Cost Estimation and Engineering Economics

- Cost Sources
- Vehicle-level Costing Heuristics
- Learning Curves
- 2 Case Studies
- Inflation
- Cost Discounting
- Return on Investment
- Cost/Benefit Ratios
- Life Cycle Costing
- 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: ~0.001%
  – Fighter jet: ~0.01%
  – X-15: 3%
  – Shuttle: 6-20%
- Major contributor to space flight costs

Spacecraft/Vehicle Level Costing Model

$$C(\$M) = a\left[m_{inert}\langle kg\rangle\right]^b$$

Spacecraft Type	Nonrecurring a	Nonrecurring b	1st unit production a	1st unit production b
Launch Vehicle Stage	8.662	0.55	0.2057	0.662
Manned Spacecraft	21.95	0.55	0.6906	0.662
Unmanned Planetary	13.89	0.55	1.071	0.662
Unmanned Earth Orbital	4.179	0.55	0.4747	0.662
Liquid Rocket Engine	34.97	0.55	0.1924	0.662
Scientific Instrument	2.235	0.50	0.3163	0.70

2008$ 2008$

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

Space Vehicle Level Costing Model

System Type	DDT&E Cost CER Coefficients		Flight Unit Cost CER Coefficients	
	k·a	b	k·a	b
Crew Capsule	285.57	0.2667	49.923	0.2409
Descent Stage (Cryogenic)	168.22	0.3152	6.8608	0.4146
Descent Stage (Storable)	168.22	0.3152	4.8935	0.4146
Ascent Stage (Cryogenic)	405.62	0.2151	92.715	0.1606
Ascent Stage (Storable)	405.62	0.2151	66.129	0.1606
Surface Habitat (4 crew)	751.64	0.1183	124.32	0.1402
In-Space Habitat (4 crew)	1457.7	0.0856	46.624	0.2146
Propulsive Stage (Cryogenic)	29.125	0.4554	2.6147	0.4782
Propulsive Stage (Storable)	29.125	0.4554	1.8650	0.4782
Propellant Depot	75.492	0.3566	11.487	0.3175

from Arney and Wilhite, "Rapid Cost Estimation for Space Exploration Systems" AIAA 2012-5183, *AIAA Space 2012*, Pasadena, California, Sept. 2012

Costing Applied to Launch Vehicle Design

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

5000 kg payload, LOX/LH2 engines

The Learning Curve

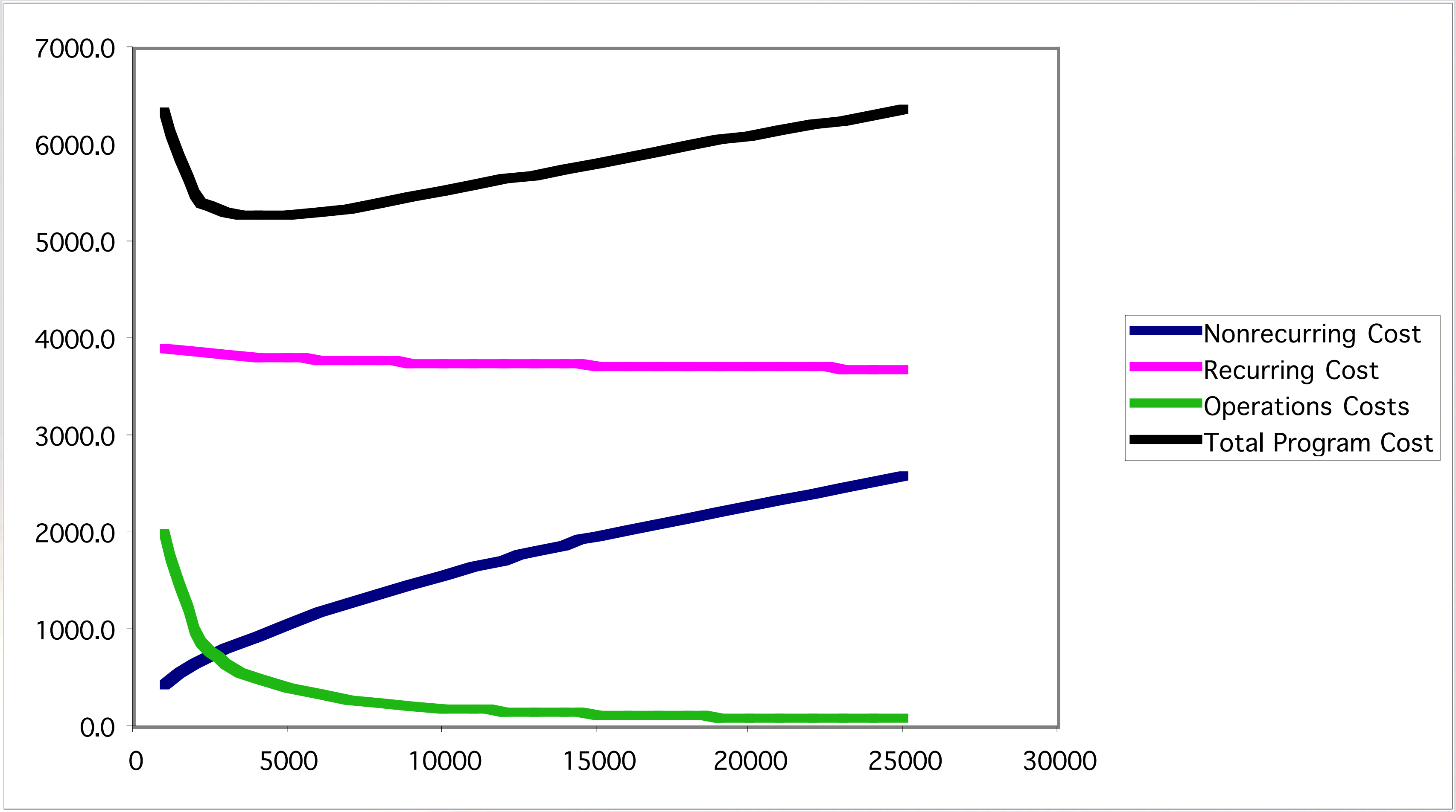
- The effort (time, cost, etc.) to perform a test decreases with repetition
- Doubling the production run results in consistent fractional reduction of effort
  - "80% learning curve" - 2nd unit costs 80% of 1st, 4th is 80% of 2nd, 8th is 80% of 4th...
  - $C_n = C_1 n^p$
  - Average cost:

