

# Cost Estimation and Engineering Economics

- Cost Sources
- Vehicle-level Costing Heuristics
- Learning Curves
- Inflation
- Cost Discounting
- Return on Investment
- Cost/Benefit Ratios
- Life Cycle Costing
- 2 Case Studies
- Cost Spreading



# Cost Analysis

- Direct Costs - directly related to designing, testing, building, and operating the system
- Indirect Costs - required to do business, but not directly associated with development or operations
  - Management
  - Profit
  - Non-operational facilities
  - Overhead



# Direct Cost Breakdown

- Non-recurring costs - only incurred once in program, such as design
- Recurring costs - reoccur throughout the life of the program
  - Per vehicle
  - Per flight
  - Per year



# Nonrecurring Cost Sources

- Research
- Design
- Development
- Test and evaluation
- Facilities
- Tooling



# Recurring Cost Sources

- Vehicle manufacturing
- Mission planning
- Pre-flight preparation and check-out
- Flight operations
- Post-flight inspection and refurbishment
- Range costs
- Consumables (e.g., propellants)
- Training



# Refurbishment

- Cost associated with maintenance and upkeep on reusable vehicles between flights
- Refurbishment fraction  $f_R$  - fraction of first unit production cost that is required for average post-flight refurbishment
  - Airliner:  $\sim 0.001\%$
  - Fighter jet:  $\sim 0.01\%$
  - X-15: 3%
  - Shuttle: 6-20%
- Major contributor to space flight costs



# Vehicle-Level Cost Estimating Relations

$$C (\$M) = a [m_i \langle kg \rangle]^b$$

Spacecraft Type	Nonrecurring a	Nonrecurring b	1st unit production a	1st unit production b
Launch Vehicle Stage	8.145	0.55	0.1934	0.662
Manned Spacecraft	20.64	0.55	0.6494	0.662
Unmanned Planetary	13.89	0.55	1.007	0.662
Unmanned Earth Orbital	3.930	0.55	0.4464	0.662
Liquid Rocket Engine	32.88	0.55	0.1809	0.662
Scientific Instrument	2.102	0.50	0.2974	0.70

2005\$

2005\$



UNIVERSITY OF  
MARYLAND

Ballistic Atmospheric Entry  
Launch and Entry Vehicle Design

# Implications of CERs

- Launch Vehicles
  - Nonrecurring \$42K-\$182K/kg inert mass
  - 1st Unit \$3600-\$10.7K/kg inert mass
- Manned Spacecraft
  - Nonrecurring \$119K-\$1.56M/kg inert mass
  - 1st Unit \$13K-\$90K/kg inert mass



# Costing Applied to Launch Vehicle Design

Optimization Approach	$\Delta V$ Distribution (m/sec)	Gross Mass (kg)	Inert Masses (kg)	NR Cost (\$M99)
Minimize Gross Mass	4600	134,800	2,937	576
	4600		<u>10,780</u>	<u>1177</u>
			13,721	1753
Minimize Inert Mass	3356	139,000	2,066	474
	5844		<u>11,123</u>	<u>1197</u>
			13,189	1672
Minimize Nonrecurring Cost	2556	147,000	1,666	421
	6644		<u>11,762</u>	<u>1235</u>
			13,428	1656
Single Stage to Orbit	9200	226,400	18,115	1566

5000 kg payload, LOX/LH2 engines



# The Learning Curve

- The effort (time, cost, etc.) to perform a test decreases with repetition
- Crawford formulation: doubling the production run results in consistent fractional reduction of effort
  - "80% learning curve" - 2nd unit costs 80% of 1st, 4th is 80% of 2nd, 8th is 80% of 4th...

- $C_n = C_1 n^p$

- Average cost:

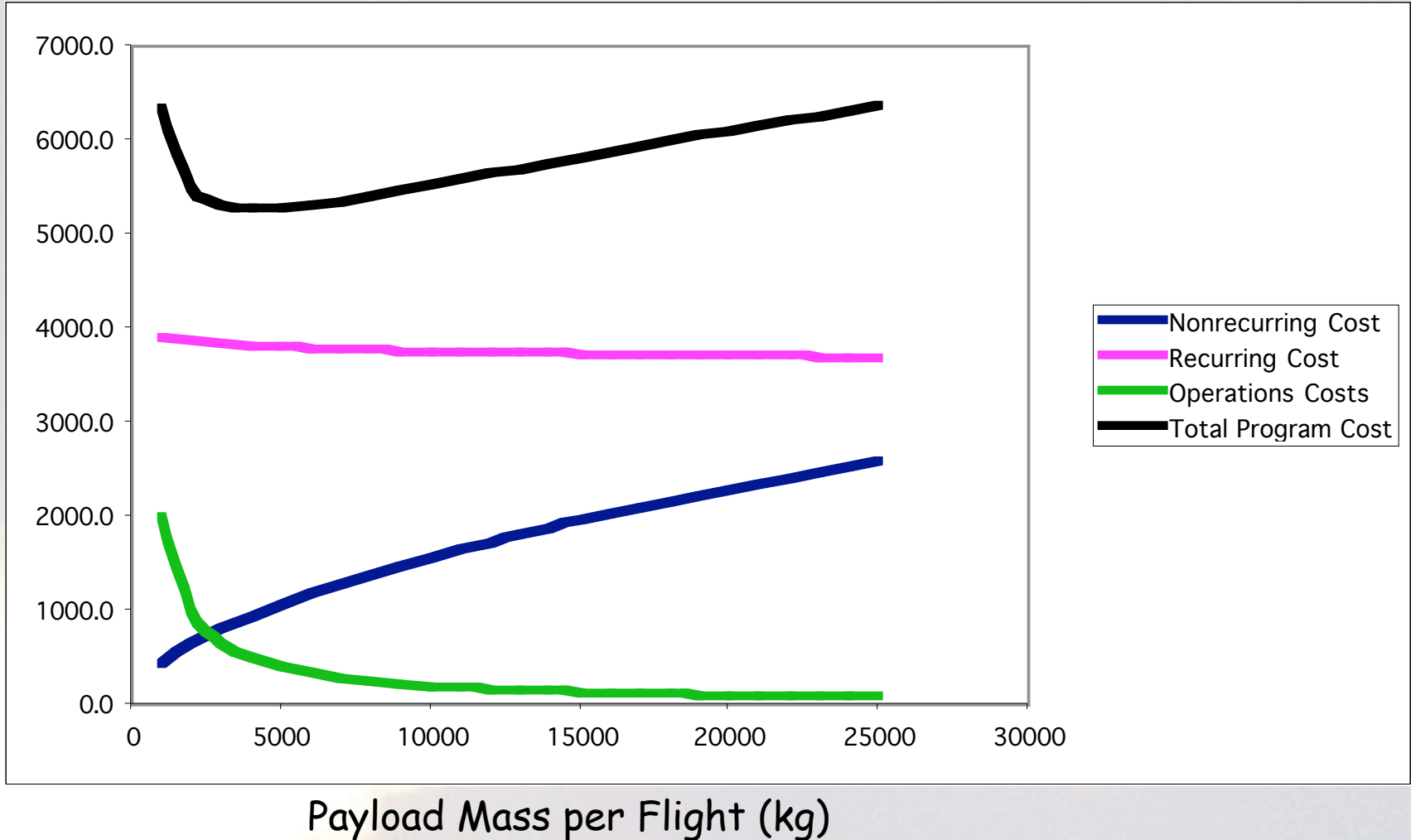
$$\bar{C}_n \approx C_1 \frac{n^p}{1+p}$$

