Cost Estimation and Engineering Economics

- Lecture #08 – September 21, 2023
- Cost sources
- Vehicle-level costing heuristics
- Learning curves
- 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

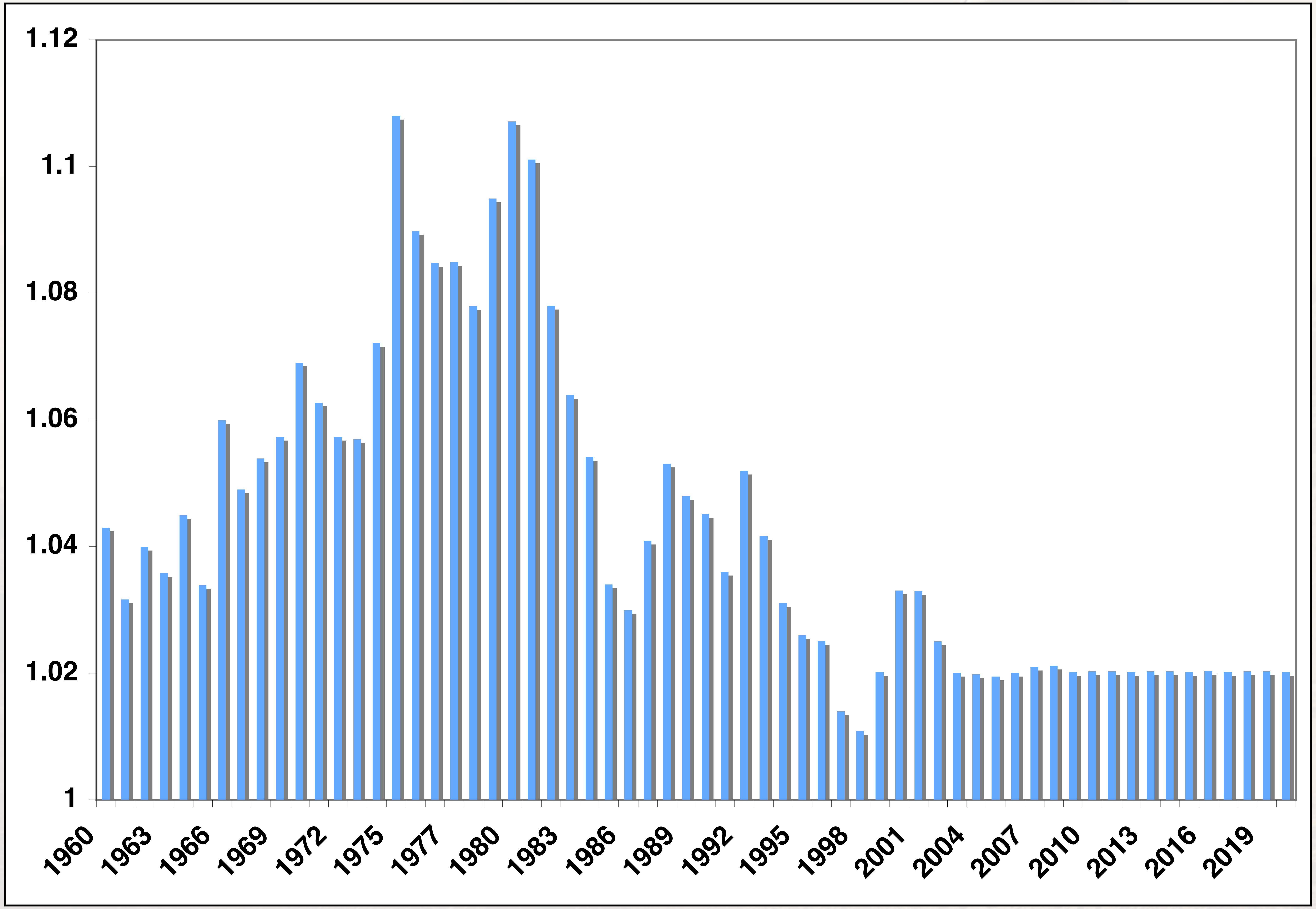
Refurbishment

- 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

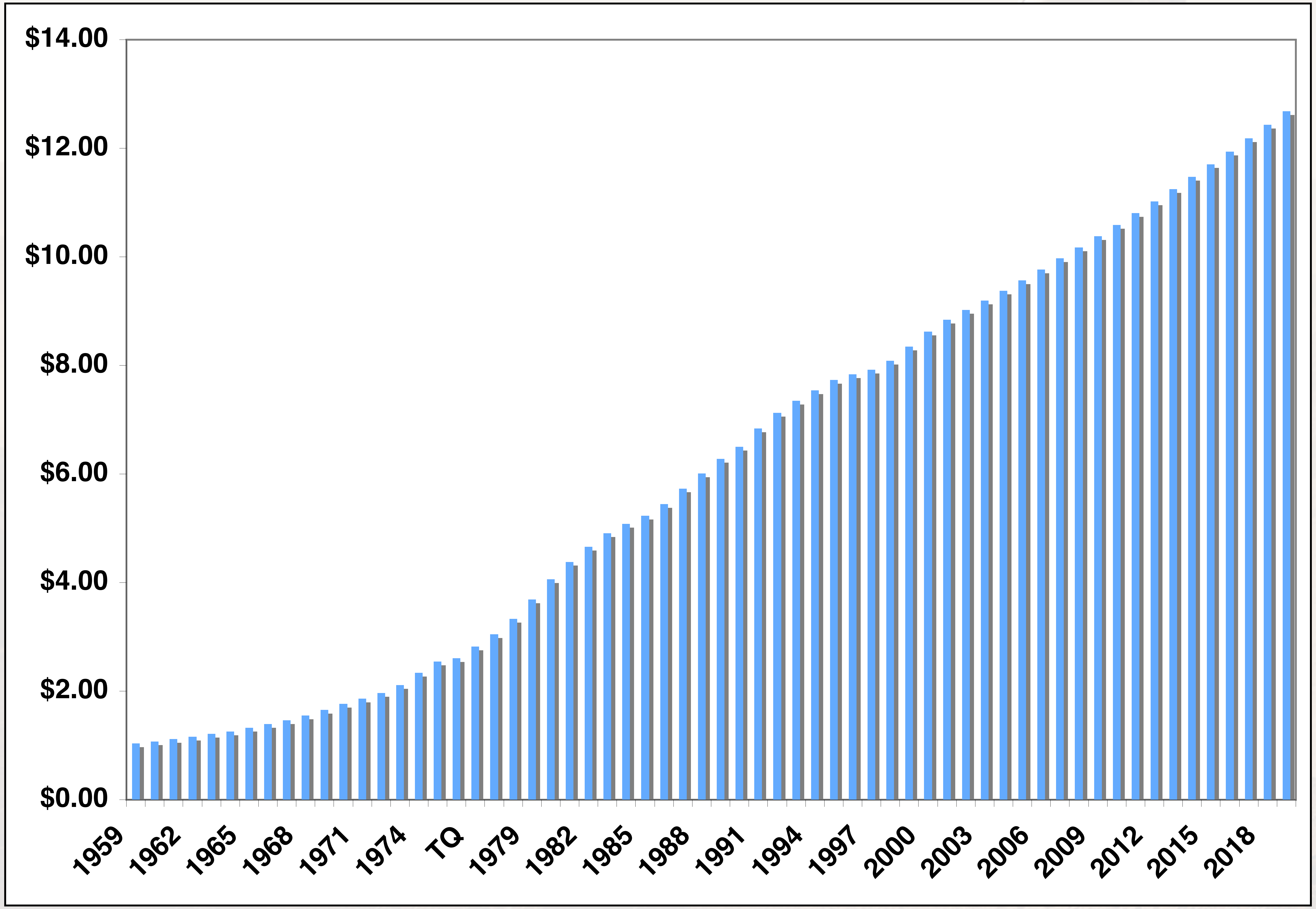
Inflation and the Changing Value of Money

- What do we mean when we talk about a specific dollar figure?
- 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)

