Automated Hypersonic Launch Vehicle Design Using ModelCenter®

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Hypersonic Airbreathing RLV Concepts
Disciplinary Analysis Tools
High-Fidelity Closure Models
ROSETTA Meta-Model
Summary and Conclusions
Hypersonic Airbreathing RLV Concepts: Quicksat and Sentinel
Quicksat TSTO RLV
Quicksat RLV

Space-Access Configuration

Strike Mission Configuration

Cargo Delivery Configuration

Takeoff from Military Space Port

Mach 9 Staging Point

SMV Orbit Delivery to 70x197 nmi. @ 28.5°
Mission Profile: Baseline
Integrated Quicksat/Upperstage 3-View

- **Gross Weight – system (lbs):** 741,670
- **Dry Weight – Quicksat (lbs):** 167,840
- **Dry Weight – Upperstage (lbs):** 4,275
- **Mass Ratio – Quicksat:** 2.418
- **Mixture Ratio – Quicksat:** 0.390
- **Length (ft):** 123.6
- **Booster Payload – Upperstage + SMV (lbs):** 89,515
- **Space Maneuver Vehicle – SMV (lbs):** 13,090
# Quicksat Weight Breakdown Summary

## Vehicle Hardware

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wings and Tails (with carry through structure)</td>
<td>14,120</td>
</tr>
<tr>
<td>Airframe Structure (bulkheads, tanks, etc.)</td>
<td>39,105</td>
</tr>
<tr>
<td>Thermal Protection</td>
<td>14,070</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>14,620</td>
</tr>
<tr>
<td><strong>Main Propulsion</strong></td>
<td></td>
</tr>
<tr>
<td>TBCC</td>
<td>39,450</td>
</tr>
<tr>
<td>DMSJ</td>
<td>13,640</td>
</tr>
<tr>
<td>Tail-Rockets</td>
<td>5,585</td>
</tr>
<tr>
<td><strong>ACS Propulsion</strong></td>
<td>730</td>
</tr>
<tr>
<td>Subsystems (power, EHAs, EC&amp;D, avionics, ECCLS)</td>
<td>8,045</td>
</tr>
<tr>
<td>Dry Weight Margin (15%)</td>
<td>18,475</td>
</tr>
</tbody>
</table>

| **DRY WEIGHT**                                 | 167,840      |

## System

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Dry Weight</td>
<td>167,840</td>
</tr>
<tr>
<td>Payload (Upperstage with SMV)</td>
<td>90,215</td>
</tr>
<tr>
<td>Residual Propellants</td>
<td>1,035</td>
</tr>
<tr>
<td>Reserve Propellants</td>
<td>3,750</td>
</tr>
<tr>
<td><strong>LANDED WEIGHT</strong></td>
<td>262,840</td>
</tr>
<tr>
<td>Flyback Propellants</td>
<td>25,780</td>
</tr>
<tr>
<td><strong>ENTRY WEIGHT</strong></td>
<td>288,620</td>
</tr>
<tr>
<td>ACS Propellants</td>
<td>4,855</td>
</tr>
<tr>
<td>Unusable Propellants</td>
<td>13,280</td>
</tr>
<tr>
<td><strong>INSERTION WEIGHT</strong></td>
<td>306,755</td>
</tr>
<tr>
<td>Ascent Propellants</td>
<td></td>
</tr>
<tr>
<td>JP-7 Fuel</td>
<td>312,875</td>
</tr>
<tr>
<td>H2O2 Oxidizer</td>
<td>122,040</td>
</tr>
<tr>
<td><strong>GROSS WEIGHT</strong></td>
<td>741,670</td>
</tr>
<tr>
<td>Startup Losses</td>
<td>4,430</td>
</tr>
</tbody>
</table>