$$p = \frac{\log\left(\frac{C_2}{C_1}\right)}{\log(2)}$$



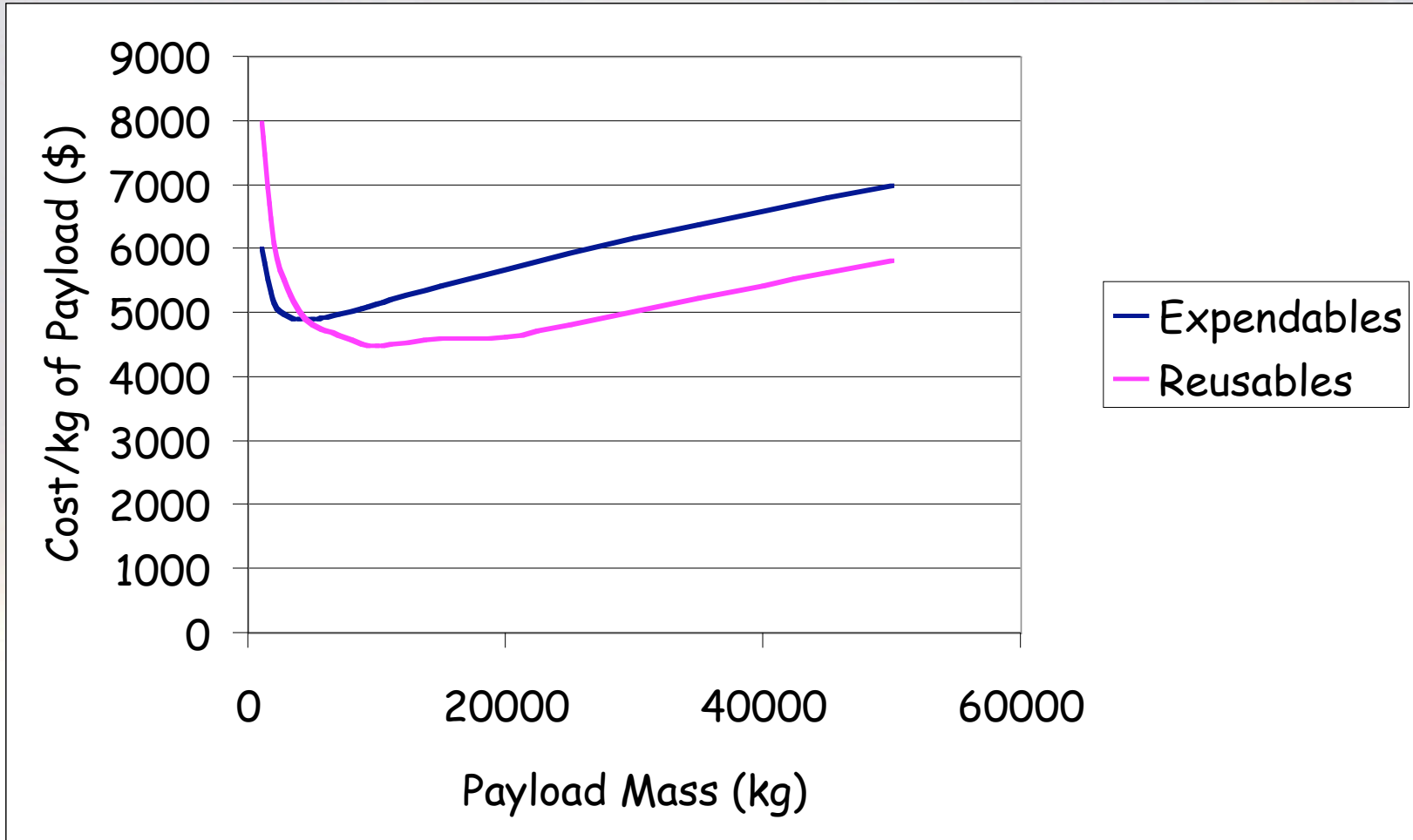
# Cost and Learning Effects

Total Program Payload Mass = 1,000,000 kg



# Expendable/Reusable Trade Study

Total Market to Orbit=1,000,000 kg

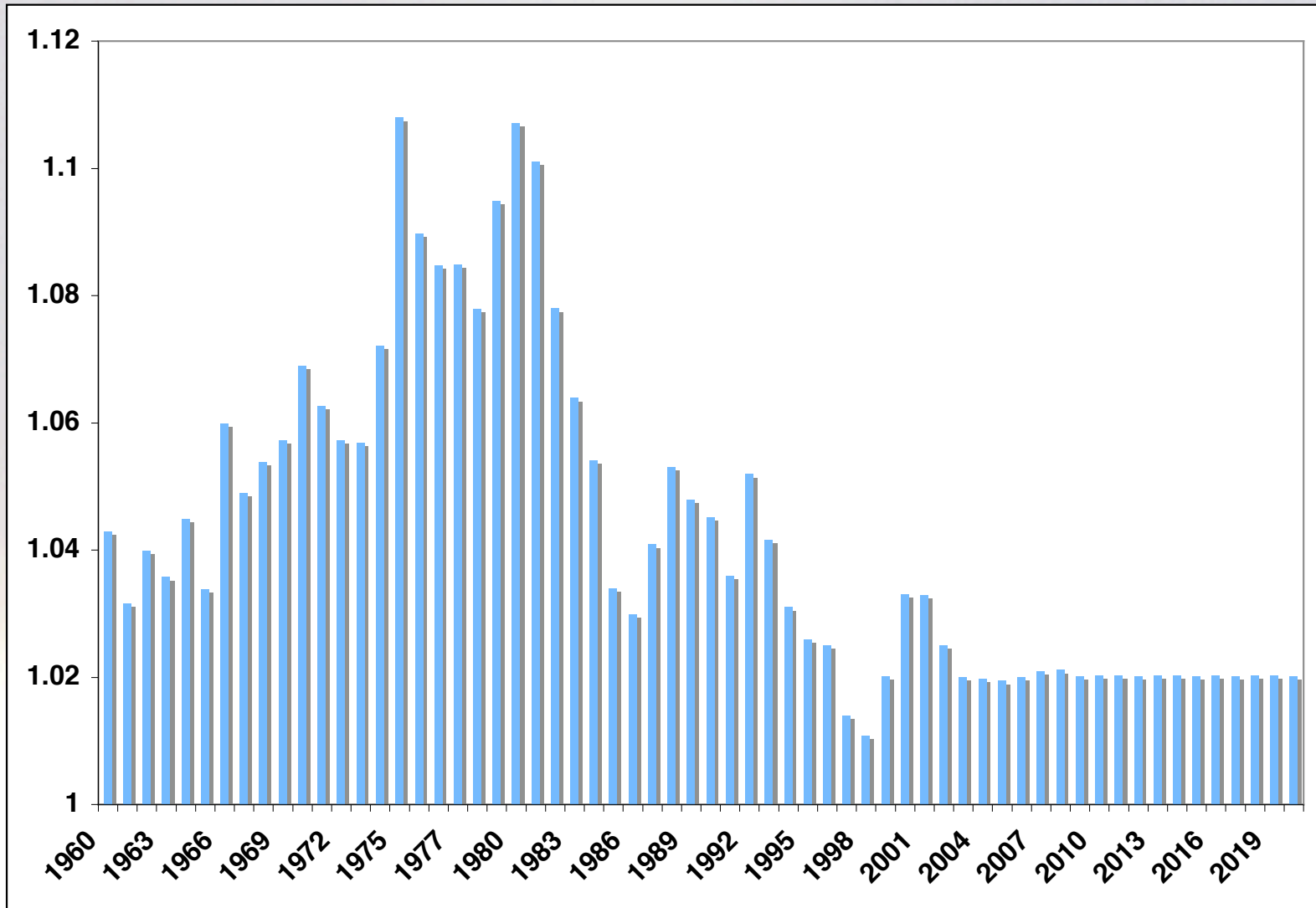


# Inflation

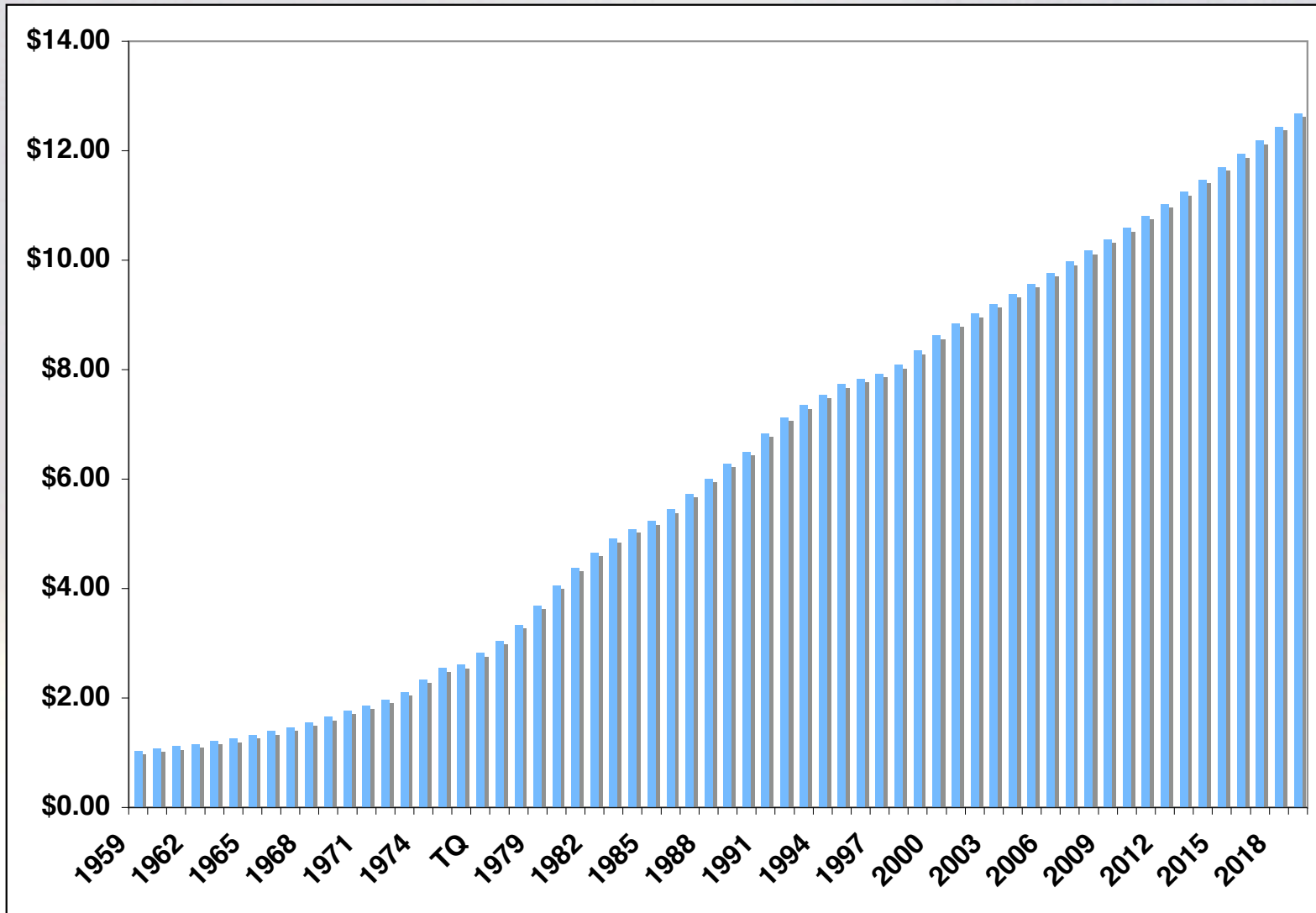
- As money supply and economy expand, buying power of money decreases
- A fixed sum of money is worth less from year to year
- "Real year dollars" - what specific year the money is quoted for (e.g., "\$M2000")
- "Constant year dollars" - costing multiyear program based on buying power in single specified year (inflation added later)



# Annual NASA Inflation Rates 1960-2020



# Cost of Comparable NASA Components



# NASA Inflation Factors 1959-1987

Year	1959=1	2006=1	Year	1959=1	2006=1	Year	1959=1	2006=1
1959	1	0.1046	1969	1.551	0.1622	1978	3.044	0.3183
1960	1.043	0.1091	1970	1.658	0.1734	1979	3.333	0.3485
1961	1.076	0.1125	1971	1.762	0.1842	1980	3.69	0.3858
1962	1.119	0.1170	1972	1.863	0.1948	1981	4.063	0.4248
1963	1.159	0.1212	1973	1.969	0.2059	1982	4.38	0.4580
1964	1.211	0.1266	1974	2.111	0.2207	1983	4.66	0.4873
1965	1.252	0.1309	1975	2.339	0.2446	1984	4.912	0.5136
1966	1.327	0.1388	1976	2.549	0.2665	1985	5.079	0.5311
1967	1.392	0.1456	TQ	2.603	0.2722	1986	5.231	0.5470
1968	1.467	0.1534	1977	2.824	0.2953	1987	5.445	0.5693



# NASA Inflation Factors 1988-2020

Year	1959=1	2006=1	Year	1959=1	2006=1	Year	1959=1	2006=1
1988	5.734	0.5996	1999	8.083	0.8452	2010	10.378	1.0852
1989	6.009	0.6283	2000	8.35	0.8731	2011	10.588	1.1071
1990	6.28	0.6567	2001	8.625	0.9019	2012	10.802	1.1295
1991	6.506	0.6803	2002	8.841	0.9244	2013	11.021	1.1524
1992	6.844	0.7156	2003	9.018	0.9430	2014	11.244	1.1757
1993	7.129	0.7454	2004	9.197	0.9617	2015	11.471	1.1994
1994	7.35	0.7685	2005	9.376	0.9804	2016	11.704	1.2238
1995	7.541	0.7885	2006	9.5636	1.0000	2017	11.94	1.2485
1996	7.73	0.8083	2007	9.7646	1.0210	2018	12.182	1.2738
1997	7.838	0.8196	2008	9.9708	1.0426	2019	12.429	1.2996
1998	7.923	0.8285	2009	10.172	1.0636	2020	12.68	1.3259