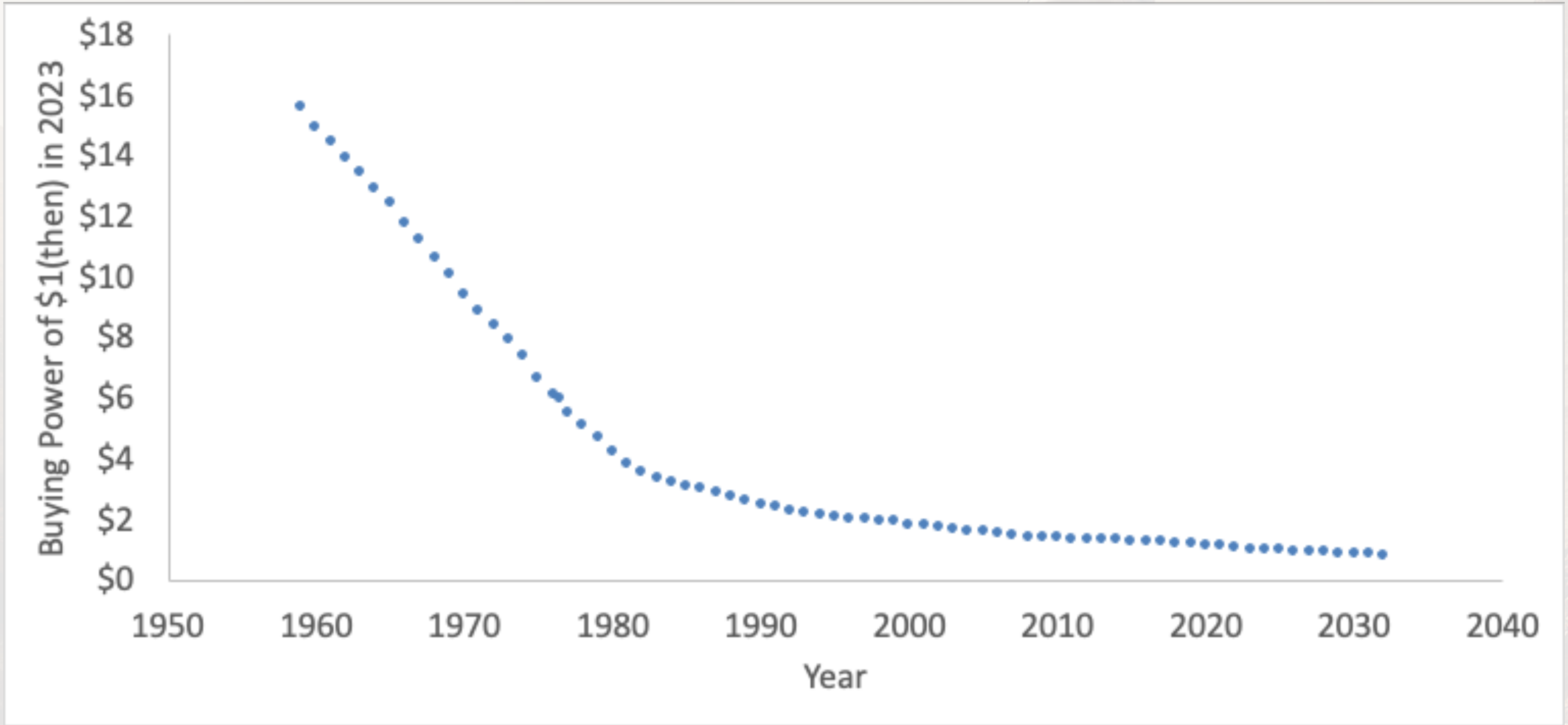
Annual NASA Inflation Rates 1960-2020



Cost of Comparable NASA Components



Effect of Inflation on Buying Power in 2023



NASA Inflation Factors 1988-2020

TION INDEX--(ACTUALS THRU September 2022)

YEAR	.017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
INFL.RATE	.1%	2.5%	1.9%	2.2%	3.8%	5.7%	4.1%	2.5%	2.3%	2.3%	2.4%	2.48%	2.55%	2.58%	2.56%	2.53%
FACTORS	.021	1.025	1.019	1.022	1.038	1.057	1.041	1.025	1.023	1.023	1.024	1.025	1.026	1.026	1.026	1.025
FROM 2016	.021	1.047	1.067	1.091	1.132	1.197	1.246	1.278	1.307	1.337	1.369	1.403	1.439	1.476	1.514	1.552
FROM 2017	.000	1.025	1.045	1.068	1.109	1.172	1.220	1.251	1.280	1.309	1.340	1.374	1.409	1.445	1.482	1.520
FROM 2018		1.000	1.019	1.042	1.081	1.143	1.190	1.220	1.248	1.277	1.307	1.340	1.374	1.409	1.445	1.482
FROM 2019			1.000	1.022	1.061	1.121	1.167	1.197	1.225	1.253	1.282	1.314	1.348	1.383	1.418	1.454
FROM 2020				1.000	1.038	1.097	1.142	1.171	1.198	1.225	1.255	1.286	1.319	1.353	1.387	1.422
FROM 2021					1.000	1.057	1.100	1.128	1.154	1.181	1.209	1.239	1.271	1.303	1.337	1.370
FROM 2022						1.000	1.041	1.067	1.092	1.117	1.144	1.172	1.202	1.233	1.264	1.296
FROM 2023							1.000	1.025	1.049	1.073	1.099	1.126	1.155	1.184	1.215	1.245
FROM 2024								1.000	1.023	1.046	1.071	1.098	1.126	1.155	1.185	1.215
FROM 2025									1.000	1.023	1.047	1.073	1.101	1.129	1.158	1.187
FROM 2026										1.000	1.024	1.049	1.076	1.104	1.132	1.161
FROM 2027											1.000	1.025	1.051	1.078	1.106	1.134
FROM 2028												1.000	1.026	1.052	1.079	1.106
FROM 2029													1.000	1.026	1.052	1.079
FROM 2030														1.000	1.026	1.052
FROM 2031															1.000	1.025
FROM 2032																1.000

Image from "2020 NASA New Start Inflation Index" (spreadsheet) – download at https://www.nasa.gov/offices/ocfo/sid/publications

Example: Saturn V Development Costs

Year	Real-Year $M	$M2023
1964	763.4	9239
1965	964.9	11,296
1966	1177.3	13,007
1967	1135.6	11,961
1968	998.9	9985
1969	534.5	5051
1970	484.4	4284
1971	189.1	1574
1972	142.5	1122
1973	26.3	195.9
Totals ($M)	6417	67,716

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	12.73	0.55	0.3024	0.662
Crewed Spacecraft	36.12	0.55	1.015	0.662
Uncrewed Planetary	20.42	0.55	1.574	0.662
Uncrewed Earth Orbital	6.145	0.55	0.6977	0.662
Liquid Rocket Engine	51.43	0.55	0.2829	0.662
Scientific Instrument	3.284	0.5	0.4651	0.7

2023$ 2023$

Implications of CERs

- Launch Vehicles
  - Model range 3480→89,507 kg
  - Nonrecurring $1.13B→$6.74B ⇒ $324K→$75K/kg inert mass
  - 1st Unit $67M→$574M ⇒ $19.2K→$6.4K/kg inert mass
- Crewed Spacecraft
  - Model range 231-69,638 kg
  - Nonrecurring $721M→$16.6M ⇒ $3120K→$239K/kg inert mass
  - 1st Unit $37M→$1631M1 ⇒ $161K→$23.4K/kg inert mass
- All costs in $2023

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	380.09	0.2667	66.448	0.2409
Descent Stage (Cryogenic)	223.90	0.3152	9.1413	0.4146
Descent Stage (Storable)	223.90	0.3152	6.5132	0.4146
Ascent Stage (Cryogenic)	539.88	0.2151	123.40	0.1606
Ascent Stage (Storable)	539.88	0.2151	88.018	0.1606
Surface Habitat (4 crew)	1000.4	0.1183	165.47	0.1402
In-Space Habitat (4 crew)	1940.2	0.0856	62.057	0.2146
Propulsive Stage (Cryogenic)	38.765	0.4554	3.4802	0.4782
Propulsive Stage (Storable)	38.765	0.4554	2.4823	0.4782
Propellant Depot	100.48	0.3566	15.289	0.3175

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

Costs corrected to $M2023

More Notes about Cost Estimation

- There are multiple cost models
  - Each has their own cost estimating relations
  - They won't agree between models
- Choose the model best suited for the case being modeled – for this class,
  - Launch vehicles: use SVLCM
  - Other (in-space) systems: use Arney & Wilhite
- There are far more detailed costing models… which are highly proprietary!

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 10,780 13,721	576 1177 1753
Minimize Inert Mass	3356 5844	139,000	2,066 11,123 13,189	474 1197 1672
Minimize Nonrecurring Cost	2556 6644	147,000	1,666 11,762 13,428	421 1235 1656
Single Stage to Orbit	9200	226,400	18,115	1566

