Preliminary Cost Analysis

- 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

Vehicle-Level Cost Estimating Relations

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

Spacecraft Type	Nonrecurring a	Nonrecurring b	1st Unit Prod. a	1st Unit Prod. b
Launch Vehicle Stage	7.125	0.55	0.1693	0.662
Manned Spacecraft	18.06	0.55	0.5686	0.662
Unmanned Planetary	12.15	0.55	0.8818	0.662
Unmanned Earth Orbital	3.440	0.55	0.3908	0.662
Liquid Rocket Engine	28.78	0.55	0.1584	0.662
Scientific Instrument	1.840	0.50	0.2604	0.70

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	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

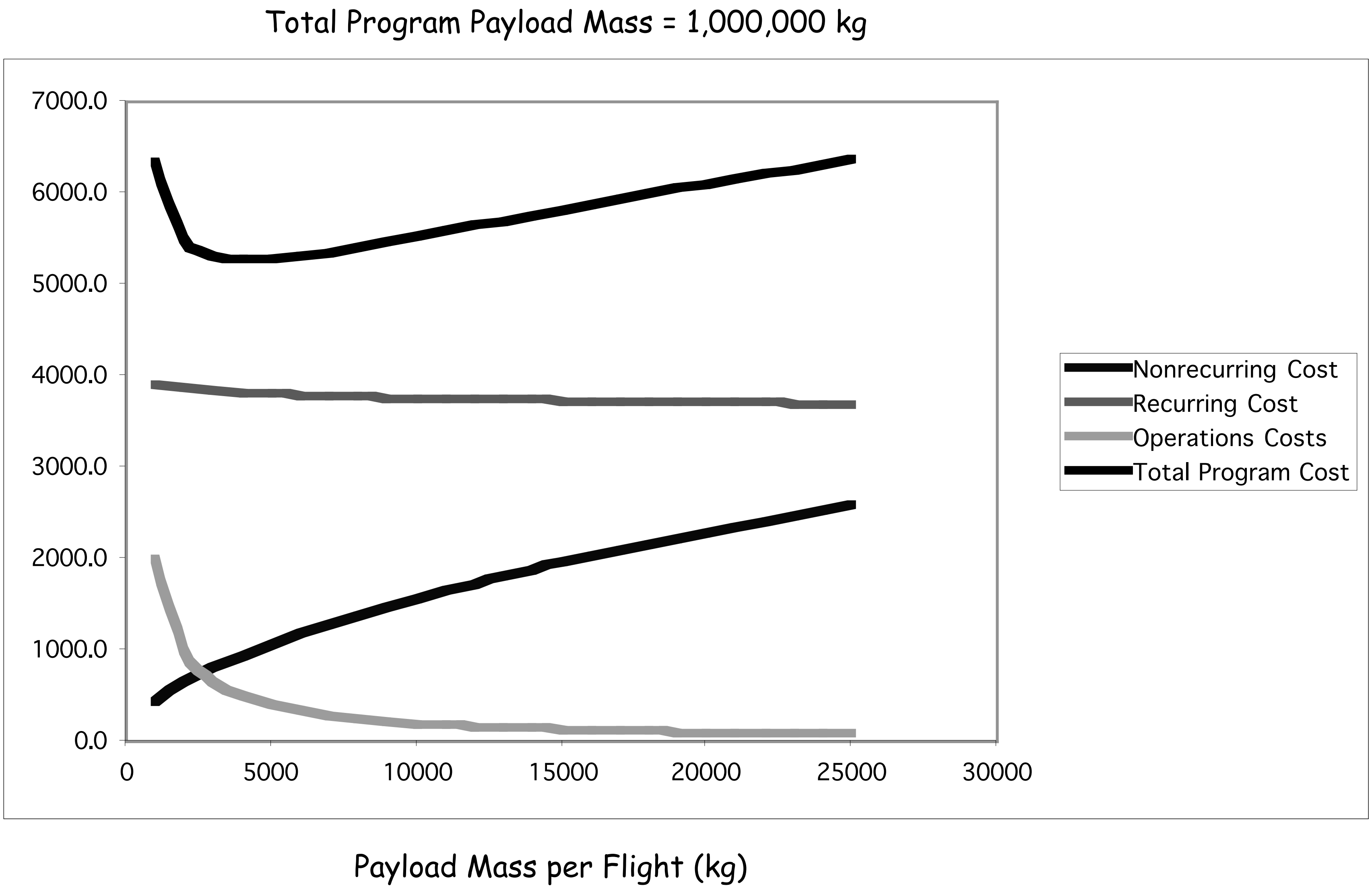
5000 kg payload, LOX/LH2 engines

The Learning Curve

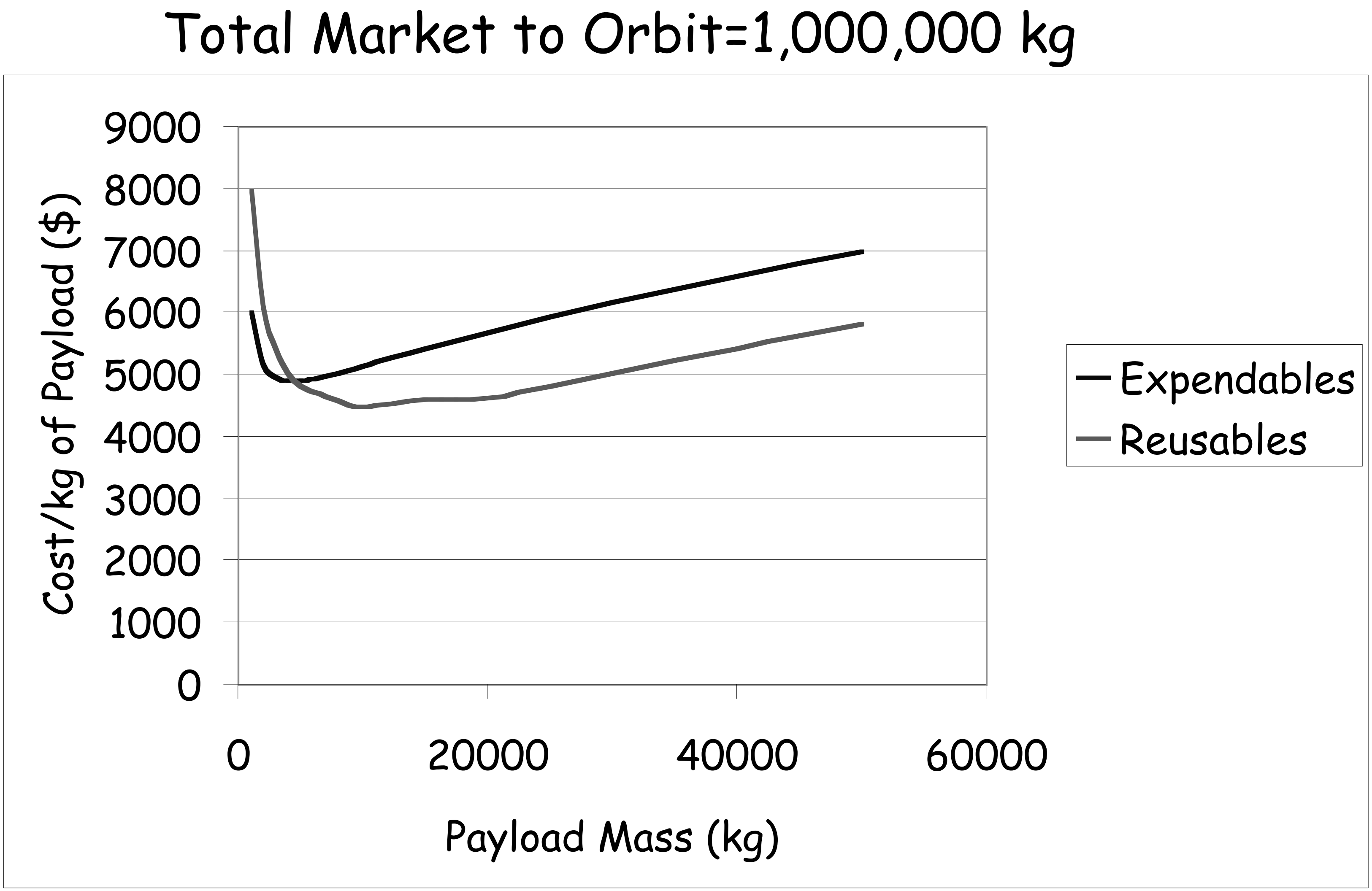
- The effort (time, cost, etc.) to perform a test decreases with repetition
- Crawford formulation: doubling the production run results in consistent fractional reduction of effort
  - "80% learning curve" - 2nd unit costs 80% of 1st, 4th is 80% of 2nd, 8th is 80% of 4th…
  - $C_n = C_1 \; n^p$
  - Average cost: $\overline{C}_n \approx C_1 \dfrac{n^p}{1+p}$

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

Cost and Learning Effects



Expendable/Reusable Trade Study



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)

