Chimera

A Low Cost Solution to Small Satellite Space Access

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17th Annual Small Satellite Conference

Project Definition

- Design Justification
  - RASCAL – Development of a low cost air assisted launch vehicle
  - Space Explorations Technologies – Falcon launch vehicle
- Business requirements
  - Launch price $5 M
  - 6 launches/year for 20 years
  - $200 M "gift" for Non-recurring costs
- Design Reference Missions

– 100 kg payload (75 cm*25 cm radius)	– 50 kg (50 cm*50 cm)
– 60°	– 110°
– 700 km	– 700 km
– 5 g axial limit	– 5 g axial limit

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Design Process

Brainstorming, affinity diagram, morphological matrices

20 Initial Concepts

Pugh Matricies →

10 Top Concepts

TOPSIS (Technique for Ordered Preference by Similarity to Ideal Solution) →

2 Point Designs

TOPSIS →

I Detailed Design

ROSETTA Model

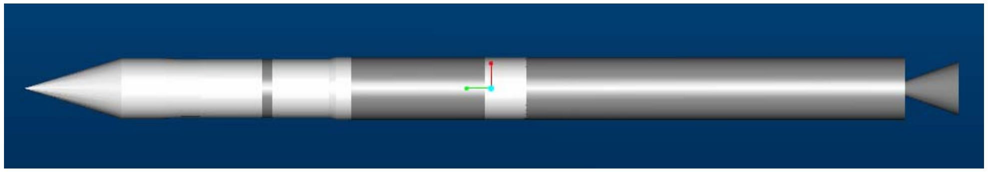
Parametric Model

Monte Carlo Analysis

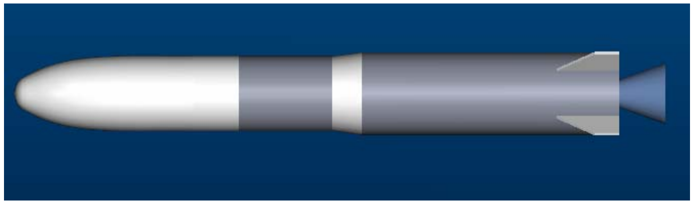
Probabilistic Assessment of Model

Alternative Concepts

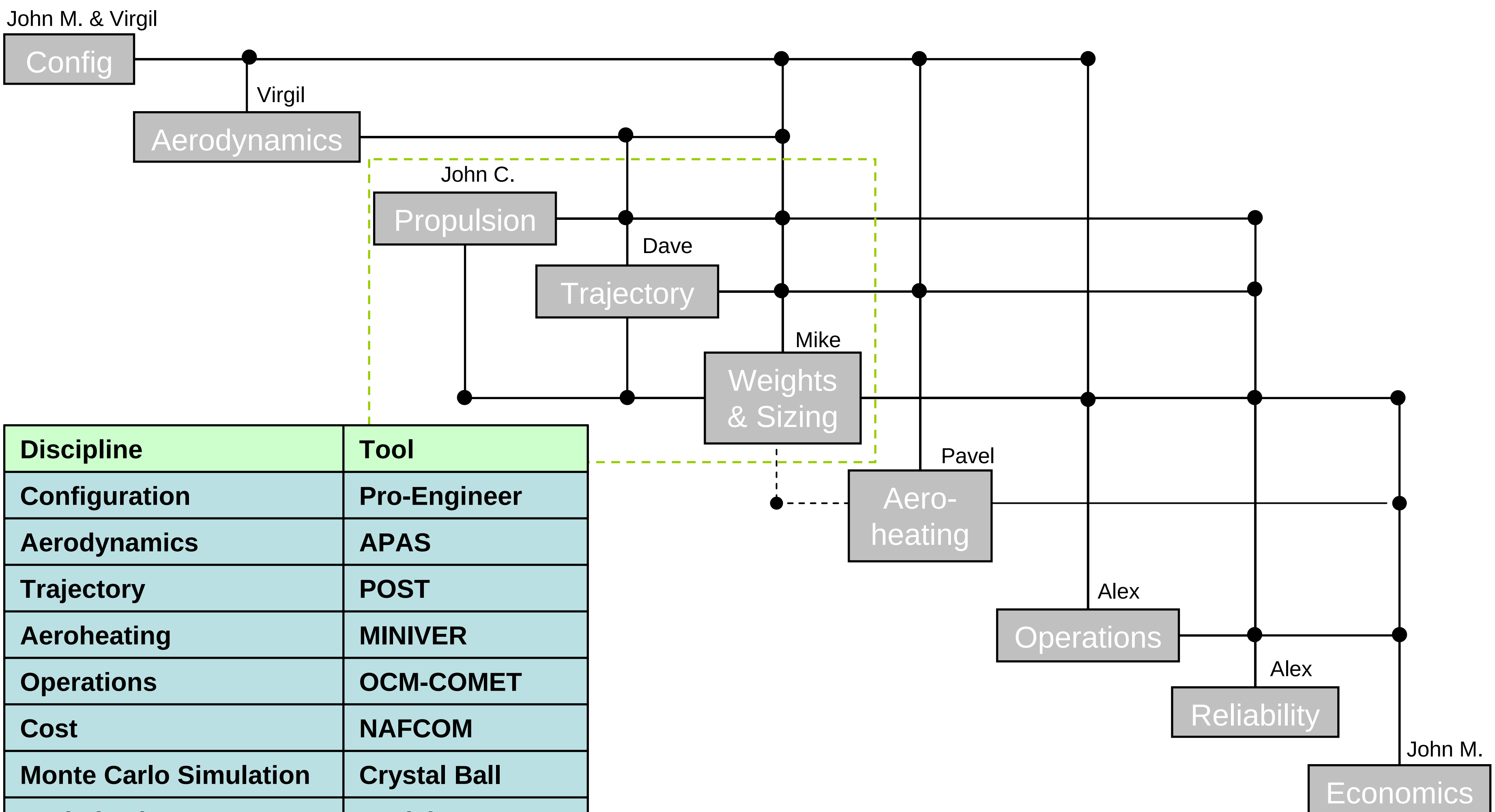
- Assumptions
  - Solid, preexisting stages will be cheapest option
  - US based solids engines would allow the launch of government payloads
- Alternatives chosen based on TOPSIS of point designs
  - 4 stage solid ground launched vehicle



  - 3 stage air launched vehicle



Design Structure Matrix



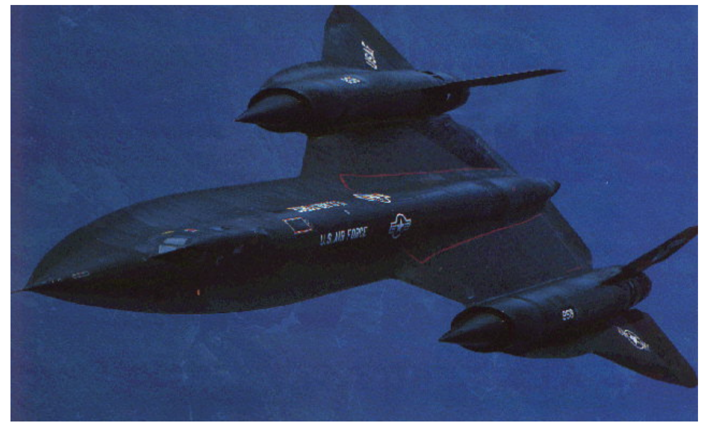
Discipline	Tool
Configuration	Pro-Engineer
Aerodynamics	APAS
Trajectory	POST
Aeroheating	MINIVER
Operations	OCM-COMET
Cost	NAFCOM
Monte Carlo Simulation	Crystal Ball
Optimization	Model Center

