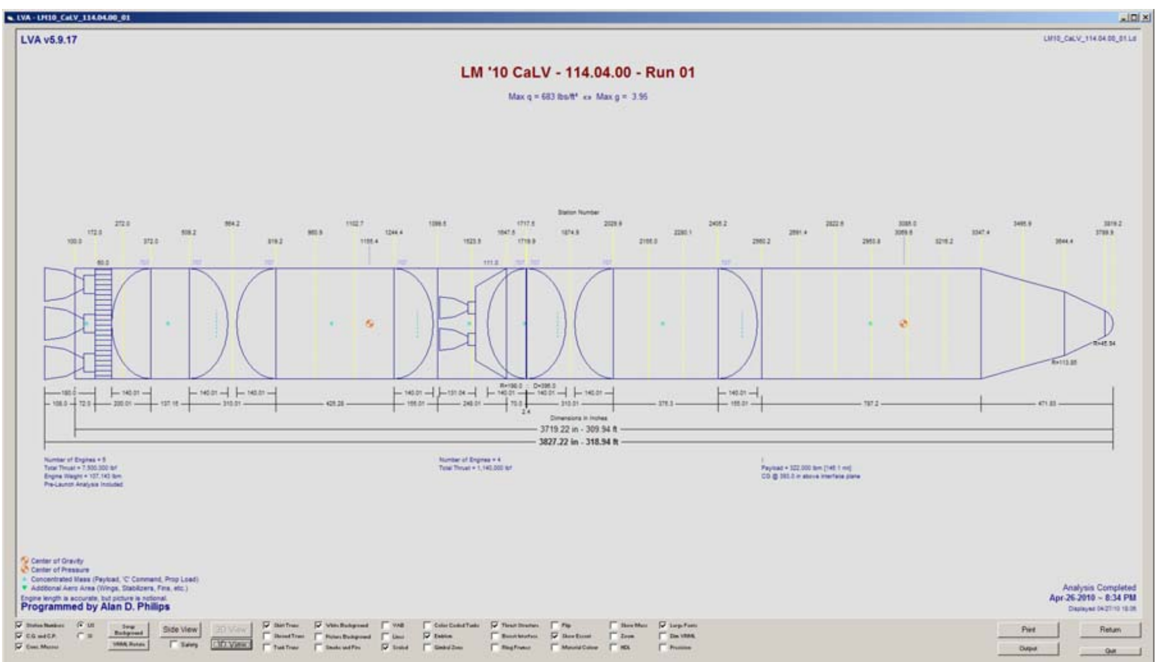

Figure 3. Dimensional Vehicle Layout.