# Example: Saturn V Development Costs

Year	Real-Year \$M	\$M2006
1964	763.4	6028.8
1965	964.9	7370.5
1966	1177.3	8484.7
1967	1135.6	7802.0
1968	998.9	6512.0
1969	534.5	3295.8
1970	484.4	2794.1
1971	189.1	1026.4
1972	142.5	731.5
1973	26.3	127.7
<b>Totals (\$M)</b>	<b>6417</b>	<b>44,174</b>



# Cost Discounting

- Opportunity costs of money
- Analogous to compound interest at a bank
- **Not** the same thing as inflation
- Basic Definitions:
  - Net Present Value (NPV) - value of future sum today
  - Net Future Value (NFV) - value of sum today in the future
  - Discount Rate (  $r$  ) - annual interest rate
- Provides a method of comparing costs across multiple years

# Basic Equations of Cost Discounting

- Net Present Value (NPV)

$$C_i = C_{i+n} (1+r)^{-n}$$

- Net Future Value (NFV)

$$C_{i+n} = C_i (1+r)^n$$

- NPV of constant annual payments of R

$$C_i = R \frac{1 - (1+r)^{-n}}{r}$$

- NFV of constant annual payments of R

$$C_{i+n} = R \frac{(1+r)^n - 1}{r}$$



# Cost Discounting Example: Saturn V

Year	\$M2000	NPV (2000) ( $r=0.10$ )	NFV (2010) ( $r=0.10$ )
2001	3255.4	2959.4	7676.0
2002	4045.8	3343.6	8672.5
2003	4831.0	3629.6	9414.3
2004	4515.3	3084.0	7999.1
2005	3830.1	2378.2	6168.5
2006	1962.0	1107.5	2872.6
2007	1687.9	866.2	2246.6
2008	626.2	292.1	757.7
2009	450.1	190.9	495.1
2010	79.5	30.6	79.5
Totals	25283.4	17882.3	46382.0



# Cost Discounting and Breakeven

Year	\$M2000	Flights	Revenue	NPV (2000)	
				Costs	Revenue
2001	3255			2959.4	
2002	4046			3343.6	
2003	4831			3629.6	
2004	4515			3084.0	
2005	3830			2378.2	
2006	1962	3	5057	1107.5	2854.4
2007	1688	3	5057	866.2	2594.9
2008	626	3	5057	292.1	2359.0
2009	450	3	5057	190.9	2144.5
2010	79	3	5057	30.6	1949.6
Totals	25283	15	25283	17882.3	11902.3

\$8428/lb



# Breakeven with Discounting

Year	\$M2000	Flights	Revenue	Costs	Revenue
2001	3255			2959	
2002	4046			3344	
2003	4831		\$12,660/lb	3630	
2004	4515			3084	
2005	3830			2378	
2006	1962	3	7597	1108	4288
2007	1688	3	7597	866	3899
2008	626	3	7597	292	3544
2009	450	3	7597	191	3222
2010	79	3	7597	31	2929
Totals	25283	15	37986	17882	17882



# Effect of Moving Revenue Forward

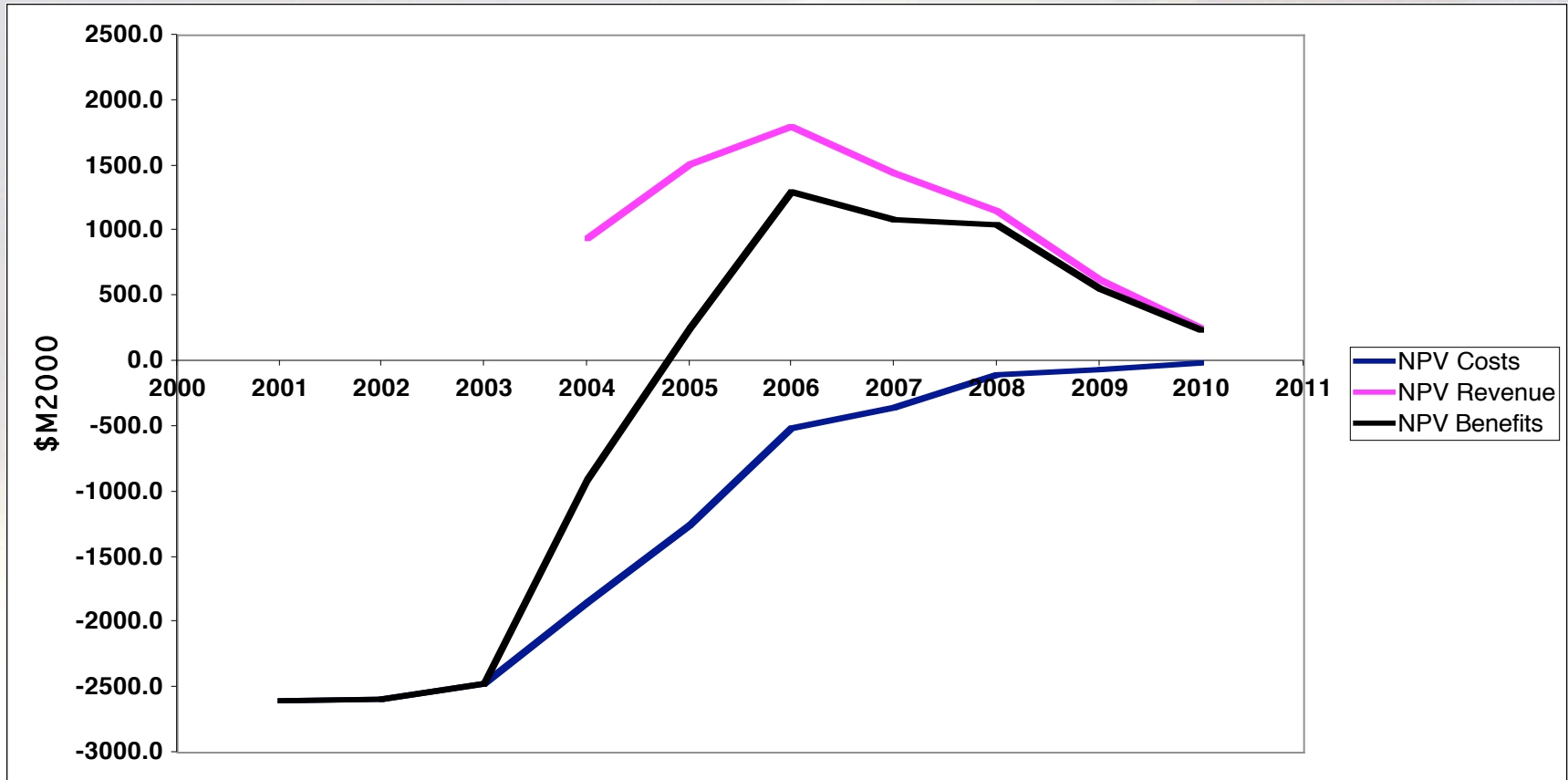
Year	\$M2000	Flights	Revenue	NPV (2000)	
				Costs	Revenue
2001	3255			2959.4	
2002	4046			3343.6	
2003	4831			3629.6	
2004	4515	1	2295.2	3084.0	1567.7
2005	3830	2	4590.5	2378.2	2850.3
2006	1962	3	6885.7	1107.5	3886.8
2007	1688	3	6885.7	866.2	3533.5
2008	626	3	6885.7	292.1	3212.2
2009	450	2	4590.5	190.9	1946.8
2010	79	1	2295.2	30.6	884.9
Totals	25283	15	34429	17882.3	17882.3

\$11,480/lb



# Internal Rate of Return

- Discount rate that produces breakeven

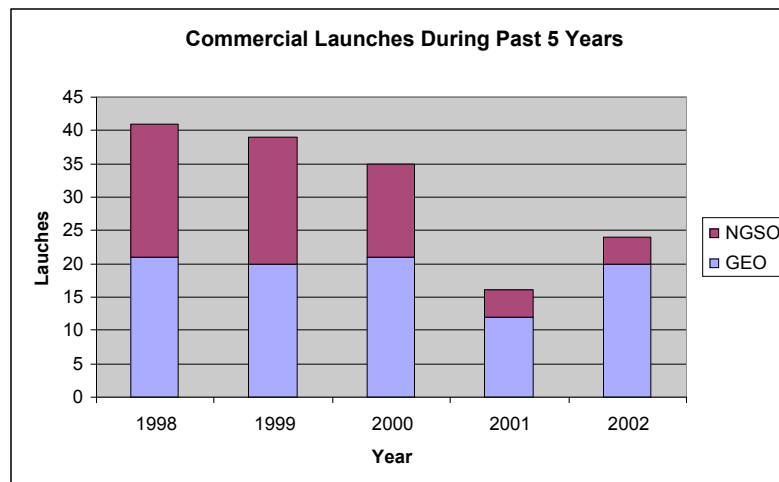
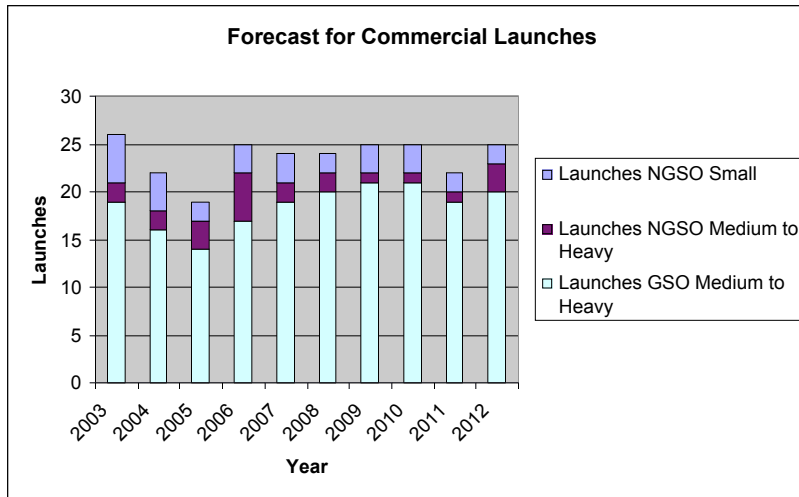


# Effect of IRR Targets

- Investors generally require specific minimum values of IRR
- Have to increase revenue stream to achieve IRR
- Saturn V launch case:
  - 10% IRR \$11,480/lb
  - 25% IRR \$17,580/lb
  - 50% IRR \$32,700/lb
- Venture capitalists general look for 70-100% IRR with 18-month payback