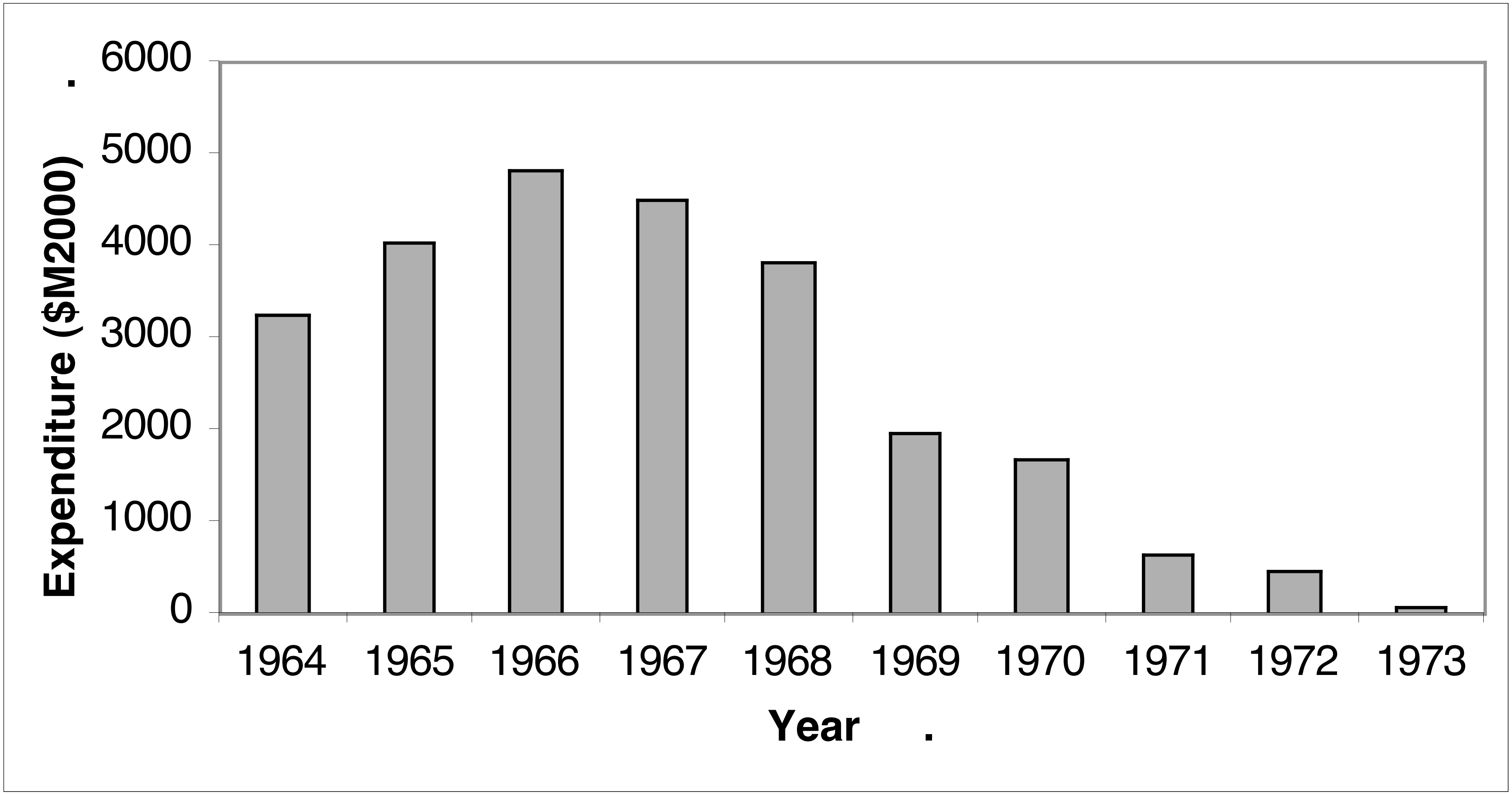
GDP Deflation Factors

Year	GDP factor	2002 value	Year	GDP factor	2002 value	Year	GDP factor	2002 value
1940	0.1032	$10.68	1963	0.2315	$4.76	1985	0.7382	$1.49
1941	0.1077	$10.23	1964	0.2345	$4.70	1986	0.7558	$1.46
1942	0.1155	$9.54	1965	0.2385	$4.62	1987	0.7758	$1.42
1943	0.1228	$8.97	1966	0.2437	$4.52	1988	0.8008	$1.38
1944	0.1275	$8.64	1967	0.2515	$4.38	1989	0.8318	$1.32
1945	0.1308	$8.42	1968	0.2608	$4.22	1990	0.8634	$1.28
1946	0.1401	$7.86	1969	0.2724	$4.04	1991	0.8953	$1.23
1947	0.1568	$7.03	1970	0.287	$3.84	1992	0.916	$1.20
1948	0.1695	$6.50	1971	0.3019	$3.65	1993	0.9392	$1.17
1949	0.1766	$6.24	1972	0.3165	$3.48	1994	0.9608	$1.15
1950	0.1738	$6.34	1973	0.331	$3.33	1995	0.9811	$1.12
1951	0.184	$5.99	1974	0.3545	$3.11	1996	1	$1.10
1952	0.1906	$5.78	1975	0.3898	$2.83	1997	1.017	$1.08
1953	0.1941	$5.68	1976	0.4179	$2.64	1998	1.03	$1.07
1954	0.1961	$5.62	TQ	0.432	$2.55	1999	1.0434	$1.06
