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Advanced Cost Model (ACM)

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Overview

I. Describe the Advance Cost Model

II. CER Development

III. Technical Maturity Cost Factor (TMCF) Developed by TRL

IV. Risk

V. Conclusion

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Description of ACM

- Advance Cost Model (ACM) for rocket motors is a cost model intended to cost alternative designs of future systems
  - Build cost estimating relationships (CERs) for both solid stages and liquid stages
  - Use the CERs to perform an initial estimate of a new system
  - Apply technical maturity factors to grow the initial estimate to a level consistent with a mature system
  - Integrate treatment of risk in all facets of the program

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CER Development

- Requirements
  - Data Collection
  - Methodology Development
  - Data Analysis
  - Validation
- Data Targets are:
  - ATLAS V
  - DELTA IV

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ATLAS V SPECIFICATIONS

	GTO Payload* (27 degree inclination)	GSO Payload* (0 degree inclination)	Estimated Launch Price	Configuration	Launch Mass
Atlas V 401	11,000 lb 5,000 kg	---	US $90 M	Common Core + Centaur (1x RL-10A-4-1)	734,850 lb 334,045 kg
Atlas V 501	9,000 lb 4,100 kg	1,500 lb 3,300 kg	US $85 M	Common Core + Centaur (1x RL-10A-4-2)	741,165 lb 336,895 kg
Atlas V 511	10,800 lb 4,900 kg	3,900 lb 1,750 kg	US $90 M	Common Core + 1 SRB + Centaur (1x RL-10A-4-2)	831,180 lb 377,805 kg
Atlas V 521	13,200 lb 6,000 kg	4,900 lb 2,200 kg	US $95 M	Common Core + 2 SRB's + Centaur (1x RL-10A-4-2)	921,200 lb 418,725 kg
Atlas V 531	15,200 lb 6,900 kg	6,600 lb 3,000 kg	US $100 M	Common Core + 3 SRB's + Centaur (1x RL-10A-4-2)	1,011,220 lb 459,545 kg
Atlas V 541	16,700 lb 7,600 kg	7,500 lb 3,400 kg	US $105 M	Common Core + 4 SRB's + Centaur (1x RL-10A-4-2)	1,101,230 lb 500,365 kg
Atlas V 551	18,080 lb 8,200 kg	8,200 lb 3,750 kg	US $110 M	Common Core + 5 SRB's + Centaur (1x RL-10A-4-2)	1,191,250 lb 541,195 kg
Atlas V Heavy ++	30,000 lb 13,605 kg	13,000 lb 5,900 kg	US $130 M	Common Core + 2 Common Core Boosters + Centaur (1x RL-10A-4-2)	2,120,000 lb 961,451 kg

Source: www.spaceandtech.com/elvs/atlasv_specs.shtml, Copyright 2001 - Andrews Space & Technology

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ATLAS V CONFIGURATIONS

	Solid Strap-Ons	Stage 1 (Common Core)	Stage 2 (Centaur)	Stage 2 (Stretched Centaur)
Length	39 ft 17.7 m	106.2 ft 32.4 m	33.5 ft 10.2 m	38.5 ft 11.7 m
Diameter	3.4 ft 1.55 m	12.5 ft 3.8 m	10 ft 3.0 m	10 ft 3.0 m
Gross Mass	90,000 lb 40,824 kg	683,650 lb 310,045 kg	41,800 lb 18,960 kg	51,200 lb 23,220 kg
Propellant **Propellant Mass**	HTPB 85,300 lb 38,770 kg	LOX / RP 627,000 lb 284,350 kg	LOX / LH2 37,000 lb 16,780 kg	LOX / LH2 45,000 lb 20,410 kg
Engine** **Thrust** **Isp**	Atlas 5 SRB 255,405 lbf SL 1,134 kN SL 275 sec SL	RD-180 860,400 lbf SL 3,820 kN SL 311 sec SL	RL-10A-4-1 22,300 lbf 99,000 N 451 sec	RL-10A-4-2 22,300 lbf 99,000 N 451 sec
Number of Engines	0 - 5	1	1	2
Nominal Burn Time	94 sec	236 sec	894 sec	429 sec

** Note: Vacuum engine performance unless otherwise specified.

Source: www.spaceandtech.com/elvs/atlasv_specs.shtml, Copyright 2001 - Andrews Space & Technology