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

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

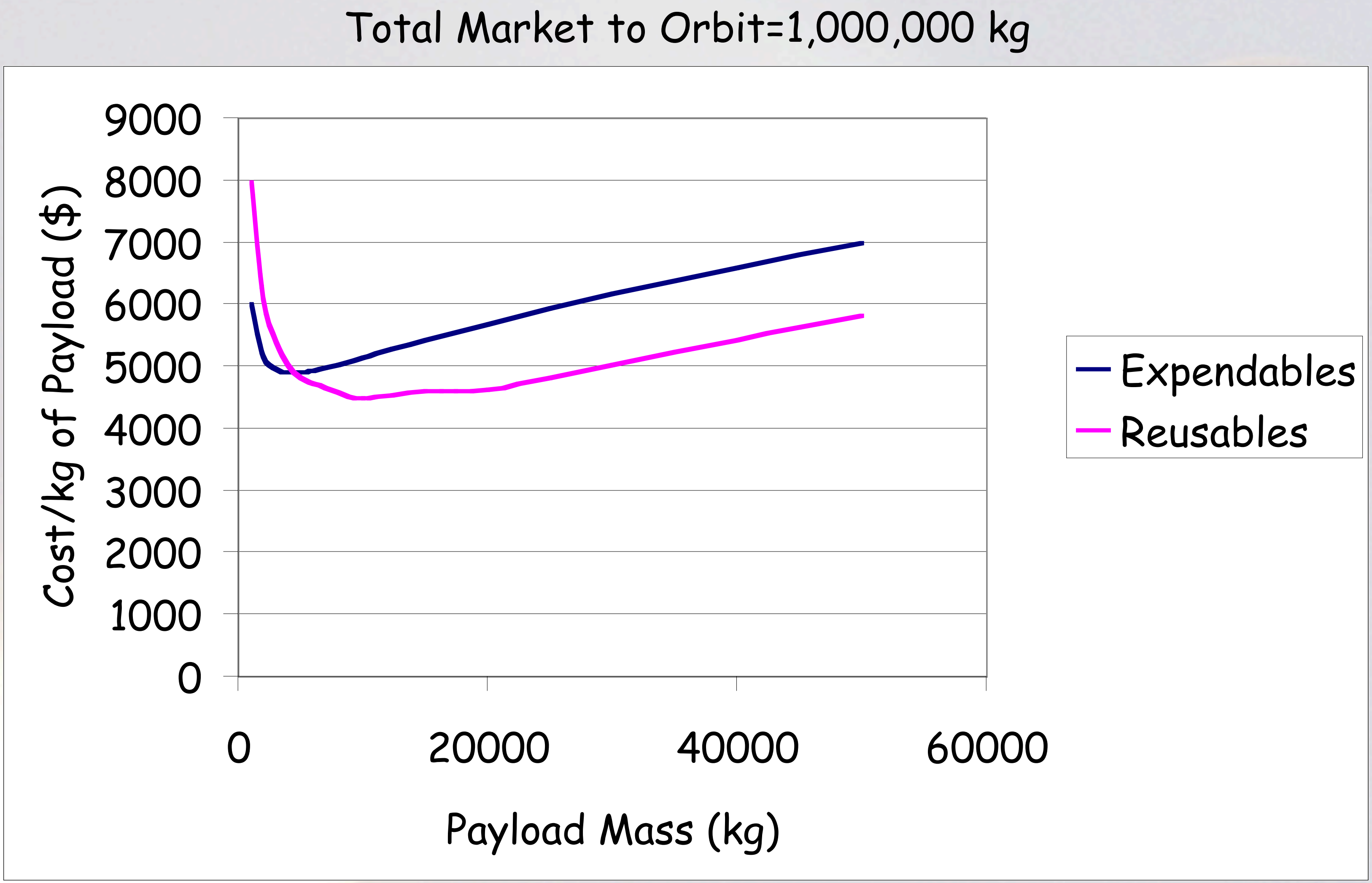
Cost and Learning Effects

Total Program Payload Mass = 1,000,000 kg

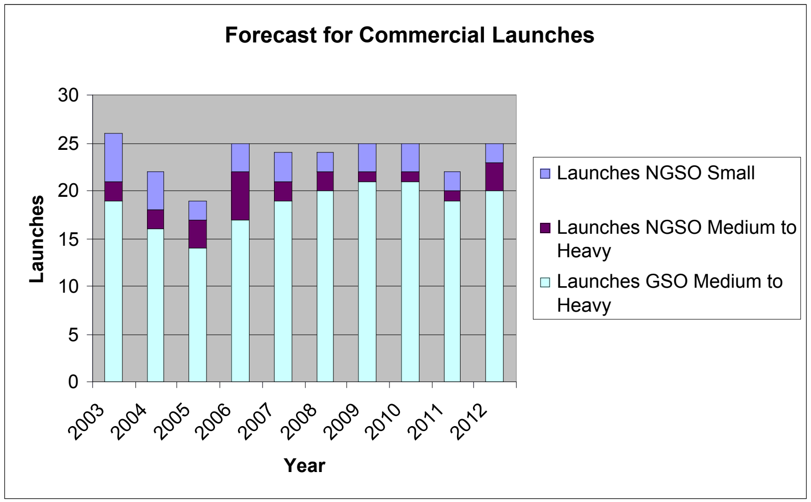


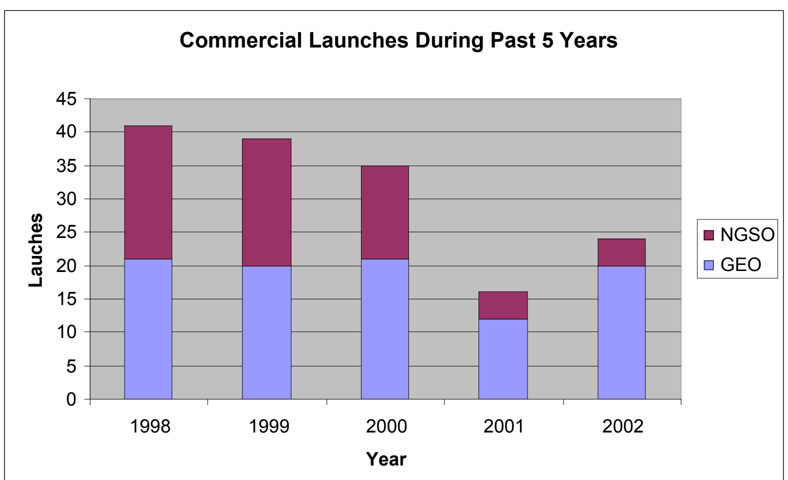
Payload Mass per Flight (kg)

Expendable/Reusable Trade Study



Cost Modeling



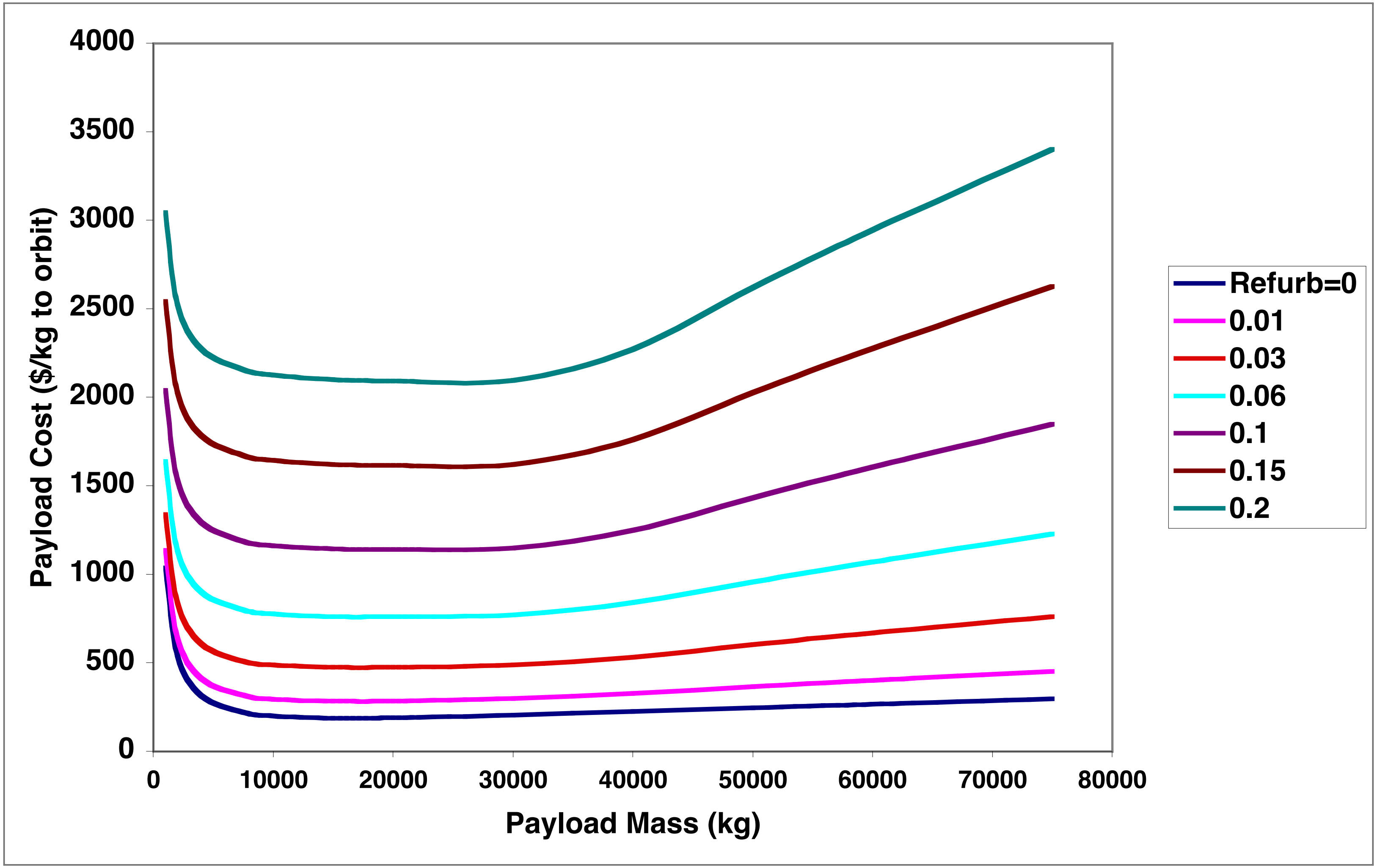


- At ~\$100M/launch, worldwide annual launch revenue is ~\$6-8 B
- Potential savings by cutting costs by factor of 2 is ~\$3-4 B
- Given a 10 year development program and a 10% discount rate (government support), maximum feasible program cost for new vehicle is ~\$2.5 B/yr
- At a 50% ROI (commercial), 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!!!*