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

- JP-7 and H2O2 at 95% purity (5% H2O)
- “Staged Combustion”, closed-cycle design with H2O2-catalyst pack for turbine drive gases
- Multiple restart capability (minimum 2)
- Gimbals
- Similar flowpaths on both vehicle stages (different thrust classes):
  - 4 engines aft section of Quicksat
  - 1 engine on Upperstage
- Upperstage engine sized to provide T/W of 1.15 at staging condition (Mach 9)
- Quicksat engines sized to provide T/W of 0.475 at takeoff condition (though not operating, provides abort option)

### ENGINE SPECIFICATIONS:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quicksat</th>
<th>Upperstage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidizer/Fuel (OF) Ratio</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Chamber Pressure – Pc (psia)</td>
<td>2,200</td>
<td></td>
</tr>
<tr>
<td>Area Ratio</td>
<td>50:1</td>
<td>100:1</td>
</tr>
<tr>
<td>Isp – Vacuum/Sea-Level (s)</td>
<td>329.91 / 270.24</td>
<td>336.1 / 216.5</td>
</tr>
<tr>
<td>Thrust - Vacuum/Sea-Level (lbs)</td>
<td>107,520 / 88,073</td>
<td>102,940 / 66,310</td>
</tr>
<tr>
<td>Uninstalled Weight (each, lbs)</td>
<td>1,188</td>
<td>1,393</td>
</tr>
<tr>
<td>Engine T/W – Vacuum / SLS</td>
<td>90.5 / 74.1</td>
<td>73.9 / 47.6</td>
</tr>
</tbody>
</table>
Quicksat Low-Speed Propulsion System

- 6 JP-7 fueled low-bypass ratio turbofans with afterburners
- Forebody/inlet system analysis performed using in-house tools integrated in ModelCenter©

### ACTUAL ENGINE SPECIFICATIONS (Scaled Engine):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Compressor Face Mach Number</td>
<td>0.7</td>
</tr>
<tr>
<td>Compressor Face Diameter</td>
<td>4.19 ft</td>
</tr>
<tr>
<td>Bypass Ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Overall Pressure Ratio (OPR)</td>
<td>17.5</td>
</tr>
<tr>
<td>Core Pressure Ratio (CPR)</td>
<td>5.0</td>
</tr>
<tr>
<td>Maximum Effective Turbine Inlet Temperature (TIT)</td>
<td>3,400 R</td>
</tr>
<tr>
<td>Uninstalled T/W</td>
<td>15.0</td>
</tr>
<tr>
<td>Installed T/W</td>
<td>9.96</td>
</tr>
<tr>
<td>Hub-to-Tip Diameter Ratio</td>
<td>0.20</td>
</tr>
<tr>
<td>Thrust, SLS (φ = 0.95)</td>
<td>65,660 lbs</td>
</tr>
<tr>
<td>Isp, SLS (φ = 0.95)</td>
<td>1,897 sec</td>
</tr>
</tbody>
</table>
Aerodynamics Model - Mated Configuration
Quicksat Aeroheating Results - Maximum Surface Temperatures

Temperature (R)

- 3,120
- 2,883
- 2,646
- 2,409
- 2,172
- 1,935
- 1,698
- 1,461
- 1,224
- 987

FRONTSIDE

SIDE

LEEWARD

WINDWARD

FRONT
Sentinel RLV

Space-Access Configuration

Liftoff from Military Space Port
Integrated Sentinel/Upperstage MSP 3-View

- **Gross Weight – system (lbs):** 756,545
- **Dry Weight – Sentinel (lbs):** 158,060
- **Dry Weight – Upperstage (lbs):** 4,250
- **Mass Ratio – Sentinel:** 2.638
- **Mixture Ratio – Sentinel:** 1.185
- **Length (ft):** 143.3
- **Booster Payload – Upperstage + SMV (lbs):** 78,735
- **Space Maneuver Vehicle – SMV (lbs):** 13,090
Sentinel RBCC MSP - Ascent Trajectory Profiles

- Altitude (ft) vs. Time (seconds)
- Dynamic Pressure (psf) vs. Mach Number
- Mach Number vs. Time (seconds)
Disciplinary Analysis Tools
## Quicksat and Sentinel Engineering Design Tools