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DELTA IV SPECIFICATIONS

	GTO Payload* (ETR)	ETR* Reference Orbit	Estimated Launch Price	Configuration	Launch Mass
Delta IVM	8,600 lb 3,900 kg	14,900 lb 6,760 kg	US $70 M	Core + 4m Fairing	349,140 lb 158,340 kg
Delta IVM+ (4,2)	11,700 lb 5,300 kg	20,000 lb 9,070 kg	US $90 M	Core + 2 GEMS + 4m Fairing	377,990 lb 171,420 kg
Delta IVM+ (5,2)	9,600 lb 4,350 kg	17,300 lb 7,850 kg	US $80 M	Core + 2 GEMS + 5m Fairing	522,190 lb 231,670 kg
Delta IVM+ (5,4)	13,500 lb 6,120 kg	22,700 lb 10,300 kg	US $100 M	Core + 4 GEMS + 5m Fairing	522,190 lb 231,670 kg
Delta IVH	27,400 lb 12,400 kg	45,200 lb 20,500 kg	US $140 M	Core + 2 Core Boosters + 5m Fairing	522,190 lb 231,670 kg

Source: www.spaceandtech.com/elvs/atlasv_specs.shtml, Copyright 2001 - Andrews Space & Technology

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DELTA IV CONFIGURATIONS

	Solid Strap-Ons	Stage 1 (Common Core)	Stage 2 (4-m Fairing)	Stage 2 (5-m Fairing)
Length	50 ft 15.2 m	120 ft 36.6 m	40 ft 12.2 m	45 ft 13.7 m
Diameter	5.0 ft 1.52 m	16.8 ft 5.13 m	8.0 ft 4.0 m	16.7 ft 5.1 m
Gross Mass	(Non-TVC / TVC) 41,990 / 42,500 lb 19,082 / 19,327 kg	480,750 lb 218,030 kg	51,000 lb 23,130 kg	68,000 lb 30,840 kg
Propellant **Propellant Mass**	HTPB 37,500 lb 17,045 kg	LOX / LH2 440,000 lb 200,000 kg	LOX / LH2 45,000 lb 24,410 kg	LOX / LH2 60,000 lb 27,200 kg
Engine** **Thrust** **Isp**	GEM - 60 (ground lit / air lit) 136.7 / 141.3 klbf 606.1 / 626.5 kN 273.8 sec	RS-68 650,000 lbf SL 2,886.0 kN SL 365 sec SL	RL-10B-2 24,750 lbf 110,094 N 462.4 sec	RL-10B-2 24,750 lbf 110,094 N 462.4 sec
Number of Engines	0 - 4	1	1	1
Nominal Burn Time	78 sec	249 sec	850 sec	1125 sec

** Note: Vacuum engine performance unless otherwise specified.

Source: www.spaceandtech.com/elvs/atlasv_specs.shtml, Copyright 2001 - Andrews Space & Technology

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CER Characteristics

- These types of rockets are of an integrated design
- Consist of liquid core with solid/liquid strap-ons and possible solid upper stages
- Thus need 2 different CERs to estimate top level costs, one to cost solids and one to cost the liquids
- In developing the CERs, the new rocket was fit into a power function form $(y = ax^b)$

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Solid and Liquid WBSs

1.0 Solid Rocket Motor

- 1.1 Nozzle
- 1.2 Case
- 1.3 Insulation & Liner
- 1.4 External Insulation
- 1.5 Propellant
- 1.6 Igniter
- 1.7 Thrust Vector Control
- 1.8 Integration & Assembly
- 1.9 Raceway
- 1.10 Interstage Assembly

2.0 Liquid Rocket Launch System

- 2.1 Nozzles
- 2.2 Fuel Tank
- 2.3 Oxidizer Tank
- 2.4 Engines
- 2.5 Thrust Structure
- 2.6 Pressurant System
- 2.7 Propellant
- 2.8 TVC
- 2.9 Integration & Assembly
- 2.10 Raceway
- 2.11 Interstage Assembly

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Solid CER

Develop CER:

$$(1) \qquad AUC_{new}(Prod)_i = \alpha_s * \left(W_{new_i}\right)^{\beta_s} \left(Q_{new}\right)^{c} * Factor(Prod)$$

$$(2) \qquad AUC_{New}(Dev)_i = AUC_{New}(Prod)_i * \frac{BaselineDevelopmentCosts}{BaselineProductionCosts} * \frac{Factor(Dev)}{Factor(Prod)} = AUC_{New}(Prod)_i * 925.7\% * \frac{Factor(Dev)}{Factor(Prod)}$$