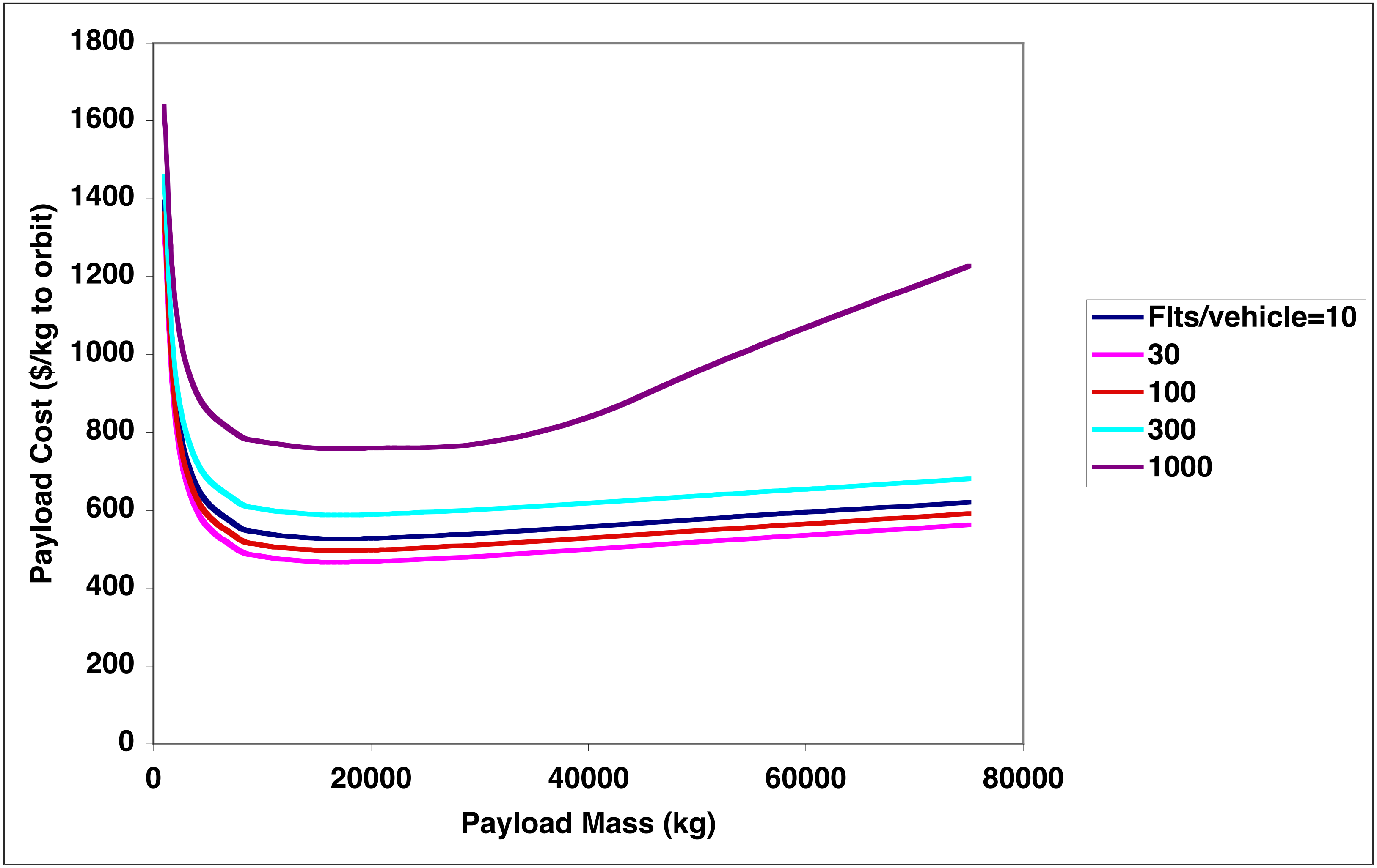
Parametric Cost Analysis

- 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 (δ=0.08; I_{sp}=420 sec avg.)