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Tools, Models, Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD and Packaging</td>
<td>Solid Edge</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>APAS, S/HABP, NASCAR GT (3-D CFD)</td>
</tr>
<tr>
<td>Propulsion</td>
<td>SRGULL, NEPP, REDTOP, REDTOP-2, PARADIGM, RJPA</td>
</tr>
<tr>
<td>Trajectory Optimization</td>
<td>POST, POST-2, Flyback-Sim</td>
</tr>
<tr>
<td>Aeroheating and TPS</td>
<td>TPS-X, Sentry</td>
</tr>
<tr>
<td>Weights and Sizing</td>
<td>SEI-Sizer</td>
</tr>
<tr>
<td>Subsystems</td>
<td>SESAW (avionics)</td>
</tr>
<tr>
<td>Operations</td>
<td>AATe, FGOA</td>
</tr>
<tr>
<td>Safety and Reliability</td>
<td>GTSafety-II</td>
</tr>
<tr>
<td>Economics and Cost</td>
<td>CABAM, CABAM_A, NAFCOM 2002</td>
</tr>
<tr>
<td>System Engineering</td>
<td>OptWorks, ProbWorks, SAS JMP ModelCenter®, Analysis Server®</td>
</tr>
</tbody>
</table>

**Note:** Wrapped for Closure in ModelCenter®

**Vehicle Performance Toolsets**

**Economic Closure Toolsets**

**Collaborative Design & Optimization**
### Non-Wrapped Analysis Tools

<table>
<thead>
<tr>
<th>Engineering Area</th>
<th>Tool(s):</th>
<th>Approach:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerodynamics</strong></td>
<td>APAS, S/HABP with NASCART-GT CFD verification</td>
<td>Generated vehicle lift and drag coefficient (Cl and Cd) database and photographically scaled data.</td>
</tr>
<tr>
<td><strong>Turbine Propulsion</strong></td>
<td>NASA Engine Performance Program (NEPP)</td>
<td>Generated reference engine performance estimates (thrust and TSFC) and scaled with vehicle size. Engine weight derived from constant uninstalled T/W value.</td>
</tr>
<tr>
<td><strong>Scramjet Propulsion</strong></td>
<td>SRGULL</td>
<td>Fixed flowpath geometry and engine scaled with vehicle outer mold line. Engine weight based on panel unit weights (lbs/ft²) and turbomachinery/injectors sizing estimates that varied with fuel flowrate requirements.</td>
</tr>
<tr>
<td><strong>Solid Modeling</strong></td>
<td>SolidEdge</td>
<td>Established reference vehicle for booster and upperstage (L=100 ft) Photographically scaled OML and tracked packaging efficiency variation with size.</td>
</tr>
<tr>
<td><strong>Subsystem: Avionics</strong></td>
<td>SESAW</td>
<td>Curve fit results and inserted directly into Weights &amp; Sizing model.</td>
</tr>
</tbody>
</table>
SpaceWorks Engineering, Inc. (SEI) introduces the **Rocket Engine Design Tool for Optimal Performance (REDTOP)**, an analysis code for quick and accurate prediction of liquid propellant rocket engine performance. REDTOP features a Graphical User Interface (GUI) for operating the tool on the PC platform (Windows XP, 2000, NT, and ME).

For a user specified propellant combination (bi or mono-propellant), chamber pressure, nozzle expansion ratio, and mixture ratio, REDTOP will compute performance parameters such as: ideal, sea-level, vacuum and ambient thrust and specific impulse (Isp), nozzle throat and exit area, chamber temperature, nozzle exit pressure, and mass flow-rate. REDTOP features a number of sizing options for the engine. These include designing for a required thrust level (at a specified ambient condition), sizing at a specified total mass flow-rate, or designing for a specific throat area.

This package is currently available for purchase through individual licenses. The full product suite includes self-installing executable, documentation with case study examples, and selected online support. Free, two-year, site-wide university licenses are available.

