# 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 | 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$

# Falcon 9 NAFCOM Cost Estimate

(All Costs Are In FY2010 $M)

| | | Cost Plus Fee | | | | Cost Plus Fee | | |
|---|---|---|---|---|---|---|---|---|
| | | Space-x Approach | | | | NASA Approach | | |
| Elements | Weight (lbs) | DDT&E (FY2010 $M) | Flight Unit (FY2010 $M) | Total (FY2010 $M) | | DDT&E (FY2010 $M) | Flight Unit (FY2010 $M) | Total (FY2010 $M) |
| Stage One (Including Engines) | 39,080 | $614 | $87 | $701 | | $1,535 | $206 | $1,741 |
| SVLCM Model | | | | | | $3057 | $237 | |
| Stage Two (Including Engine) | 6,520 | $331 | $12 | $343 | | $608 | $44 | $651 |
| | | | | | | $1142 | $72.5 | |
| Fee (12.5%) | | $118 | $12 | $130 | | $268 | $30 | $298 |
| Program Support (10%) | | $107 | $4 | $111 | | $241 | $21 | $263 |
| Contingency (30% Vehicle, 10% Engine)) | | $251 | $11 | $262 | | $674 | $68 | $741 |
| Vehicle Level Integration (8%) | | $106 | $5 | $111 | | $258 | $24 | $282 |
| **Total** | **45,600** | **$1,528** | **$131** | **$1,659** | | **$3,584** | **$393** | **$3,977** |

- Based on November, 2010 weight estimate and technical data from SpaceX
- Represents DDT&E and one flight unit
- Both estimates represent cost plus fee acquisition approach (include fee, program support, and contingency)

NASA Assoc. Dep. Admin. for Space Policy, *Falcon 9 Launch Vehicle NAFCOM Cost Estimates*, August 2011

# Falcon 9 Updated Cost Estimate

(Cost Plus Fee Vs. Firm Fixed Price)

| | | Firm Fixed Price Acquisition | | | Cost Plus Fee Acquisition | | |
|---|---|---|---|---|---|---|---|
| Elements | Weight (lbs) | DDT&E (FY2010 $M) | 2 Test Flt Units (FY2010 $M) | Total (FY2010 $M) | DDT&E (FY2010 $M) | 2 Test Flt Units (FY2010 $M) | Total (FY2010 $M) |
| Stage One (Including Engines) | 39,080 | $188.7 | $109.3 | $298.0 | $370.6 | $218.3 | $588.9 |
| Stage Two (Including Engine) | 6,506 | $89.0 | $23.6 | $112.6 | $184.7 | $59.6 | $244.4 |
| Fee (12.5%) | | $0.0 | $0.0 | $0.0 | $69.4 | $34.7 | $104.2 |
| Program Support (10%) | | $0.0 | $0.0 | $0.0 | $62.5 | $31.3 | $93.7 |
| Contingency (30% Vehicle, 10% Engine)) | | $0.0 | $0.0 | $0.0 | $193.2 | $91.7 | $284.9 |
| Vehicle Level Integration (8%) | | $22.2 | $10.6 | $32.8 | $44.4 | $22.2 | $66.7 |
| Total | 45,586 | $299.9 | $143.6 | $443.4 | $924.9 | $457.9 | $1,382.7 |

NASA Assoc. Dep. Admin. for Space Policy, *Falcon 9 Launch Vehicle NAFCOM Cost Estimates*, August 2011

# Implications of CERs

- Launch Vehicles
  - Model range 3480-89,507 kg
  - Nonrecurring $63K-$273K/kg inert mass
  - 1st Unit $5400-$16.1K/kg inert mass
- Manned Spacecraft
  - Model range 231-69,638 kg
  - Nonrecurring $201K-$2.62M/kg inert mass
  - 1st Unit $19.7K-$136K/kg inert mass

# SVLCM – In-Space Systems

| 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<br>4600 | 134,800 | 2,937<br>10,780<br>13,721 | 576<br>1177<br>1753 |
| Minimize Inert Mass | 3356<br>5844 | 139,000 | 2,066<br>11,123<br>13,189 | 474<br>1197<br>1672 |
| Minimize Nonrecurring Cost | 2556<br>6644 | 147,000 | 1,666<br>11,762<br>13,428 | 421<br>1235<br>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…