Final Concept Chosen

- Both designs evaluated using industry standard tools
- TOPSIS used to choose final concept
- Economic baseline scenario cost number
  - 1.255 relative cost for Ground Launch
  - 1.0 relative cost for Air Assist
- 3-stage air assist rocket chosen

Air Drop Aircraft

- Nine civil and military aircraft variants investigated



	Payload (kg)	Ceiling (m)	Velocity (m/s)
B-52	19320	15362	290
F-15E	11136	20000	840
SR-71	22250	26000	900

Stage Summary

- First two stages chosen from off the shelf SRMs
  - Approximately 20 different SRMs
  - Explored design space of both SRM and launch aircraft options
- Third stage is a spherical solid rocket motor designed specifically for Chimera.
  - Steel motor casing
  - 15° half-cone Carbon/Carbon nozzle with $\varepsilon=50$
  - HTBP/AP/Al solid fuel used in baseline motor

	1st Stage Minuteman 2-2	2nd Stage PAM-S	3rd Stage Utah 2003
Propellant Mass (kg)	6237	1962	30.86
Structural Mass (kg)	795	220	54.43
Area Exit (m2)	0.929	0.4645	0.157
Thrust (N)	267716	66708	2668
Isp (secs)	287.5	288	295

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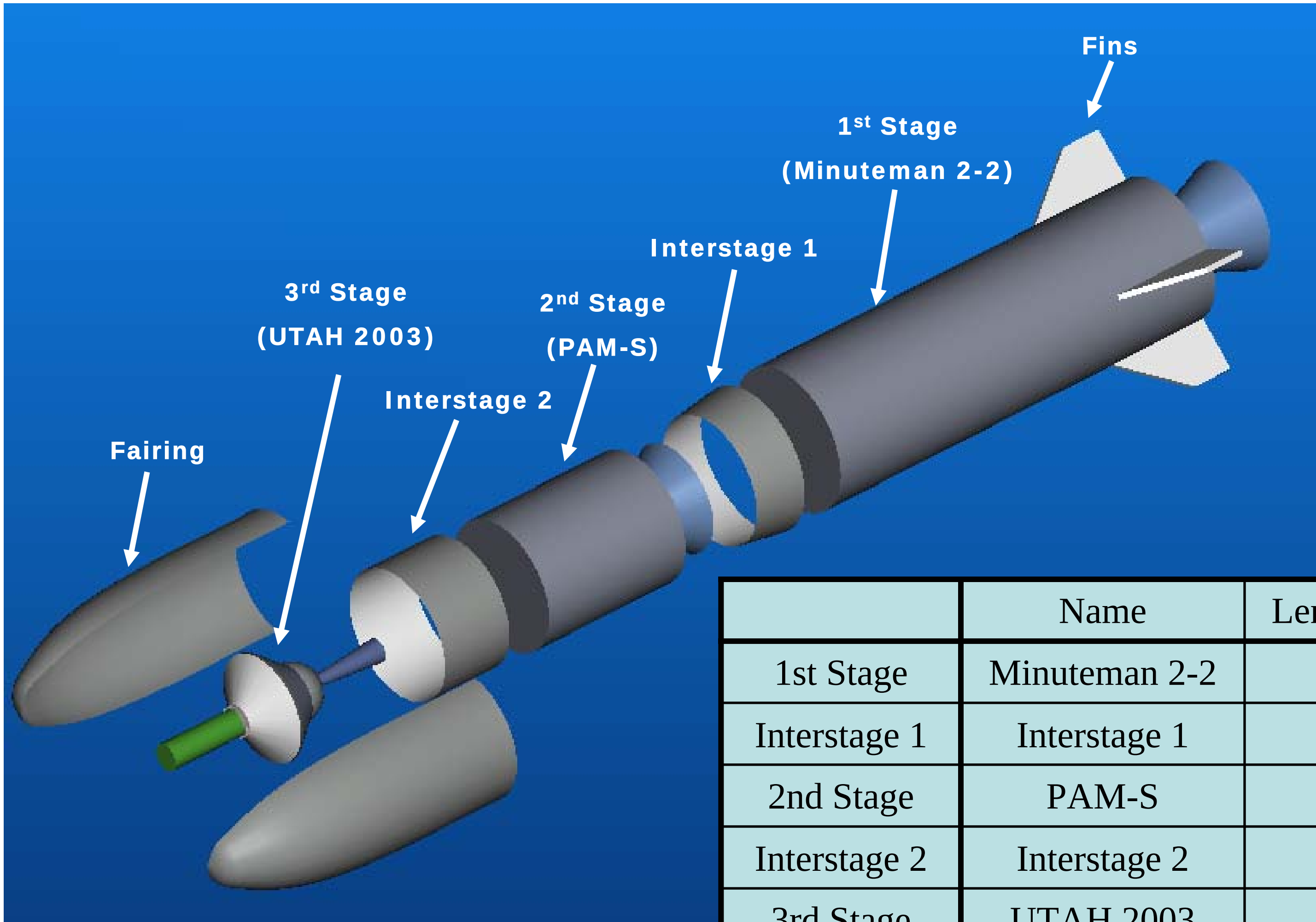
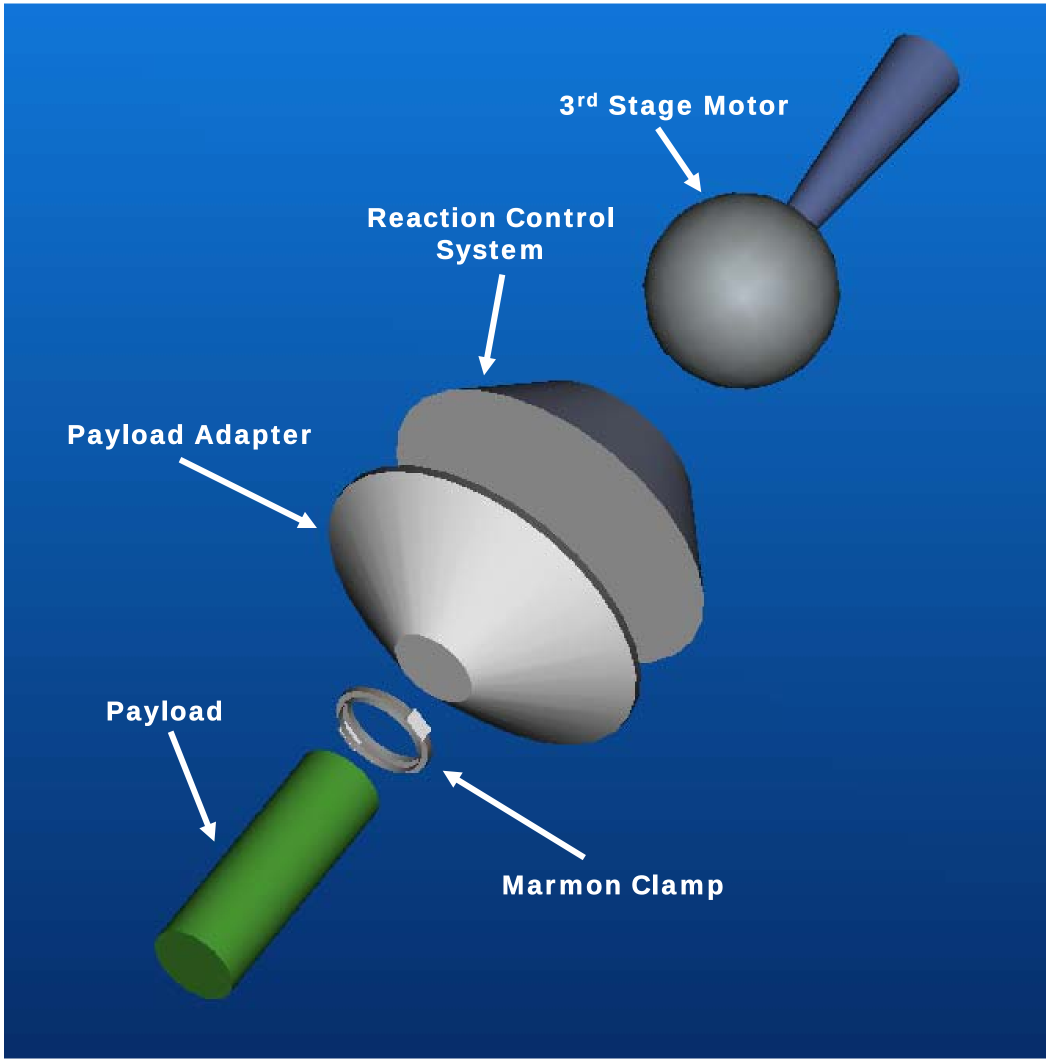
Overall Vehicle