**Liquid Rocket Performance: REDTOP**
REDTOP Capabilities

Built-in Oxidizer Propellant Options
- Oxygen
- Nitrogen Tetraoxide (NTO)
- Hydrogen Peroxide (at various purity levels of 100%, 98%, 95%, 90%, and 85%)

Built-in Fuel Options
- Hydrogen
- Methane
- Propane
- Octane
- RP/Kerosene
- Monomethyl Hydrazine (MMH)
- Unsymmetrical Dimethyl Hydrazaine (UDMH)

Other Propellant Options
- Model generic fuel or oxidizer by specifying molecular structure and initial enthalpy

Built-in Engine Efficiency Database
- Performance corrections based on engine cycle type (e.g., Expander vs. Gas Generator), nozzle flow losses, degree of reaction, and combustor efficiency, efficiency used to correct the theoretical (ideal) engine’s performance

Throttled Engine Performance
- User determined engine throttle range with new thrust, flow-rate, chamber pressure, and Isp
SpaceWorks Engineering, Inc. (SEI) introduces the Rocket Engine Design Tool for Optimal Performance (REDTOPI-2), an analysis code for the propulsion expert conducting conceptual and preliminary rocket engine design studies. REDTOP-2 features a Graphical User Interface (GUI) for operating the tool on the PC (Windows XP, 2000, NT, and ME) platform.

REDTOPI-2 is capable of performing a steady-state engine power balance for a variety of cycles, predicting engine weight on a component basis, and computing the estimated development cost. REDTOP-2 allows for parametric engine design and sizing which include designing for a required thrust level (at a specified ambient condition), sizing at a specified total mass flow-rate, or designing for a specific throat area.

This package is currently available for purchase through individual licenses. The full product suite includes self-installing executable, documentation with case study examples, and selected online support.

Liquid Rocket Propulsion: REDTOP-2
REDTOP-2 Capabilities

**Built-in Oxidizer Propellant Options**  
Oxygen, Hydrogen Peroxide, Water

**Built-in Fuel Options**  
Hydrogen, Methane, Propane, Octane, RP/Kerosene

**Generic Equilibrium Model**  
Can easily add new fuel, oxidizers, and product species by supplying simple property table of specific heat, enthalpy, density, and entropy versus temperature and pressure.

**Cycle Options**  
Staged-Combustion, Gas Generator, Expander, and Tap-Off  
Fuel and/or Oxidizer-Rich Preburners  
Dual versus Single Preburner  
Series, Parallel, or Single-Shaft Turbines

**Throttled Engine Analysis**  
Will size engine at maximum operating condition to determine weight, then analyze at throttled engine setting for performance assessment.

**Weight Breakdown Statement**  
Detailed weight predictions for chamber(s), nozzle(s), valves, low and high pressure pumps/turbines, controllers, etc.

**Cost Modeling**  
Program to Optimize Simulated Trajectories (POST & POST-2)

Three degree of freedom (3-DOF), untrimmed point mass simulation for ascent phase of booster and 2nd Stage. Simulation will determine optimal flight path to maximize insertion weight.

Aerodynamics database and air-breathing propulsion data supplied as tables with multiple independent variables.

Monitor vehicle angle-of-attack, dynamic pressure, Gs, normal force, and minimum engine throttle setting, with appropriate constraints imposed.

Ascent Trajectory
Primary Tool(s)  - SEI In-House Flyback Simulator (Flyback-Sim)

Description  - First-order C++ and spread-sheet model consisting of unpowered turn maneuver with
descent to a cruise-back altitude and powered flyback. Execution times on order of a few
seconds allows for in-the-loop analysis.

- User specifies vehicle data (weight, Sref, etc.), aerodynamic database, propulsion system
Isp, cruise Mach number and cruise Altitude.