Where,
c = ln(LC%)/ln(2) = -.158
α_s, β_s = coefficients to be solved for
W = weight
AUC = Average Unit Cost
Factor = Unit Adjustment between MMIII rocket and new rocket
Q = quantity of new rockets

Liquid CER

Develop CER:

$$(2) \qquad AUC_{new}(Prod)_i = \alpha_l * \left(W_{new\,i}\right)^{\beta_l} * Factor(Prod) - J * W_{new\,i} * S_i$$

$$(3) \qquad AUC_{New}(Dev)_i = AUC_{New}(\mathrm{Pr}od)_i * \frac{BaselineDevelopmentCosts}{BaselineProductionCosts} * \frac{Factor(Dev)}{Factor(\mathrm{Pr}od)} = AUC_{New}(\mathrm{Pr}od)_i * 605.03\% * \frac{Factor(Dev)}{Factor(\mathrm{Pr}od)}$$

Where,
α_l, β_l, J = coefficients to be solved for
W = weight
AUC = Average Unit Cost
Factor = Unit Adjustment between EELV rocket and new rocket
S = Number of liquid Strap-ons

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Final Coefficient Values

Results from optimization software (Microsoft Solver) in BY 06$:

Number of Coefficients Estimated =	5
Sample Size =	26

	solids	liquids
alpha	10819.946	7169.987
beta	0.561	0.675

Liquid Strapon Adjustment (J) =	27.878

Mean Absolute Relative Error (MARE) =	5.90%
Standard Percentage Error of the Estmiate (SPEE) =	9.53%
Avg % Bias =	0.18%
R^2 =	0.92855

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Shred of Costs to Lower WBS Elements

Solid:

Stage/ Component	Dev %	Prod %
Stage I Tot	100.00%	100.00%
Nozzle	34.88%	34.24%
Case	25.30%	23.16%
Insul	3.70%	1.39%
Liner		
External Inst	0.37%	0.09%
Propellant	3.90%	8.56%
Igniter	7.94%	8.25%
TVC	7.95%	17.78%
Intg/Sep Sys	8.16%	4.47%
Raceway	0.50%	0.09%
Stage Assembly	7.31%	1.97%
Stage II Tot	100.00%	100.00%
Nozzle	37.03%	35.48%
Case	12.01%	21.94%
Insul	4.83%	1.46%
Liner		
External Inst	0.13%	0.11%
Propellant	5.50%	10.70%
Igniter	9.59%	7.84%
TVC	6.33%	12.38%
Intg/Sep Sys	15.89%	7.42%
Raceway	1.27%	0.30%
Stage Assembly	7.43%	2.37%
Stage III Tot	100.00%	100.00%
Nozzle	42.44%	38.02%
Case	9.03%	16.19%
Insul	5.94%	1.68%
Liner		
External Inst	0.15%	0.13%
Propellant	6.49%	12.34%
Igniter	13.45%	10.04%
TVC	8.38%	16.29%
Intg/Sep Sys	1.33%	0.29%
Raceway	8.95%	2.64%
Stage Assembly	3.84%	2.38%

Liquid:

Component	Dev %	Prod %
Stage I Tot	100.00%	100.00%
Nozzles	0.00%	0.00%
Fuel Tank	7.03%	3.19%
Oxidizer Tank	15.00%	7.35%
Engines	42.22%	33.00%
Thrust Structure	2.33%	0.99%
Pressurant System	7.21%	3.29%
Wiring Harness	1.84%	0.71%
Propellant	1.83%	33.81%
Interstage	15.70%	16.40%
LRE Intg & Test	6.83%	1.28%
Integ Stg 1 & 2	0.00%	0.00%
Stage II Tot	100.00%	100.00%
Nozzles	0.00%	0.00%
Fuel Tank	14.59%	11.41%
Oxidizer Tank	19.62%	9.72%
Engines	41.10%	34.72%
Thrust Structure	0.51%	0.63%
Pressurant System	14.59%	14.11%
Wiring Harness	0.89%	0.74%
Propellant	1.87%	25.01%
Interstage	0.00%	0.00%
LRE Intg & Test	3.87%	0.44%
Integ Stg 1 & 2	2.95%	3.21%

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CERs Are Not the Complete Estimate