5000 kg payload, LOX/LH2 engines

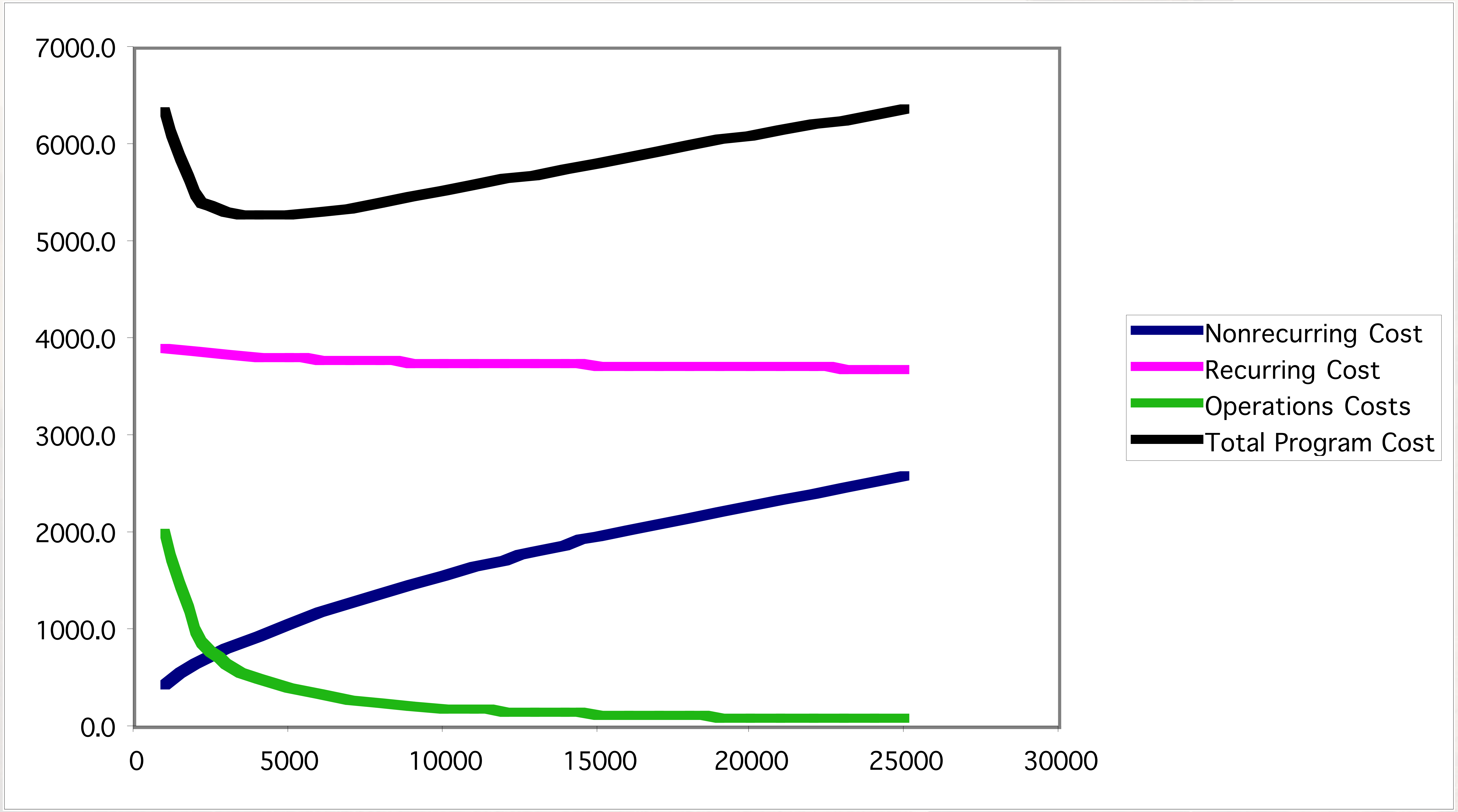
The Learning Curve

- 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…
  - Cost of unit n: $C_n = C_1 n^p$
  - 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

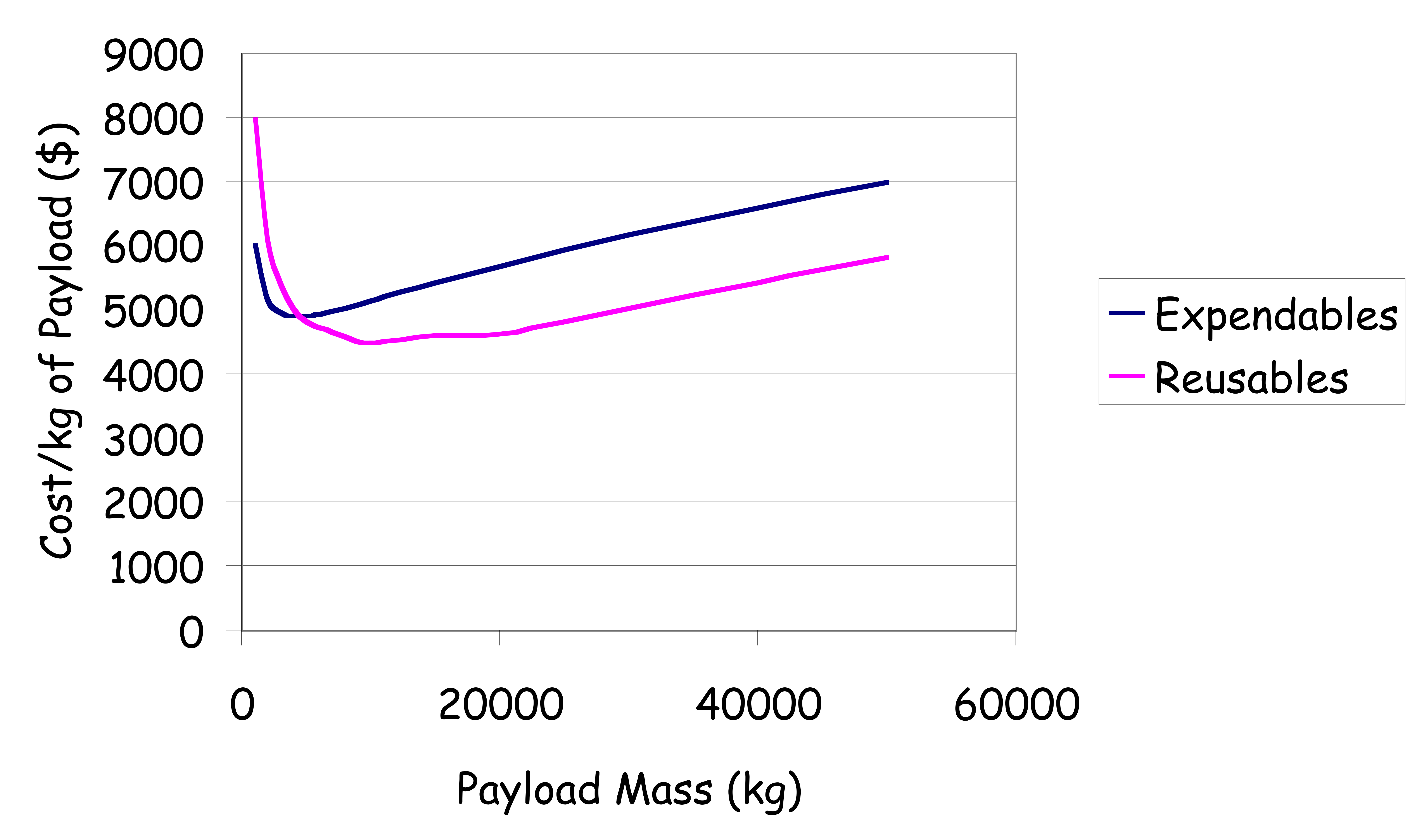
Total Program Payload Mass = 1,000,000 kg



Payload Mass per Flight (kg)