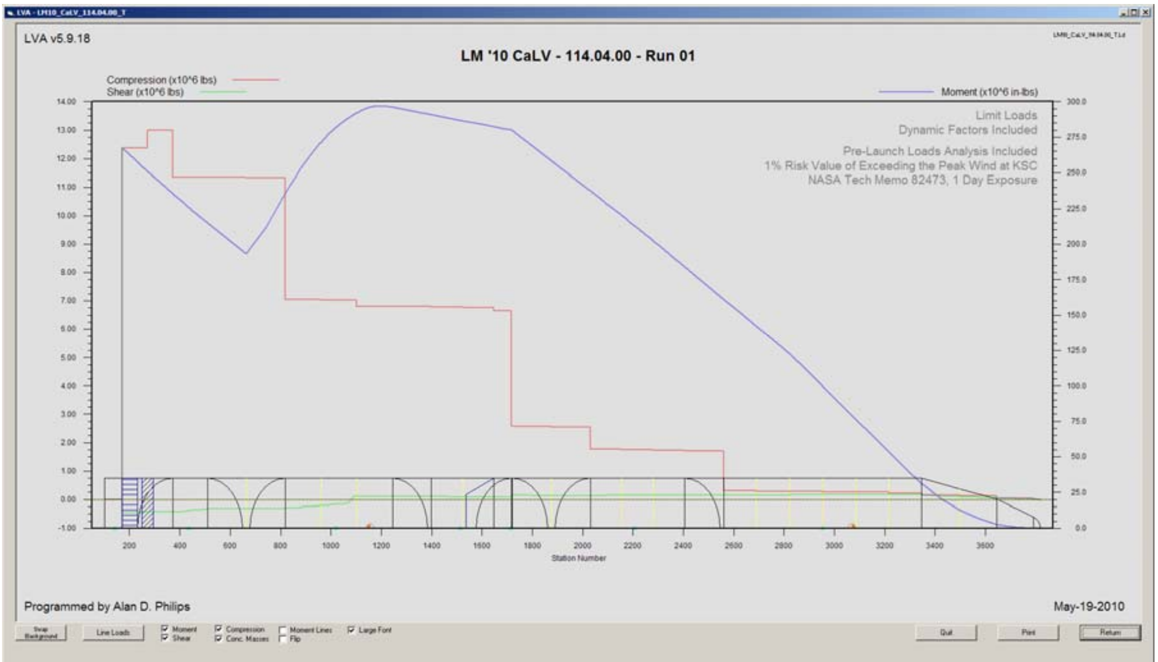

Figure 4. Applied Loads.

The heart of the LVA structural analysis process is its isogrid and orthogrid structural stiffening analysis modules. The isogrid module is directly derived from Isogrid Design Handbook (NASA CR-124075) by McDonnell-Douglas Astronautics Co., April 2004 revision. The equations for the orthogrid module came from the lecture "Launch Vehicle Structural Design" by H. Stanley Greenberg, August 2012 revision. Both modules take the loads and dimensions as compiled by the initial or previous iteration and uses highly effective adaptive iteration routines to determine the optimized stiffened structural weight. The time the module takes to optimize the structural stiffening is less than a second. That weight is compared to the monocoque (or non-stiffened) weight and the lightest design is chosen. The user can also specify monocoque only designs.

All weights produced by LVA are "nominal" weights, i.e. they include tolerances but not mass growth allowance. The structural weights are forwarded to the weights and sizing analyst who then applies the appropriate mass growth allowance and then routes them to the next step of the analysis process.

IV. Finished Product

A. Vehicle Base-Ball Cards (BBC)

After each vehicle is considered closed, determined by the payload mass criteria reported from both POST and INTROS, a one page summary of the vehicle is generated by the weights and sizing discipline. Figure 5 is a blank version of what is called a vehicle base-ball card. The cards are the final product that is delivered to the customer to represent the notional vehicle ACO was requested to analyze. A BBC combines the highlights of the trajectory closed case summary, the stage summed mass totals, as well as engine parameters used in analysis, and a few of the ground rules and assumptions for easy comparison between concepts. Additionally, the BBC's are dated and stamped with the ACO internal vehicle identification number. The inclusion of the vehicle identification number makes ACO's job easier when a customer requests follow on work related to a specific vehicle concept.