# Cost Modeling



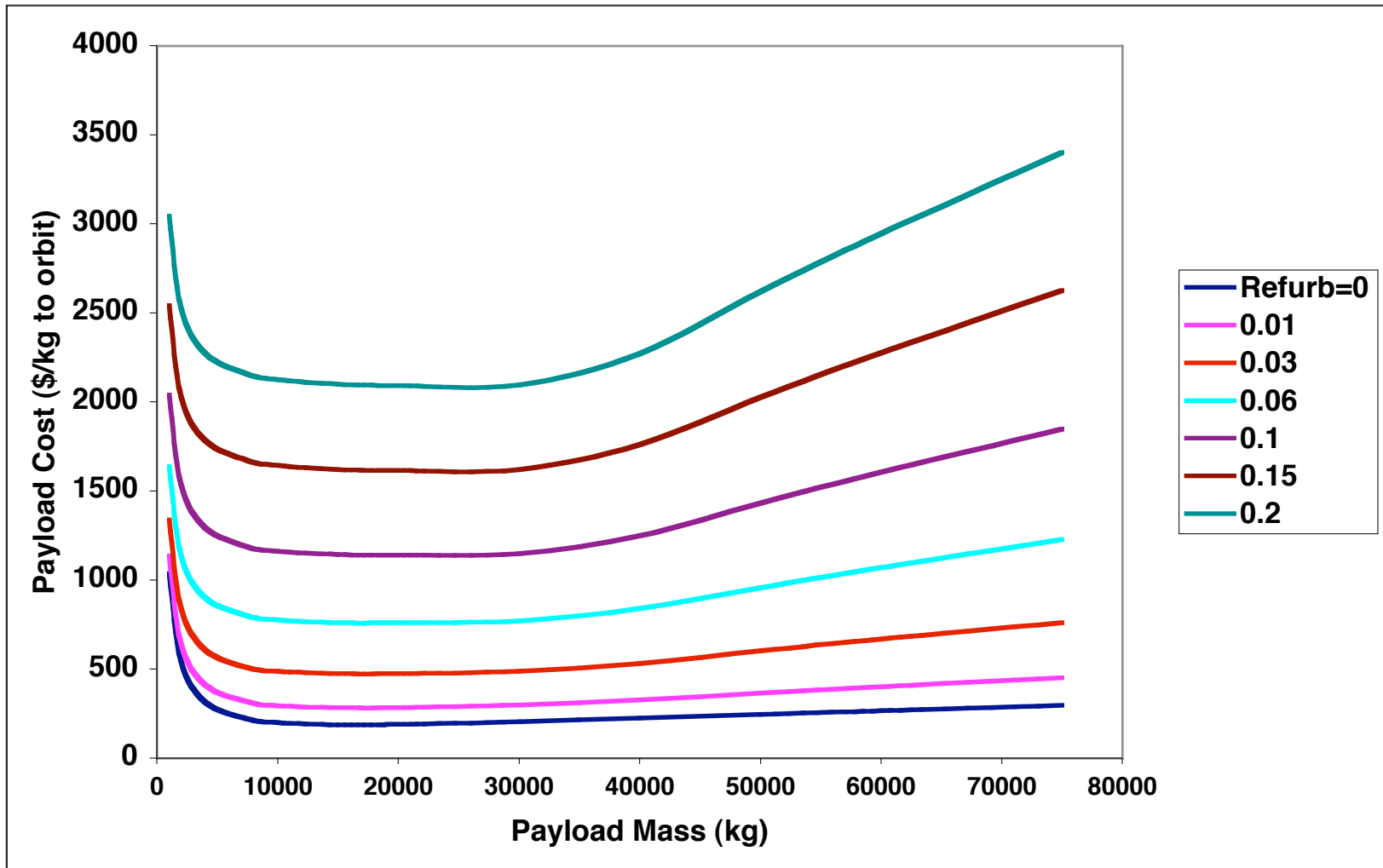
- At ~\$100M/launch, worldwide annual launch revenue is ~\$6-8 B
- Potential savings by cutting costs by factor of 2 is ~\$3-4 B
- Given a 10 year development program and a 10% discount rate (government support), maximum feasible program cost for new vehicle is ~\$2.5 B/yr
- At a 50% ROI (commercial), maximum yearly expenditure is ~\$70 M
- Only economically feasible as a government program
- Budget caps reduced if launch costs don't drop as much (e.g., 75% of current launch costs gives annual NTE of \$1.25 B)
- Incorporation of advanced technology is only justified insofar as it reduces launch costs
- *Design goal is effective, not efficient!!!*

# Parametric Cost Analysis

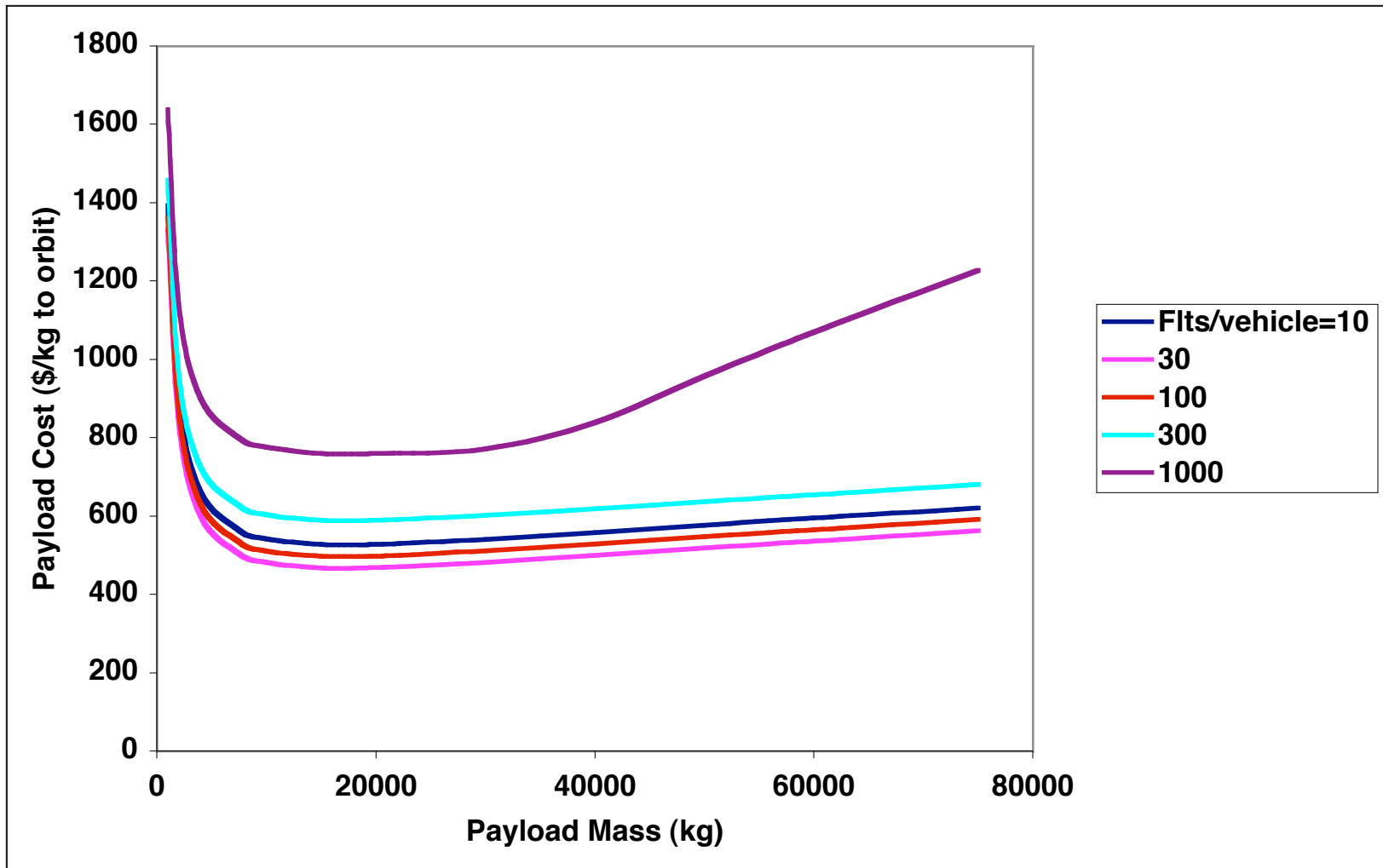
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- Preliminary model developed to bound problem, identify critical parameters
- Assumptions:
  - Total program launch mass 20,000 MT
  - Program lifetime 20 years
  - NASA SLVLC model for cost estimates
  - 80% learning curve
  - Vehicle modeled as LOX/LH2 SSTO ( $\delta=0.08$ ;  $I_{sp}=420$  sec avg.)