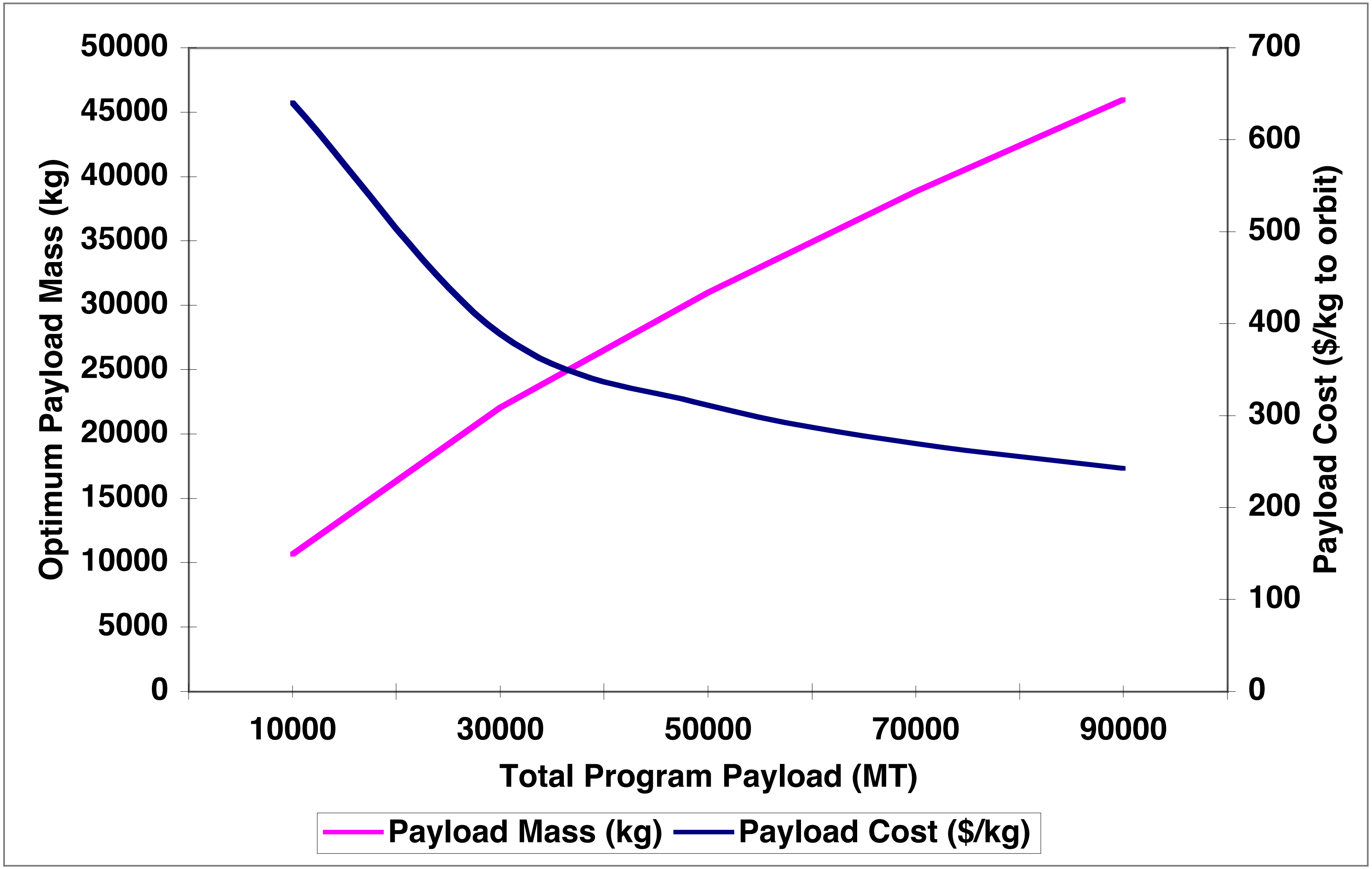
Effect of Refurbishment Rate



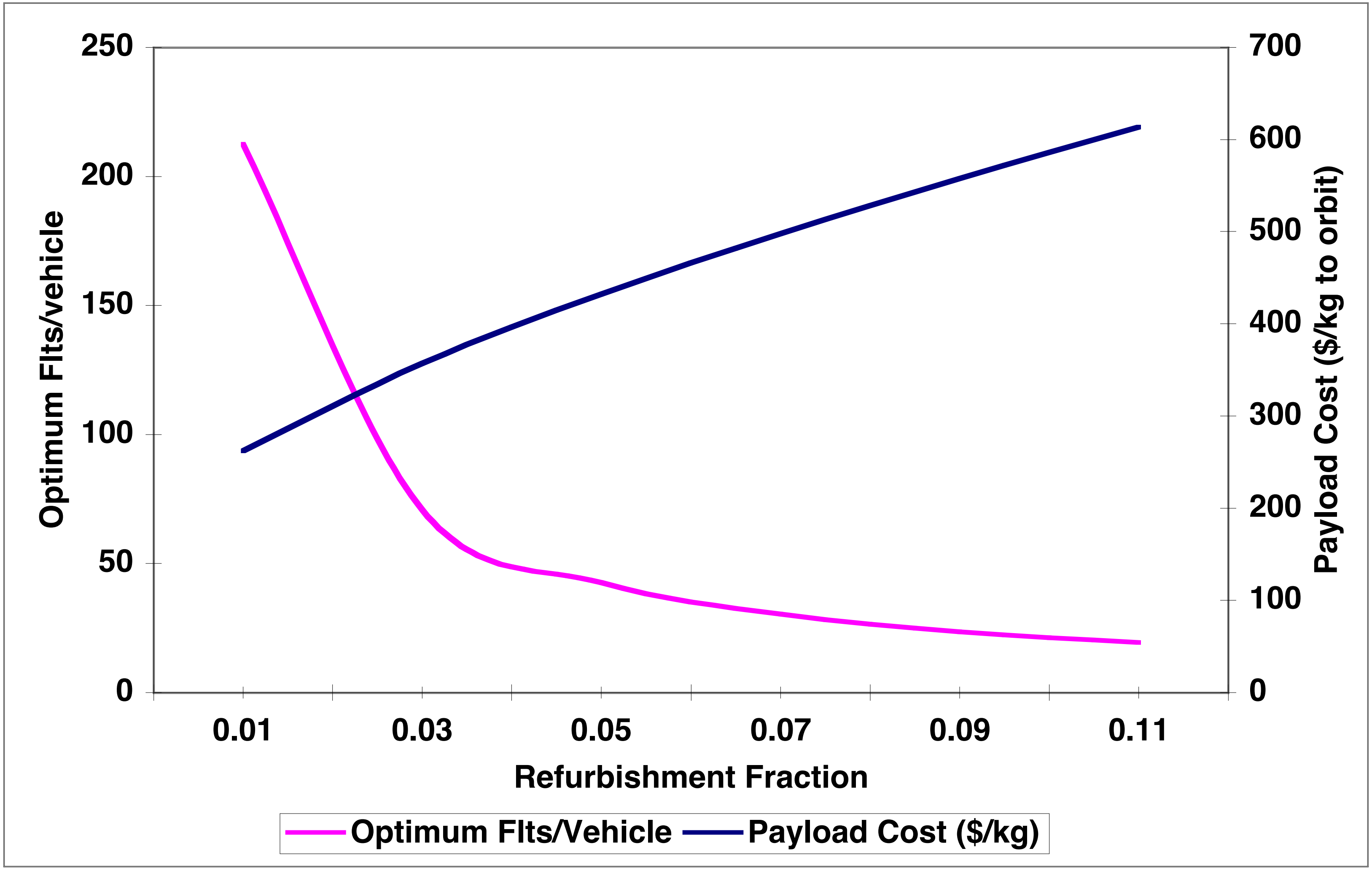
Effect of Vehicle Lifetime



Effect of Total Launch Mass



Effect of Refurbishment Fraction



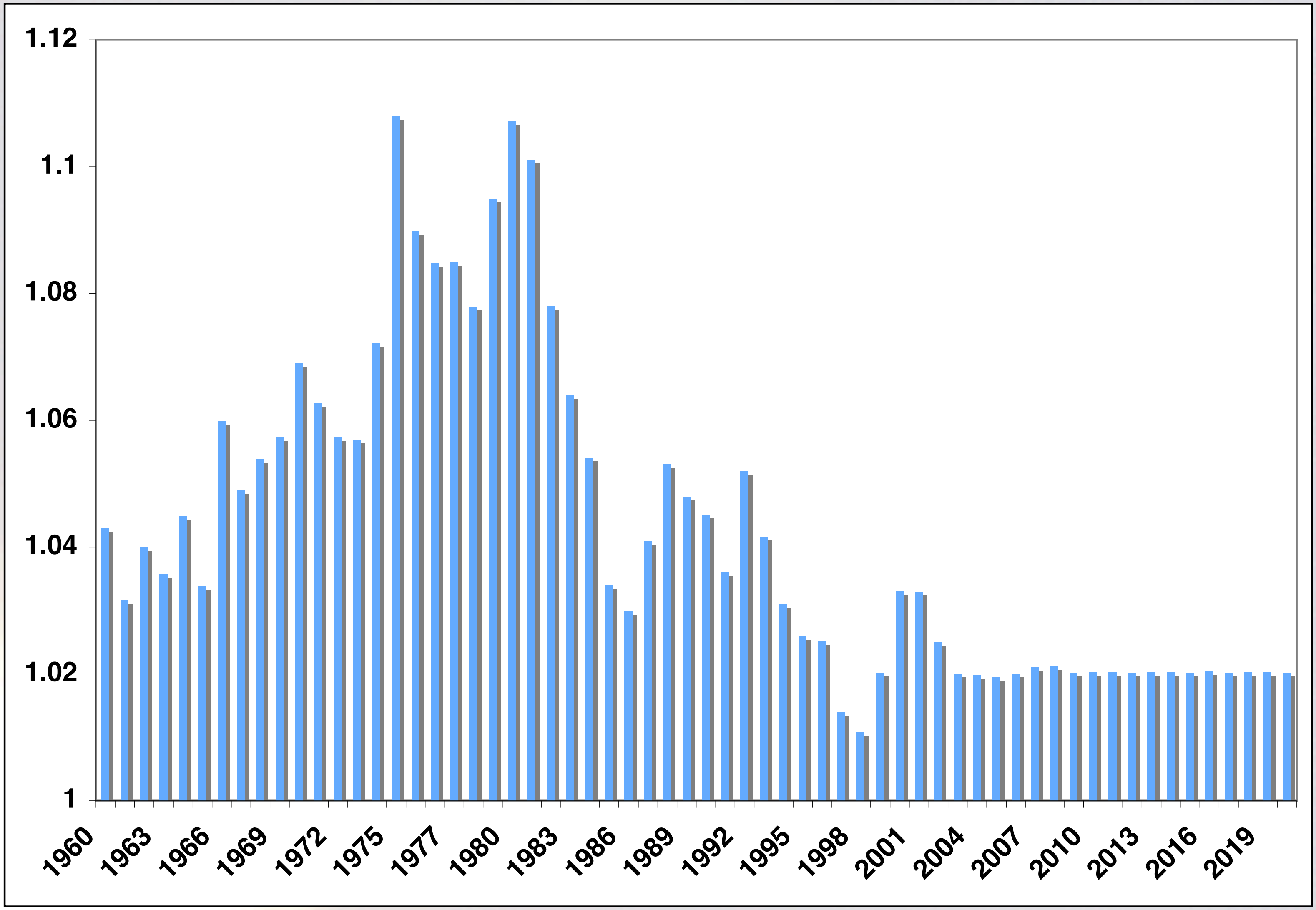
Costing Conclusions (to date)

- 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!)