- The outputs from the CERs are considered the "initial point estimate" or "most likely" costs
- The price quotes taken relatively early in the program (ie. CY2000) do not capture the cost growth due to:
  - Collapse of the commercial market
  - Addition of program resources for development
  - Costs associated with changing the contract from a "FAR Part 12" commercial type contract to a more conventional government development and production contract
  - Does not account for TRL levels

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Relationship of NASA TRLs to DOD Acquisition Management Framework

TRL	NASA Definition	Defense Acquisition Management Framework Analogy
1	Basic principles observed and reported	Paper studies of alternative concepts for meeting a mission
2	Technology concept and/or application formulated	Analysis of alternatives; Validated and approved MNS; **Exit criteria:** Having specific concept to be pursued and technology exists
3	Analytical and experimental critical function and/or characteristic proof of concept	Concept in hand, but system architecture to be developed; **Exit criteria:** Development Contract Awarded
4	Component and/or breadboard validation in laboratory environment	Architecture complete, but components need to be integrated into complete system; **Exit criteria:** Preliminary Design Review (PDR)
5	Component and/or breadboard validation in relevant environment	System prototypes demonstrated in relevant environment; **Exit criteria:** Critical Design Review (CDR)
6	System/subsystem model or prototype demonstration in a relevant environment	System demonstrated in its intended environment; **Exit criteria:** System Verification Review (SVR)
7	System prototype demonstration in a space (if applicable) environment	Technically Mature; Low Rate Initial Production; **Exit Criteria:** Initial Operational Capability (IOC)
8	Actual system demonstration and "flight qualified"	Initial Operational Capability; System operationally effective; **Exit Criteria:** Manufacturing ready for full-rate production
9	Actual system "flight-proven" through successful mission	Full-rate production; Deploy System; **Exit Criteria**: Full Operational Capability

"Measurement of System Cost Growth Associated with TRLs Using SARs"
by Roy Smoker and Sean Smith. ISPA/SCEA 2005.

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Technical Maturity Cost Factor Development

- TMCFs are essentially a multiplier against an early estimate calibrated to mature the estimate to a future point in time.
- SAR data was used to identify key milestones
  - ATP
  - PDR
  - CDR
  - FCA/PCA
  - IOC
  - FOC
  - TRL 4
  - TRL 5
  - TRL 6
  - TRL 7
  - TRL 8
  - TRL 9
- TMCF = e^{rt}
  - "r" is the rate of cost growth
  - "t" is the time between the respective milestones

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Notional SAR Data to Illustrate Methodology

Notional Program										
			Initial							
			Proc SAR							
Source: Selected Acquisition Reports		12/31/X1	12/31/X2	12/31/X3	12/31/X5	9/30/X6	12/31/X6	9/30/X7	12/31/X7	12/31/X8
		Current	Current	Current	Current	Current	Current	Current	Current	Current
TRL Marker	**TRL**	Est	Est	Est	Est	Est	Est	Est	Est	Est
Milestone I	3	12/1/X0	12/1/X0	12/1/X0	12/1/X0	12/1/X0	12/1/X0	12/1/X0	12/1/X0	12/1/X0
Milestone II ATP	4	6/1/X2	6/1/X2	10/1/X2	10/1/X2	10/1/X2	10/1/X2	10/1/X2	10/1/X2	10/1/X2
PDR	5	7/1/X2	7/1/X3	10/1/X3	10/1/X3	10/1/X3	10/1/X3	10/1/X3	10/1/X3	10/1/X3
CDR	6	12/1/X5	12/1/X5	12/1/X5	7/1/X6	8/1/X6	8/1/X6	8/1/X6	8/1/X6	8/1/X6
FCA/PCA	7	6/1/X7	6/1/X7	6/1/X7	6/1/X7	6/1/X7	6/1/X7	6/1/X7	6/1/X7	7/1/X7
1st Flight		7/1/X7	3/1/X7	3/1/X7	1/1/X7	9/1/X8	7/1/X7	7/3/X8	3/1/X9	12/1/X8
IOC	8	4/1/X7	4/1/X7	4/1/X7	4/1/X7	4/1/X7	9/1/X8	2/1/X9	3/1/X9	12/1/X8
Baseline # of Months Planned		58.0	58.0	54.0	54.0	54.0	71.1	76.1	77.0	74.1
%Sched			0.00%	-6.91%	-6.91%	-6.91%	22.49%	31.16%	32.75%	27.65%
Dev Quantity		2	1	1	1	1	1	1	1	1
Procurement Quantity		0	200	200	200	200	200	200	200	149
Total Quantity		2	201	201	201	201	201	201	201	150
Development		$1,419.4	$918.6	$788.4	$836.3	$1,013.6	$1,002.3	$1,076.3	$1,137.5	$1,121.9
Procurement		$0.0	$53,436.0	$54,039.8	$58,169.1	$59,905.8	$65,284.2	$67,736.1	$103,071.3	$94,060.7
Milcon										
O&M										
Total Program BY$ M		$1,419.4	$54,354.6	$54,828.2	$59,005.4	$60,919.5	$66,286.6	$68,812.4	$104,208.8	$95,182.6
Total Program BY$ M (AUC)			$270.4	$272.8	$293.6	$303.1	$329.8	$342.4	$518.5	$634.6
Percent Cost Growth			0.0%	0.9%	8.6%	12.1%	22.0%	26.6%	91.7%	134.7%
Months from Milestone I		13.0	7.0	15.0	39.0	48.0	51.0	60.0	63.0	75.1