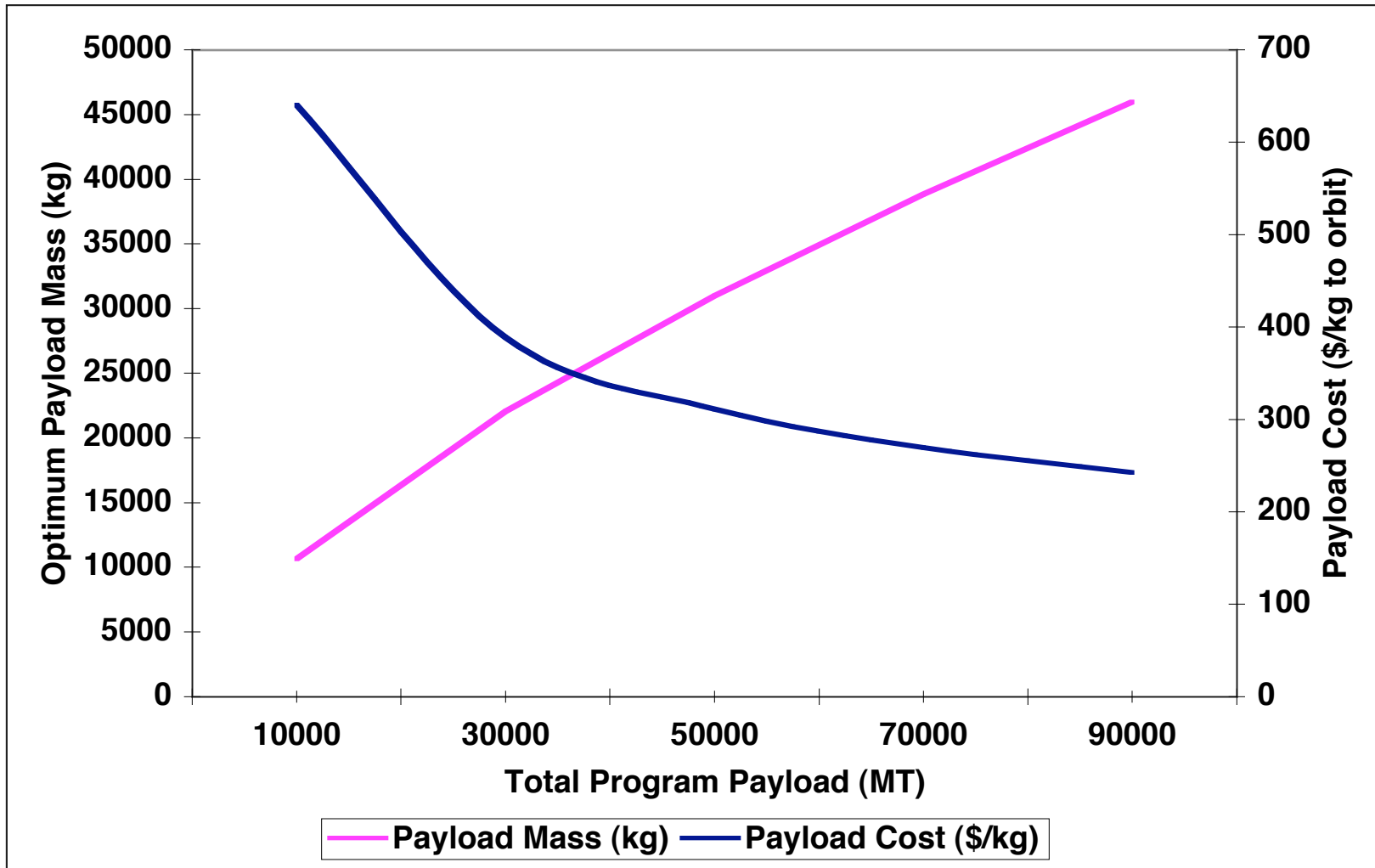
# Effect of Refurbishment Rate



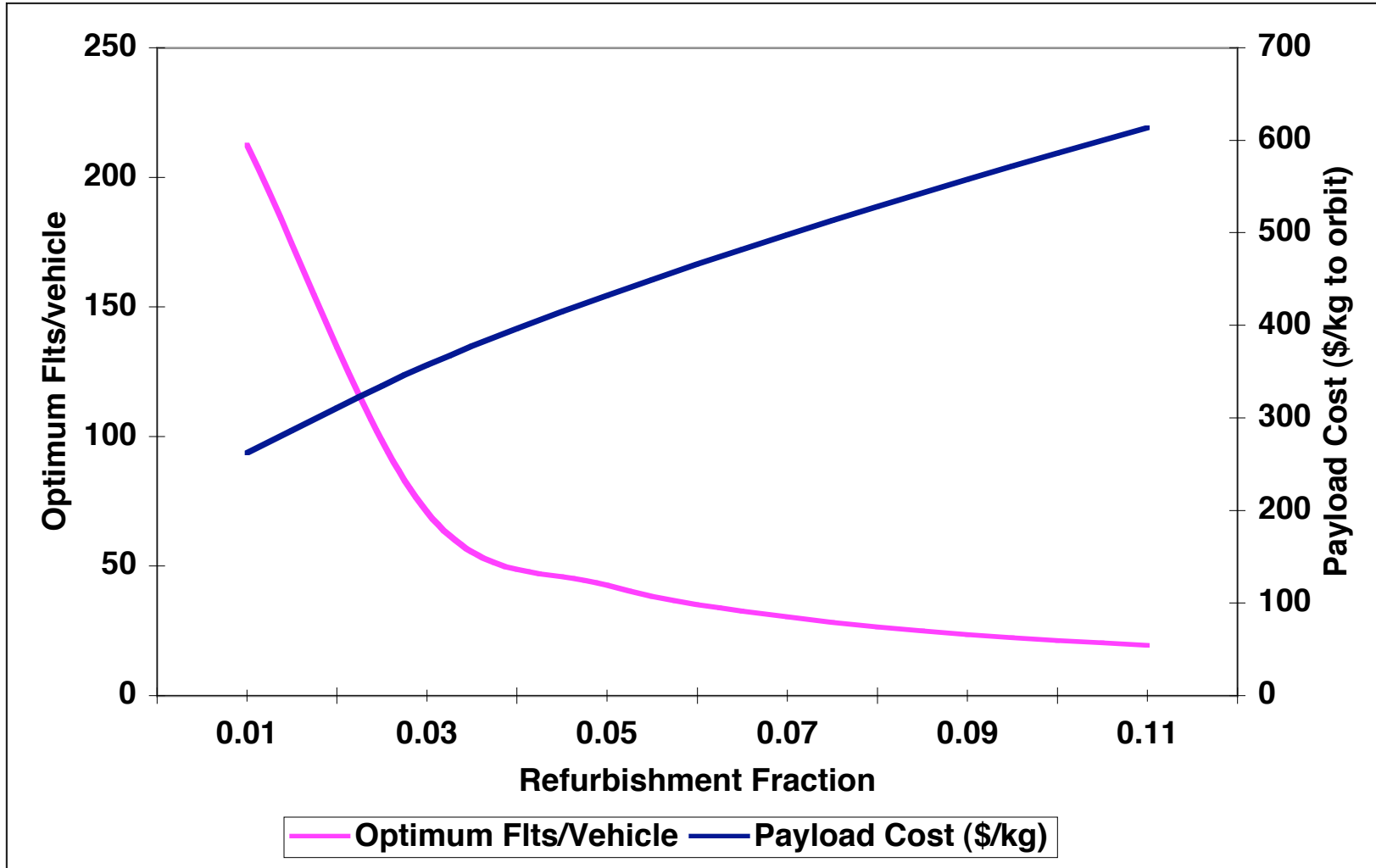
# Effect of Vehicle Lifetime



# Effect of Total Launch Mass



# Effect of Refurbishment Fraction



# Costing Conclusions (to date)

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- Primary cost drivers are refurbishment and mission operations costs
  - Keep flight rate *and* production rates high to take advantage of learning curve
  - Strong sensitivity to fleet size
- Prediction: effects will be *worse* with RLV
  - Smaller fleet sizes
  - Higher (inert mass)/(payload mass) ratios
  - Effects of vehicle losses on program resiliency
- Need to add cost discounting
- Bottom line: compare cost of airbreathing RLV vs. rocket RLV vs. expendable launch vehicle (*not* a foregone conclusion!)



# Case Study:

## Utilizing On-Orbit Assembly and Servicing to Enable Minimum-Cost Space Mission Architectures

David L. Akin  
Mary L. Bowden

AIAA Space 2005 Conference  
Long Beach, CA  
August 31, 2005



# NASA Plan (Monolithic Architecture)

- **Launch entire mission vehicle on single heavy-lift vehicle**
- **Launch crew in CEV on human-rated vehicle**
- **Earth orbit rendezvous docks crew and CEV to mission spacecraft**
- **Lunar orbit staging site leaves CEV in orbit while crew descends to lunar surface**
- **Lunar orbit rendezvous for crew to return to CEV**
- **CEV departs lunar orbit and travels back to earth (direct atmospheric entry)**



# Modular Architecture

- **Multiple boost modules launched on EELVs and docked together**
- **Lunar landing/ascent vehicle launched on EELV and docked to boost module stack**
- **Launch crew in CEV on human-rated EELV**
- **Earth orbit rendezvous docks crew and CEV to mission spacecraft**
- **Lunar orbit staging site leaves CEV in orbit while crew descends to lunar surface**
- **Lunar orbit rendezvous for crew to return to CEV**
- **CEV departs lunar orbit and travels back to earth (direct atmospheric entry)**

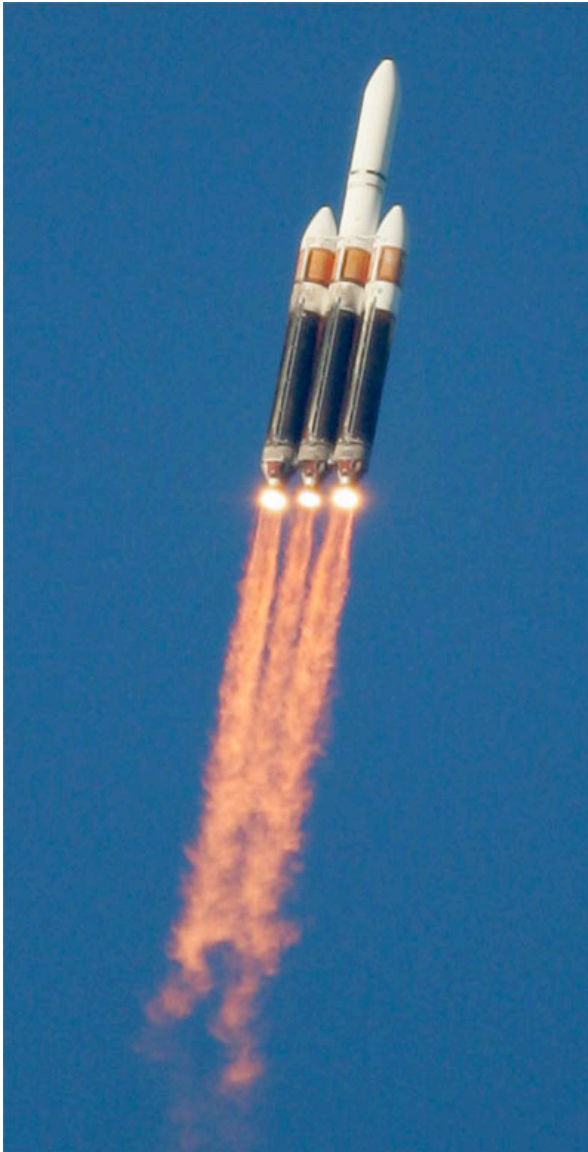


# Lunar Program Assumptions

- **2 lunar missions/year**
- **First lunar mission 2015**
- **10 lunar missions total**
- **CEV entry vehicle mass 6000 kg**
- **Lander cabin mass 3000 kg**
- **ELOR mission with CEV as return craft**
- **LOX/LH2  $I_{sp}=450$  sec**
- **Storables  $I_{sp}=320$  sec**
- **Inert mass fraction  $\delta=0.1$  except 0.15 for landing stage**
- **All launch vehicles asymptotically approach 97% reliability**
- **Rendezvous and docking reliability 99%**



# Candidate Cargo Launch Vehicles



- **Delta IV Heavy**
  - 23K kg to LEO
  - Operational
  - Unmanned
  - Representative of current large EELVs
- **In-line SDLV**
  - 125K kg to LEO
  - Conceptual
  - Manned heritage





# In-line SDLV Assumptions



- **\$8.4B nonrecurring (published estimate)**
- **6 year development cycle**
- **\$400M first unit production (shuttle parallel)**
- **10 units at 85% learning curve**
- **\$285M average flight cost**