	Name	Length (m)	Diameter (m)
1st Stage	Minuteman 2-2	4.12	1.33
Interstage 1	Interstage 1	0.47	1.33 - 1.22
2nd Stage	PAM-S	2.00	1.22
Interstage 2	Interstage 2	0.71	1.22
3rd Stage	UTAH 2003	1.64	—
Fairing	Fairing	2.88	1.22

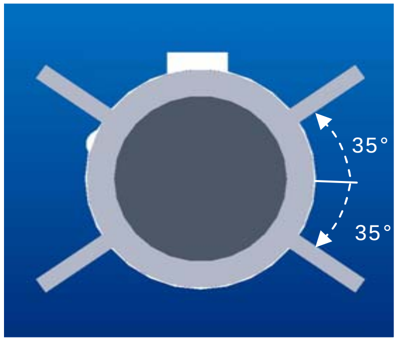
3rd Stage – UTAH 2003

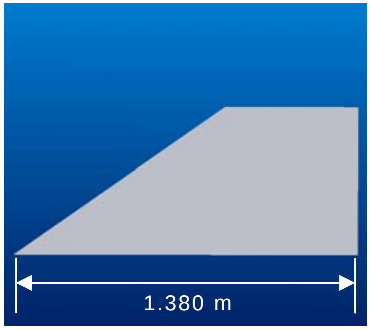
	Length (m)	Diameter (m)
Nozzle	0.71	0.1 - 0.22
Motor	0.54	0.54
Reaction Control System	0.35	0.54 to 1.00
Payload Adapter	0.25	1.00 to 0.25
Marmon Clamp	0.06	0.25
Payload	0.75	0.25



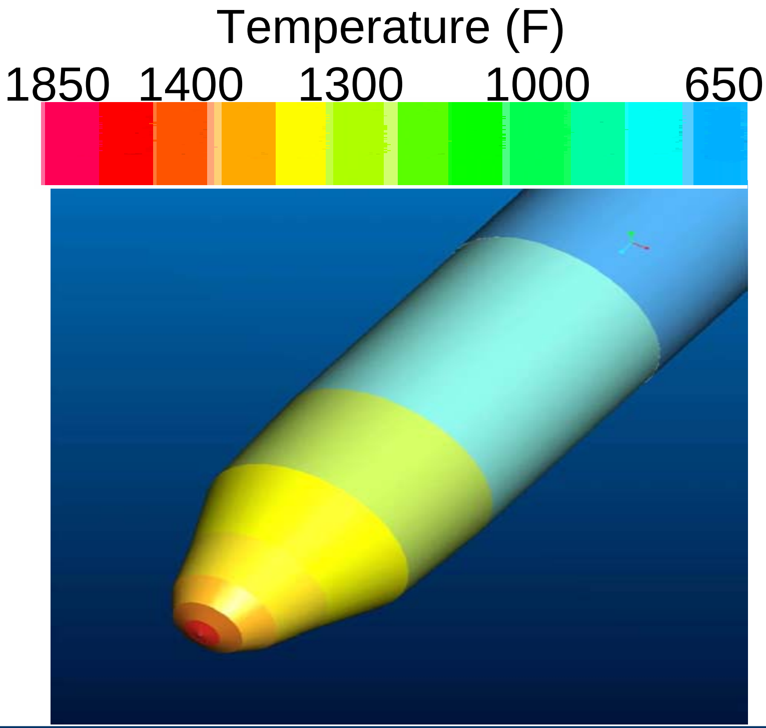
Aerodynamics & Aeroheating

- Aerodynamics calculated using APAS
- Four fins provide stability and small addition of lift for subsonic/sonic flight (C_L=0.175)



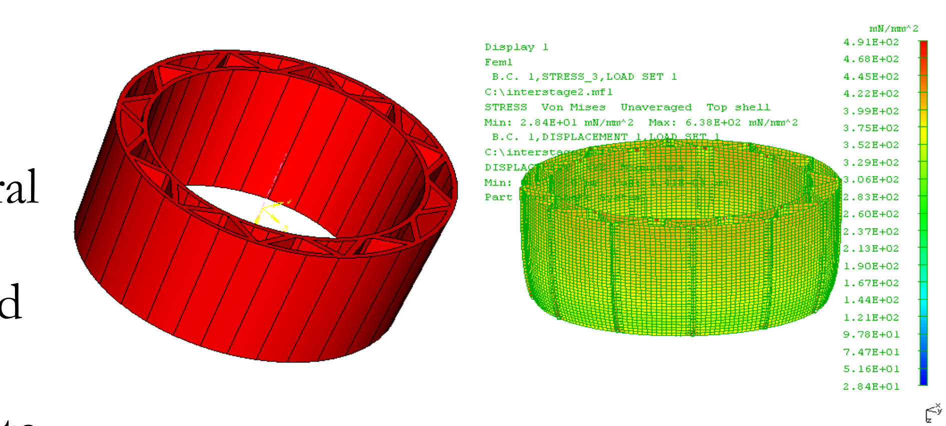


- Aeroheating analysis conducted using MINIVER (engineering aeroheating code)
- TPS: Ma 25(sprayable ablator)
- TPS application areas: fairing and fins