Actual

Forecast

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Missile System Programs

From SAR Data:

Time to Mature Technology from TRL=4 to TRL = 9

TRL	EELV	MMIII-GRP	Average
4	0.00	0.00	0.00
5	12.00	30.05	21.02
6	46.03	47.01	46.52
7	56.02	55.00	55.51
8	74.10	83.05	78.57
9	—	194.10	194.10

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Risk for the “r” & “t” Coefficients

Utilizing the average schedule of EELV and GRP from the previous slide and the cost growth of EELV:

$$r = \frac{\ln(1 + Cost\ \ Growth\%\ \ )}{\#\ Months}$$

	"r" Rate of Cost Growth / Mo.			"t" Time to Mature Technology		
Phase Po	L	M	H	L	M	H
ATP	0.00%	0.00%	0.00%	0.0	0.0	0.0
PDR	0.03%	0.04%	0.04%	12.0	21.0	30.0
CDR	0.20%	0.25%	0.28%	46.0	46.5	47.0
FCA	0.38%	0.42%	0.47%	55.0	55.5	56.0
IOC	0.92%	1.09%	1.13%	74.1	78.6	83.0

Inflation Factor From BY 95 to FY 06: 1.157

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Technical Maturity Cost Factors (TMCF)

For EELV:

$$TMCF = e^{rt}$$

	L	M	H
ATP	1	1	1
PDR	1.003	1.009	1.011
CDR	1.097	1.121	1.123
FCA	1.104	1.266	1.392
IOC	1.978	2.347	2.545

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GAO Study Comparison

The program unit cost (FY 07 $M) comparison from the GAO study:

Beginning of Program:	**$88.256**
Latest 12/2005:	**$207.101**
Percent Change:	**134.7%**
Percent Change from SAR:	**134.7%**