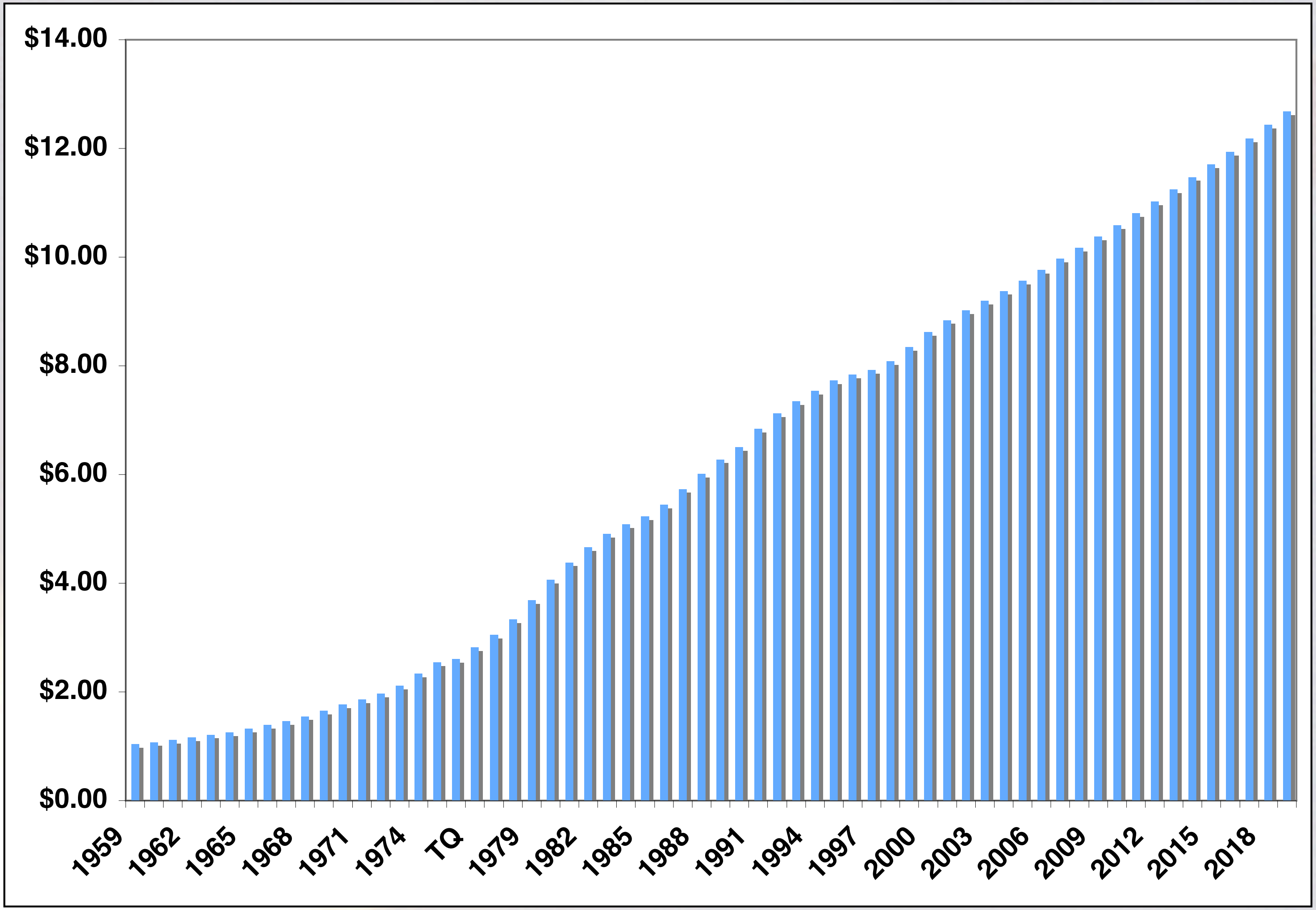
Inflation

- 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	2008=1	Year	1959=1	2008=1	Year	1959=1	2008=1
1959	1	0.1003	1969	1.551	0.1556	1978	3.044	0.3053
1960	1.043	0.1046	1970	1.658	0.1663	1979	3.333	0.3343
1961	1.076	0.1079	1971	1.762	0.1767	1980	3.69	0.3701
1962	1.119	0.1122	1972	1.863	0.1868	1981	4.063	0.4075
1963	1.159	0.1162	1973	1.969	0.1975	1982	4.38	0.4393
1964	1.211	0.1215	1974	2.111	0.2117	1983	4.66	0.4674
1965	1.252	0.1256	1975	2.339	0.2346	1984	4.912	0.4926
1966	1.327	0.1331	1976	2.549	0.2556	1985	5.079	0.5094
1967	1.392	0.1396	TQ	2.603	0.2611	1986	5.231	0.5246
1968	1.467	0.1471	1977	2.824	0.2832	1987	5.445	0.5461

NASA Inflation Factors 1988-2020

Year	1959=1	2008=1	Year	1959=1	2008=1	Year	1959=1	2008=1
1988	5.734	0.5751	1999	8.083	0.8107	2010	10.378	1.0408
1989	6.009	0.6027	2000	8.35	0.8374	2011	10.588	1.0619
1990	6.28	0.6298	2001	8.625	0.8650	2012	10.802	1.0834
1991	6.506	0.6525	2002	8.841	0.8867	2013	11.021	1.1053
1992	6.844	0.6864	2003	9.018	0.9044	2014	11.244	1.1277
1993	7.129	0.7150	2004	9.197	0.9224	2015	11.471	1.1505
1994	7.35	0.7372	2005	9.376	0.9403	2016	11.704	1.1738
1995	7.541	0.7563	2006	9.5636	0.9592	2017	11.94	1.1975
1996	7.73	0.7753	2007	9.7646	0.9793	2018	12.182	1.2218
1997	7.838	0.7861	2008	9.9708	1.0000	2019	12.429	1.2465
1998	7.923	0.7946	2009	10.172	1.0202	2020	12.68	1.2717

Example: Saturn V Development Costs

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

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 Costs

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

				NPV (2000)	
Year	$M2000	Flights	Revenue	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			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