Booster RTLS Flyback
**Primary Tool(s)**  
- MER Database, higher-order analysis

**Description**  
- For Booster
  - Iterative sizing model based on photographic vehicle scaling about an as-drawn configuration. Internal packaging efficiency is function of vehicle size.
  - Combination of ‘historical’ MERs, physics based models, and results from higher-fidelity tools

- For 2nd Stage
  - Iterative sizing model based on varying total propellants onboard.
  - Combination of ‘historical’ MERs, physics based models, and results from higher-fidelity tools

- Excel© Solver utilized to target required mass ratios.

- 15% dry-weight margin applied to both stages, not including propellant reserves, residuals, and unusables.

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**Weights and Sizing (W&S)**
1-D passive TPS sizing tool developed by SpaceWorks Engineering, Inc

Written in C++ code with command line execution on PC, Mac OS X, and SGI machines

Execution times on the order of a few minutes (2-10)

Uses POST or OTIS trajectory data for ascent profile (time, velocity, AOA, etc.)

Utilizes S/HABP code for geometry (analysis grid) and convective heating data

Dynamic memory allocation in code allows for unrestricted problem size

Tool selects minimum weight TPS tile from database of stackup options

Easily wrapped in ModelCenter© for incorporation in design iteration

Can be used as standalone TPS analysis tool for single stackup/point assessment

User can exclude analysis at any identified body panel (e.g. propulsive flowfield on an aftbody)

Supports analysis of segmented trajectory simulations (e.g. flyout followed by flyback)

Candidate regions for use of active-TPS methods (cooled or ablative) identified but not analyzed

Aeroheating and TPS Sizing: Sentry
ModelCenter© Collaborative Environment

“Phoenix Integration allows manufacturing companies to integrate and automate numerous software tools, remote locations, and different computing platforms into a cohesive environment for systems design...

...Our client software and back-end server software products help you build an integrated process for your engineering design team.”

Phoenix Integration Inc.
http://www.phoenix-int.com
Quicksat/Upperstage Design Structure Matrix (DSM):
Performance Closure Process

Design Variables (DV)
- CAD/Solid Modeling
- Aerodynamics
- Rocket MPS Upperstage
- Rocket MPS Quicksat
- RCS Upperstage
- RCS Quicksat
- Weights & Sizing
- Trajectory Flyout
- Trajectory Pullup-MECO
- TBCC Propulsion
- DMSJ Propulsion
- Flyback Simulation
- Aeroheating/TPS

--- Indicates weak coupling
Vehicle Closure Process

- Wrapped components brought into ModelCenter® and linked together
  - Approximate Setup Time: 1-2 weeks
- Utilized Fixed-Point Iteration (FPI) technique for iterating and converging design
- Established ‘Inner’ and ‘Outer’ FPI loops
  - Inner loop for faster, tightly coupled analysis
  - Outer loop incorporated TPS analysis (slower analysis with only small changes in results)
- Single-point vehicle design closure requires approximately 2-3 Outer-loop iterations each with 8-10 Inner-loop iterations
  - Single inner-loop iteration takes 5-10 minutes
  - Single outer-loop iteration requires about 45 minutes
- Trajectory analysis split into multiple phases (booster ascent, booster pullup, upperstage to MECO, etc..)
- After POST/POST-2 trajectory analysis complete, a tabular results file containing Mach number, velocity, altitude, and AOA vs. Flight Time passed to Sentry analysis components (cross-platform file transfer for Quicksat, SGI to Mac)
- ModelCenter stores (copy) all vehicle information from disciplinary analysis
  - POST and POST-2 Input and Output Files
  - REDTOP-2 power balance and engine weight estimation results
  - TPS results for fuselage, wings, tails, verticals, and control surfaces
Quicksat/Upperstage Closure Model within ModelCenter® Environment

Analysis being performed on multiple machines, including: PIV Dell PC, dual-processor 2.0GHz Mac G5, PC Server, SGI Octane, and PIII Dell Laptop
**Sentinel/Upperstage Closure Model within ModelCenter© Environment**

Analysis being performed on multiple machines, including: Dell PC with dual-Xeon processors and 64-bit Mac G5 with dual-2.0GHz
Model Capabilities