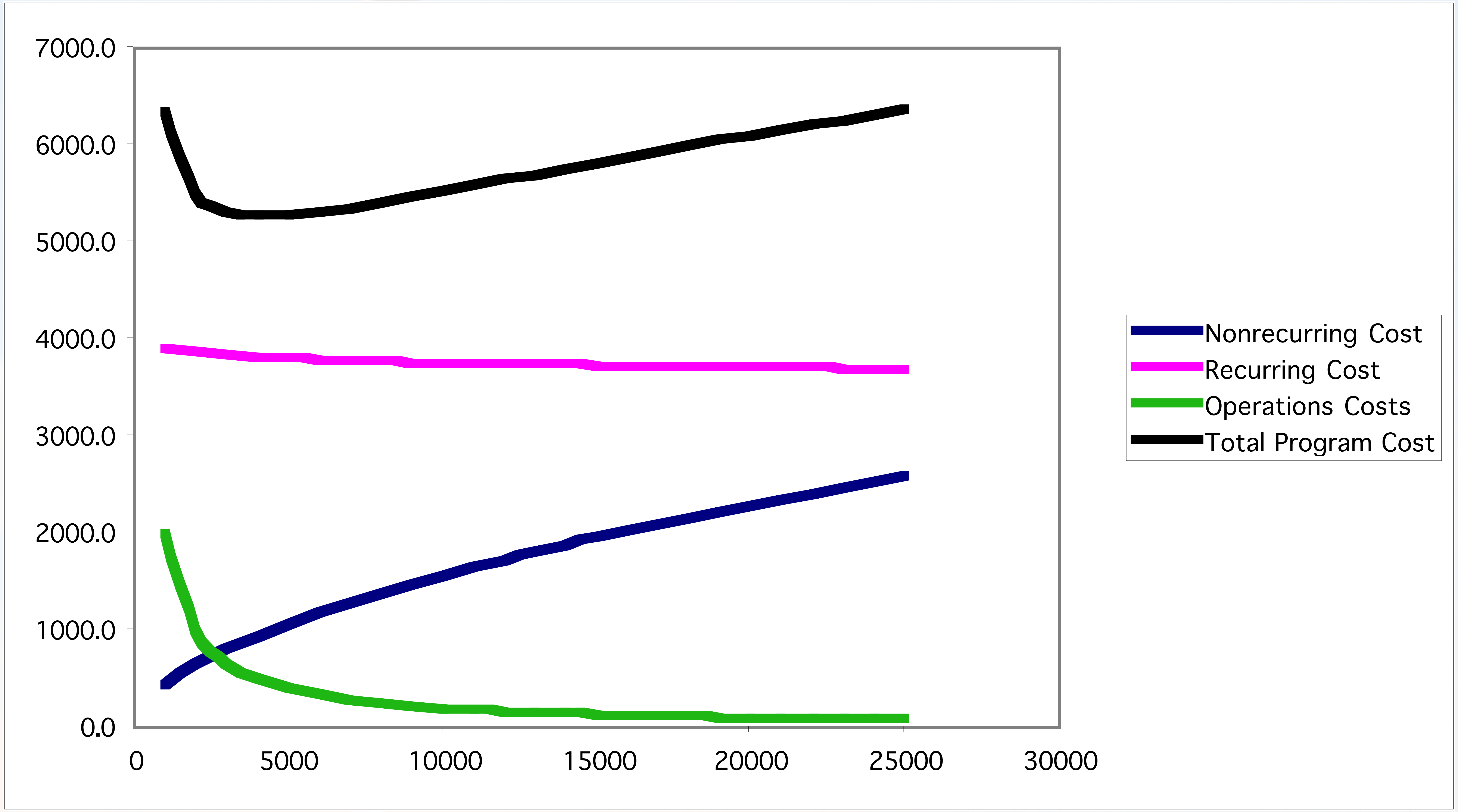
$$C_n = C_1 n^p$$

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

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

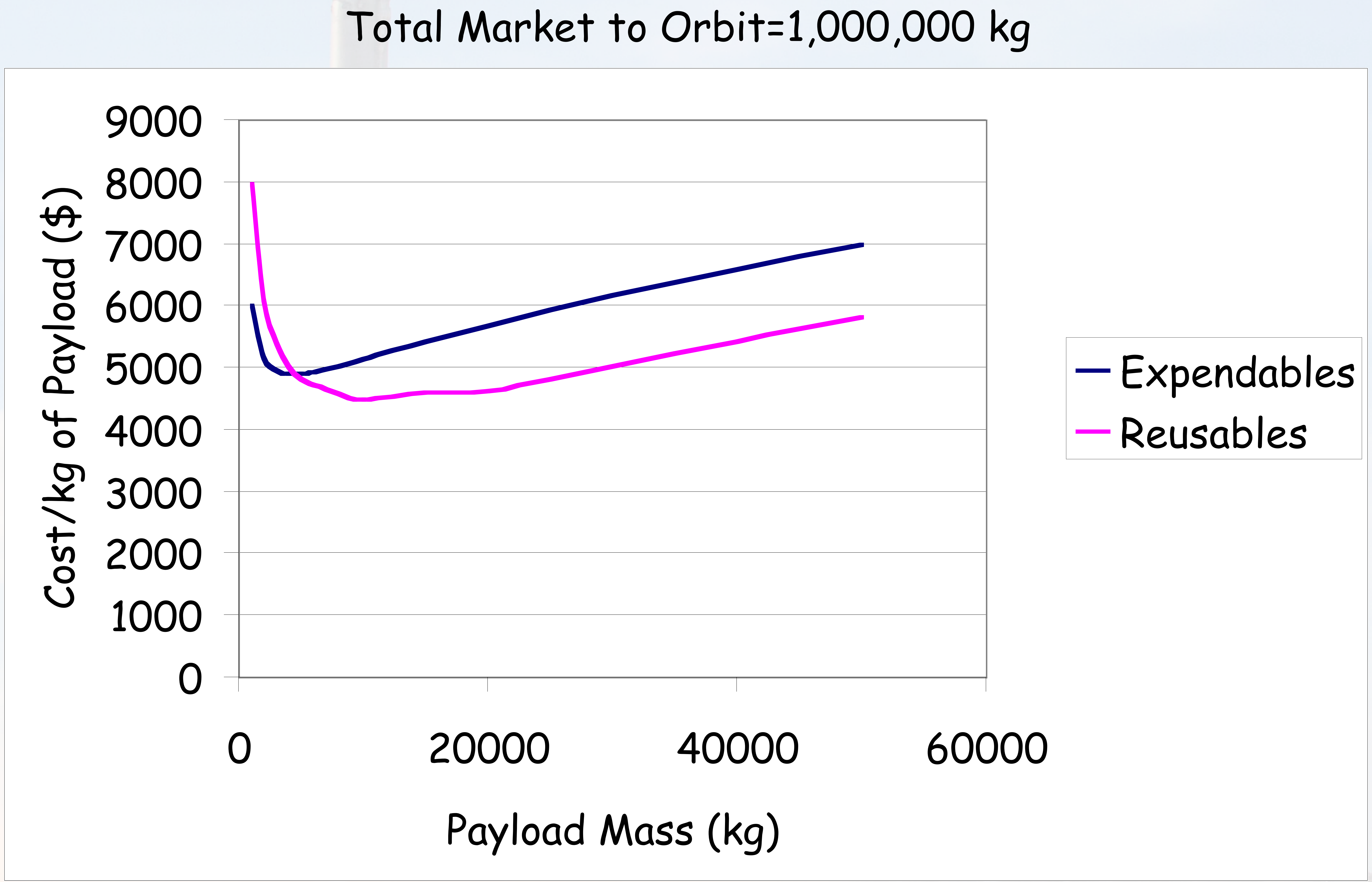
# Cost and Learning Effects

Total Program Payload Mass = 1,000,000 kg