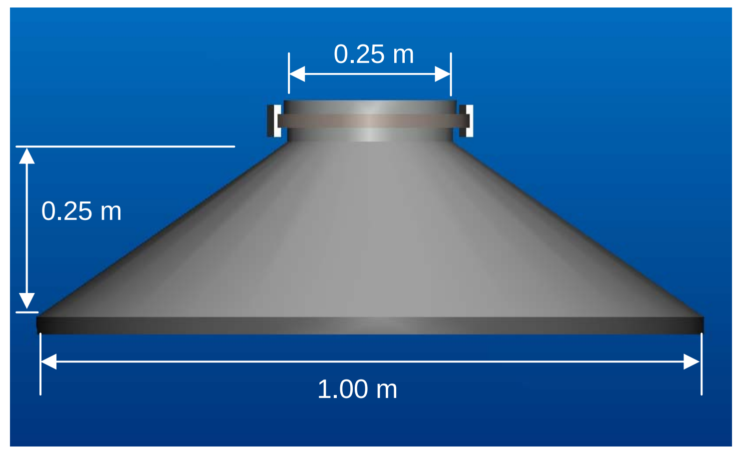


Structural Design

- Interstage Design
  - Designed using FEA
  - Designed for a minimum structural safety factor of 1.2
  - 3 geometrical concepts considered
  - 4 materials considered
  - Lightweight, high strength graphite composite, corrugated construction

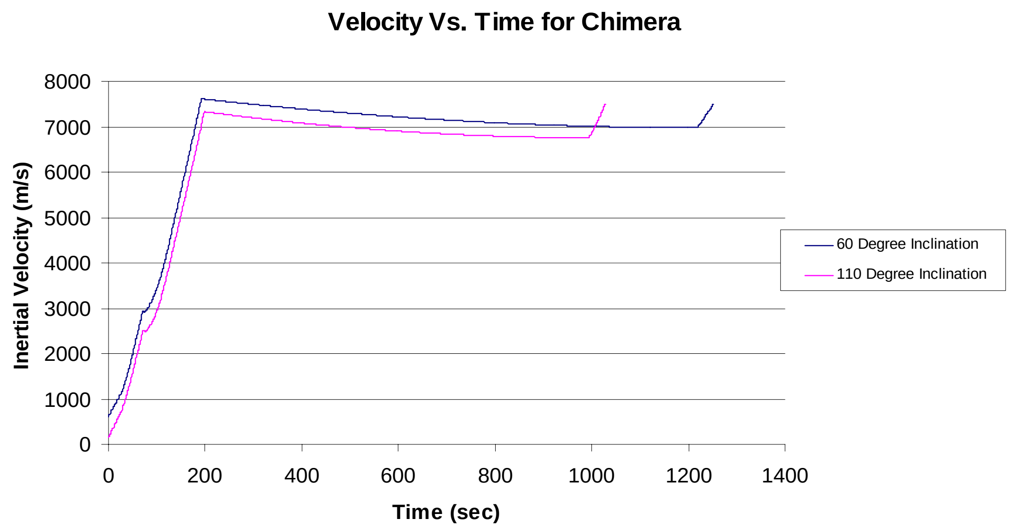


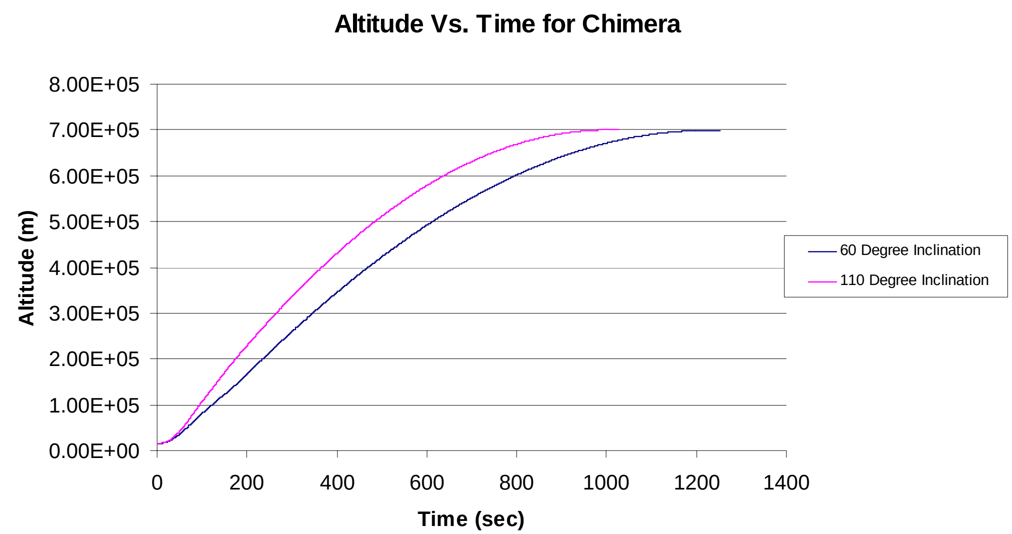
- Payload Adapter Design
  - Aluminum monocoque conical shell to support payload during flight
  - Material thickness sized based on payload mass, adapter dimensions, and launch loads



Trajectory

- POST- Program to Optimize Simulated Trajectories used in all trajectory calculations
- The 100kg to a 60 deg inclination orbit resulting in a larger rocket than the 50kg to 110 deg
- 60 deg inclination DRM was used as the reference mission