Expendable/Reusable Trade Study

Total Market to Orbit=1,000,000 kg



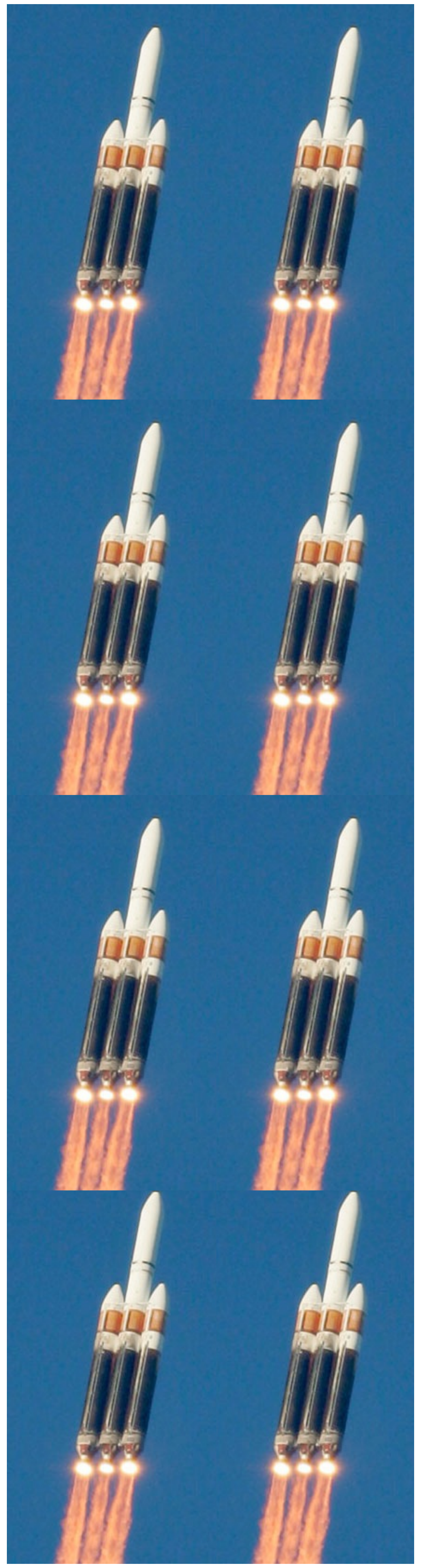
In-line SDLV Assumptions

- $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

$$p = \frac{\ln 0.85}{\ln 2} = -0.234$$

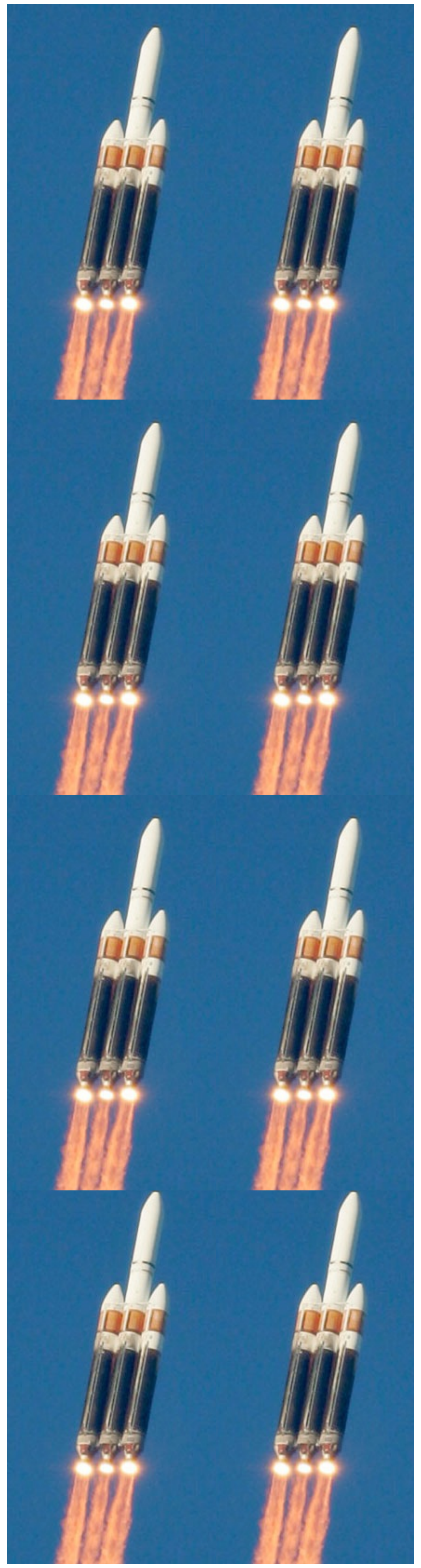
Unit	Cost ($M)	Unit	Cost ($M)
1	400	6	263
2	340	7	253
3	309	8	246
4	289	9	239
5	274	10	233

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

Beta Function for Cost Spreading

- Cumulative normalized cost function

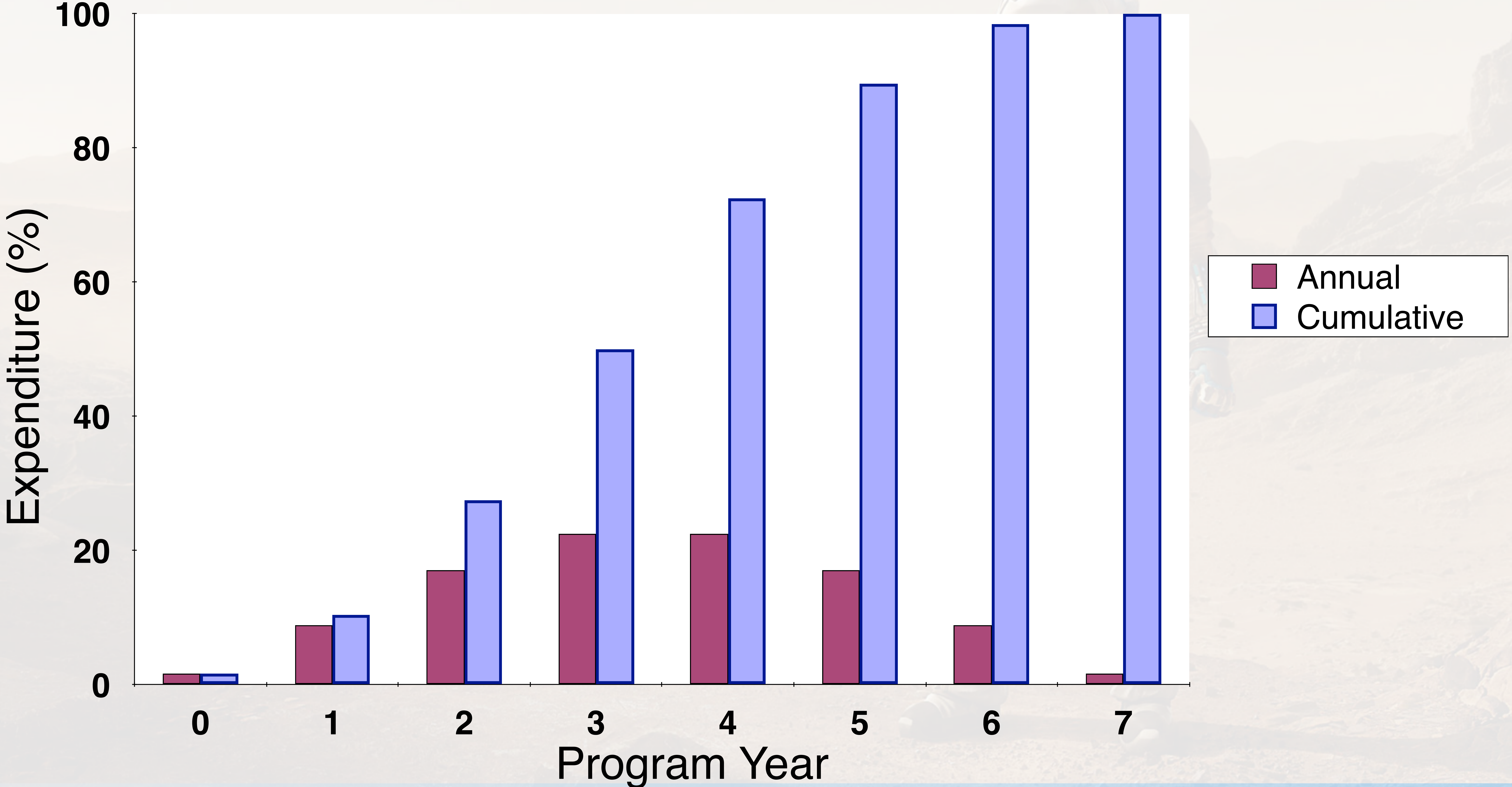
$$C(\tau) = 10\tau^2(1-\tau)^2(A+B\tau) + \tau^4(5-4\tau)$$

  - 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) – $0 \leq P \leq 1$; $0.1875 \leq c_f \leq 0.8125$

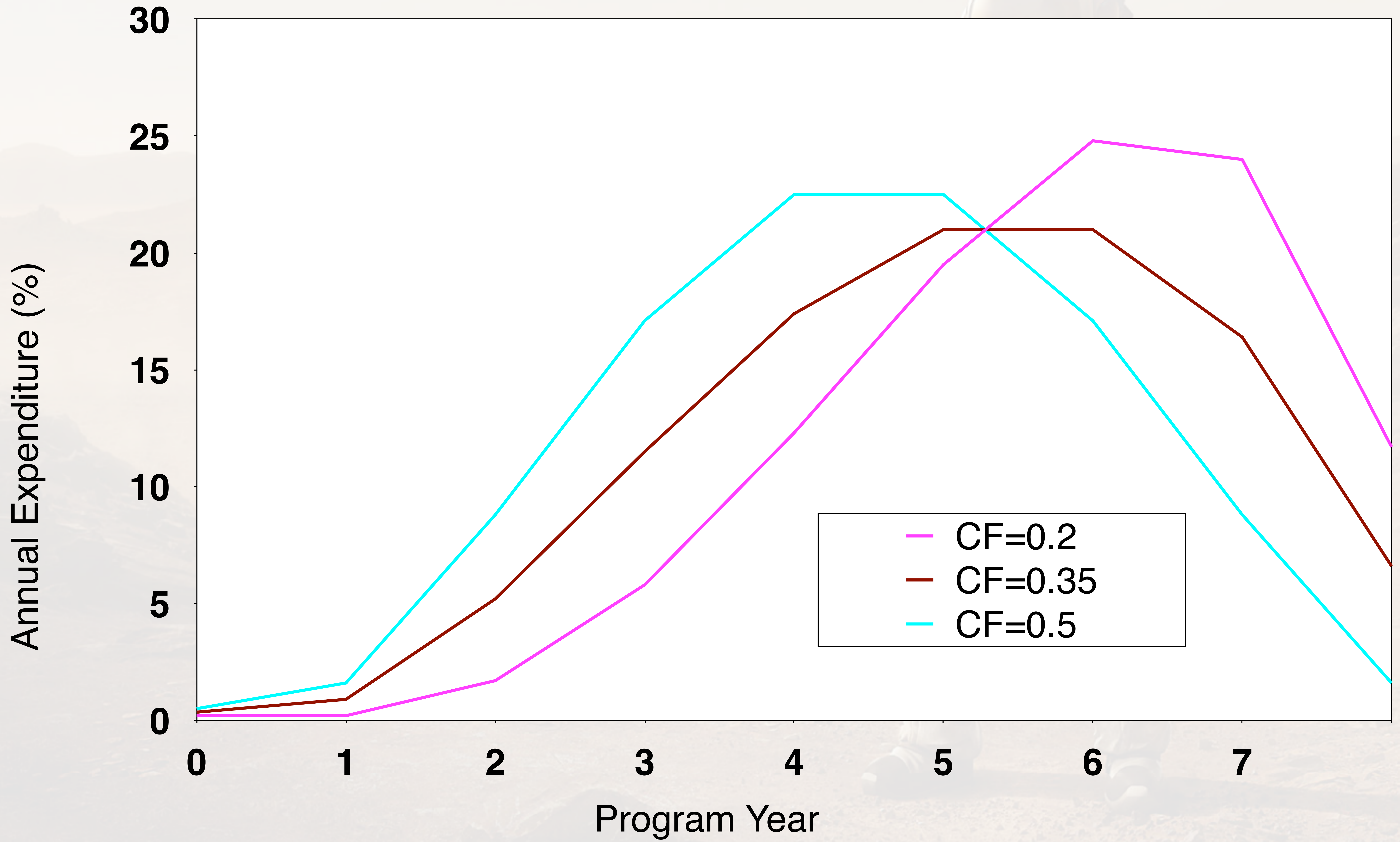
$$c_f < 0.5 : A = \frac{(1-P)\left(c_f - 0.1875\right)}{0.625}; B = P\frac{c_f - 0.1875}{0.3125}$$