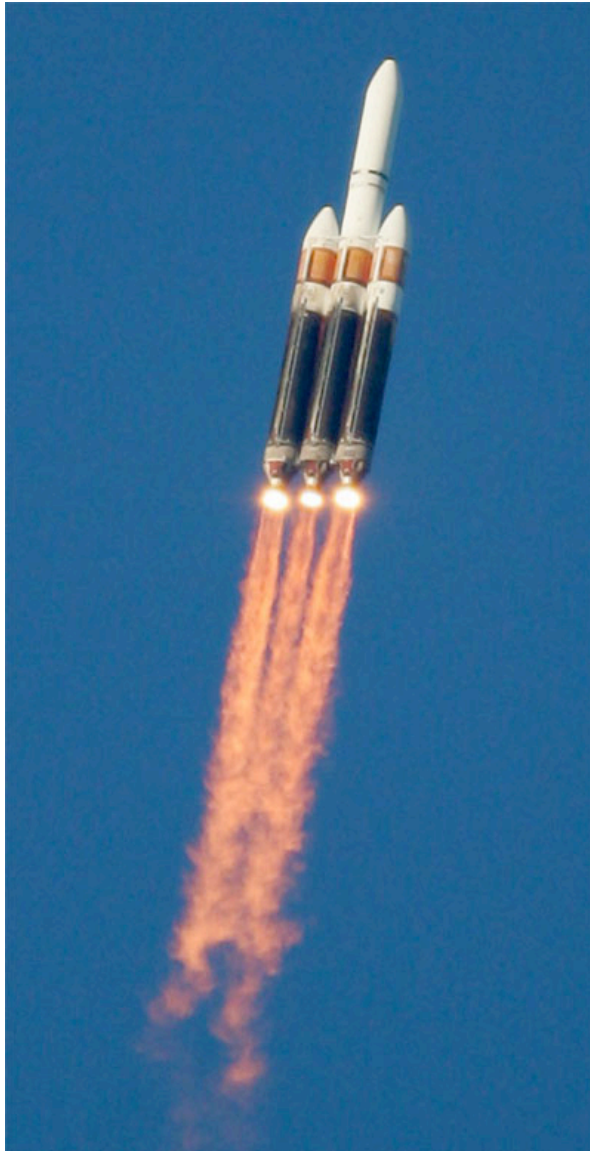
# Shuttle-Derived CEV Assumptions



- **\$2B nonrecurring (NASA SVLCM estimate for second stage alone)**
- **6 year development cycle**
- **\$200M first unit production (shuttle parallel)**
- **10 units at 85% learning curve**
- **\$144M average flight cost**



# Delta IV Heavy Assumptions

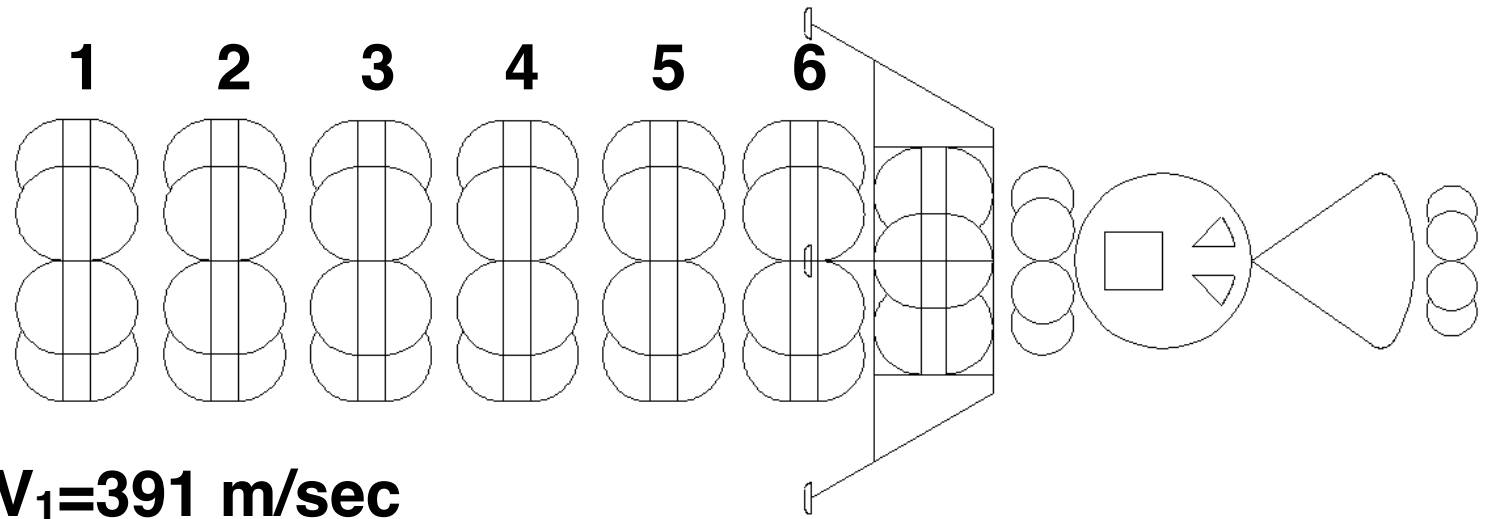


- RDT&E amortized
- \$2B nonrecurring for human rating
- \$250M first unit
- 85 vehicle block buy...
- ... and 85% learning curve...
- ... yields \$92M average cost (includes learning for 255 CBCs)
- 50% production surcharge for 11 human rated units (\$138M)



# Earth Departure Configuration

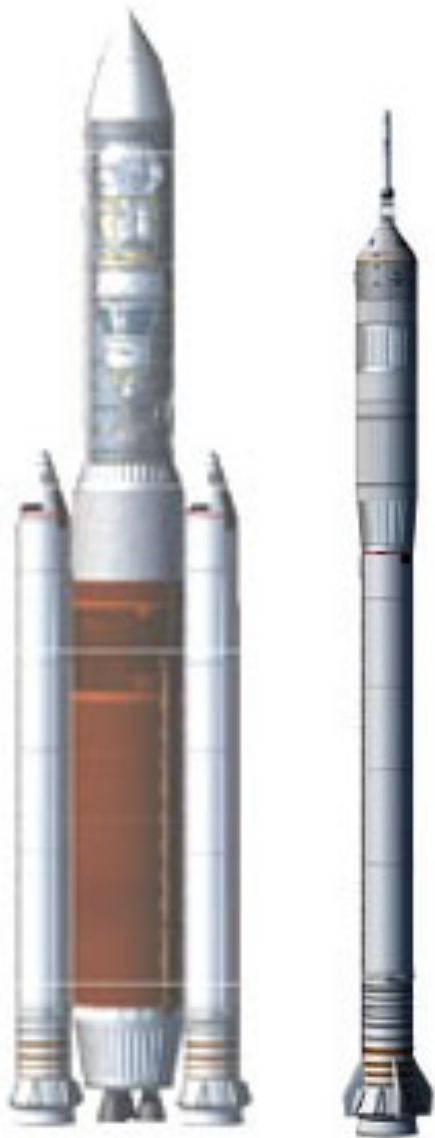
Initial Mass=176,400 kg



- $\Delta V_1=391$  m/sec
- $\Delta V_2=455$  m/sec
- $\Delta V_3=542$  m/sec
- $\Delta V_4=671$  m/sec
- $\Delta V_5=882$  m/sec



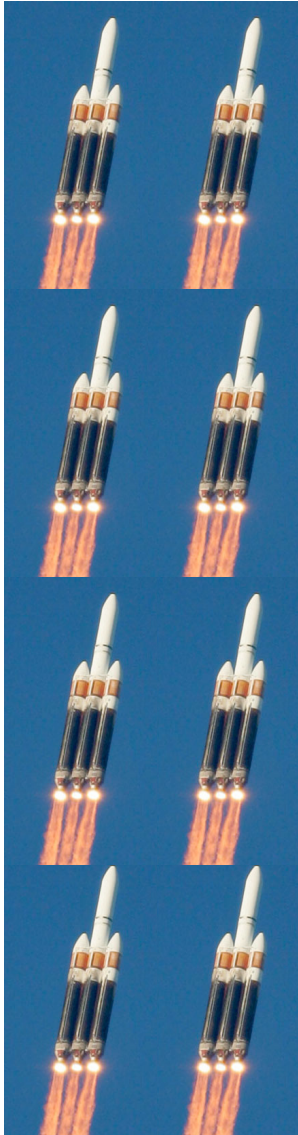
# Monolithic Launch Operations



- **\$429M average launch recurring cost**
- **Average amortized launch cost \$1.45B**
- **93% probability of individual mission initiation**
- **Probability of N missions initiating successfully**
  - 49% 10/10
  - 85% 9/10
  - 97% 8/10



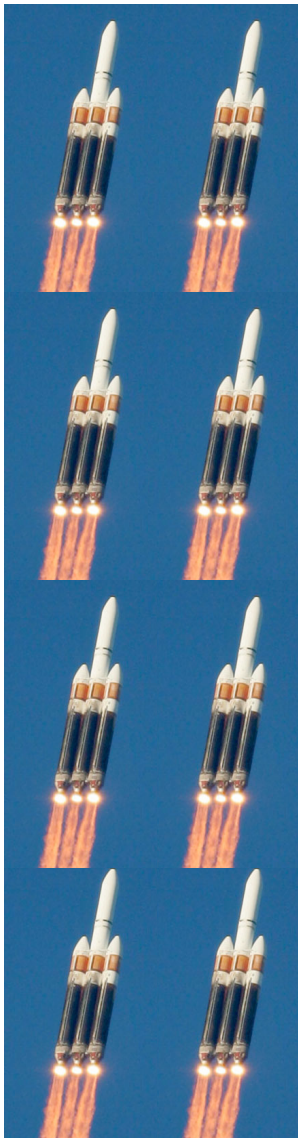
# Modular Launch Operations



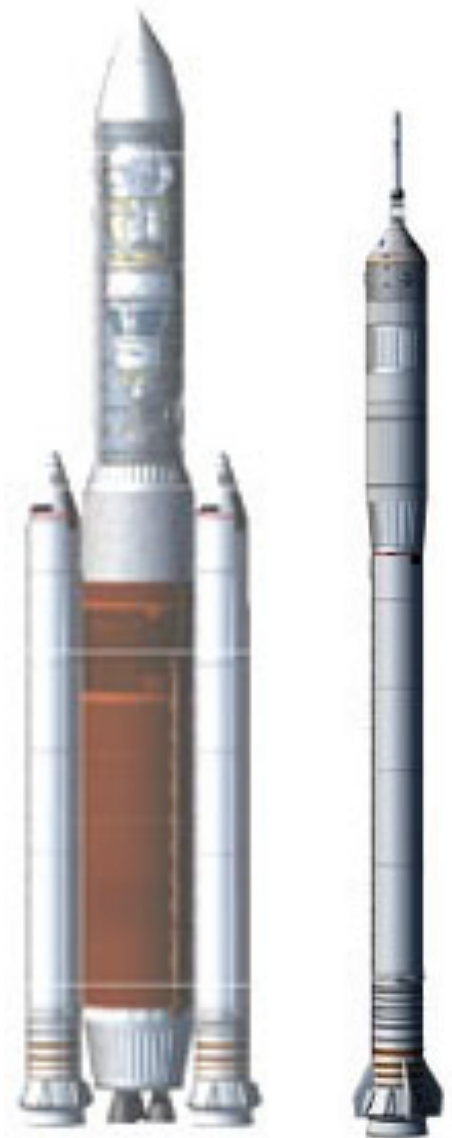
- **\$829M average launch recurring cost (includes cost of 5 fleet spares)**
- **Average amortized launch cost \$1.10B**
- **73% probability of individual mission initiation (no spares)**
- **Probability of 10 missions initiating successfully**
  - **16% (no spares)**
  - **71% (2 spares)**
  - **88% (3 spares)**
  - **96% (4 spares)**
  - **99% (5 spares)**