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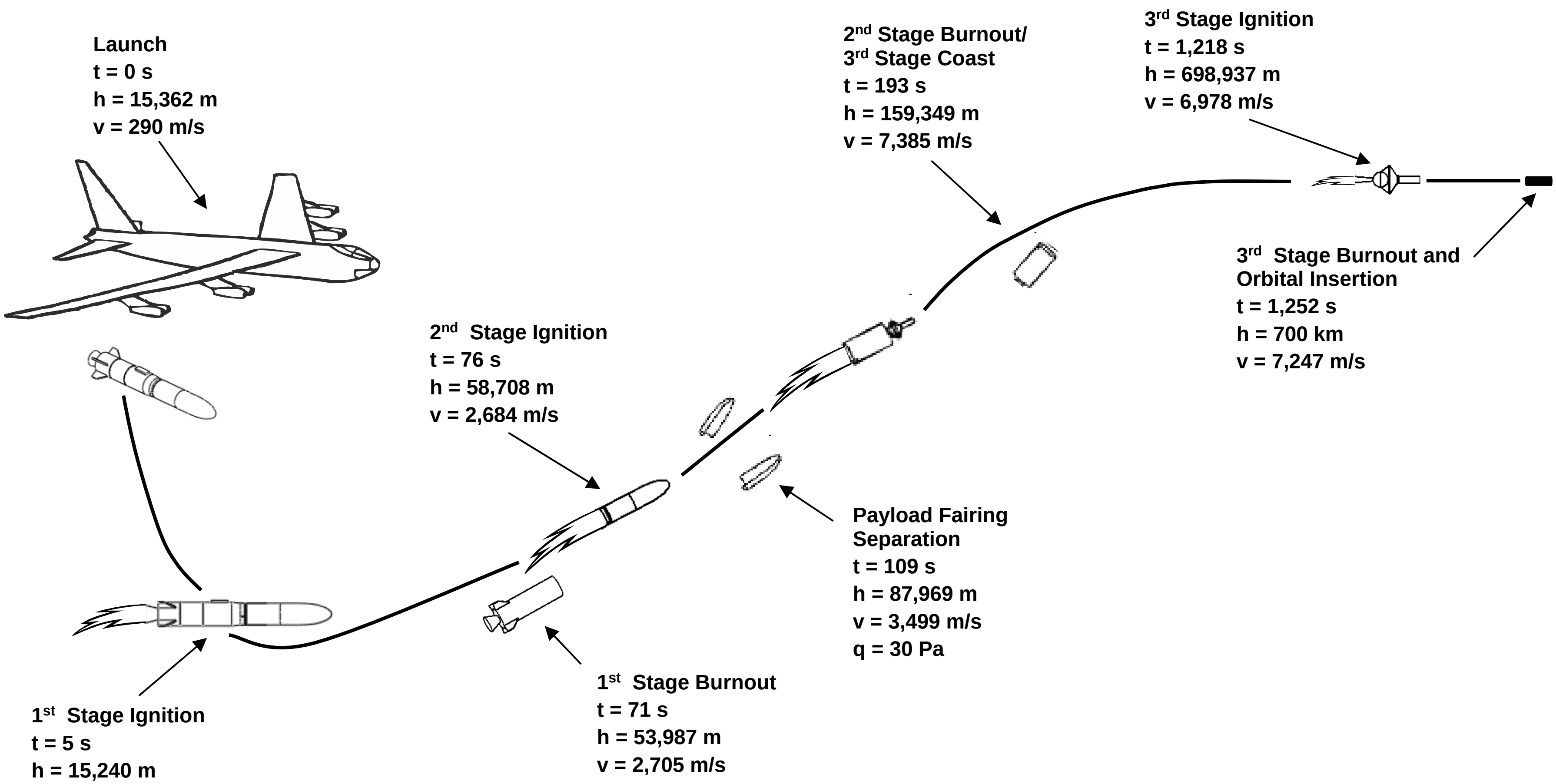
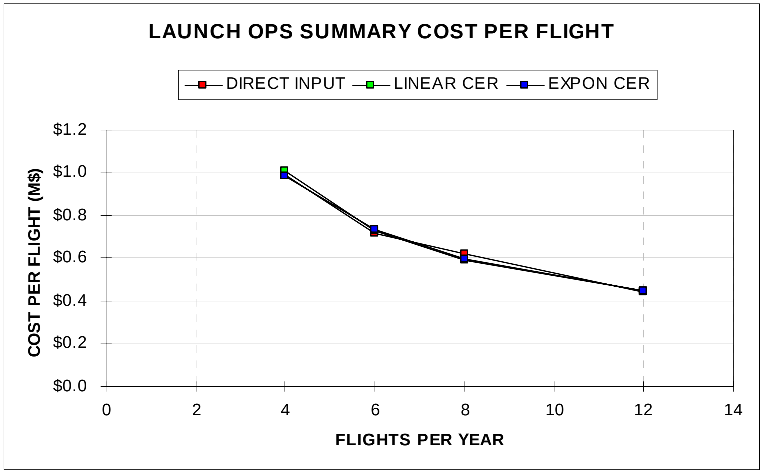
Chimera Mission Profile



Operations & Economics Model

- Operations data obtained from OCM-COMET
  - Crew size: 45 people (26 for Ground Ops, 19 for Flight Ops)
  - Integration time: 30 days
  - Total operations cost per year: $8.85M
- NAFCOM 99 (Cost Estimation)
  - Data obtained from database
  - Cost is exponential function of weight & complexity factors
- Production Schedule
  - Learning curve rate applied
  - Yearly costs
- Excel sheet that models business parameters
  - Determines the cost per flight to meet an internal rate of return of 10%



Chimera Air Assist Rocket

Desired Inclination	60°	110°
Gross Mass	9,507 kg	9,457 kg
Payload	100 kg	50.2 kg

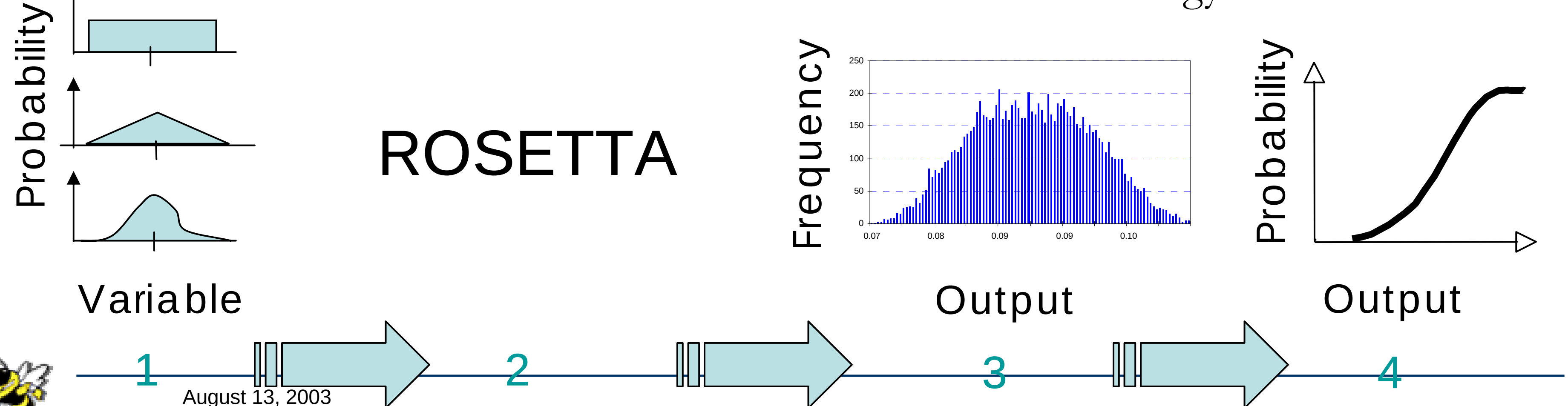
Overall Length	11.18 m
Release Altitude	15,362 m
Release Velocity	Mach 0.8
Thrust at Launch	267.7 kN