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

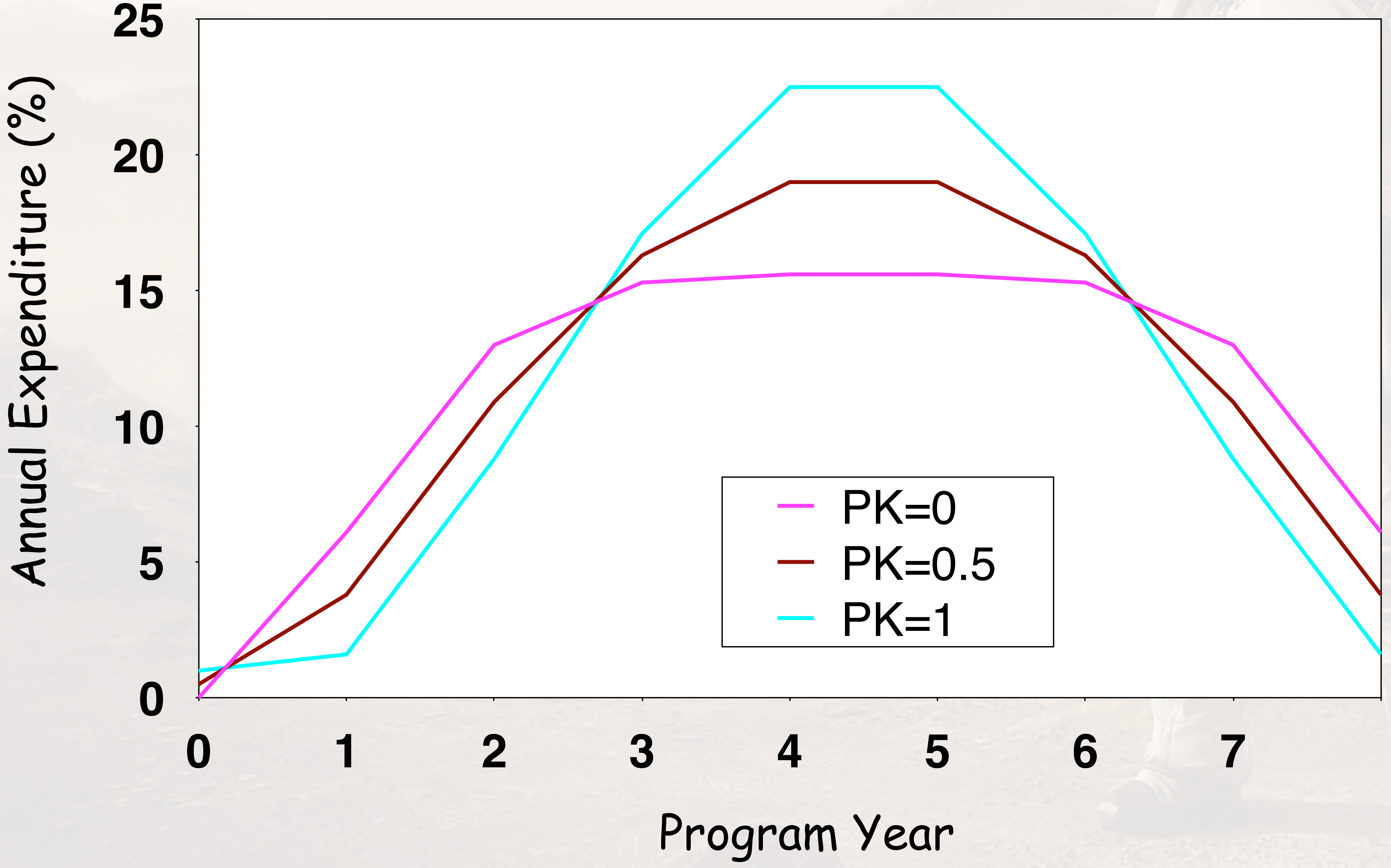
Sample of Beta Function



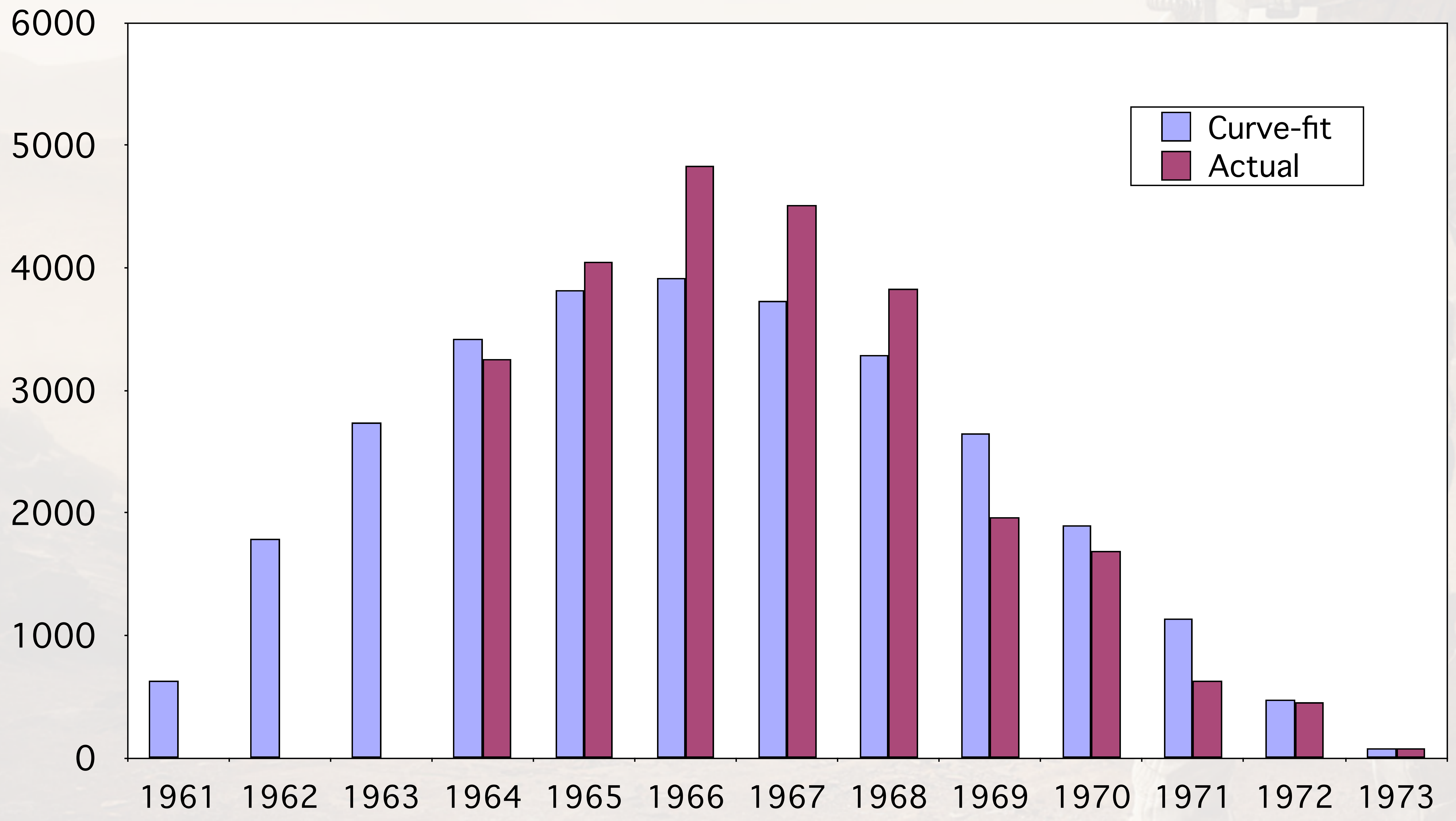
Cost Fraction in Beta Function



Peakedness in Beta Function



Beta Curve Fit to Saturn V Data



A=0.371; B=0.629

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

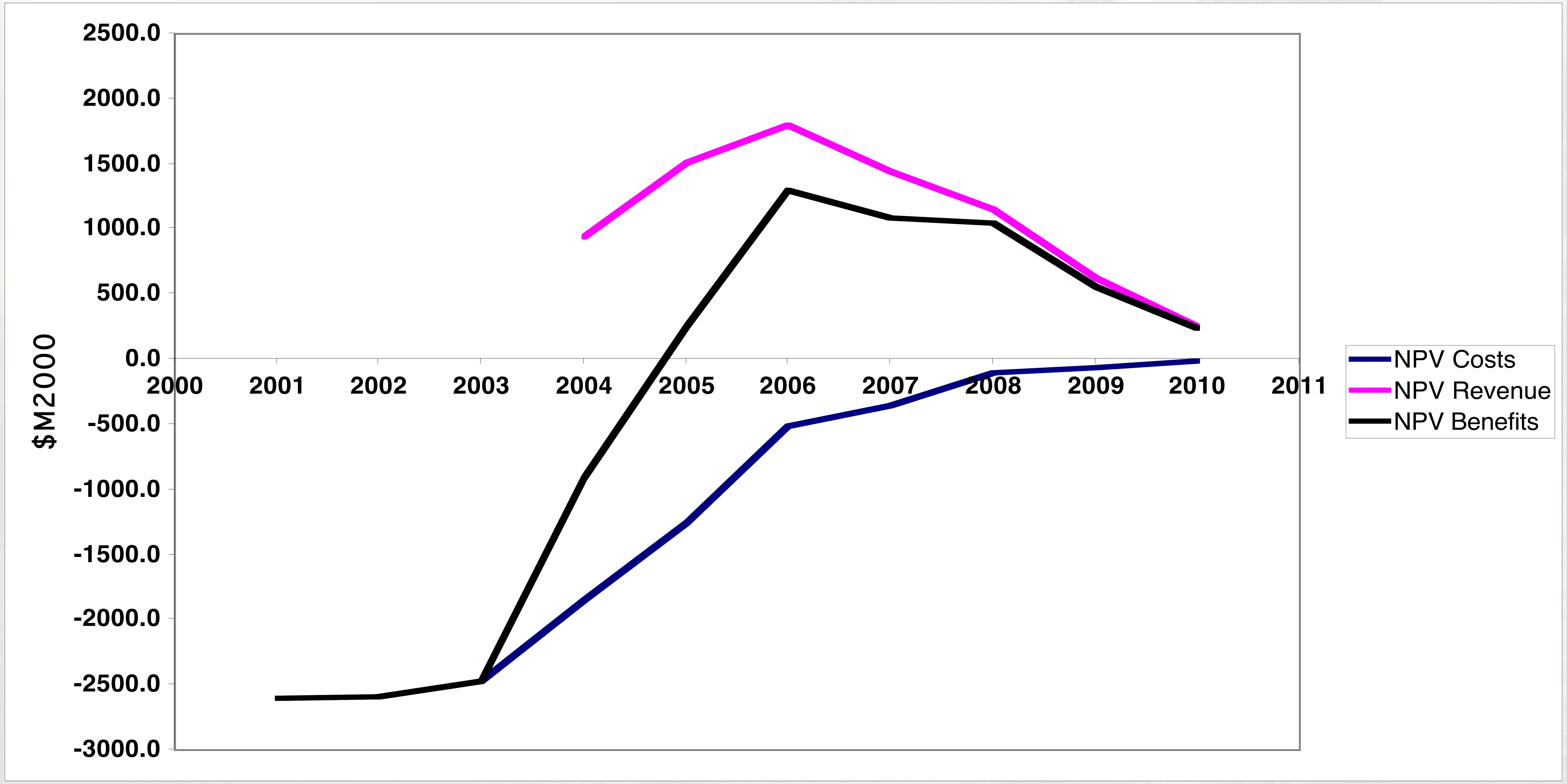
Effect of Moving Revenue Forward

Year	$M2000	Flights	Revenue	NPV (2000) Costs	NPV (2000) 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