- Vehicle closure models require up-front investment in process design and setup
  ...This expense is more than made up by benefits and future time savings

- Closure models for both systems has enabled a variety of trade studies to be conducted quickly
  - Staging Mach Number
  - DMSJ Pullup Mach Number
  - Engine T/W Sensitivity
  - Alternate Propellant Options

- Users have been able to conduct a number of one-variable at a time optimizations and sensitivity analysis
  - Rocket engine chamber pressure and expansion ratio
  - Tail-rocket ignition through transonic on Quicksat
  - RBCC IRS-mode shut-down condition on Sentinel

- Process is repeatable
- Process avoids transcription errors during data exchange
Engineering Integration and Optimization Frameworks

ROSETTA Model

Source
SEI developed Reduced Order Simulation for Evaluating Technologies and Transportation Architectures (ROSETTA)

About
Spreadsheet-based meta-model is a representation of the design process for specific architectures

Foundation
Based upon higher fidelity models and simulations and refined through updates from such models

Enables
Rapid probabilistic assessments

ModelCenter© and Analysis Server ©

Suite of tools from Phoenix Integration©

Collaborative engineering framework

Actual models and simulations are used in a standardized GUI

Enables
Networked, design process automation
Simultaneous, multi-platform analyses
Trade study and optimization options

Fast-Acting Meta-Model

High-Fidelity Simulation
ROSETTA Model Introduction

- Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures
  - A spreadsheet-based meta-model that is a representation of the design process for a specific architecture (ETO, in-space LEO-GEO, HEDS, etc.)
  - Each traditional design discipline is represented as a contributing analysis in the Design Structure Matrix (DSM)
  - Based upon higher fidelity models (i.e. POST, APAS, CONSIZ, etc.) and refined through updates from such models
  - Based upon an existing, reference baseline design
  - Can be used deterministically to examine design space of that baseline
  - Executes each architecture simulation in only a few seconds
    - Requirement for uncertainty analysis through Monte-Carlo simulation
  - Architectures are modified through Design Influence Factors (DIFs) that can be broken out:
    - PIFs: Programmatic Influence Factors (i.e. govt. contribution, market growth, etc.)
    - VIFs: Vehicle Influence Factors (i.e. Isp, wing weight, T/We, cost, etc.)
  - Outputs measure progress towards customer goals (mission capture rate, life cycle cost, safety, etc.)
    - Standard deterministic outputs as well as probabilistic through Monte Carlo simulation

ROSETTA models contain representations of the full design process. Individual developer of each ROSETTA model determines depth and breadth of appropriate contributing analyses. More assumptions, fewer DSM links than higher fidelity models due to need for faster calculation speeds.
**Monte Carlo**
Performs Monte Carlo uncertainty simulation using random variables by placing distributions (normal, triangular, Weibull, etc.) on inputs. Generates output statistics for the forecast variables (average, mean, certainty level, etc.) even as simulation is running.

**DPOMD**
Implements the Discrete Probability Optimal Matching Distribution (DPOMD) technique that serves as an efficient alternative to direct Monte Carlo simulation for certain classes of problems. Allows estimation of a probabilistic output distribution with a small number of runs.

**Pareto Sensitivity**
Determines the contribution or sensitivity of each selected input with respect to each selected output with appropriate ranking of contribution.

**RSE Generator**
Produces polynomial regression equations to approximate more complex or time-consuming components enabling faster execution of probabilistic techniques such as Monte Carlo. Generates output statistics on goodness of fit to selected data. Enables subsequent use of regression coefficients.