Probabilistic Evaluation

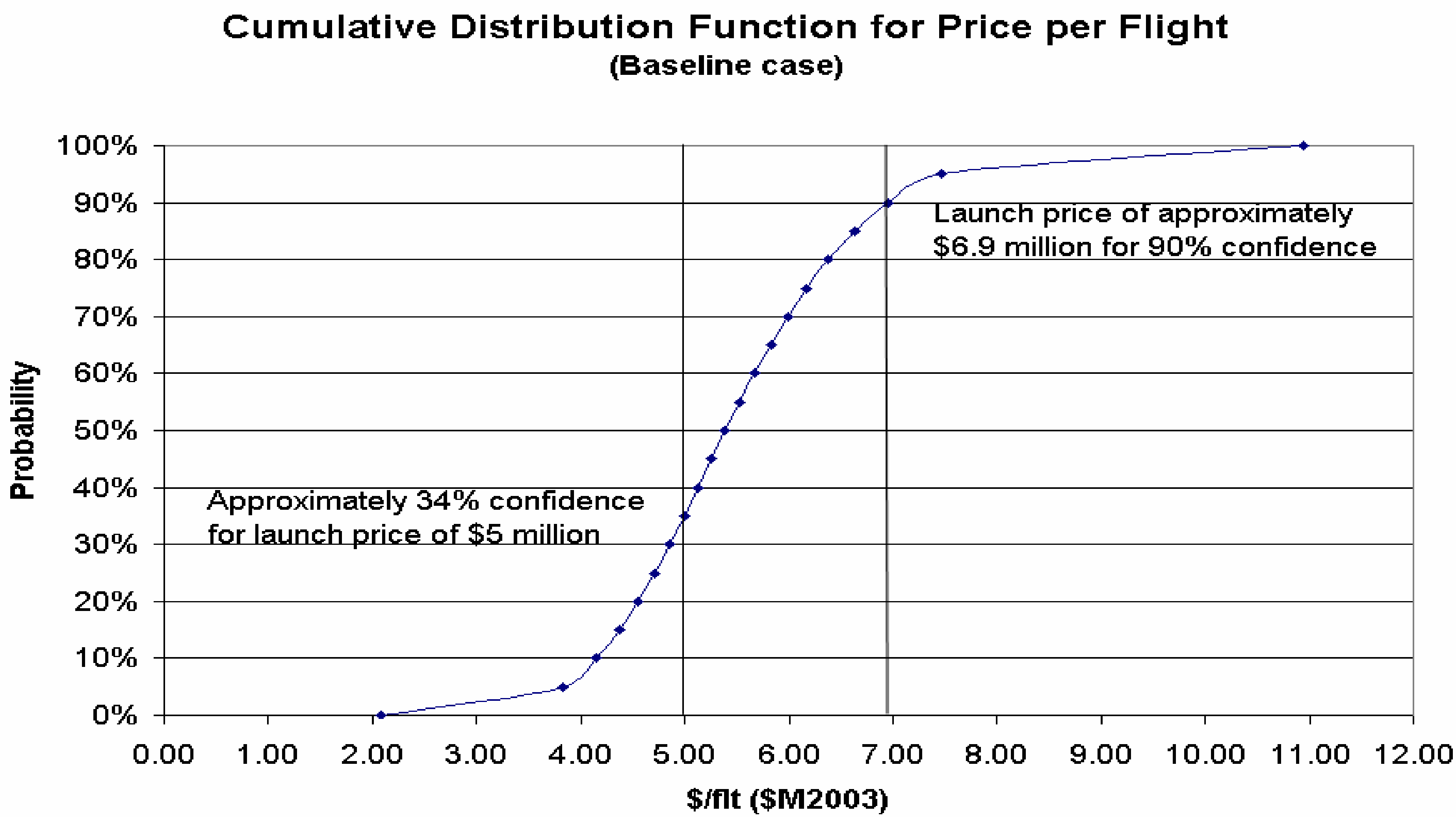
- Following the baseline design, it is necessary to probabilistically evaluate different alternatives and to investigate the implementation of technologies
- REDUCED ORDER SIMULATION FOR EVALUATING TECHNOLOGIES AND TRANSPORTATION ARCHITECTURES (ROSETTA)
- Metamodels created of the high fidelity legacy codes
  - Response surface equation of POST
    - CCD to fit Thrust and Altitude of Launch
    - Launch Velocity (three separate aircraft) and ISP manipulated through the modified rocket equation
  - NAFCOM curve fit to approximate costs
- Weights & Sizing spreadsheet parametrically scales the rocket based upon sub calculations
  - Technology reduction factors
  - Payload fairing & interstages
  - Propulsion module design
- Economics and Operations approximated using appropriate disciplinary equations and historical aircraft operations data

Monte Carlo Simulation

- Assign variables to be randomly varied over a range for a given distribution.
- Extract Cumulative Distribution Functions for cost variables
- Evaluate 4 different scenarios
  - Baseline Case
  - Minuteman Cost Reduction
    - Obtaining surplus ICBMs from US government for only transportation cost
  - Technology Infusion
    - Advanced Structural Materials & Propellants
  - Minuteman Cost Reduction combined with Technology Infusion