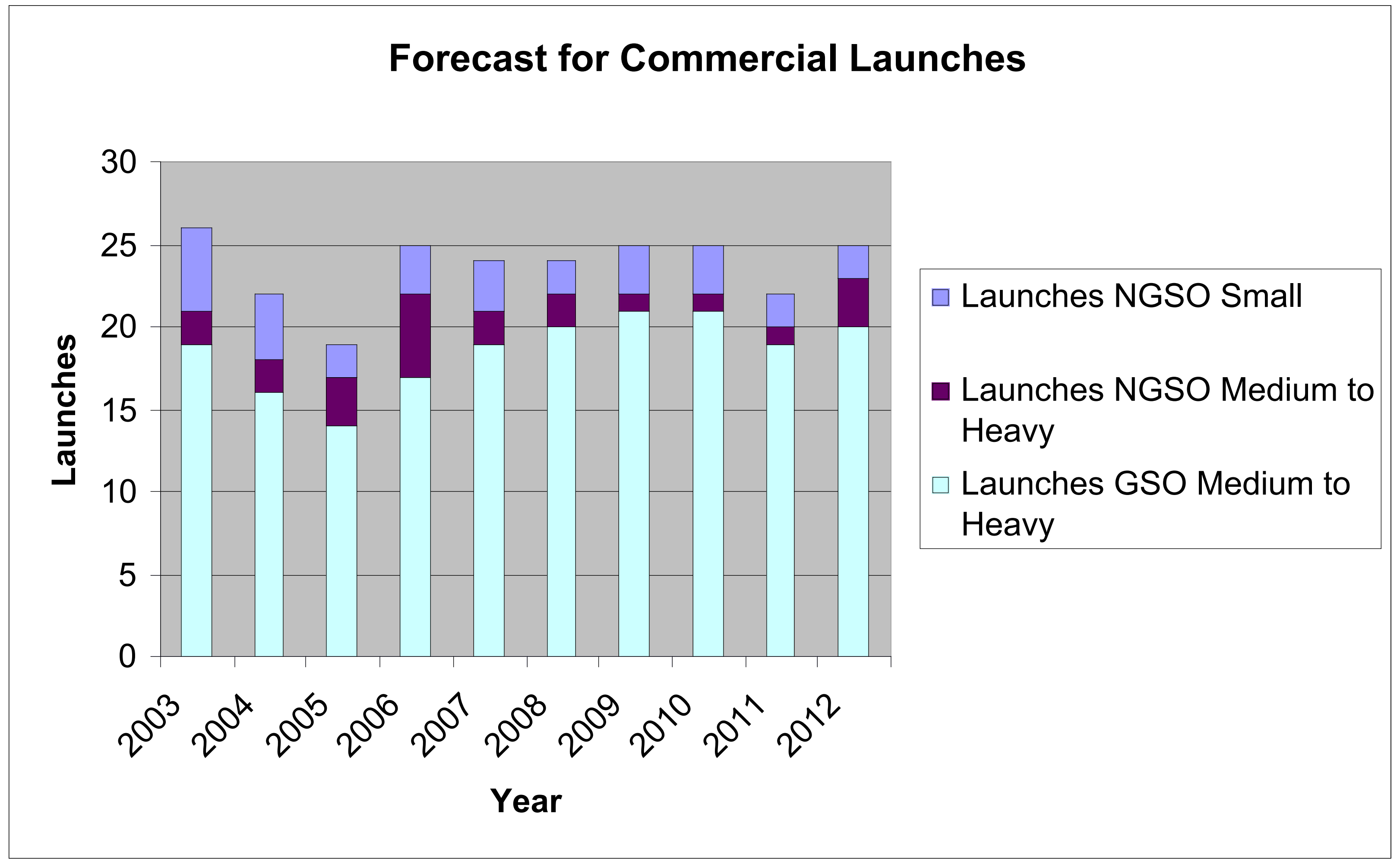


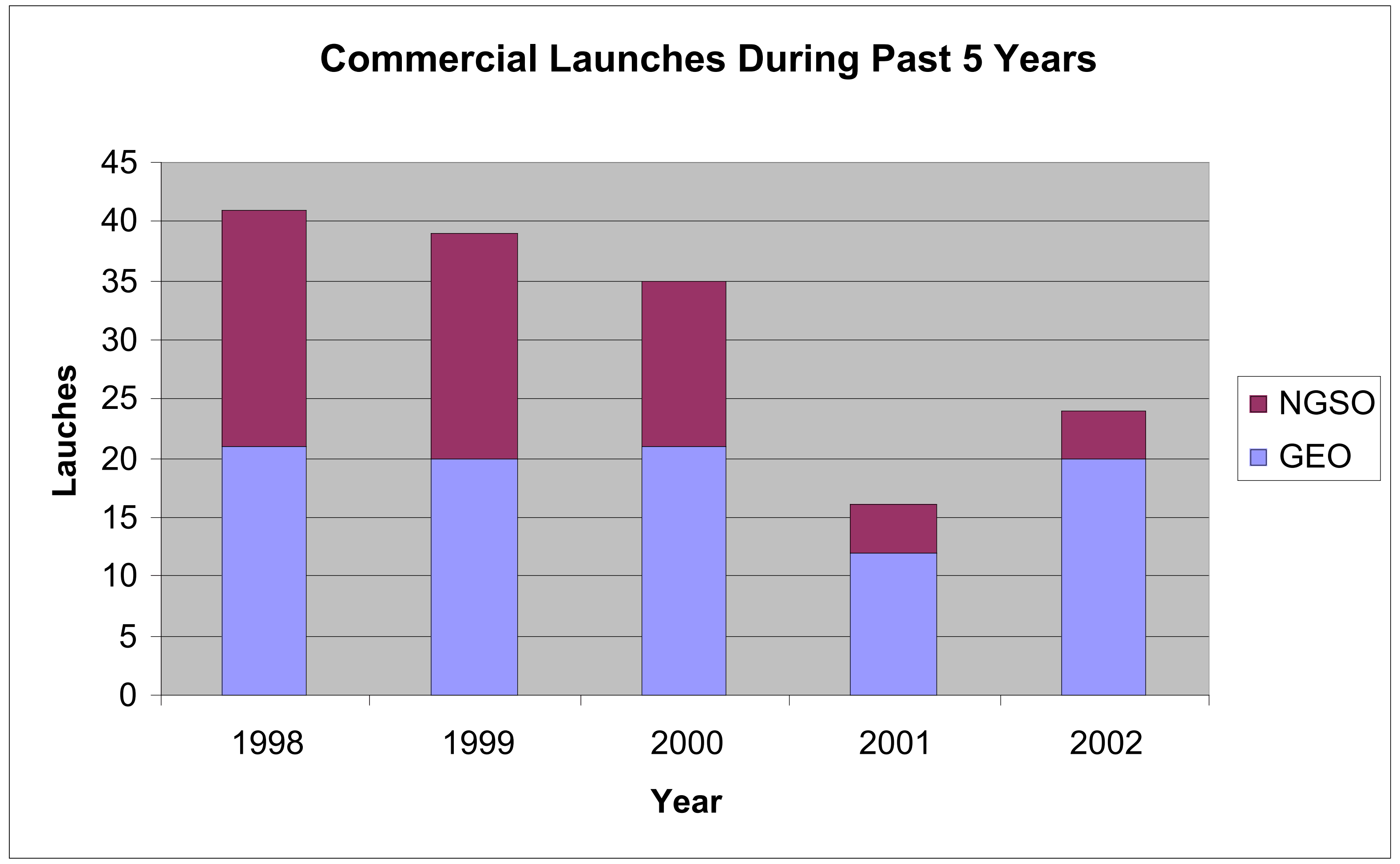

Payload Mass per Flight (kg)

# Expendable/Reusable Trade Study



# Cost Modeling



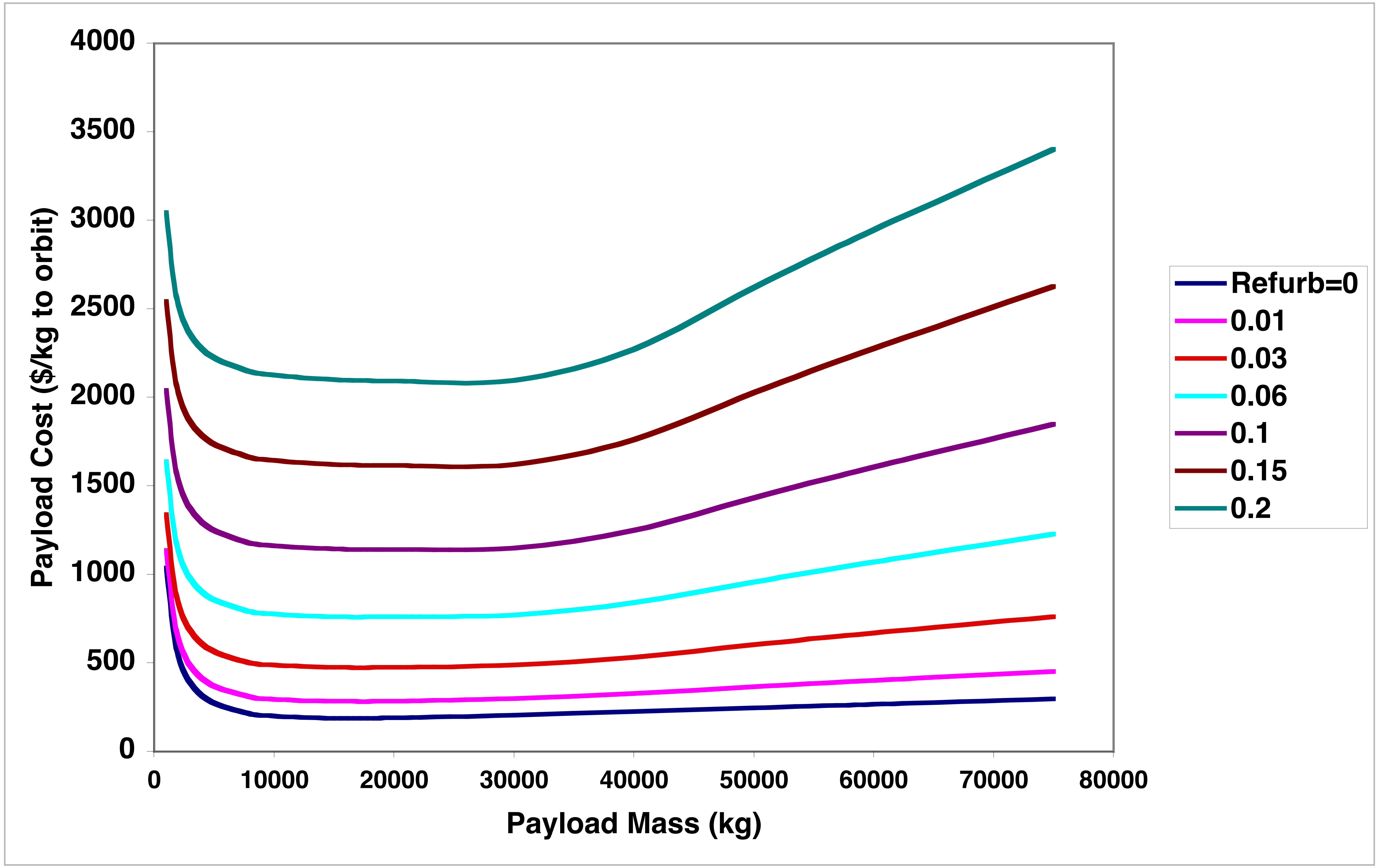




- At ~$100M/launch, worldwide annual launch revenue is ~$6-8 B
- Potential savings by cutting costs by factor of 2 is ~$3-4 B
- Given a 10 year development program and a 10% discount rate (government support), maximum feasible program cost for new vehicle is ~$2.5 B/yr
- At a 50% ROI (commercial), maximum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