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**ProbWorks Suite of Components**
*(www.piblue.com)*
ROSETTA Model Implementation Summary

- The ROSETTA spreadsheet model for the Sentinel MSP concept is MS Excel based
  - 20 worksheets of varying fidelity encompassing performance and metrics assessment
  - ~1.3 MB MS Excel workbook
  - Several VBA functions and subroutines
  - Specific performance convergence subroutine must run to converge vehicle
  - Model execution on a Pentium 1.7 GHz with 1 GB RAM running MS Office 2003 is under 10 seconds

- Any changes of the PIFs and VIFs result in the concept needing to be reconverged both physically (through vehicle lengths, propellant loads, etc.) and those results propagated through to the cost, S/R, and operations models

- Primary user interaction will be through ‘Inputs’ and ‘Outputs’ worksheets
  - Additional results data and model manipulation can be accessed in disciplinary sub-worksheets

- Performance Closure
  - Enabled through short-cut keys ‘Ctrl+u’
  - Convergence utilized Excel© Solver optimizer
  - Macro procedure:
    1. Vary propellant load on upperstage to achieve mass ratio required from trajectory analysis
    2. Vary booster length to achieve required mass ratio (and mixture ratio) from trajectory analysis
    3. Life-Cycle analysis models execute automatically

  Execution Time: 10 seconds

- Disciplinary Analysis
  - Response Surface Models:
    - Ascent Trajectory (POST-2), Upperstage Propulsion (REDTOP-2), Flyback Trajectory (Flyback-Sim)
    - Ascent trajectory split into two phases: (i) liftoff to Mach 6, (ii) Mach 6 to pullup Mach number and staging
  - Reduced Order Models:
    - RDT&E (NAFCOM-2004)
  - Full Models:
    - Weight and Sizing, FGOA, AATe, GT-SafetyII (all spreadsheet based tools)
# Quicksat ROSETTA Model

## INPUTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Thrust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propulsion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Duration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Elevation</td>
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<td></td>
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</tbody>
</table>

## OUTPUTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Thrust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propulsion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Duration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Elevation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Reducced Order Simulation for Evaluating Technologies and Transportation Architectures (ROSETTA)

**Inputs**: Quicksat Parameters
- Max Thrust
- Propulsion
- Fuel Weight
- Mission Duration
- Mission Elevation

**Outputs**: Quicksat Parameters
- Max Thrust
- Propulsion
- Fuel Weight
- Mission Duration
- Mission Elevation

**Example Parameters**
- Max Thrust
- Propulsion
- Fuel Weight
- Mission Duration
- Mission Elevation
**Sentinel ROSETTA vs. High Fidelity Verification Runs**

**Baseline System**  
Mach 8 pullup, Staging at 9,000 fps, RBCC Engine T/W=27

<table>
<thead>
<tr>
<th>Component</th>
<th>High-Fidelity Closure</th>
<th>ROSETTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>System GLOW (lbs)</td>
<td>756,011</td>
<td>756,545</td>
</tr>
<tr>
<td>Sentinel Dry Weight (lbs)</td>
<td>157,998</td>
<td>158,060</td>
</tr>
<tr>
<td>Upperstage GLOW (lbs)</td>
<td>78,592</td>
<td>78,735</td>
</tr>
<tr>
<td>Upperstage Dry Weight (lbs)</td>
<td>4,255</td>
<td>4,250</td>
</tr>
<tr>
<td>Vehicle Length (ft)</td>
<td>143.3</td>
<td>143.3</td>
</tr>
</tbody>
</table>

**Test Case #1**  
Mach 8 pullup, Staging at 10,000 fps, RBCC Engine T/W=27

<table>
<thead>
<tr>
<th>Component</th>
<th>High-Fidelity Closure</th>
<th>ROSETTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>System GLOW (lbs)</td>
<td>868,397</td>
<td>886,566</td>
</tr>
<tr>
<td>Sentinel Dry Weight (lbs)</td>
<td>181,613</td>
<td>181,231</td>
</tr>
<tr>
<td>Upperstage GLOW (lbs)</td>
<td>68,802</td>
<td>69,036</td>
</tr>
<tr>
<td>Upperstage Dry Weight (lbs)</td>
<td>3,818</td>
<td>3,817</td>
</tr>
<tr>
<td>Vehicle Length (ft)</td>
<td>153.5</td>
<td>153.3</td>
</tr>
</tbody>
</table>