$12,660/lb

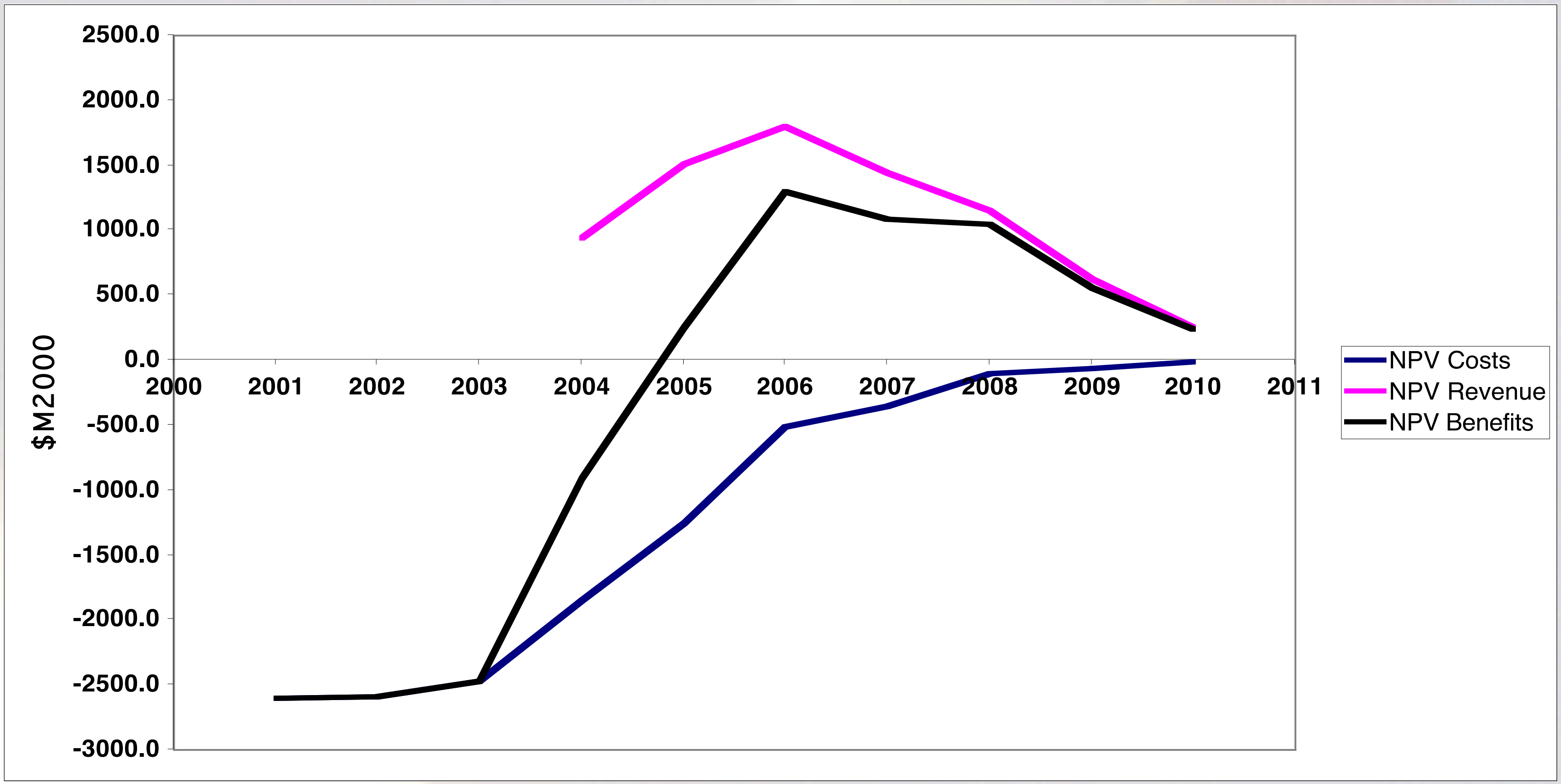
Effect of Moving Revenue Forward

				NPV (2000)	
Year	$M2000	Flights	Revenue	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

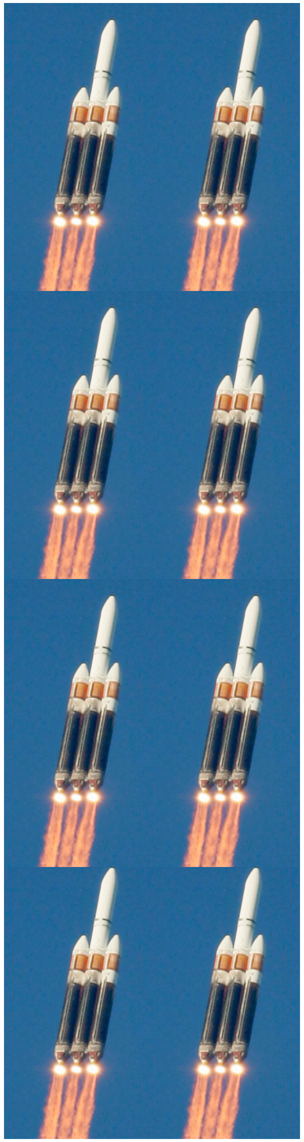
- Investors generally require specific minimum values of IRR
- Have to increase revenue stream to achieve IRR
- Saturn V launch case:
  - 10% IRR $11,480/lb
  - 25% IRR $17,580/lb
  - 50% IRR $32,700/lb
- Venture capitalists general look for 70-100% IRR with 18-month payback

In-line SDLV Assumptions

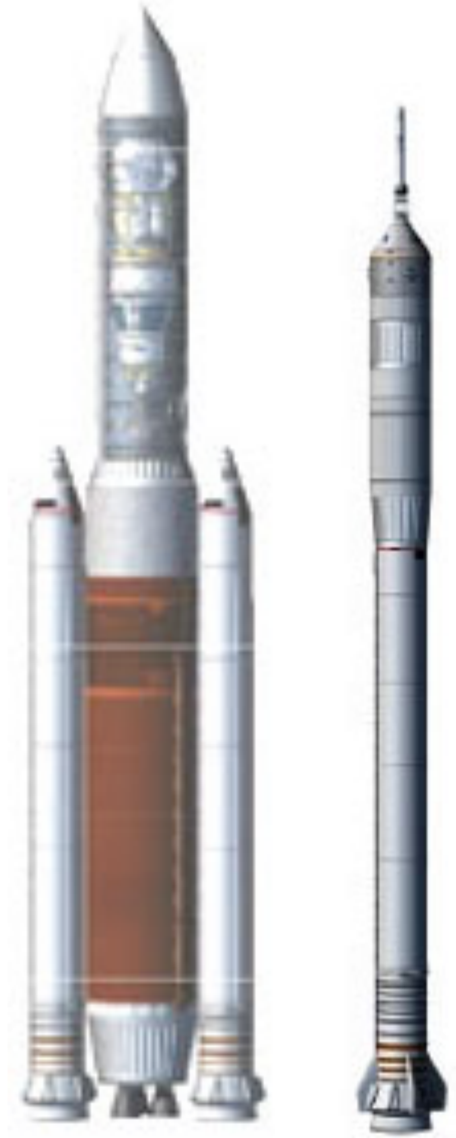
- $8.4B nonrecurring (published estimate)
- 6 year development cycle
- $400M first unit production (shuttle parallel)
- 10 units at 85% learning curve
- $285M average flight cost

Unit	Cost ($M)	Unit	Cost ($M)
1	400	6	263
2	340	7	253
3	309	8	246
4	289	9	239
5	274	10	233

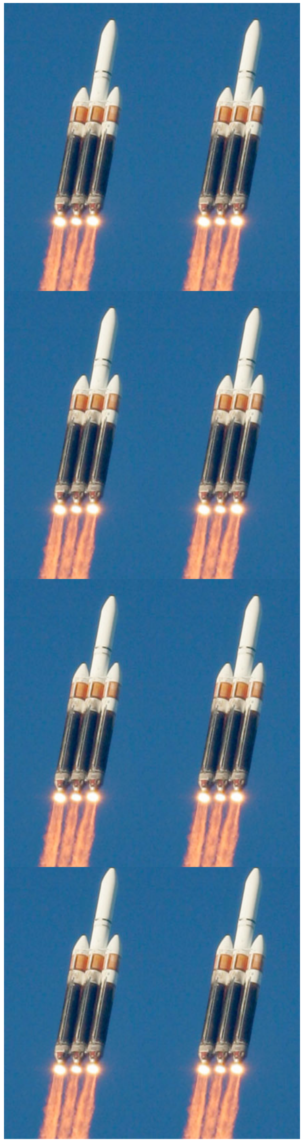
Head-to-Head Launch Comparison



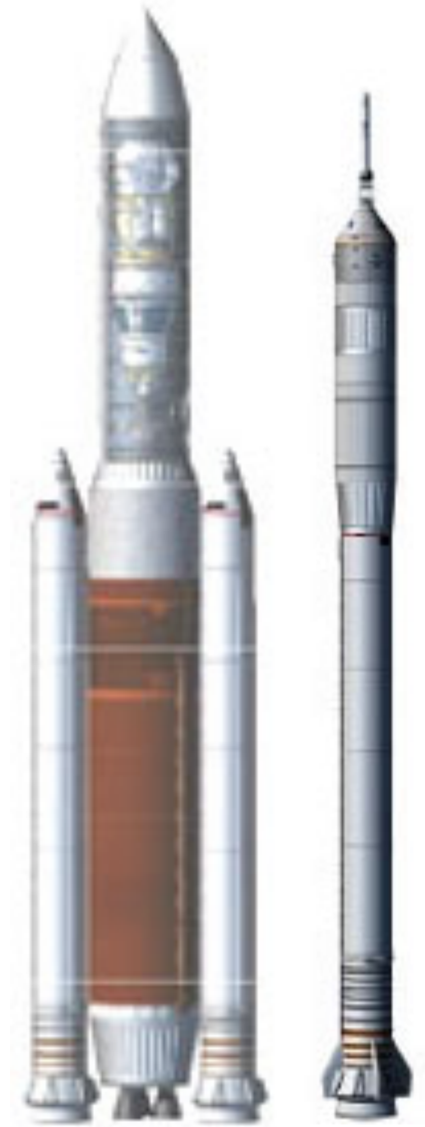
2000	Nonrecurring cost ($M)	10,200
829	Average production cost per mission ($M)	429
1096	Average amortized cost per mission ($M)	1449
85	Total production run	10+10
432	NPV discounted cost per mission ($M)	878