GAO Source: http://www.gao.gov/new.items/d07406sp.pdf

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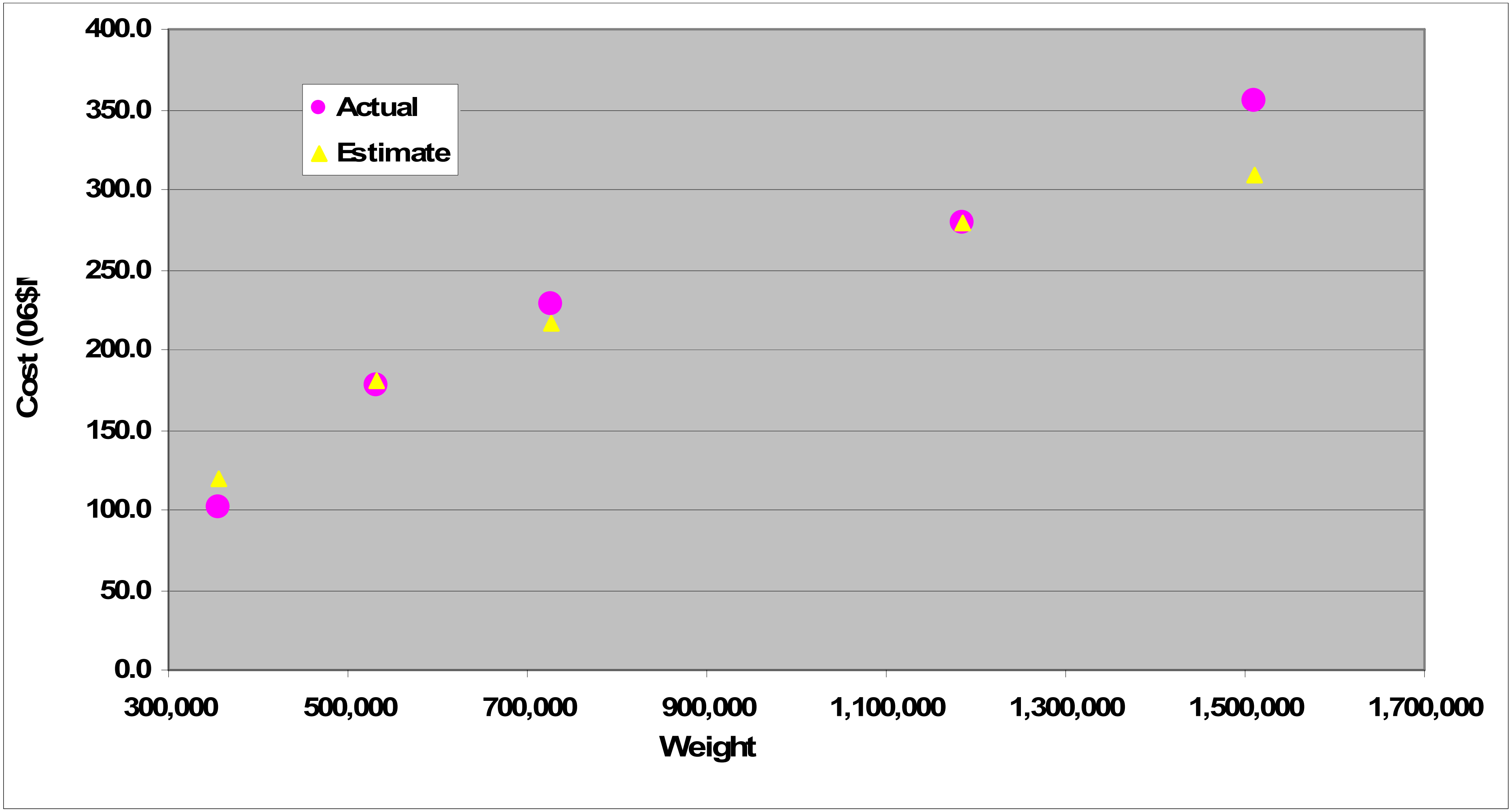
Table of Results (PAUC)

Vehicle	2001 $M ATP	BY 95 $M ATP	BY 95 $M PDR	BY 95 $M CDR	BY 95 $M FCA/PCA	BY 95 $M IOC	2006 $M IOC
Vehicle A	40	37.317	37.642	41.825	47.243	87.564	101.320
Vehicle B	70	65.305	65.873	73.193	82.676	153.237	177.310
Vehicle C	90	83.963	84.694	94.106	106.297	197.019	227.970
Vehicle D	110	102.622	103.514	115.018	129.919	240.802	278.630
Vehicle E	140	130.609	131.746	146.387	165.351	306.475	354.620

Inflation Factor From BY 95 to FY 06: 1.157

Graph of Results



Launch vehicles A, B, C, D, & E

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Risk Assumptions…

- Example Vehicle: LV-E
- Cost in FY 06$
- Buy schedule consisting of 10 Development units and 100 Production units
- -10%, +20% triangle risk bounds on all lower level WBS elements