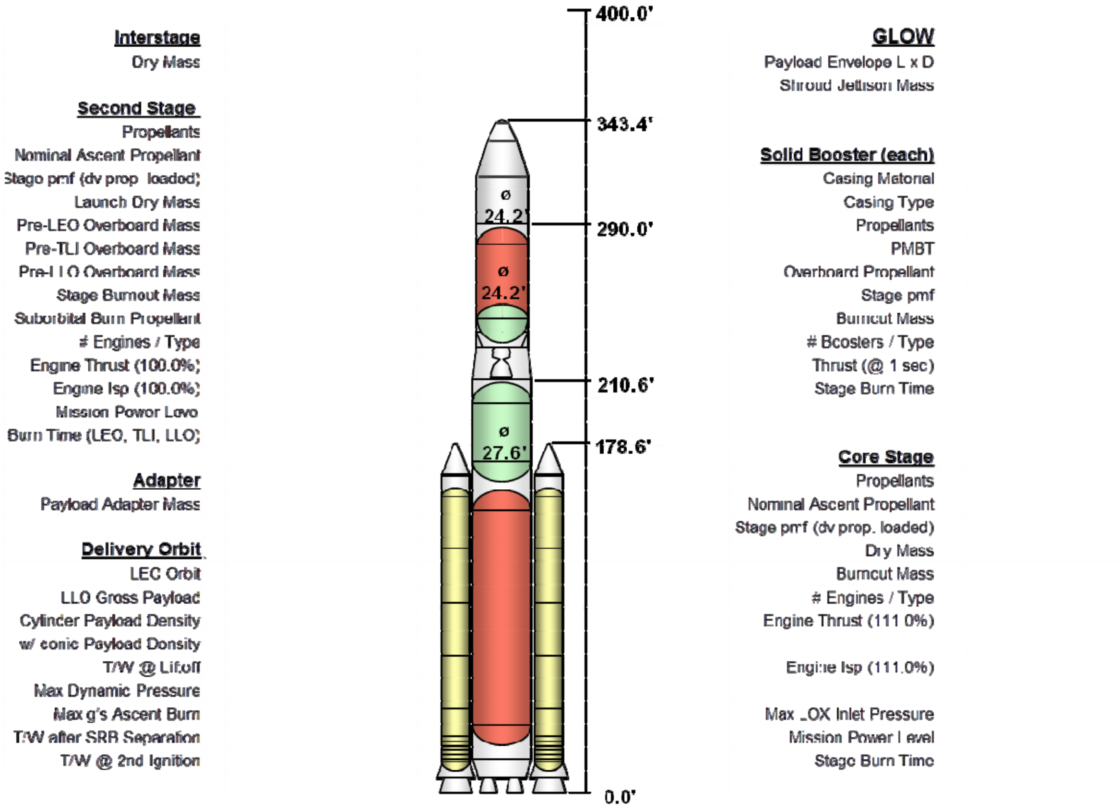

Figure 5. Sample BBC.

B. Parametric Comparison (follow on work)

Often times after a series of vehicles has been delivered or a study has been concluded the customer will request the ETO team to revisit a select few of the vehicles and expand the original trade space. This request may include something as simple as changing the delivery orbit to see what a particular vehicle could deliver for different mission criteria or new engine data is available and the customer would like to see what effect this change could have in terms of delivered payload.

Other follow on work may include running of partials. Partials are single changes to a vehicle design in a positive and negative direction to gauge the sensitivity inherent in a vehicle design. This sensitivity could be expressed by a ± 5,000 lbf of thrust to the engines in any stage of the vehicle, or an specific impulse, or mass delta on any engine or stage. By comparing how each individual change effects payload these partials can provide the customer with the knowledge necessary to decide which improvements are worth investing in or conversely the detrimental effects to payload that can be expected if certain parameters change as the design matures.

V. Conclusions

The ETO Team of the Advanced Concepts Office at MSFC over the last 10 years has developed an efficient, rapid, and accurate integrated process to size launch vehicle concepts and perform parametric trade studies and sensitivity analyses for performance and technology assessments. Each discipline has created its own approach within the integrated process and, through years of experience and application, has developed a method of best practices which have continuously improved and optimized the launch vehicle conceptual sizing process. By working cohesively together with the other disciplines involved with the process, the team, as a result, has managed to reduce the turnaround time to close and complete a vehicle design from more than a day to a few hours. A by-product of the collaboration, of years of working so closely together, is that different disciplines have become familiar with each other's model requirements and outputs and can now perform checks and balances that can identify questionable data and correct it before the error is propagated through subsequent iterations in the process.

This integrated vehicle process also makes it possible for the team to have several vehicles at different levels of maturity within the design process being worked concurrently. As such, one analyst will not sit by idly while waiting for another analyst to finish their particular analysis as would happen if the process only allowed concepts to be worked serially one at a time. It is this rapid design completion and ability to handle high volume work that has continually benefitted and pleased our customers.

The process also offers a level of consistency and detail when performing preliminary sizing analyses of launch vehicle concepts. This is especially important when several concepts are being measured against identified figures of merit for down selection. This consistency and detail in the process allows for the concepts to be analyzed evenly, on a level plane, so that decisions can be made about which vehicles are the more attractive options to move forward in the global design process. Therefore, any analysis which could be considered vehicle or configuration specific is avoided so not to disturb the evaluation process.

A final note is to indicate how strongly the ETO team is constrained in terms of ground rules and assumptions. Too often this is the limiting factor to the capability of the vehicle designs which the team evaluates. Specific stage geometries or engine choices force many other variables in the design process to either be fixed or severely limited. While this has the important effect of constraining the tradespace a bad ground rule can have far reaching detrimental effects on the entire set of vehicles being studied.