# Head-to-Head Launch Comparison

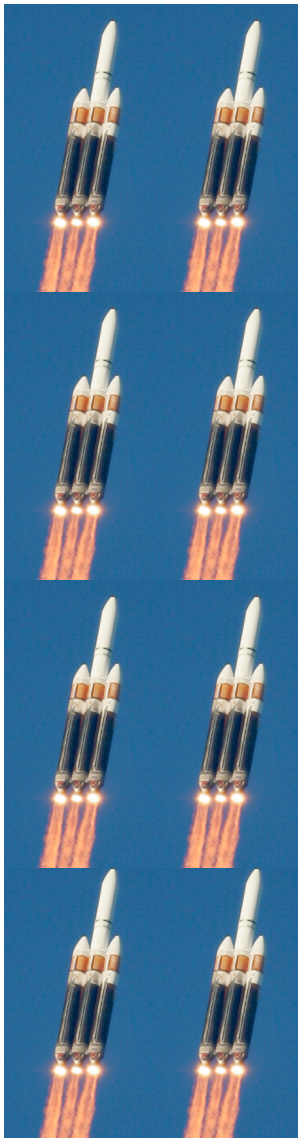


<b>2000</b>	Nonrecurring cost (\$M)	<b>10,200</b>
<b>829</b>	Average production cost per mission (\$M)	<b>429</b>
<b>1096</b>	Average amortized cost per mission (\$M)	<b>1449</b>
<b>85</b>	Total production run	<b>10+10</b>
<b>432</b>	NPV discounted cost per mission (\$M)	<b>878</b>

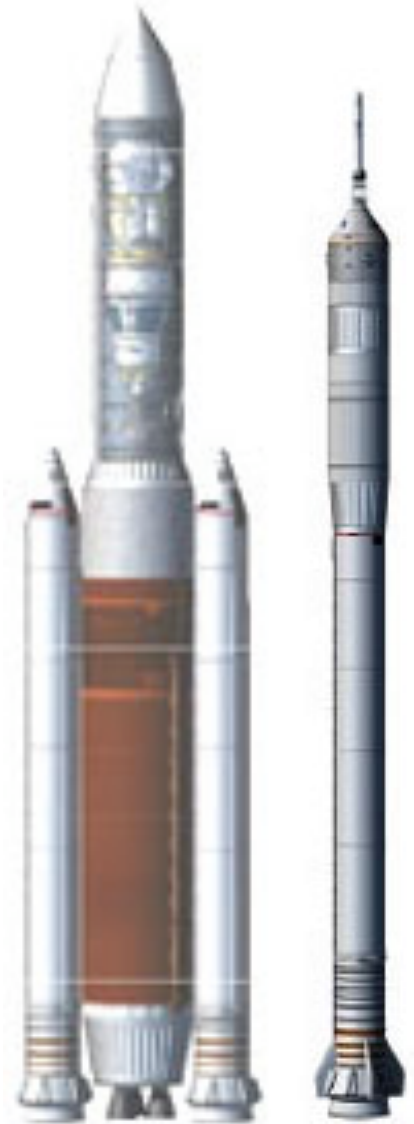




# Sensitivity to Monolithic Costing



<b>\$432M</b>	Baseline NPV discounted cost per mission	<b>\$878M</b>
<b>\$432M</b>	Development costs cut in half	<b>\$508M</b>
<b>\$432M</b>	Production costs cut in half	<b>\$809M</b>
<b>\$432M</b>	Production is free	<b>\$740M</b>
<b>\$432M</b>	All costs cut in half	<b>\$439M</b>





# Discussion of Costs

- **Cost benefits of modular systems:**
  - Learning curve effects for large production runs
  - Minimum “up-front” nonrecurring costs
- **Modular systems also benefit from other markets for the same launch vehicles**
- **Minimal market synergy for monolithic vehicles**
  - In-line SDLV too large (5x current largest vehicle)
  - SRB-based vehicle offers few intrinsic advantages to commercial/DOD payloads
- **Lesson: spend your money flying, not developing new vehicles (suggested mantra: “flight rate, flight rate, flight rate”)**



# Additional Caveats

- **Didn't consider costing of mission vehicles**
  - CEV and lander are comparable for both architectures
  - Additional cost advantages to modular system for smaller size/large production of boost modules as compared to monolithic TLI stage
- **Modular system is sensitive to docking reliability, but it primarily shows up in spares strategy (low marginal cost for larger production run)**
- **Could use modular approach with SRB-based CEV launcher - minor overall impact to cost**

# Cost Spreading Estimation

- Programs very seldom occur in a single funding year
- Costs are not constant from year to year
  - Low start-up costs
  - High costs during vehicle development and fabrication
  - Low end-of-life costs
- Costs are estimated using a beta function
- Calculation worksheet at <http://www.jsc.nasa.gov/bu2/beta.html>



# Beta Function for Cost Spreading

- Cumulative normalized cost function

$$C(\tau) = 10\tau^2(1-\tau)^2(A+B\tau) + \tau^4(5-4\tau)$$

where

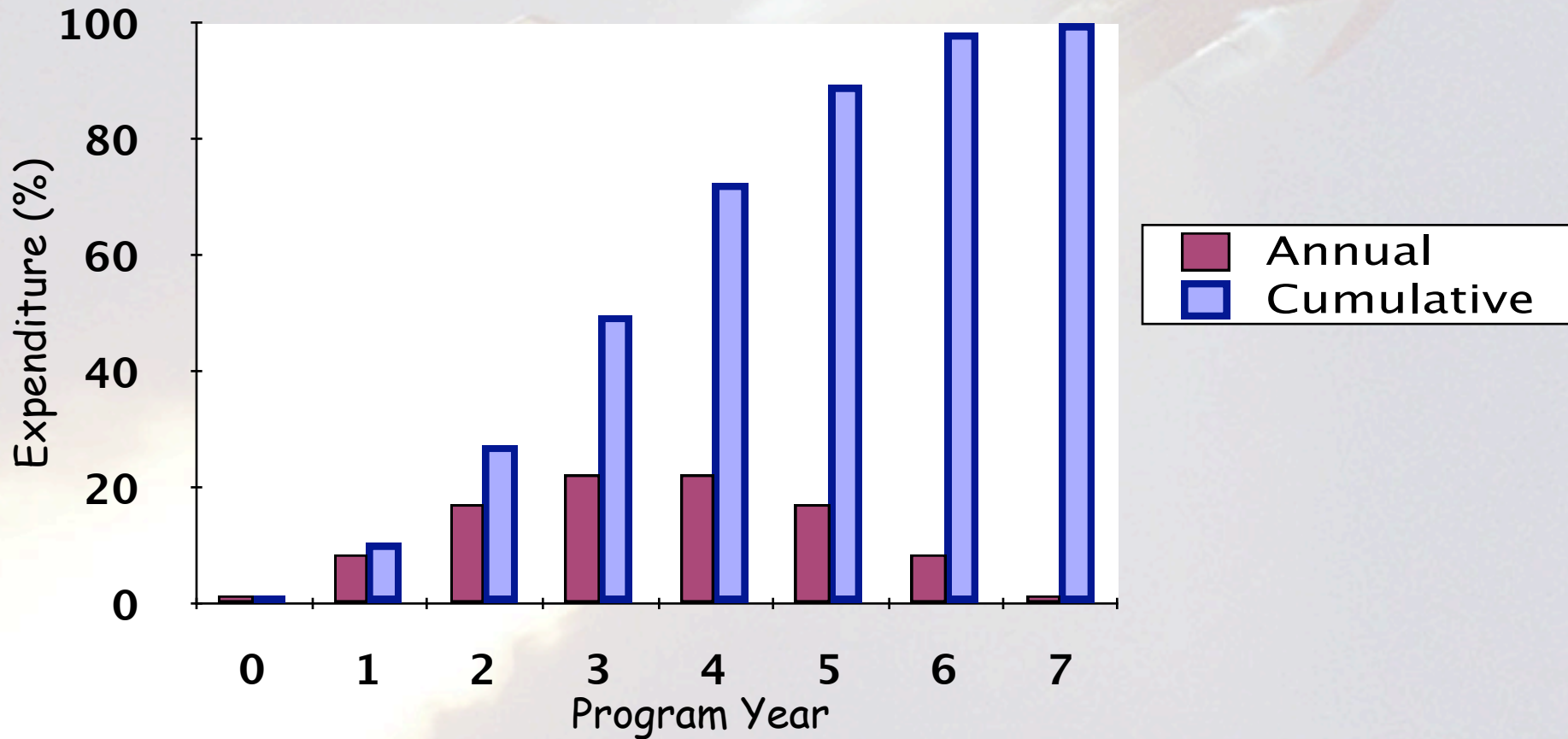
- $C$  = fraction of total program cost ( $0 \leq C \leq 1$ )
- $\tau$  = fraction of total program time ( $0 \leq \tau \leq 1$ )
- $A$  and  $B$  = shape parameters ( $0 \leq A+B \leq 1$ )
- Can also define equivalent parameters  $c_f$  (location of maximum) and  $P$  (width of peak)  
 $0 \leq P \leq 1$ ;  $0.1875 \leq c_f \leq 0.8125$

$$c_f < 0.5 : A = \frac{(1-P)(c_f - 0.1875)}{0.625}; B = P \frac{c_f - 0.1875}{0.3125}$$