1955	0.1982	$5.56	1977	0.4505	$2.45	2000	1.059	$1.04
1956	0.2036	$5.41	1978	0.4811	$2.29	2001	1.0802	$1.02
1957	0.2113	$5.21	1979	0.5186	$2.12	2002	1.1018	$1.00
1958	0.2167	$5.08	1980	0.5632	$1.96	2003	1.1238	$0.98
1959	0.2209	$4.99	1981	0.6174	$1.78	2004	1.1463	$0.96
1960	0.223	$4.94	1982	0.6596	$1.67	2005	1.1692	$0.94
1961	0.226	$4.88	1983	0.6892	$1.60			
1962	0.2288	$4.82	1984	0.715	$1.54			

Inflation Example: Saturn V Costs

Year	Real year $M	$M2000
1964	763.4	3255.4
1965	964.9	4045.8
1966	1177.3	4831.0
1967	1135.6	4515.3
1968	998.9	3830.1
1969	534.5	1962.0
1970	484.4	1687.9
1971	189.1	626.2
1972	142.5	450.1
1973	26.3	79.5
	6416.8	25283.4

Saturn V Annual Expenditures



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

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

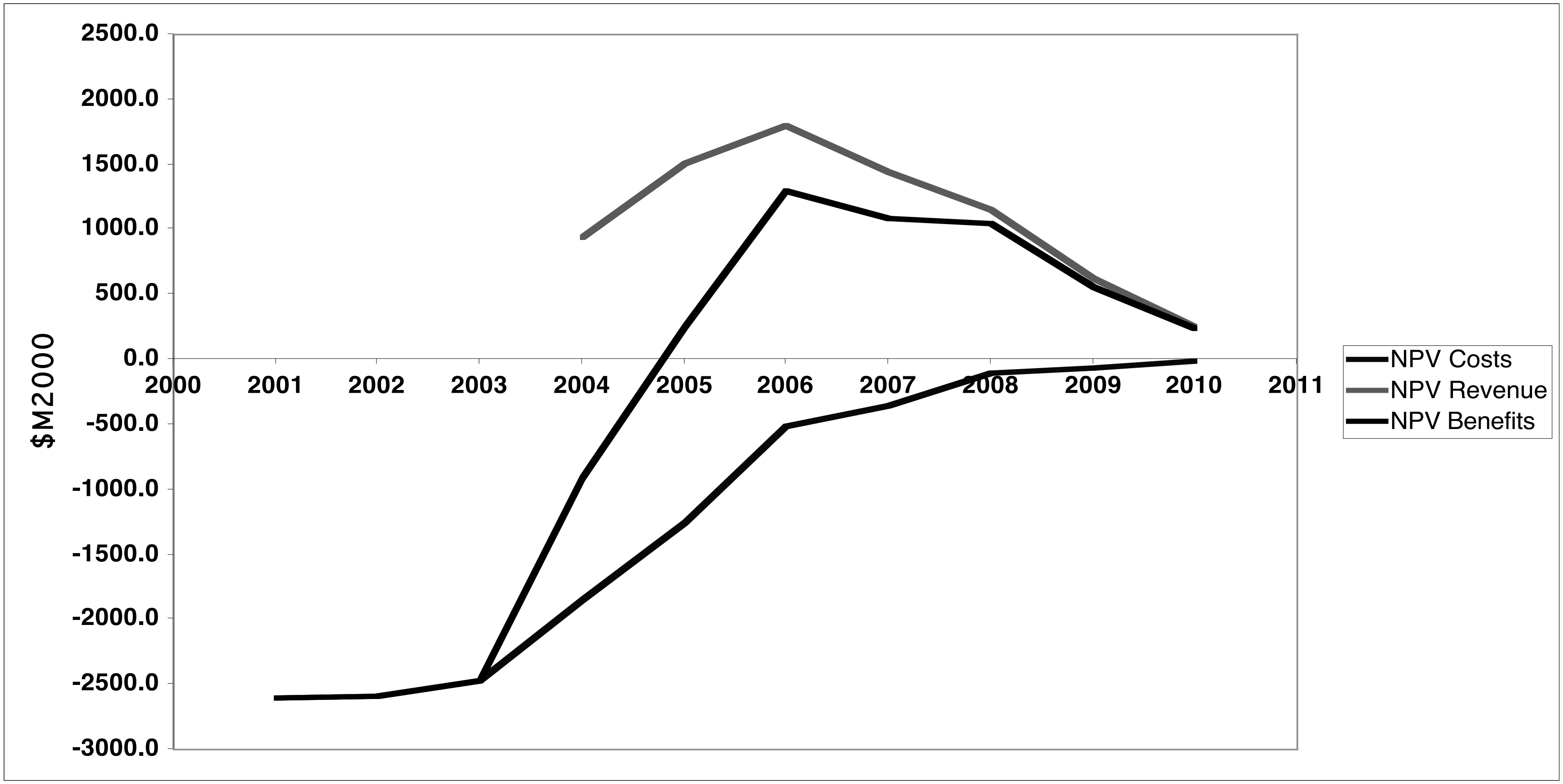
Effect of Moving Revenue Forward

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 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