**Test Case #2**  
Mach 7 pullup, Staging at 9,000 fps, RBCC Engine T/W=32

<table>
<thead>
<tr>
<th>Component</th>
<th>High-Fidelity Closure</th>
<th>ROSETTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>System GLOW (lbs)</td>
<td>737,309</td>
<td>740,132</td>
</tr>
<tr>
<td>Sentinel Dry Weight (lbs)</td>
<td>148,177</td>
<td>148,627</td>
</tr>
<tr>
<td>Upperstage GLOW (lbs)</td>
<td>78,592</td>
<td>78,721</td>
</tr>
<tr>
<td>Upperstage Dry Weight (lbs)</td>
<td>4,255</td>
<td>4,247</td>
</tr>
<tr>
<td>Vehicle Length (ft)</td>
<td>142.4</td>
<td>142.5</td>
</tr>
</tbody>
</table>
Sample Probability Analysis
Placed triangular distributions on *Sentinel* and Upperstage hardware WBS Items
Subsystem weight multipliers ranged from 0.8 to 1.2 on major groups (wing/body/tail), to 0.1-3.0 for smaller subsystems (avionics/ACS/etc.)
Ran 500 Monte Carlo Simulations (=500 closed vehicle designs) using ProbWorks
Tracked system GLOW, booster dry weight, upperstage GLOW, and Upperstage dry weight
Approximate run time: 2 hours

---

![ModelCenter screenshot](image-url)
Probabilistic Analysis Results #1: System GLOW and Booster Dry Weight PDFs

- System GLOW varied from minimum of 600Klbs to maximum of 1.1Mlbs
  - 90% Confidence Value is 918,251 lbs (90% of all simulations resulted in GLOW < 918,251 lbs)

- Booster dry weight varied from minimum of 120Klbs to maximum of 240Klbs
  - 90% Confidence Value is 195,912 lbs (90% of all simulations resulted in dry weight < 195,912 lbs)
Probabilistic Analysis Results #2: Upperstage GLOW and Dry Weight PDFs

- Upperstage GLOW varied from minimum of 72Klbs to maximum of 90Klbs
  - 90% Confidence Value is 84,543 lbs (90% of all simulations resulted in GLOW < 84,543 lbs)

- Upperstage dry weight varied from minimum of 3Klbs to maximum of 6.5Klbs
  - 90% Confidence Value is 5,568 lbs (90% of all simulations resulted in dry weight < 5,568 lbs)
Summary and Conclusions

Summary:
- Over the course of the last two years and with funding from the AFRL, SEI has been performing the conceptual design of two RLV concepts called QuickSat and Sentinel
  - QuickSat is a TSTO MSP that uses TBCC and DMSJ propulsion systems and H2O2/JP-7 propellants
  - Sentinel is a TSTO MSP that uses RBCC propulsion and LOX/JP-7 propellants
- These vehicles were designed in a multidisciplinary environment using Phoenix Integration’s ModelCenter® and Analysis Server software products to establish an automated vehicle closure model
- The engineering toolset consisted of industry-standard and in-house codes spanning propulsion, trajectory, aerodynamics, aeroheating/TPS, and weights & sizing
- Once established, the vehicle closure models were used to quickly perform a number of trade studies and sensitivity analysis
- The construction of the ROSETTA meta-model was facilitated by the use of Pi Blue’s ProbWorks suite and subsequently used to perform a probabilistic sensitivity analysis on the Sentinel vehicle concept

Conclusions:
- The closure model’s initial setup time was more than offset by later time and work savings
- Disciplinary tools distributed across multiple machines and computing platforms executed and exchanged data seamlessly
- The use of ModelCenter® came with additional benefits inherent in the software such as a single location data repository, process repeatability, and access to additional system analysis tools (ProbWorks, OptWorks, etc.)
- ModelCenter® enabled faster exploration of the design space, compared to what could be accomplished without its use for equivalent resources, and thus facilitated a greater understanding of the vehicle concepts
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