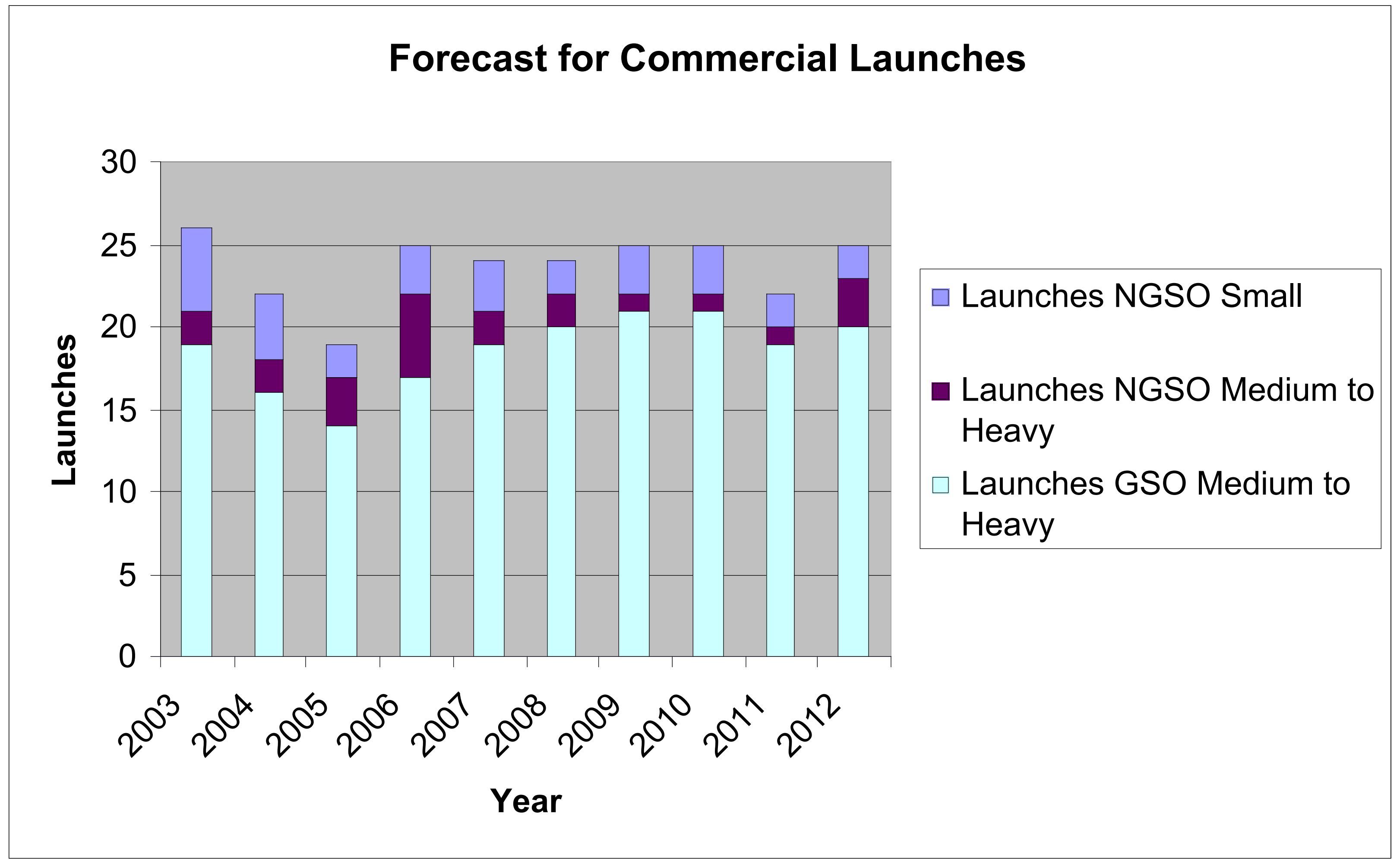
- Discount rate that produces breakeven

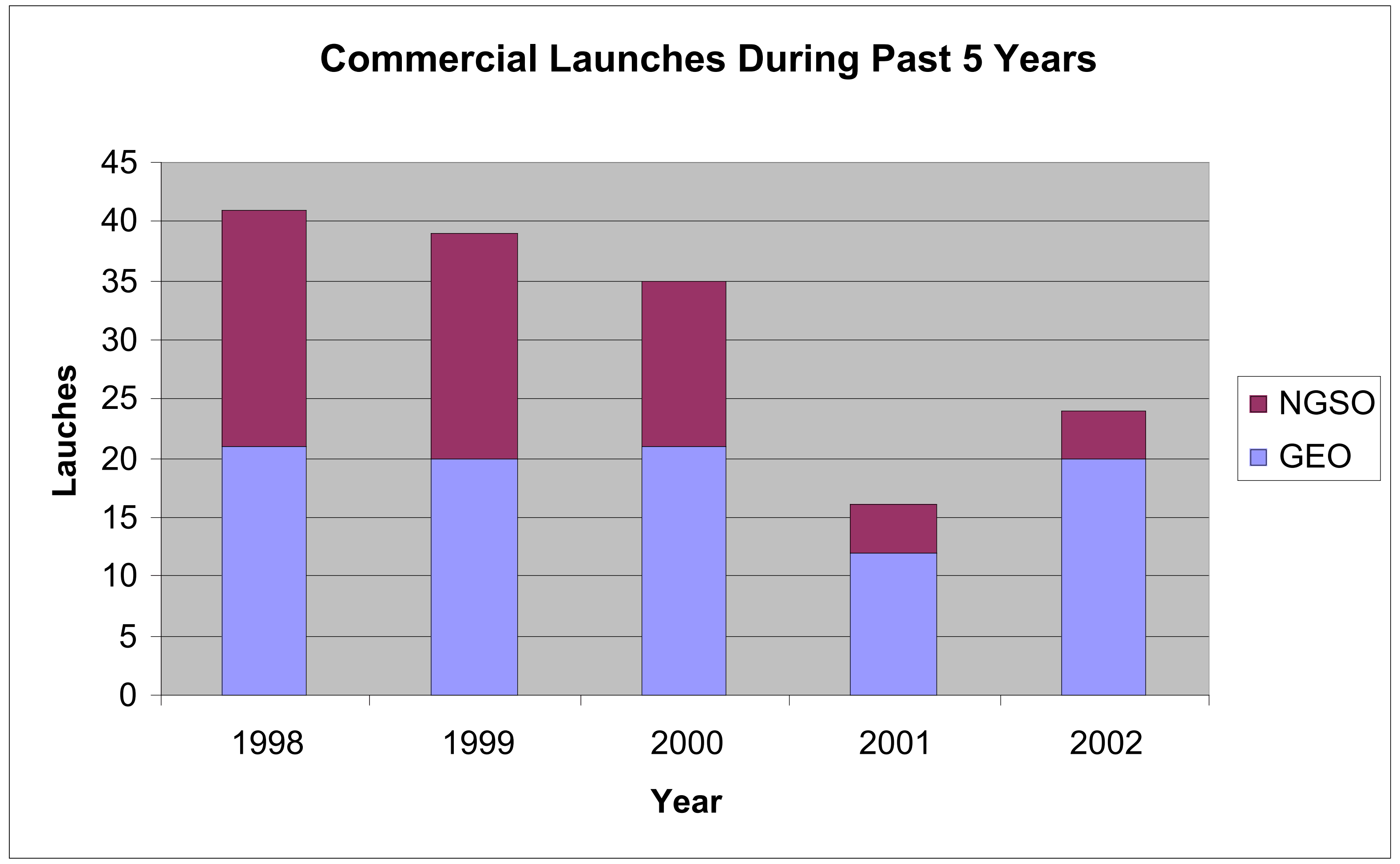


Effect of IRR Targets

- 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



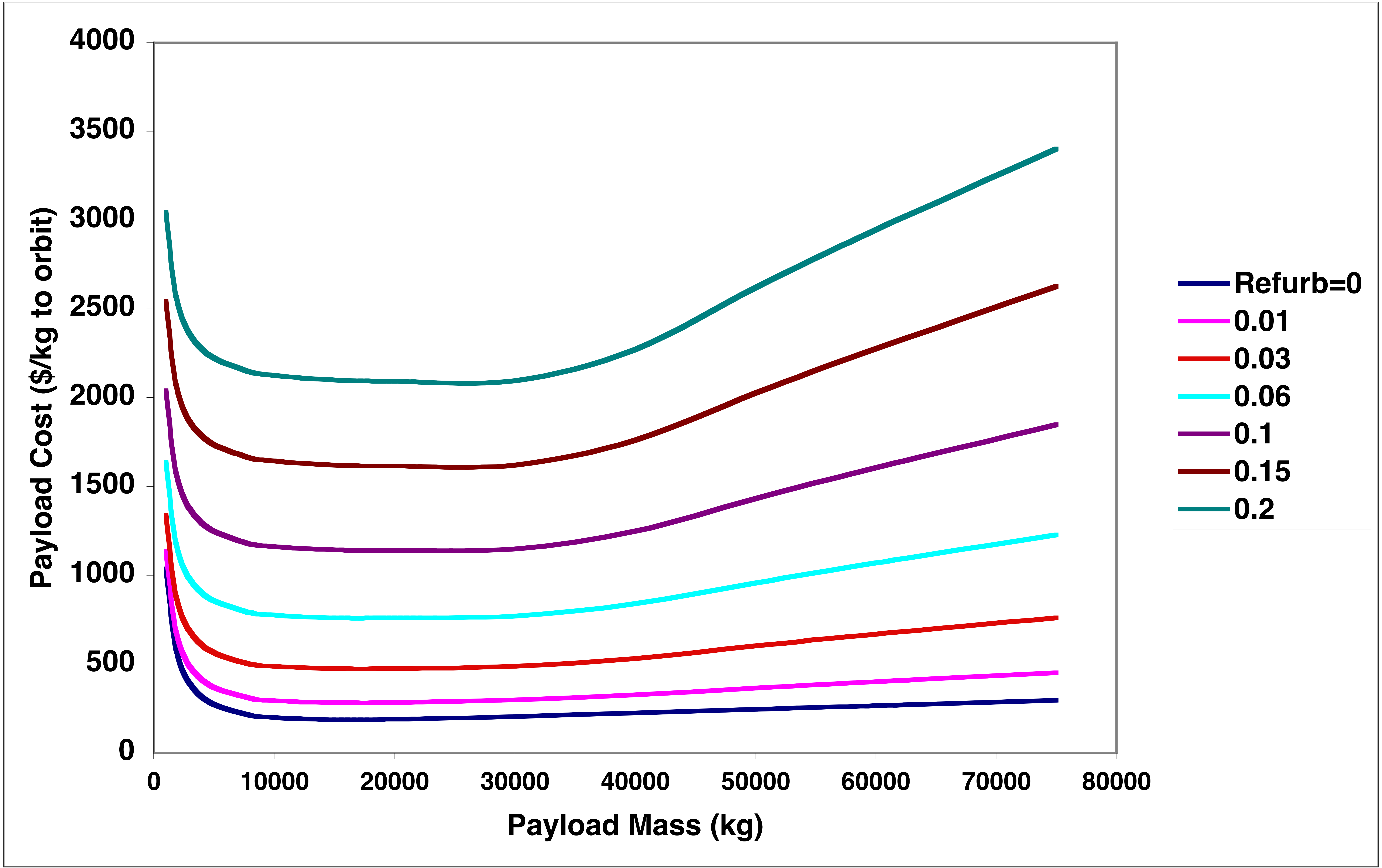


- At ~$100M/launch, worldwide annual launch revenue is ~$6-8 B
- Potential savings by cutting costs by factor of 2 is ~$3-4 B