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

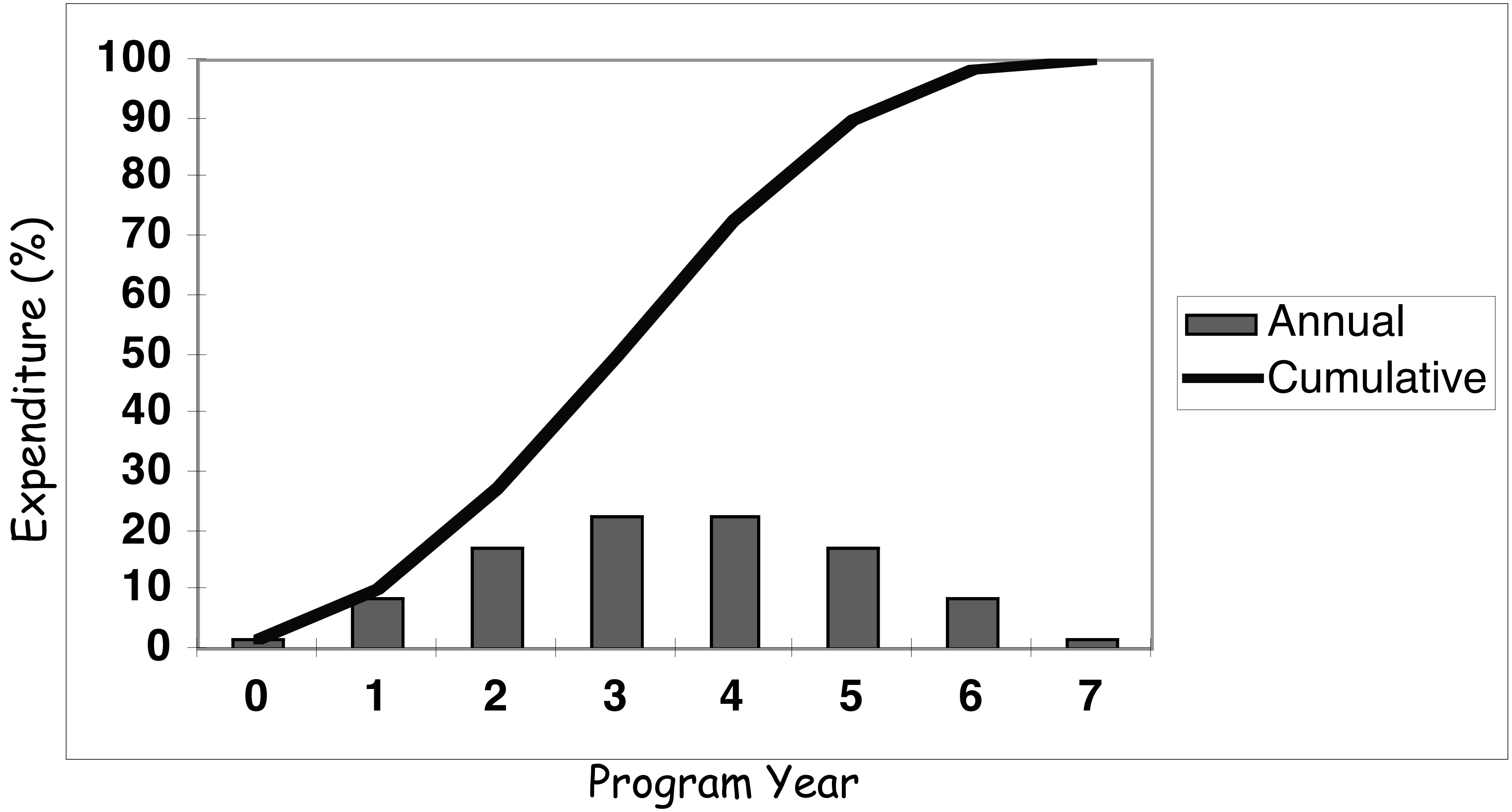
where

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

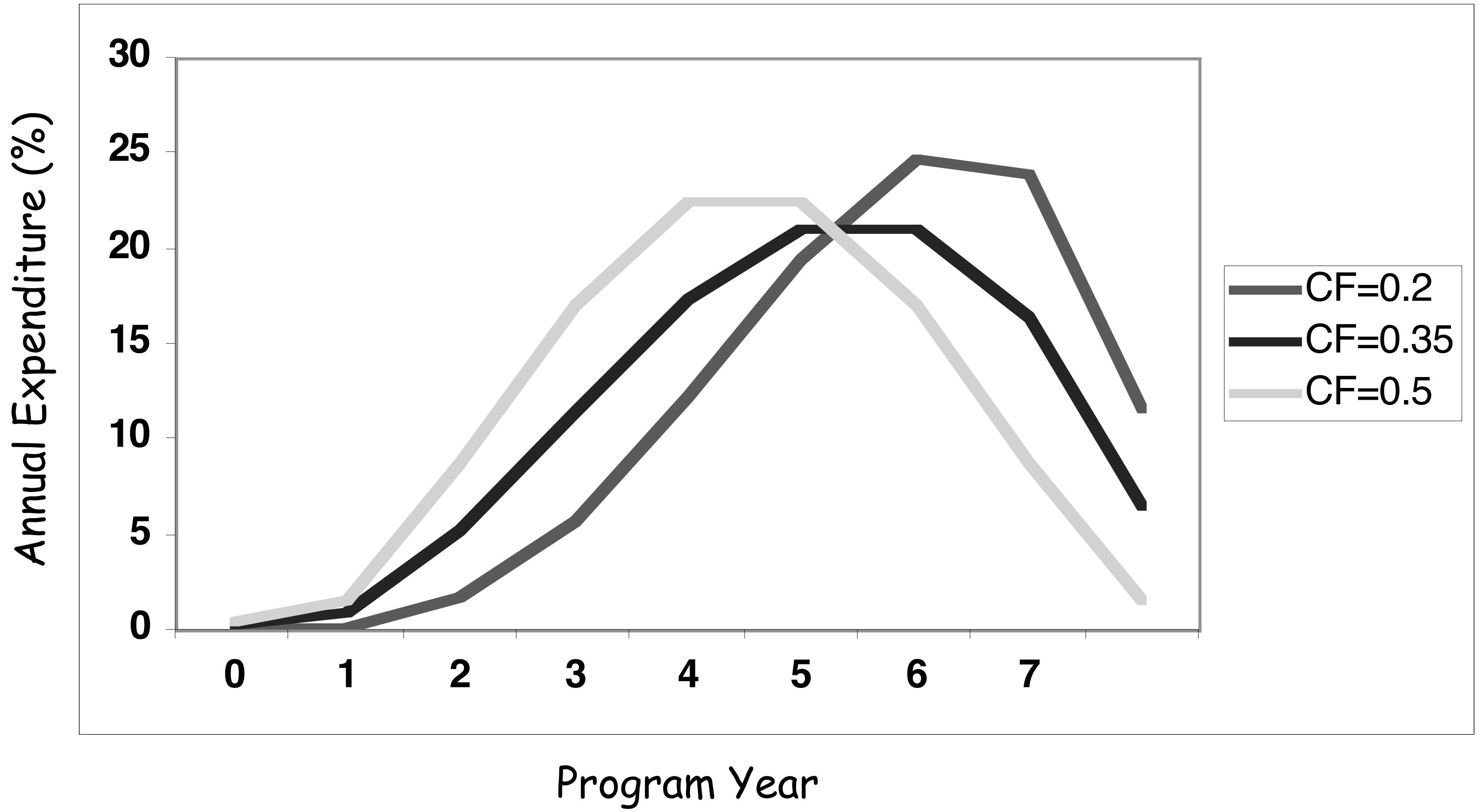
$$c_f < 0.5 : A = \frac{(1-P)(c_f - 0.1875)}{0.625}; B = P\frac{c_f - 0.1875}{0.3125}$$