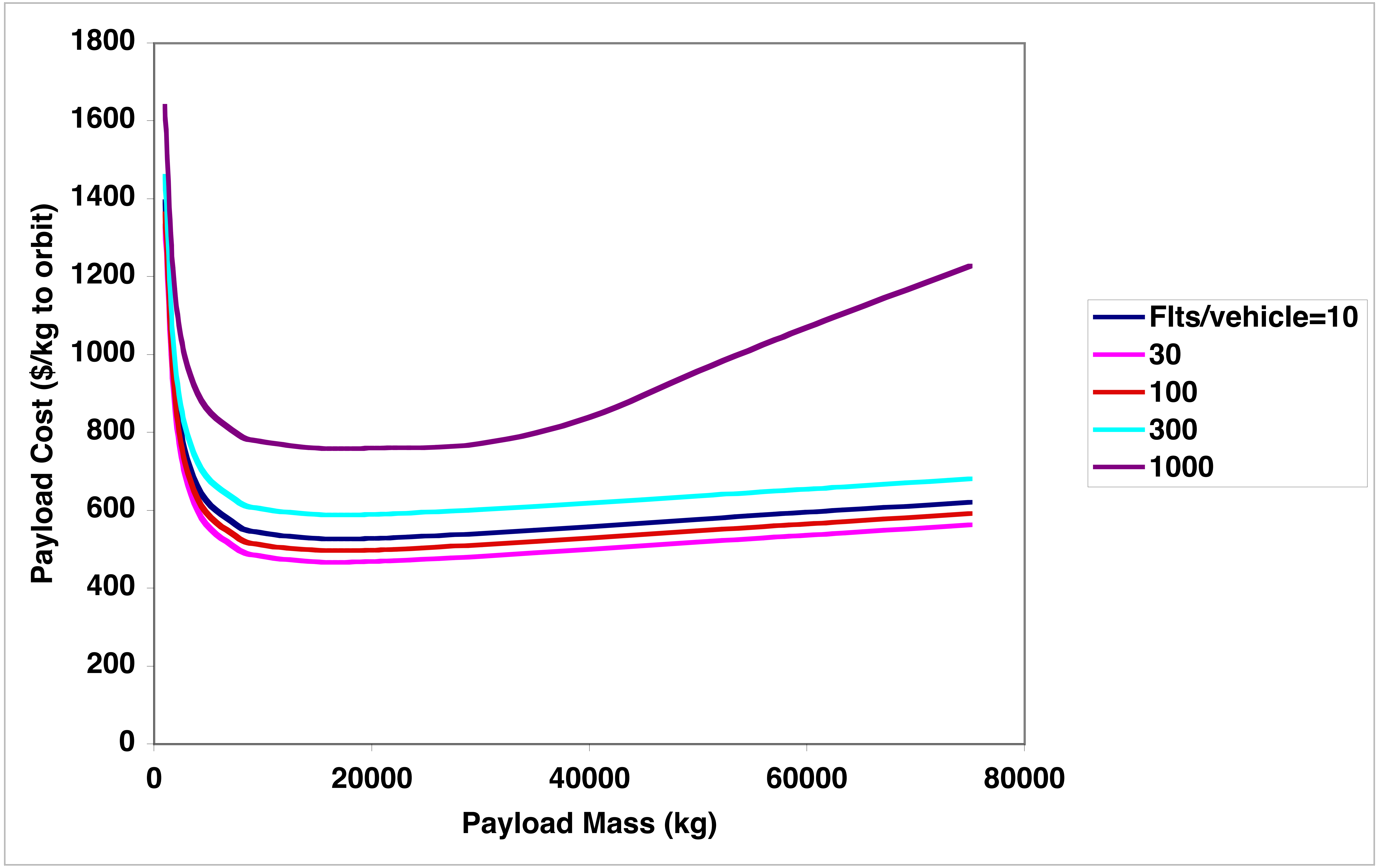
# Parametric Cost Analysis

- 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 ($\delta$=0.08; $I_{sp}$=420 sec avg.)