- Given a 10 year development program and a 10% discount rate (government support), maximum feasible program cost for new vehicle is ~$2.5 B/yr
- At a 50% ROI (commercial), maximum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

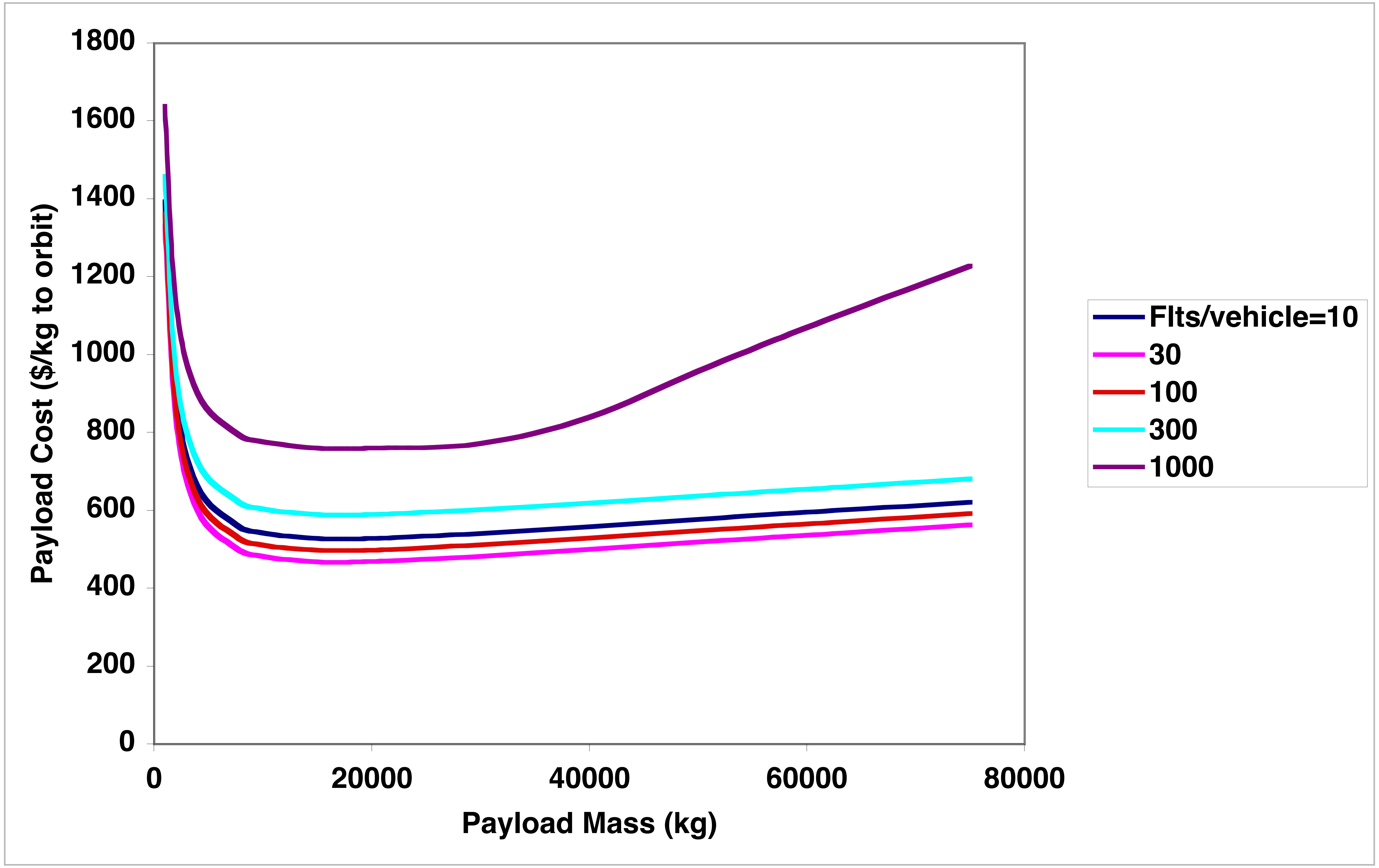
Parametric Cost Analysis

- 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.)