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

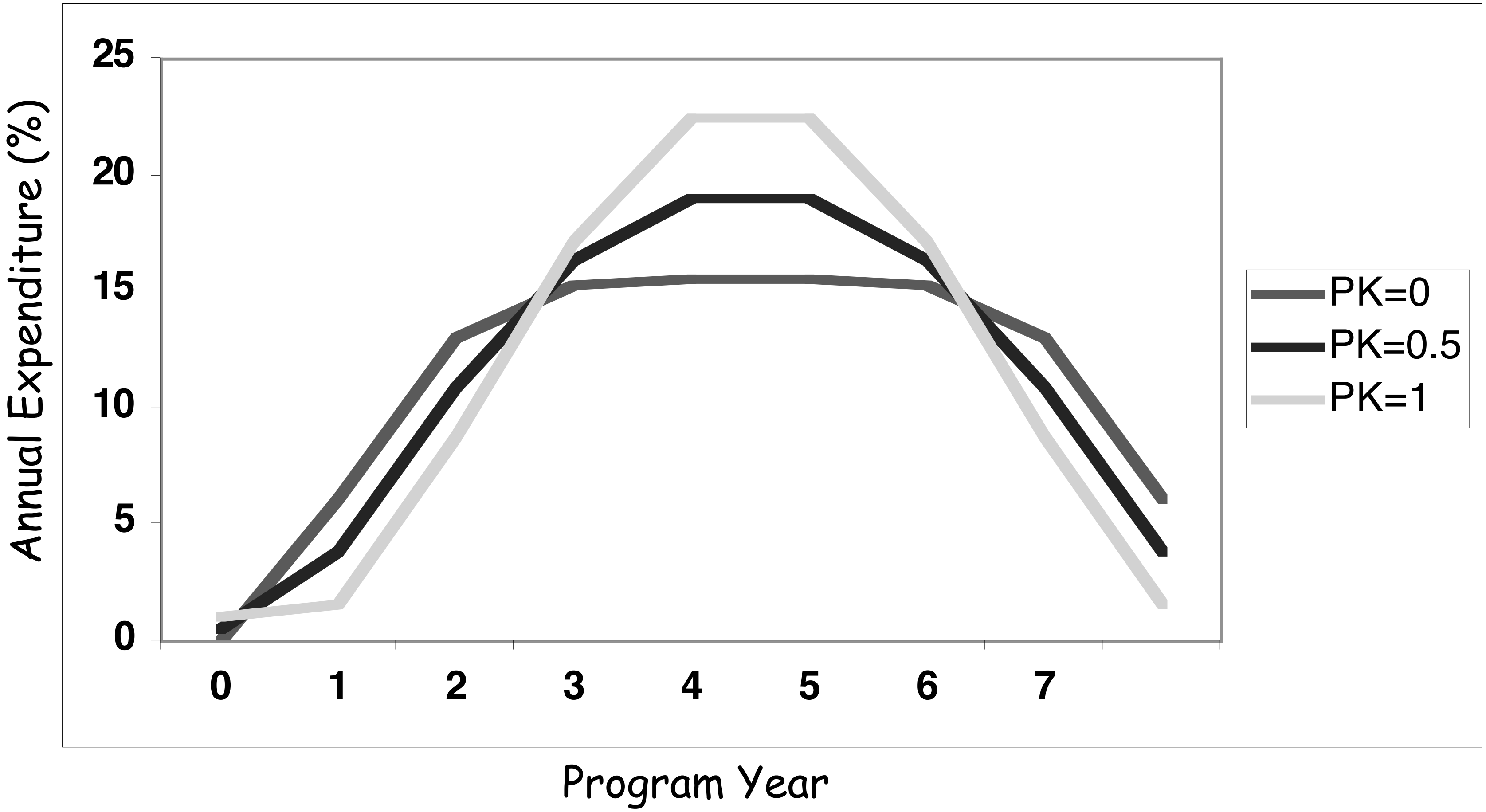
Sample of Beta Function



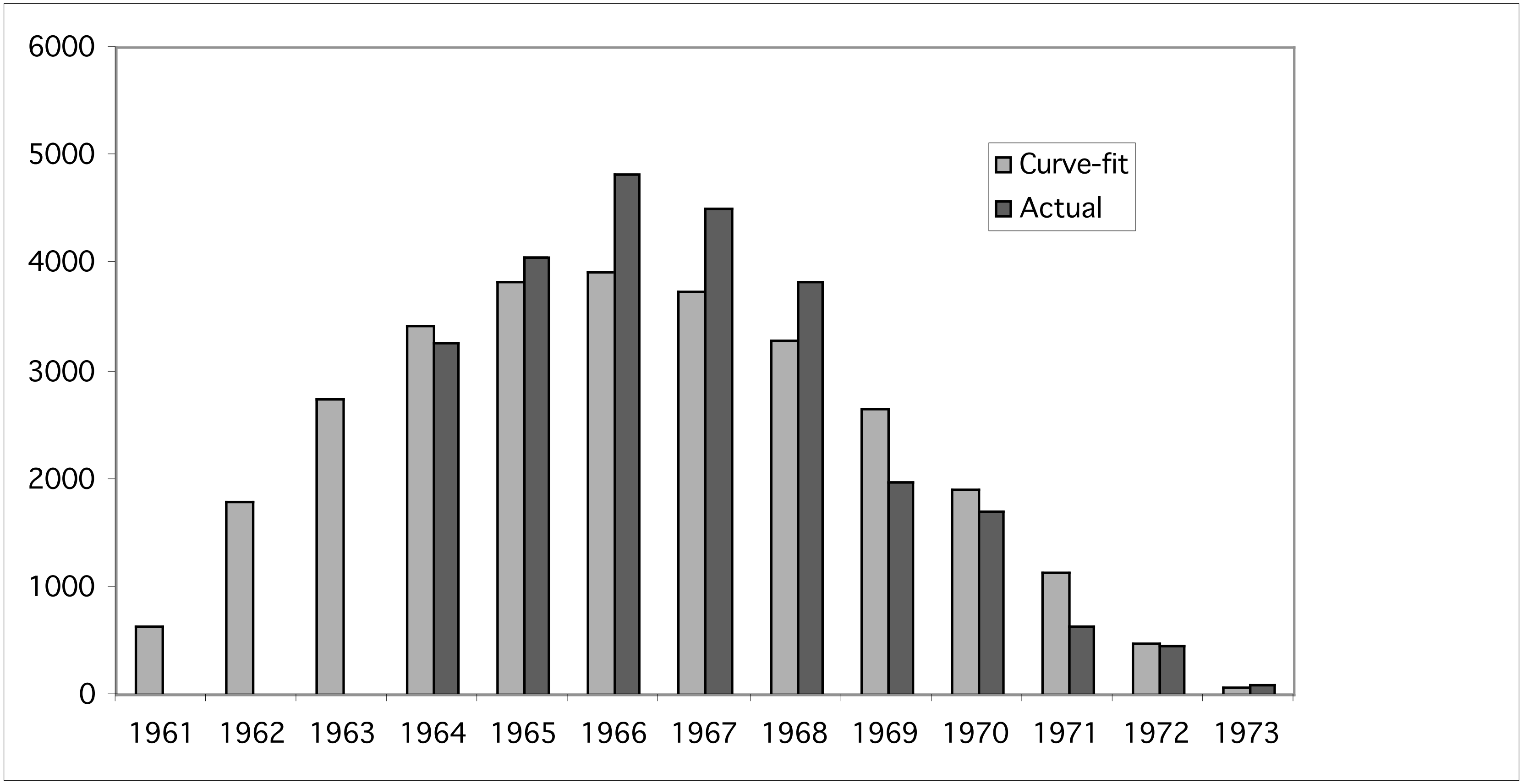
Cost Fraction in Beta Function



Peakedness in Beta Function

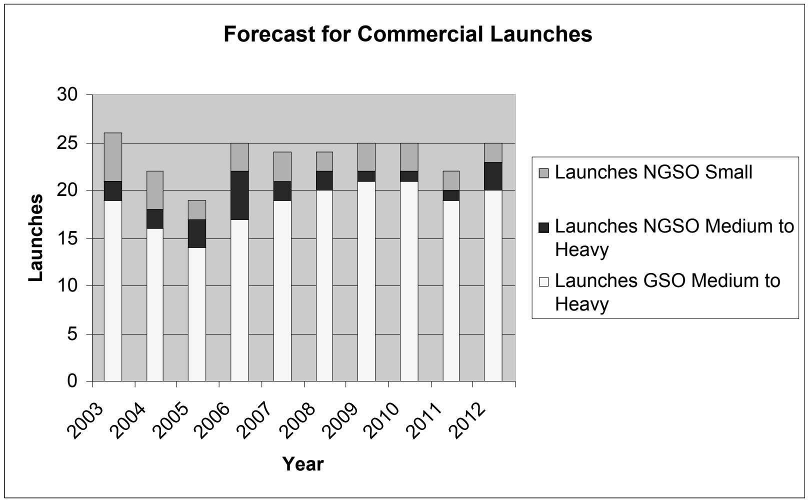


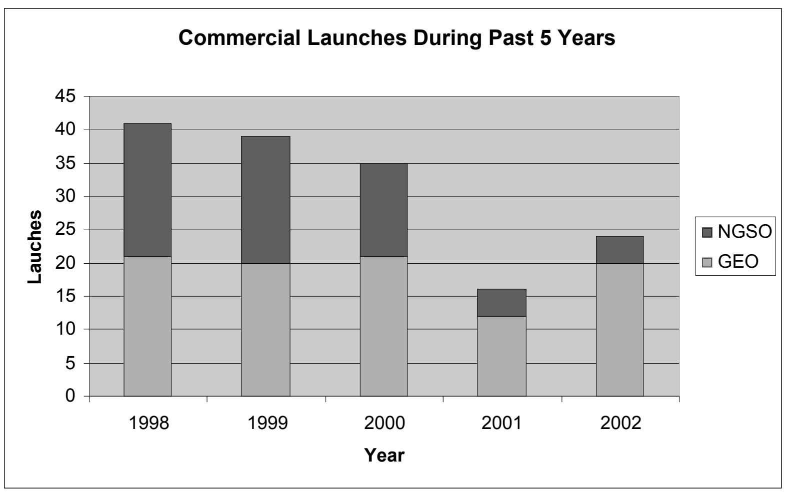
Beta Curve Fit to Saturn V Data



A=0.371; B=0.629