Monte Carlo Simulation



Monte Carlo Simulation

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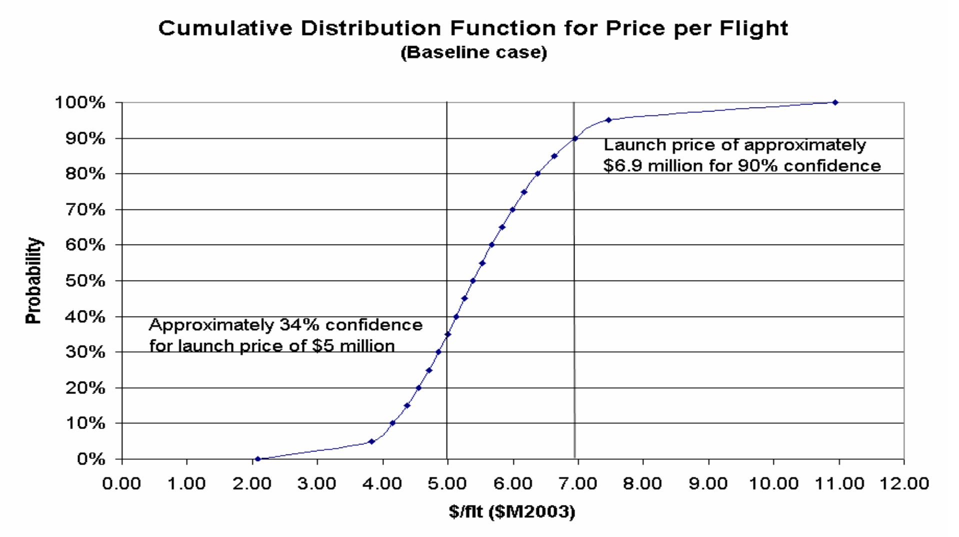
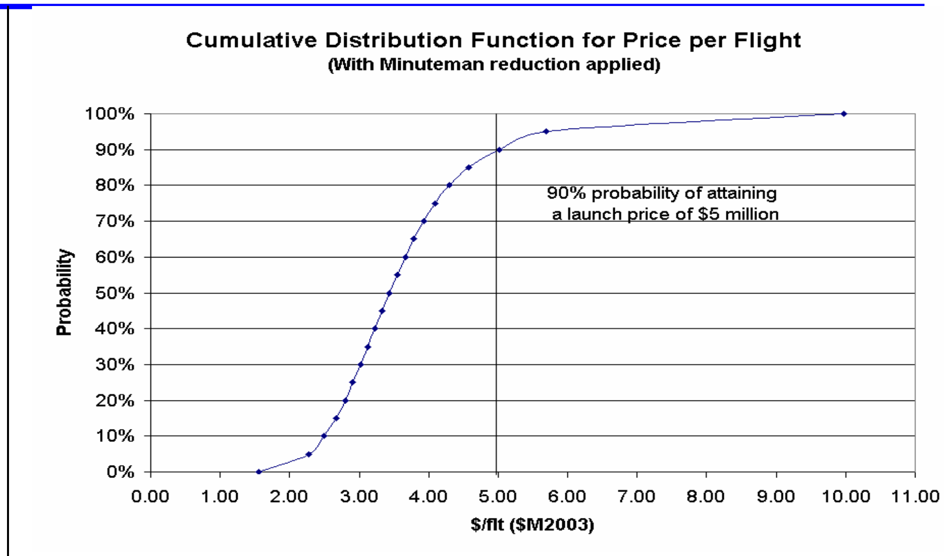
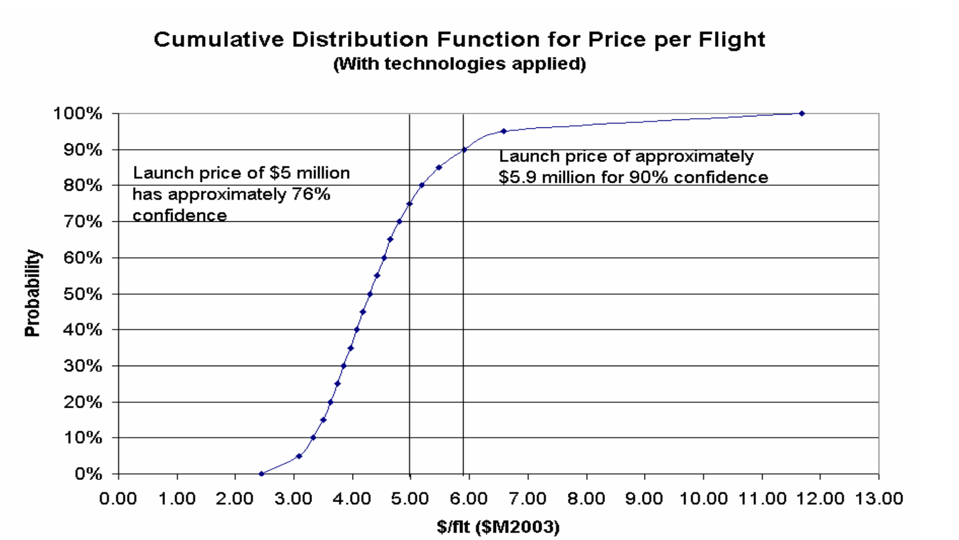
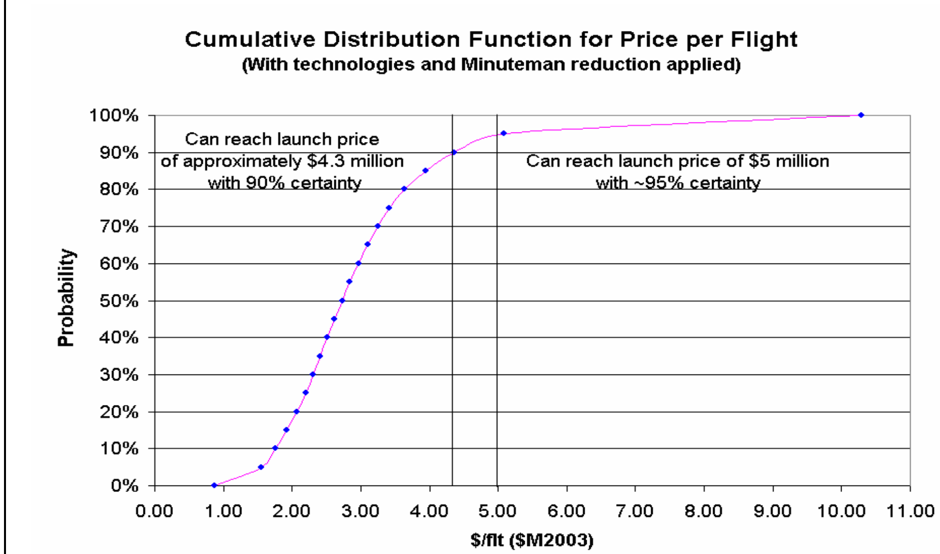








Conclusions

- Chance of achieving desired launch price of $5 million per launch and still breaking even seems unlikely.
- However, if Minuteman stage can be purchased from the government at a significantly reduced price, chances of reaching economic goals increase dramatically.
- Even with Minuteman cost reductions, the application of selected material and propellant technologies enable a much more viable launch system.

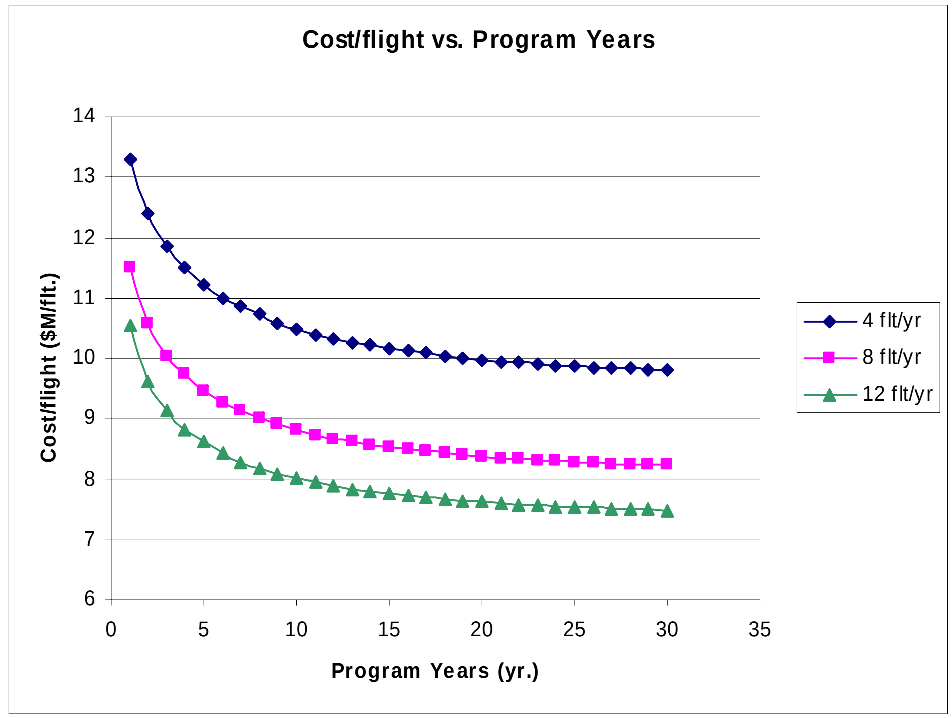
Backup Slides

Available Pre-existing Stages

Stage	Gross Mass (kg)	Empty Mass (kg)	Vacuum Thrust (kgf)	Isp (sec)	Burn time (sec)	Length (m)	Diameter (m)
Castor 4	10534	1269	41524	261	54	9.07	1.02
Algol 1	10705	1900	48022	236	40	9.12	1.01
Minuteman 2-2	7032	795	27300	287.5	66	4.12	1.33
Minuteman-2	5170	466	23300	297	60	3.96	1.13
PAM-D2	3697	431	10931	282	120	1.83	1.6
Pegasus XL-2	4331	416	15653	290	73	3.58	1.27
Castor 2	4424	695	26402	262	37	6.04	0.79
Pegasus-2	3370	345	12053	292	73	2.65	1.27
IUS-2	3919	1170	7996	304	103	2.08	1.61
Castor 1	3852	535	29164	247	27	5.92	0.79
PAM-S	2182	220	6800	288	80	2	1.22
Antares 2	1400	300	9493	293	36	2.9	0.78
Burner 3	1243	168	5216	297	60	1.86	0.94
Antares 1A	1225	294	6169	256	39	3.38	0.78
Pegasus-3	985	203	3525	293	65	2.08	0.97
Burner 2	774	116	4441	285	42	0.84	0.66
Caleb-1	1033	194	5441	204	34	0	0.6