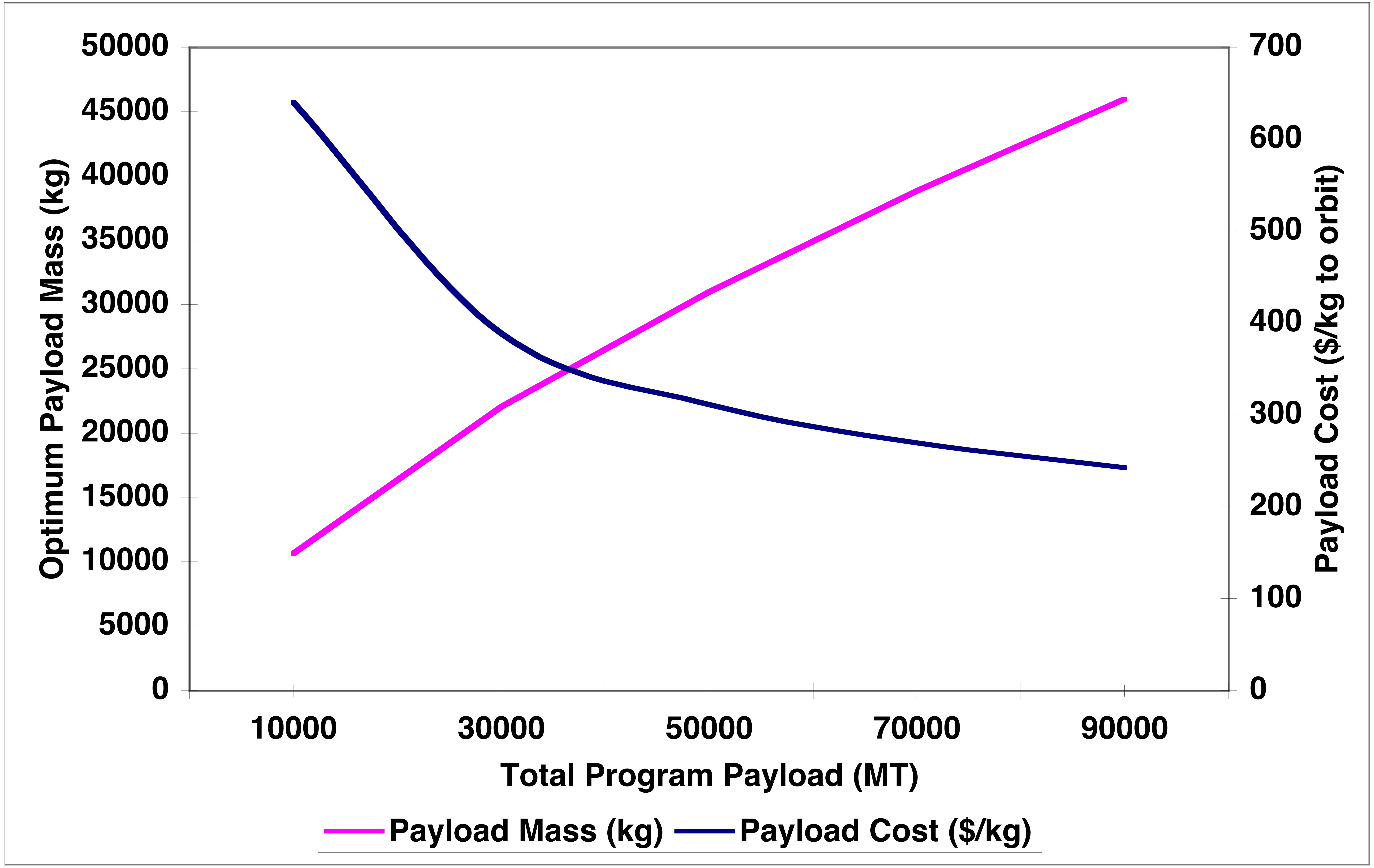
# Effect of Refurbishment Rate



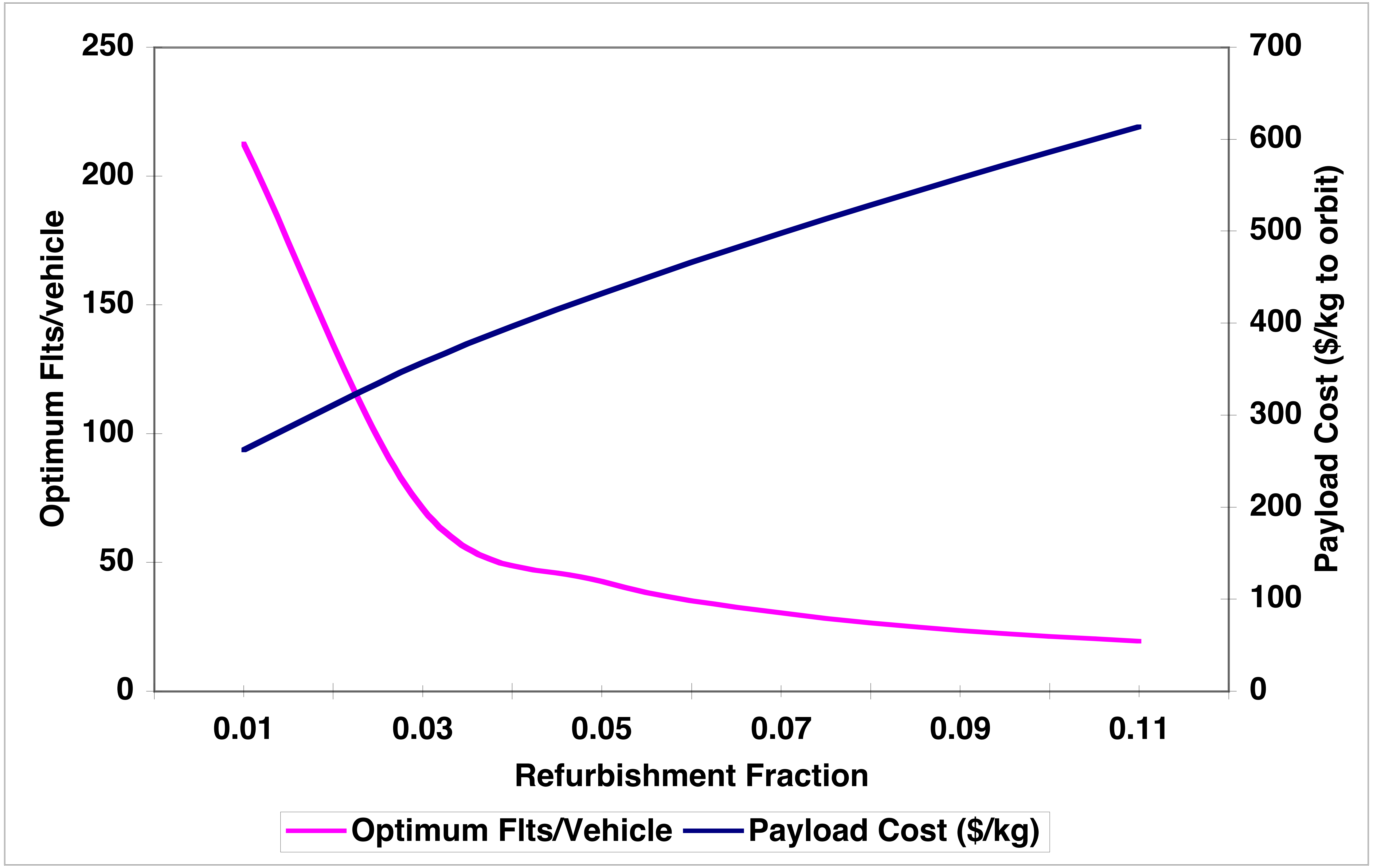
# Effect of Vehicle Lifetime



# Effect of Total Launch Mass



# Effect of Refurbishment Fraction



# Costing Conclusions

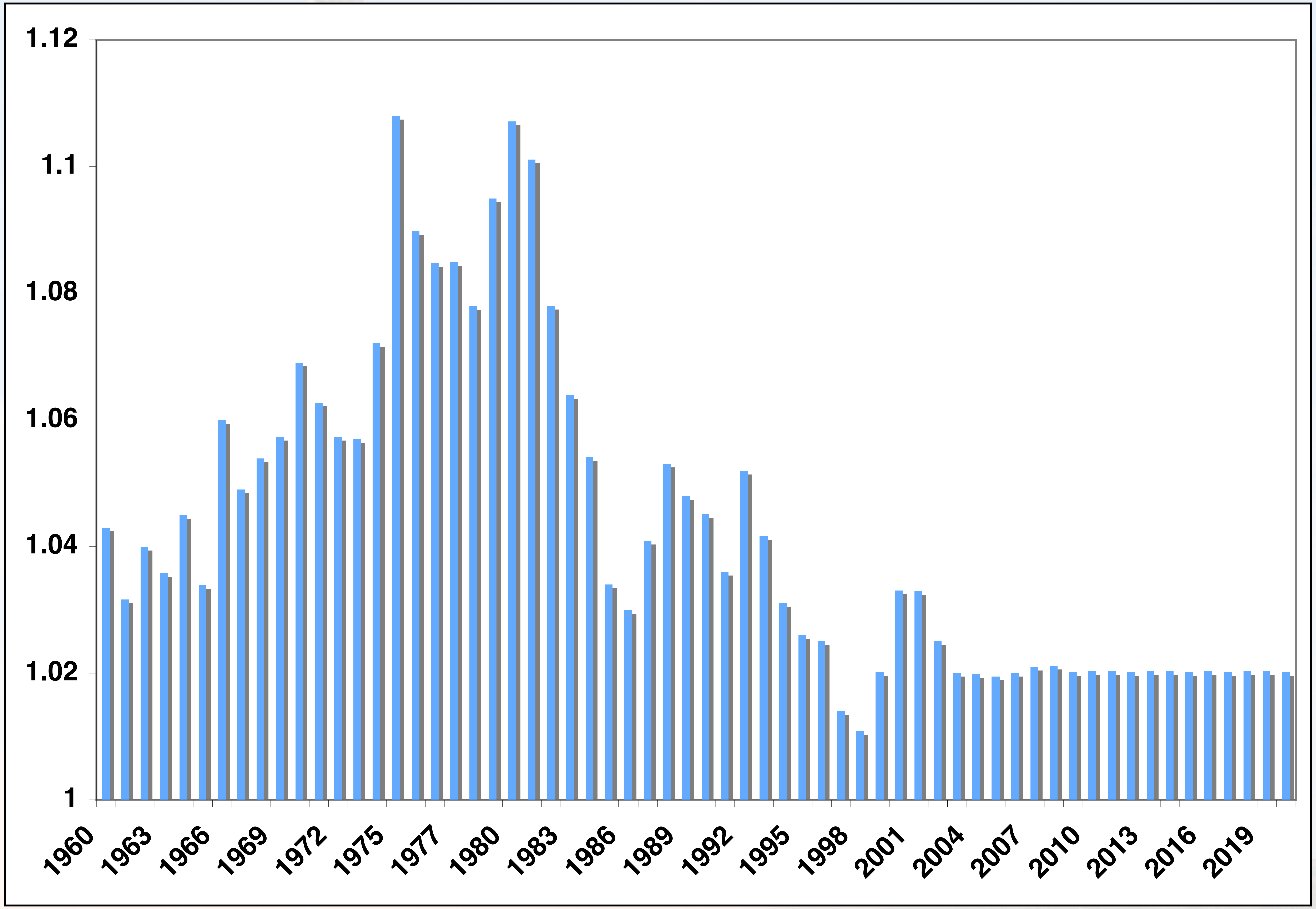


- Primary cost drivers are refurbishment and mission operations costs
  - Keep flight rate *and* production rates high to take advantage of learning curve
  - Strong sensitivity to fleet size
- Prediction: effects will be *worse* with RLV
  - Smaller fleet sizes
  - Higher (inert mass)/(payload mass) 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!)