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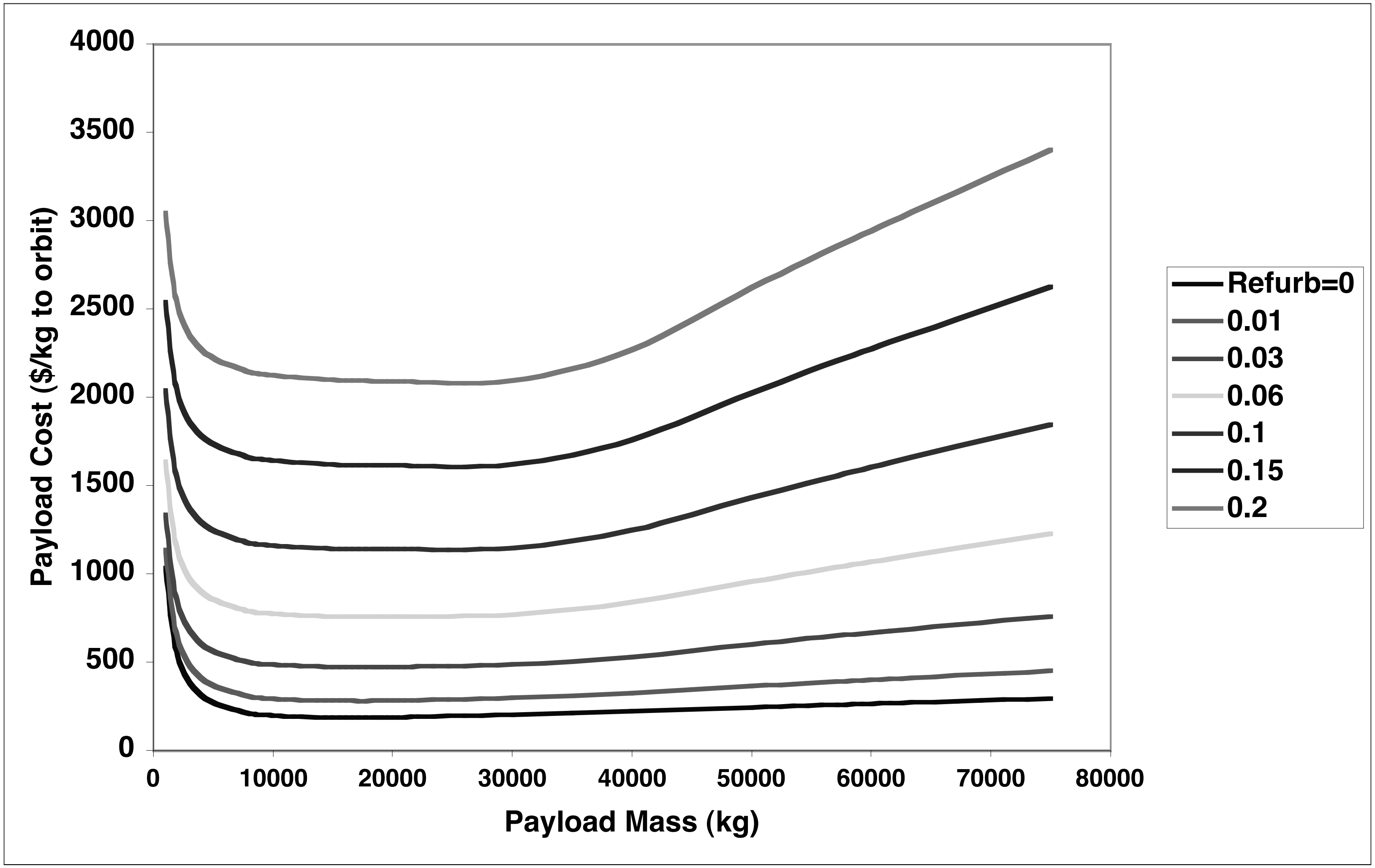
- Preliminary model developed to bound problem, identify critical parameters
- Assumptions:
  - Total program launch mass 20,000 MT
  - Program lifetime 20 years
  - NASA SLVLC model for cost estimates
  - 80% learning curve
  - Vehicle modeled as LOX/LH2 SSTO (δ=0.08; I_{sp}=420 sec avg.)