Sensitivity to Monolithic Costing



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



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://cost.jsc.nasa.gov/beta.html

Beta Function for Cost Spreading

- Cumulative normalized cost function

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

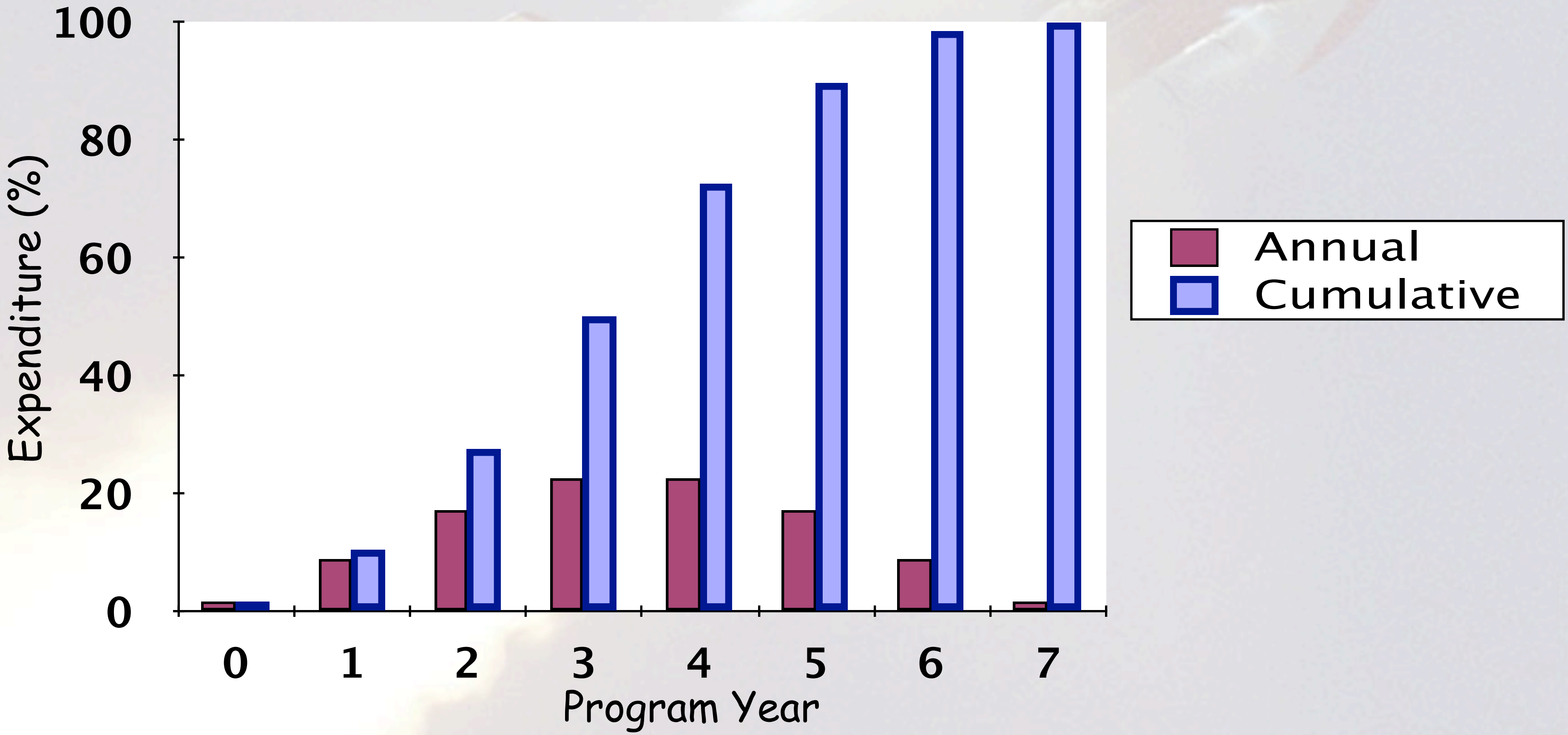
where

  - C = fraction of total program cost ($0 \leq C \leq 1$)
  - τ = 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) $0 \leq P \leq 1$; $0.1875 \leq c_f \leq 0.8125$

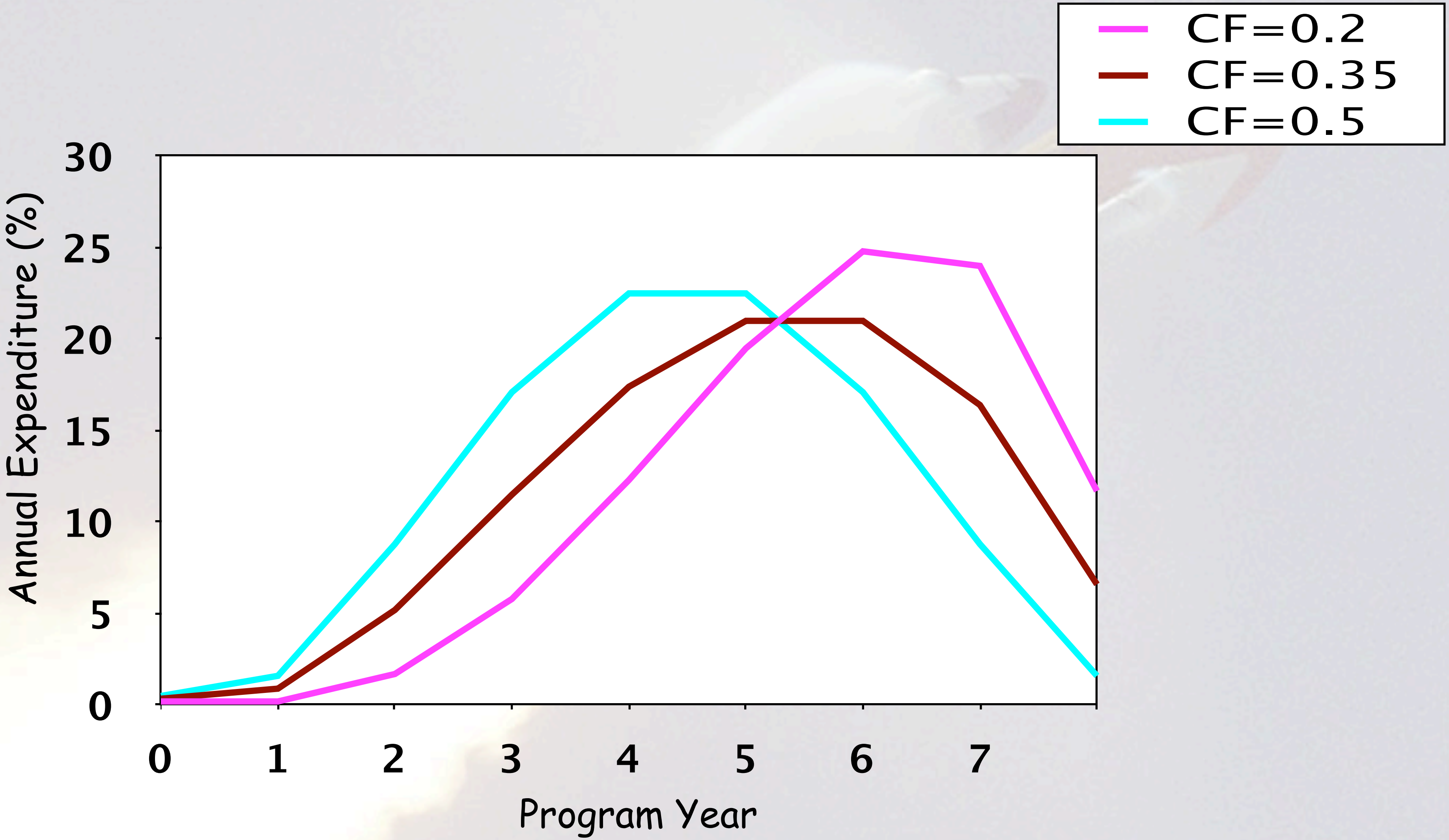
$$c_f < 0.5 : A = \frac{(1-P)(c_f - 0.1875)}{0.625}; B = P\frac{c_f - 0.1875}{0.3125}$$