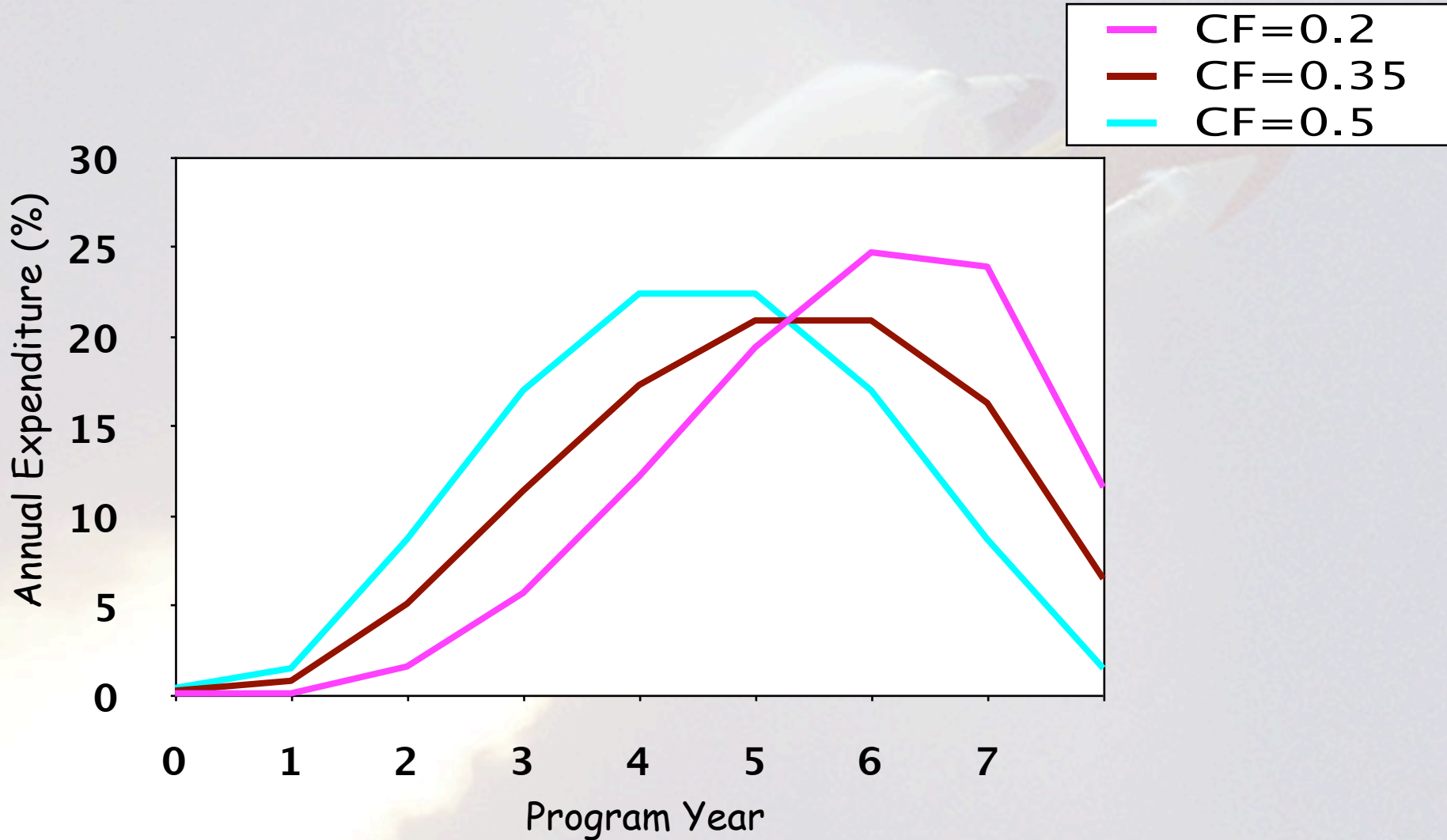
$$c_f \geq 0.5 : A = \frac{P(c_f - 0.8125) + (c_f - 0.1875)}{0.625}; B = P \frac{0.8125 - c_f}{0.3125}$$



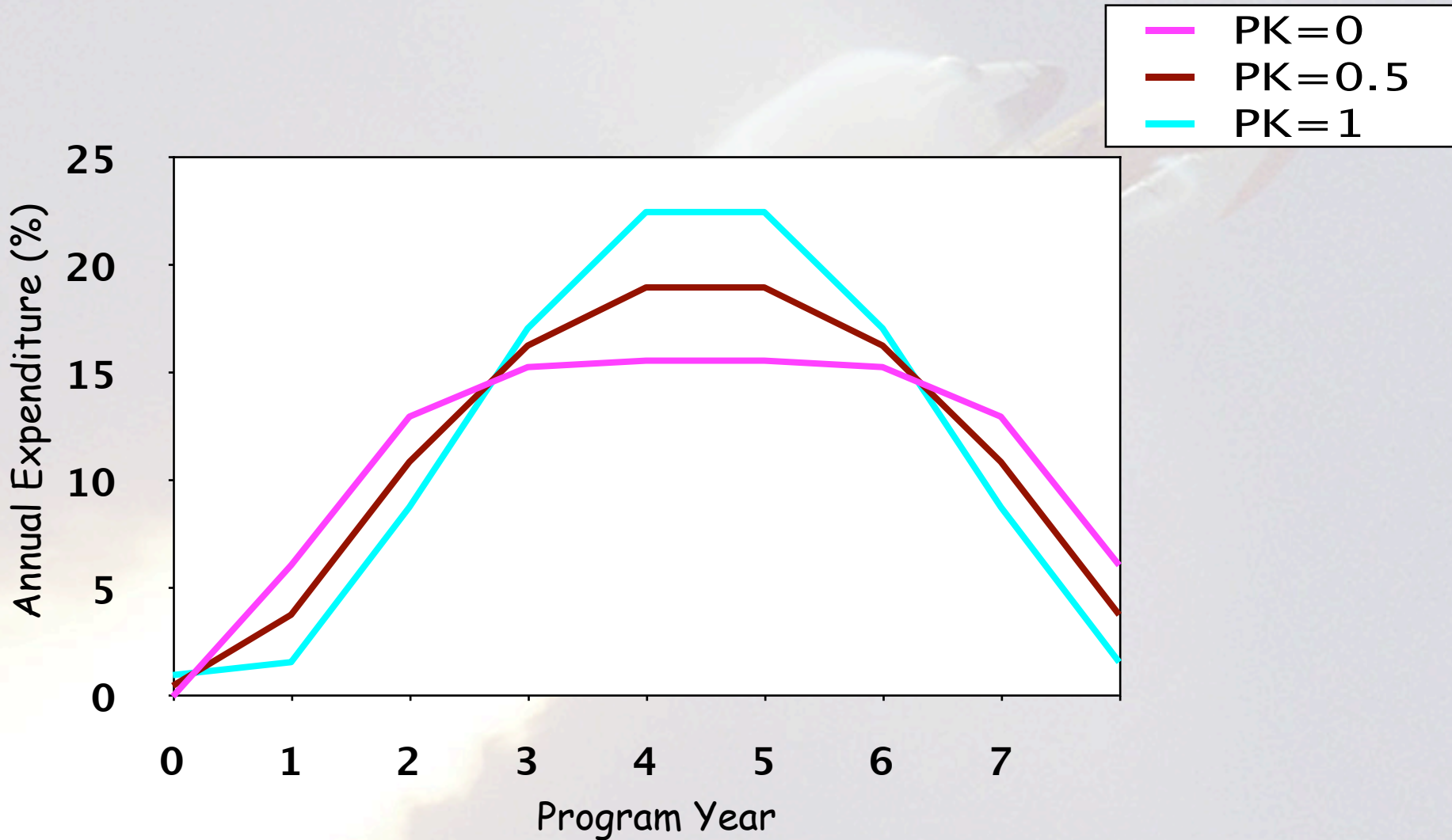
# Sample of Beta Function



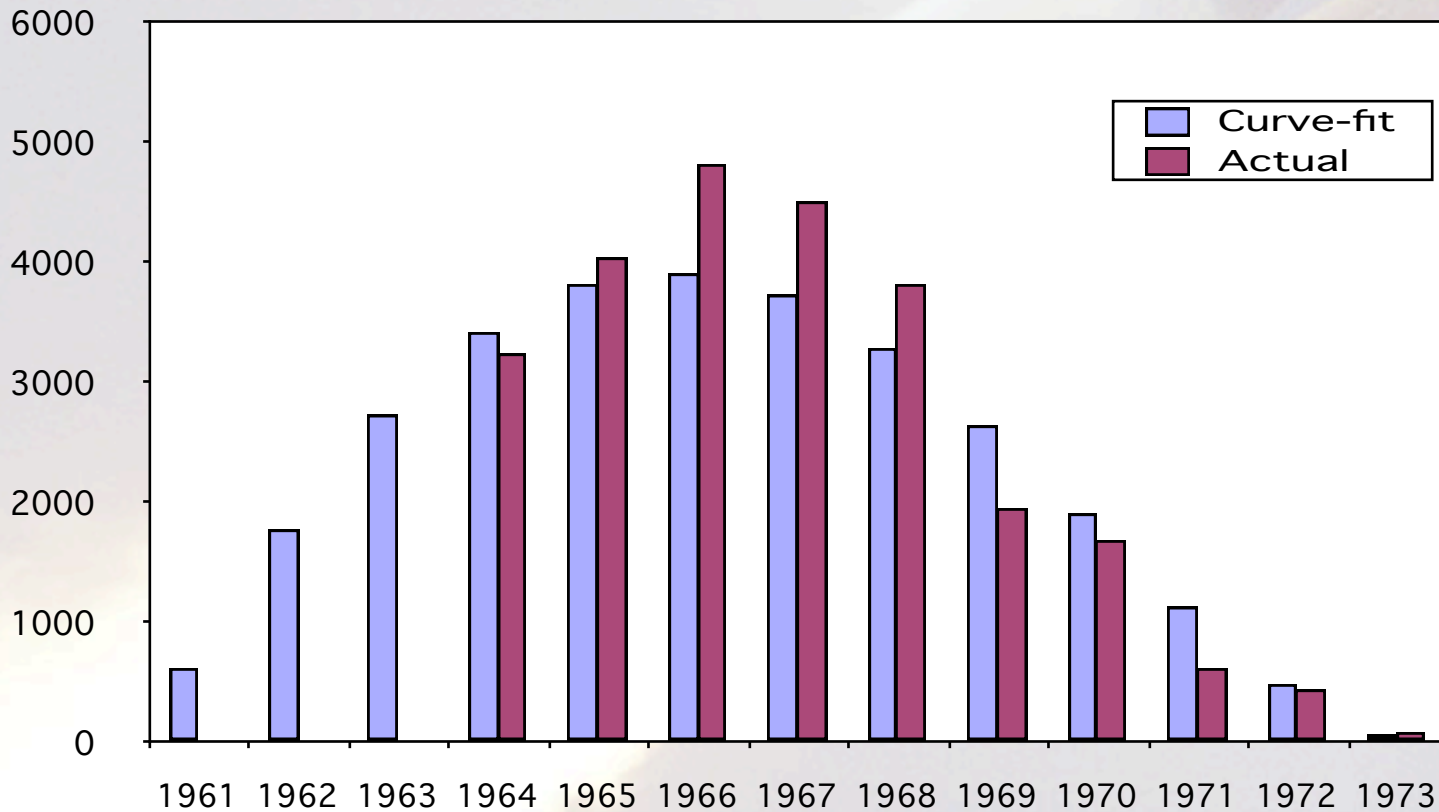
# Cost Fraction in Beta Function



# Peakedness in Beta Function



# Beta Curve Fit to Saturn V Data



$A=0.371; B=0.629$



# References

- Richard de Neufville and Joseph H. Stafford, *Systems Analysis for Engineers and Managers* McGraw-Hill, 1971



# Web-Based Costing References

- NASA Cost Estimation Web Site  
<http://www.jsc.nasa.gov/bu2/index.html>
- Vehicle-Level Costing Models  
<http://www.jsc.nasa.gov/bu2/SVLCM.html>
- Inflation Adjustment  
<http://www.jsc.nasa.gov/bu2/inflate.html>
- Learning Curves
  - <http://www.jsc.nasa.gov/bu2/learn.html>
  - <http://www1.jsc.nasa.gov/bu2/inflation/nasa/inflateNASA.html>