Effect of Refurbishment Rate



Effect of Vehicle Lifetime

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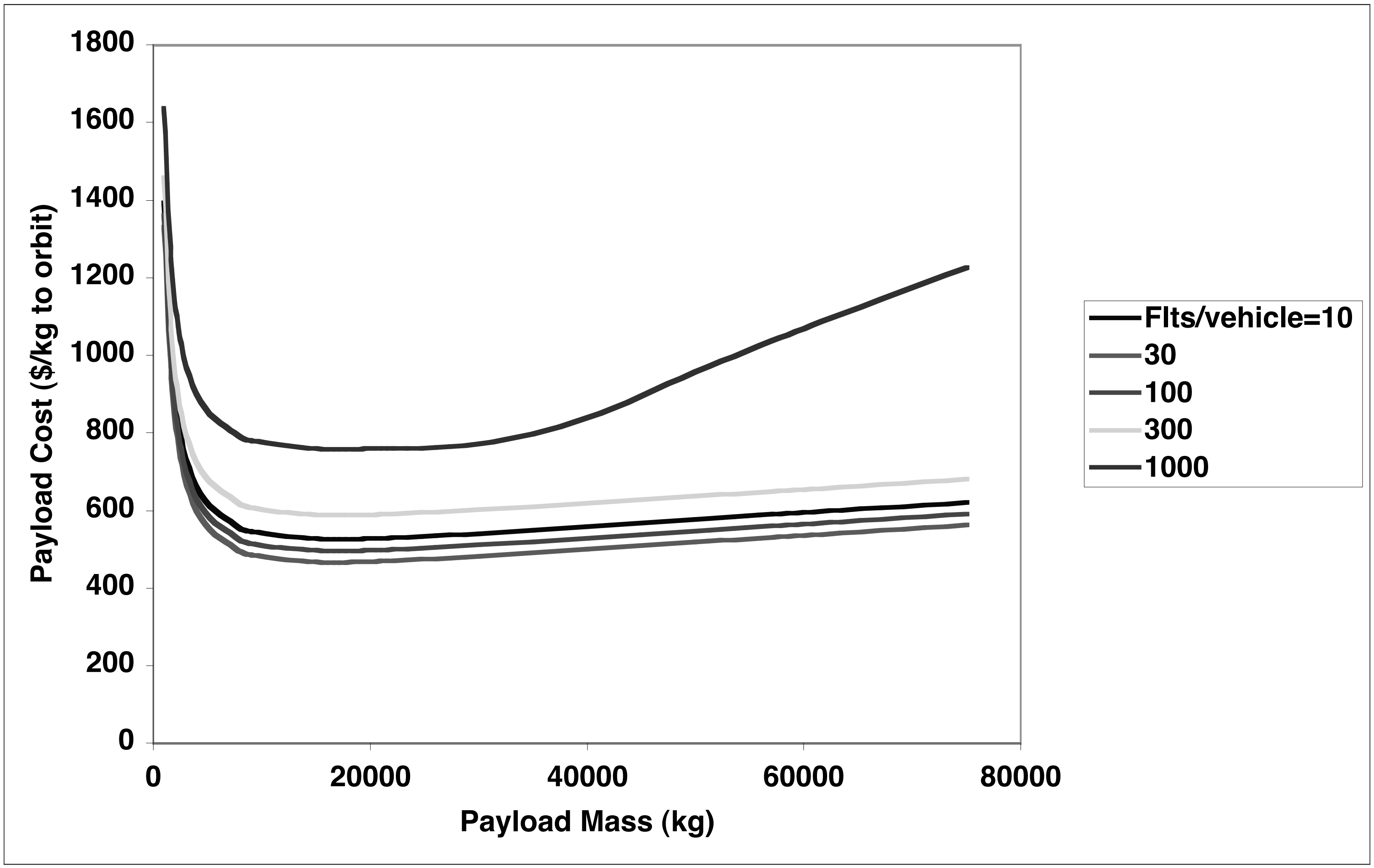
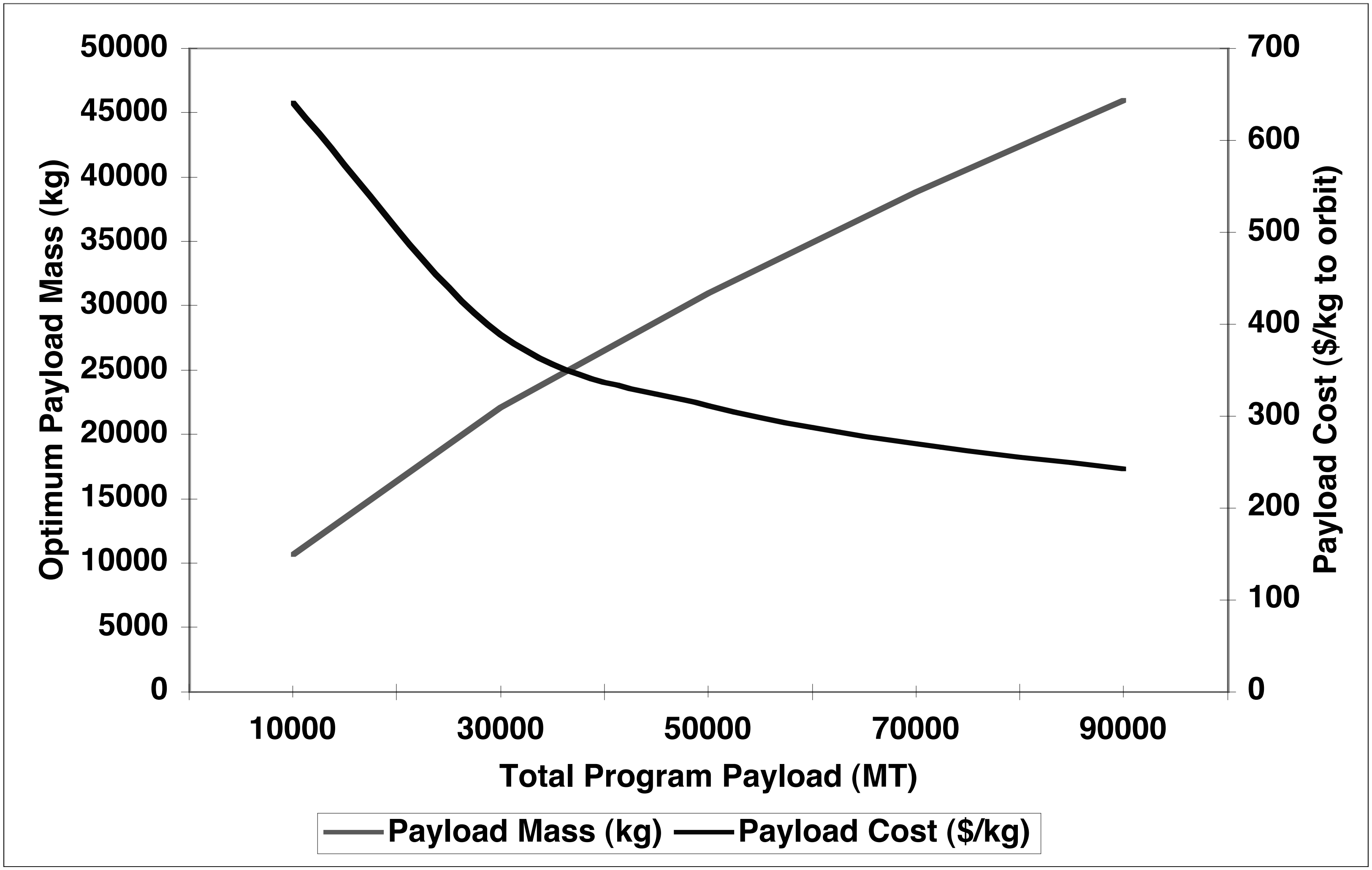