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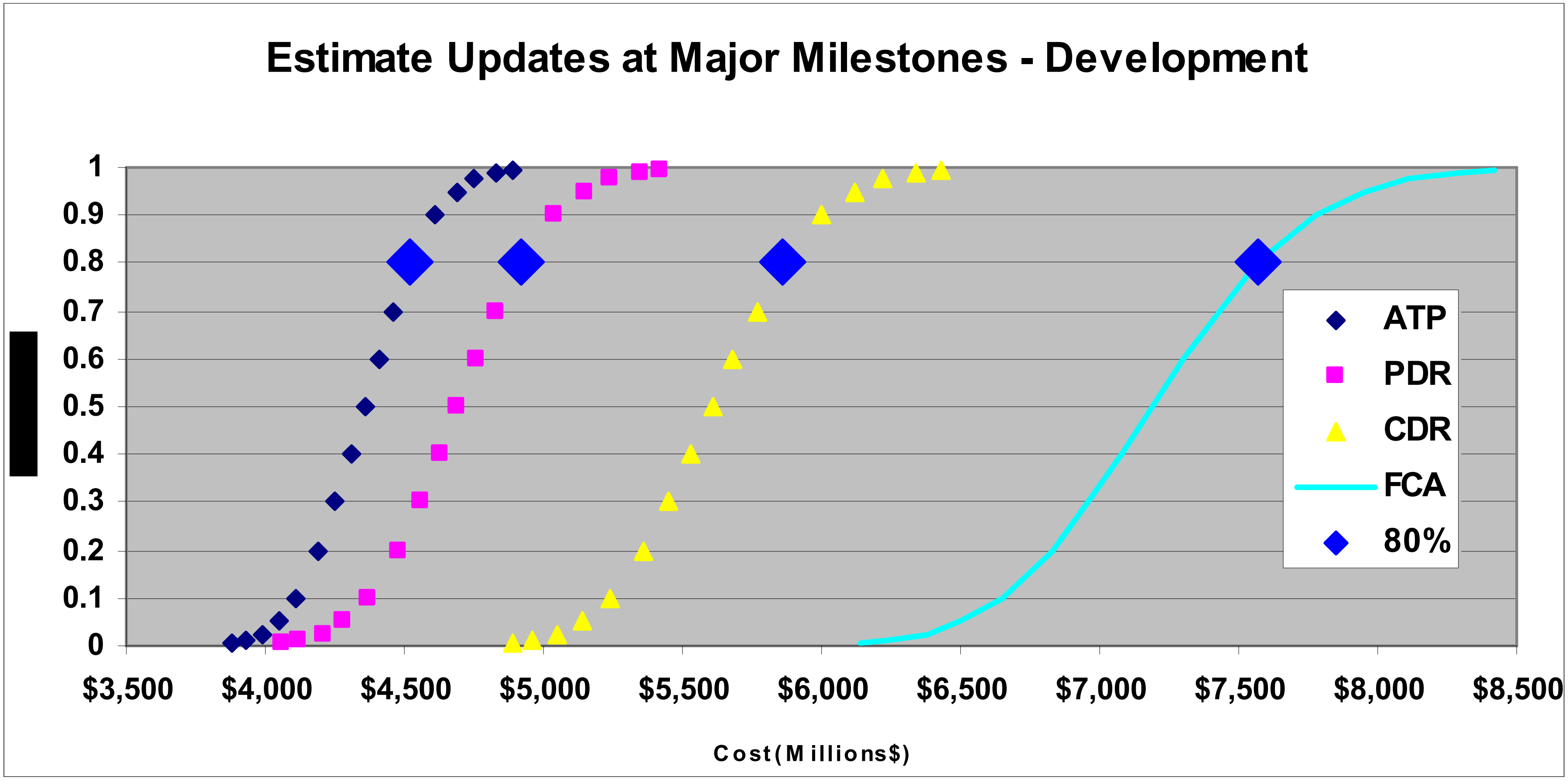
S-Curves Through Development