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

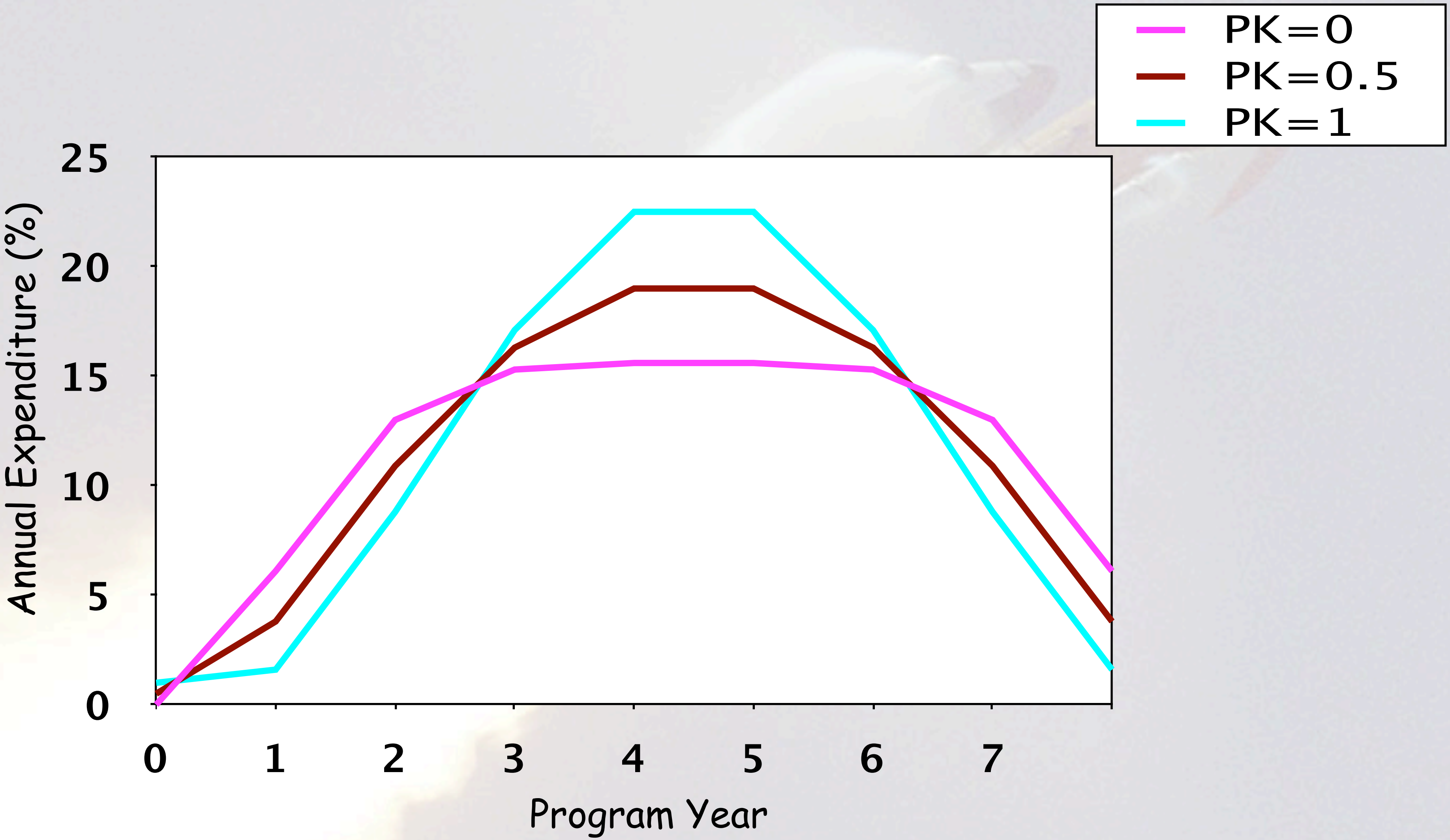
Sample of Beta Function



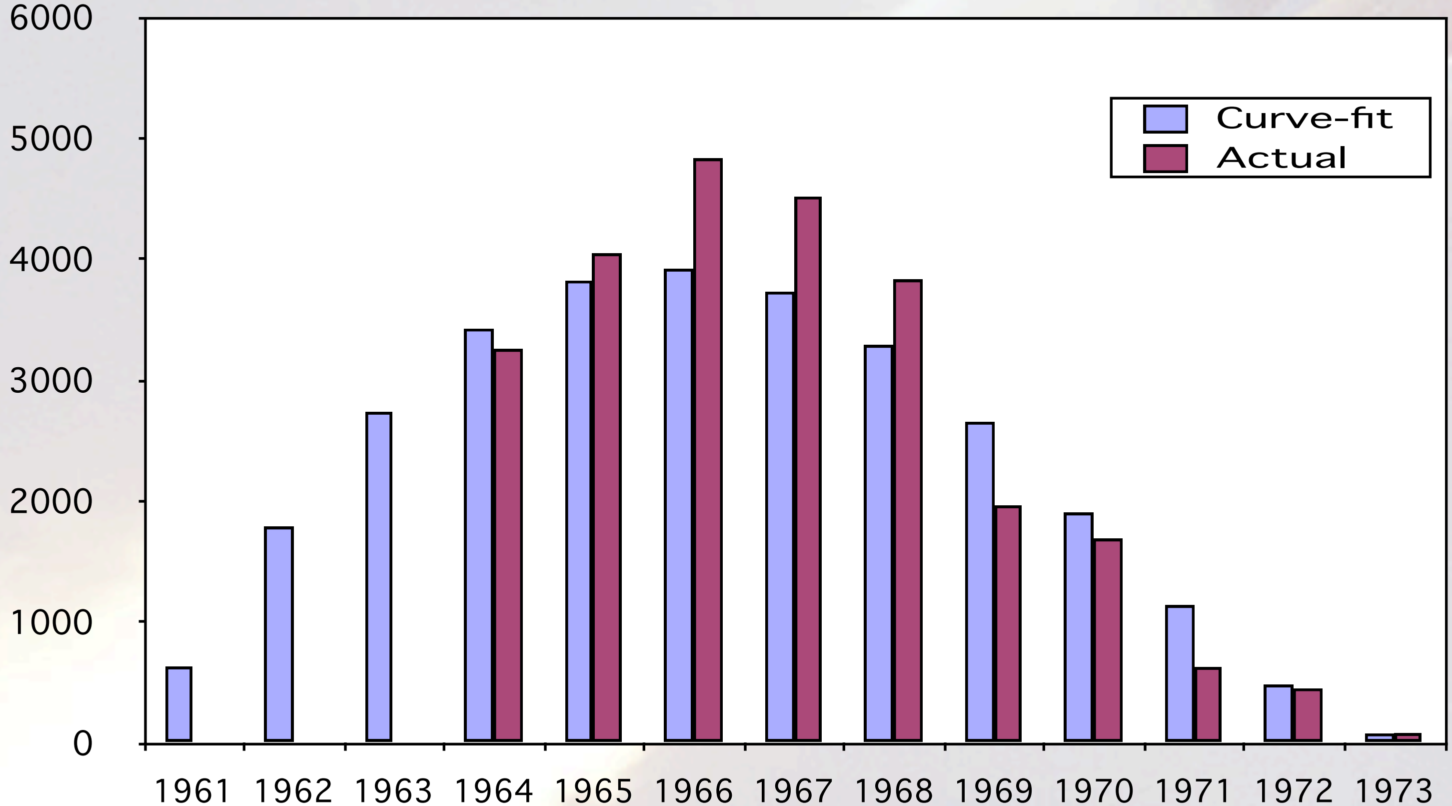
Cost Fraction in Beta Function



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