Effect of Total Launch Mass



Effect of Refurbishment Fraction

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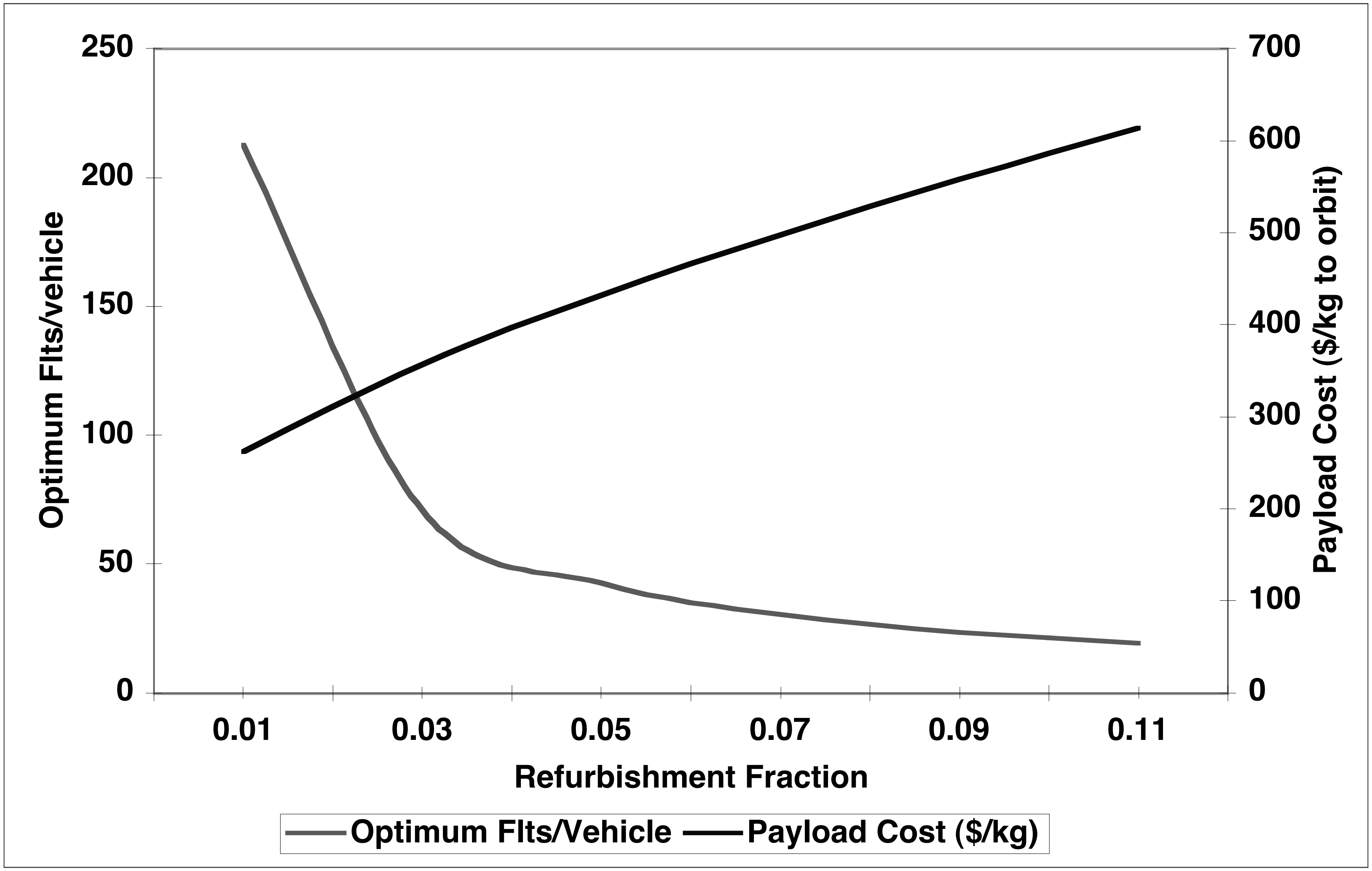

Costing Conclusions (to date)

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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!)

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