Business Model Trends

- Marginal Cost Improvements
  - Greatest in first 15 Years
  - Levels Out After 9 flt./yr.
- Non-Traditional Suppliers
  - Lower TFU Complexity Factor
- Learning Curve needs to be Quicker

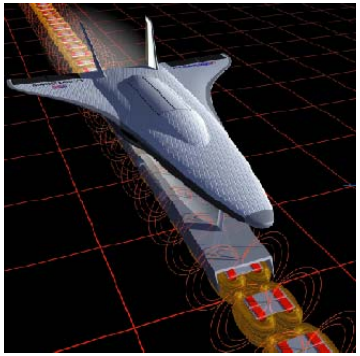


System Morphological Matrix

- 2 Morphological Charts
  - Component Concepts
  - System Concepts
- Objective
  - Create 11 concepts

Characteristics \ Concepts	1	2	3	4	5	6	7	8	9	10	11
Launch Type	Balloon	Balloon	Aircraft	Aircraft	Aircraft	Ground	Ground	Ground	**Maglev**	Cannon	Ground
Stages	3	2	3	3	2	4	4	3	**2-3**	3	3
Expendable	Full	Full	Full	Partial	Full	Full	Full	Full	**Partial**	Full	Partial
Strap-ons	No	Yes	No	No	No	No	No	No	**Yes**	No	Yes/Ramjet
Propulsion	R/B	R/B							**Rocket**	Rocket	
Fuel	L/S	L/S	Solid	Solid	H/S	Single	H/S	Solid	**L/S**	Solid	L/S
Wing	No	No	Delta	Delta	Delta	No	No	No	**Delta**	No	No
Materials	Comp	Aluminum	Comp	Aluminum	Comp	Comp	Steel/Comp	Comp	**Comp**	Steel	Aluminum
TPS	No	No	No	No	No	No	No	No	**No**	Dependant	No
Fairing	Single	Multiple	Single	Multiple	Single	Single	Multiple	Multiple	**Multiple**	Single	Single

Characteristics \ Concepts	9
Launch Type	**Maglev**
Stages	**2-3**
Expendable	**Partial**
Strap-ons	**Yes**
Propulsion	**Rocket**
Fuel	**Liquid/Solid**
Wing	**Delta**
Materials	**Composite**
TPS	**No**
Fairing	**Multiple**



Quality Function Deployment

- **A decision tool to plan, generate, and prioritize solutions to complex problems.**
- **Emphasis on mapping:**
  - Customer Requirements (CR) needed to satisfy purpose of project
  - Engineering Characteristics (EC) that enable satisfying the customer requirements

Eng. Characteristics		Mass	T/W	Cost	Operations	Reusability
Customer Reqs.		Product		Process		
Cost	5	9	3	9	9	9
Flight Rate	3			9	9	9
Reliability	5	3		9	3	3
Availability	3				9	
Pay. Config.	4	3	3	3	3	3
Relative		0.0549	0.06	0.0216	0.0706	0.02

Concept Selection Process

- **TOPSIS- Technique for Ordered Preference by Similarity to Ideal Solution**

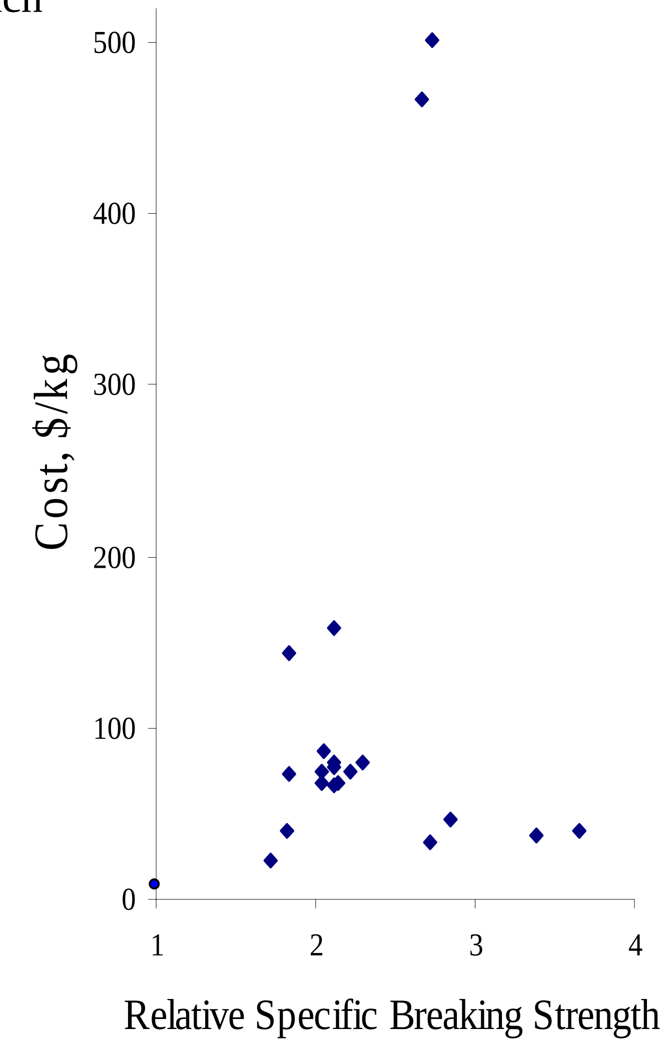
Criteria	Weight	2	4	6	9
Mass	0.055	10	5	2	7
T/W	0.06	3	9	9	3
Material	0.055	9	10	6	1
Reliability	0.059	1	9	7	4
Configuration	0.12	3	6	10	1
Cost	0.082	5	10	7	1
Operations	0.071	2	6	10	1

	2	4	6	9
S+	0.076	0.037	0.036	0.089
S-	0.038	0.077	0.084	0.026
C	**0.338**	**0.675**	**0.698**	**0.227**

Design 1	6
Design 2	4

Technology Investigation

Types of Materials	Number of Each
High Strength Metal Alloys	12
Discontinuous Reinforced Aluminum	8
Other Metal Matrix Composites	9
Graphite Fiber Composites	53
Silicon Carbide Fiber Composites	13
Alumina Fiber Composites	13
Aramid Fiber Composites	8
Glass Fiber Composites	7
Boron Fiber Composites	2
Other Advanced Materials	3



Advanced Propellants Study

Fuels	Oxidizers
Aluminum	Hydrazinium Nitroformate
Magnesium	Ammonium Dinitramide
Boron	and several others

Maximum Specific Impulse	318 s
Minimum Cost	$220/kg