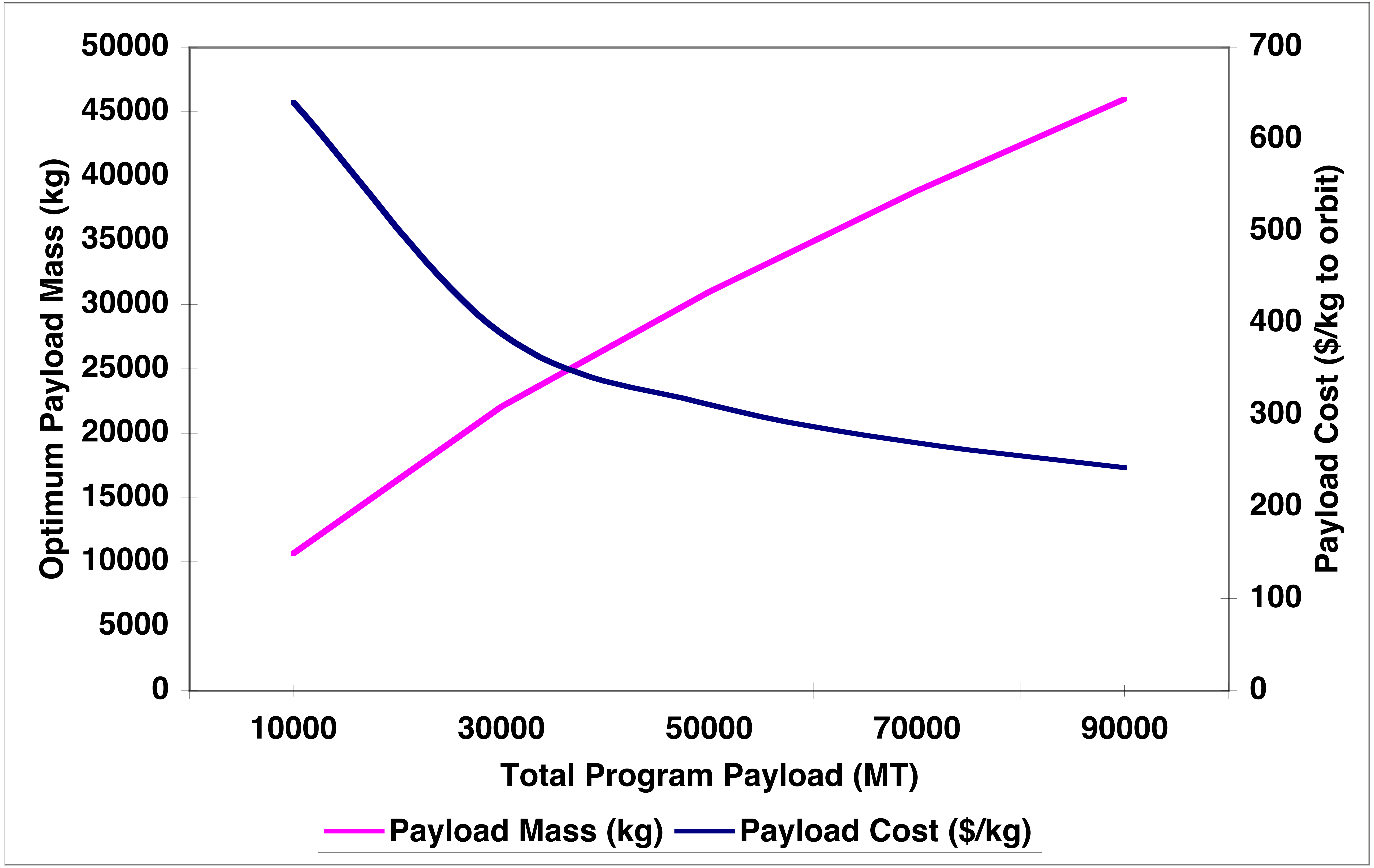
Effect of Refurbishment Rate



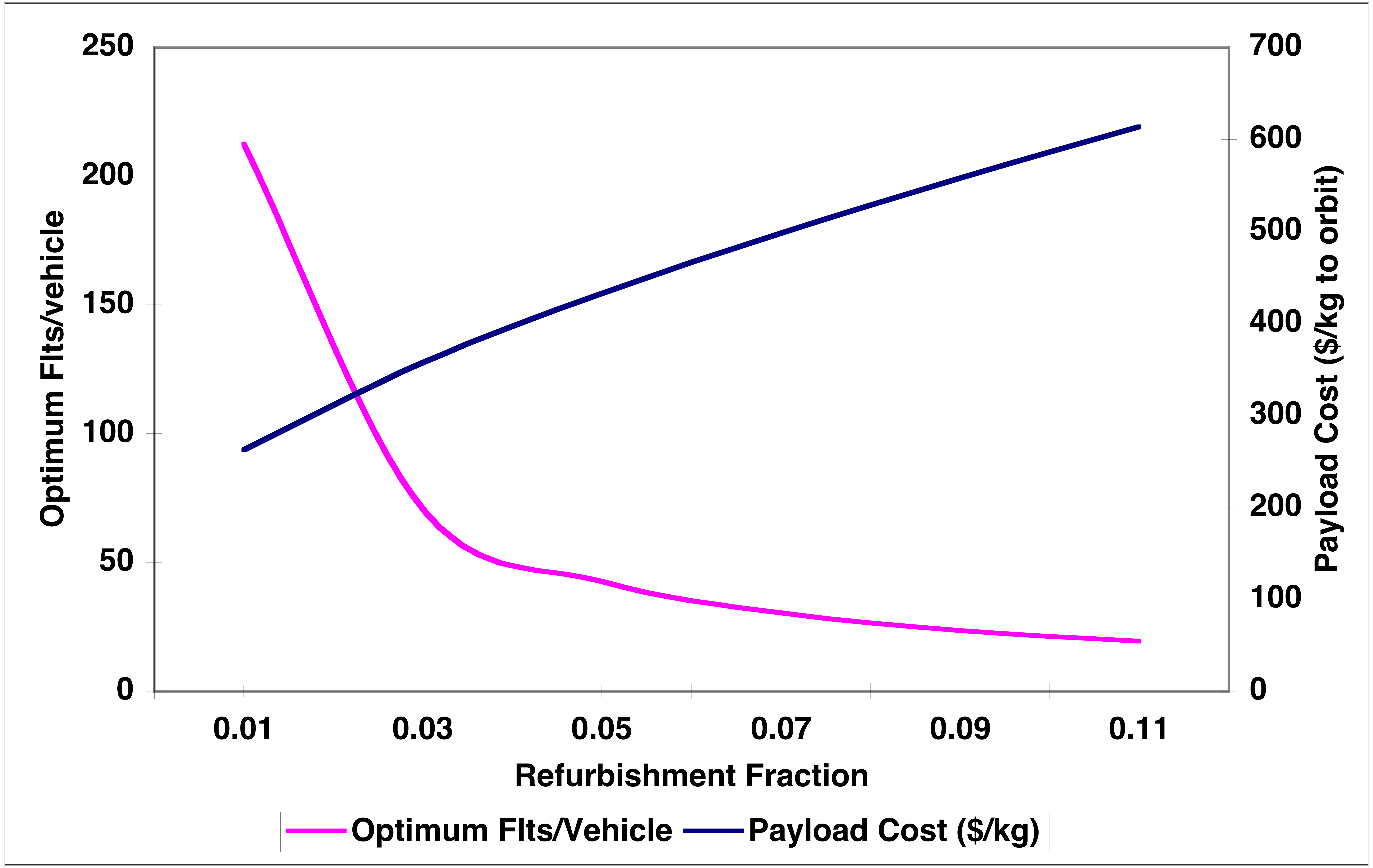
Effect of Vehicle Lifetime



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!)

References

- Richard de Neufville and Joseph H. Stafford, *Systems Analysis for Engineers and Managers,* McGraw-Hill, 1971
- Arney and Wilhite, "Rapid Cost Estimation for Space Exploration Systems" AIAA 2012-5183, AIAA Space 2012, Pasadena, California, Sept. 2012
- Wertz, Everett, and Puschell, ads., *Space Mission Engineering: The New SMAD,* Space Technology Library, Microcosm Press, 2011