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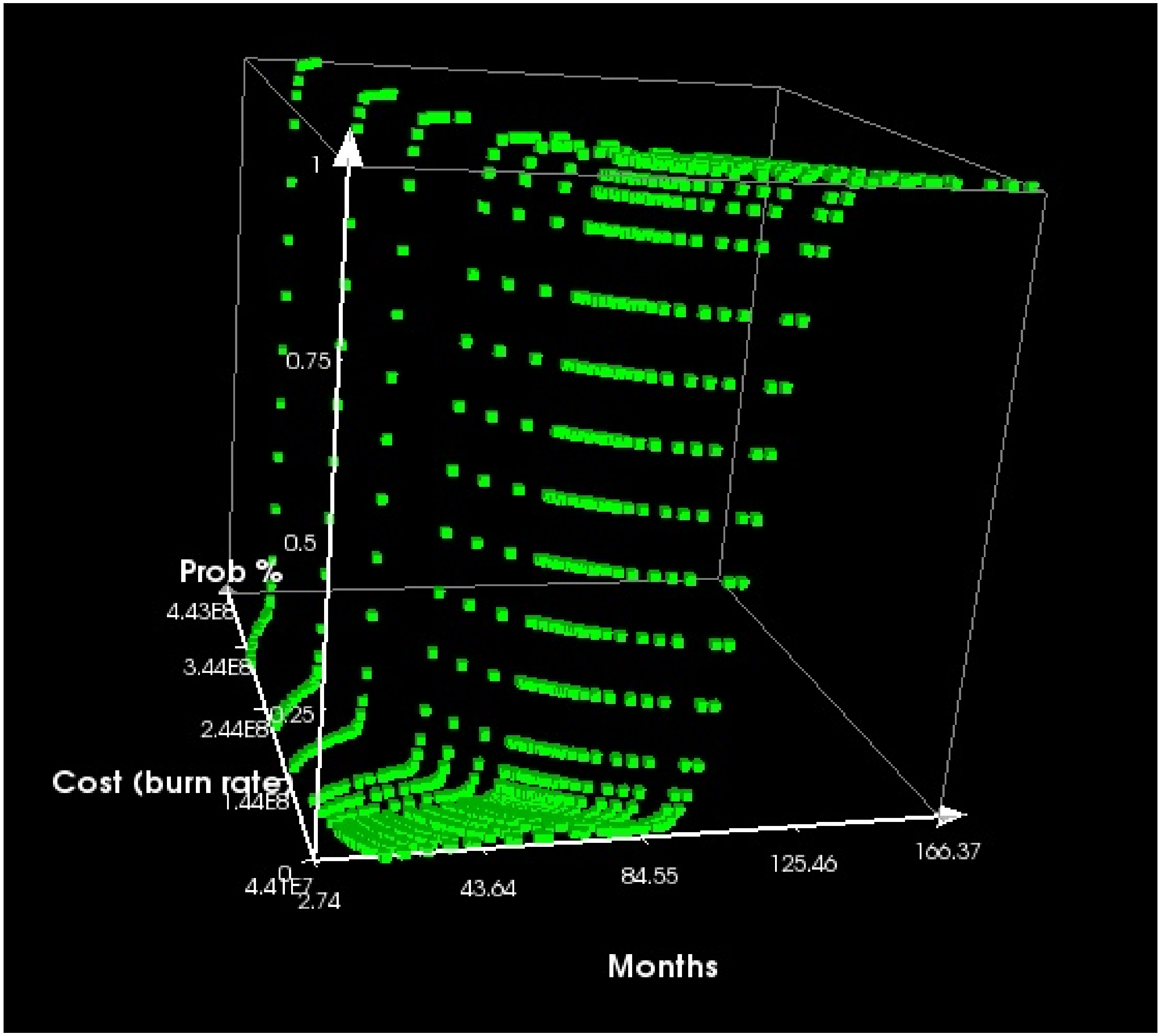
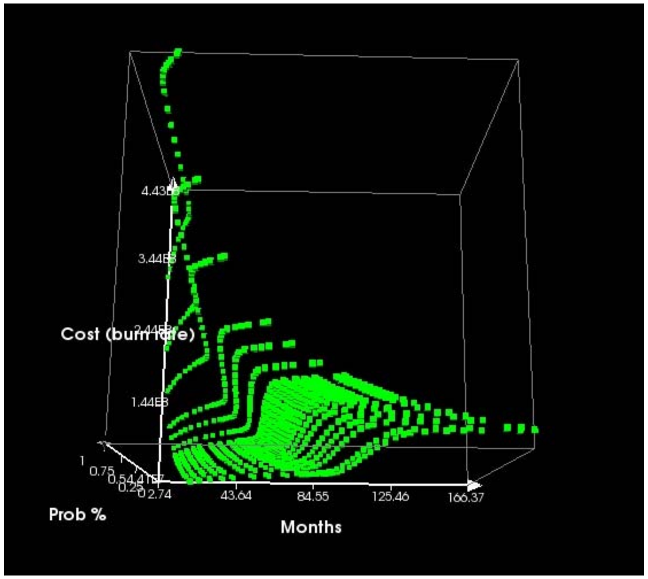
Burn Rate v. Schedule v. Probability of Success



Top View:



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Summary

- SAR data provides information on trends, cost growth, and schedule
- Deficiencies in SAR data from EELV since the program is "family of families" (ATLAS & DELTA)
- Dependent variable represents commercial price quotes for each vehicle configuration for liquid with or without solid strap-ons
- Cost growth rates developed from historical data in SARs
- This methodology can be applied to mature the expected cost on an ongoing program to a TRL 8 or 9 level
- Our model's prediction level is validated by a GAO study