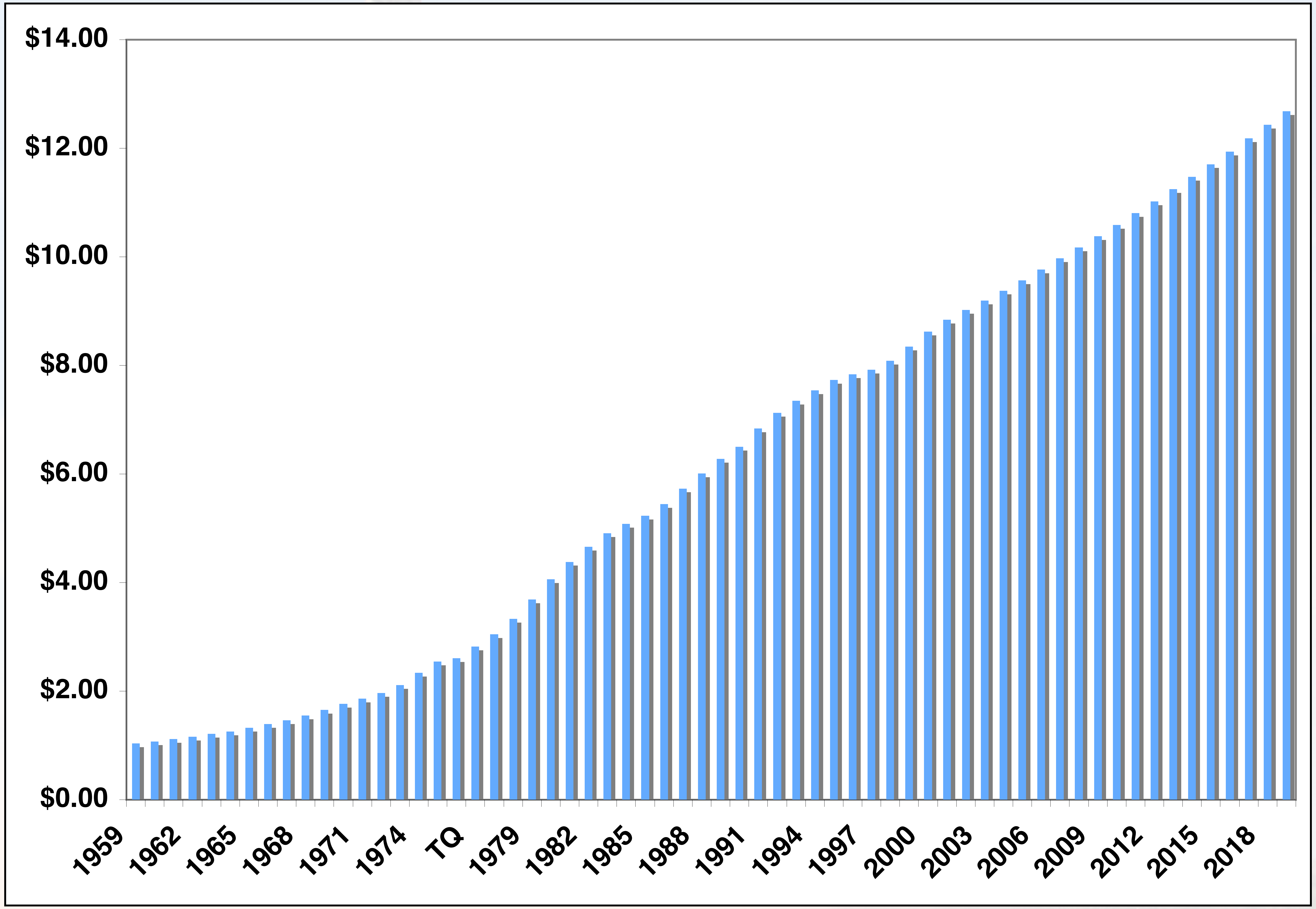
# Inflation

- 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 | 0.865 | 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 | 0.715 | 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 | 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 | $M2023 |
|---:|---:|---:|
| 1964 | 763.4 | 9239 |
| 1965 | 964.9 | 11,296 |
| 1966 | 1177.3 | 13,007 |
| 1967 | 1135.6 | 11,961 |
| 1968 | 998.9 | 9985 |
| 1969 | 534.5 | 5051 |
| 1970 | 484.4 | 4284 |
| 1971 | 189.1 | 1574 |
| 1972 | 142.5 | 1122 |
| 1973 | 26.3 | 195.9 |
| Totals ($M) | 6417 | 67,716 |

# 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

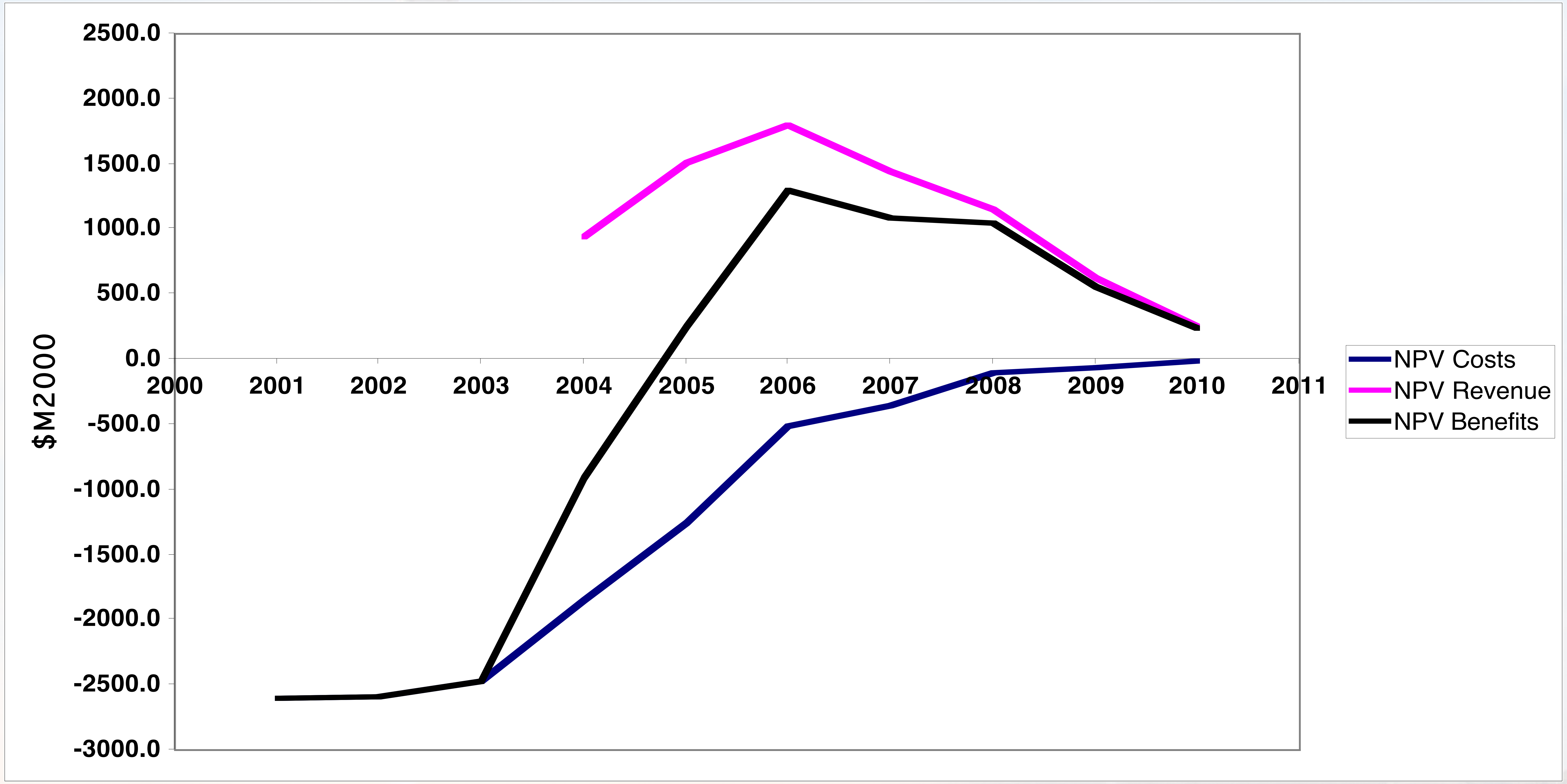
# Effect of Moving Revenue Forward

| | | | | 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

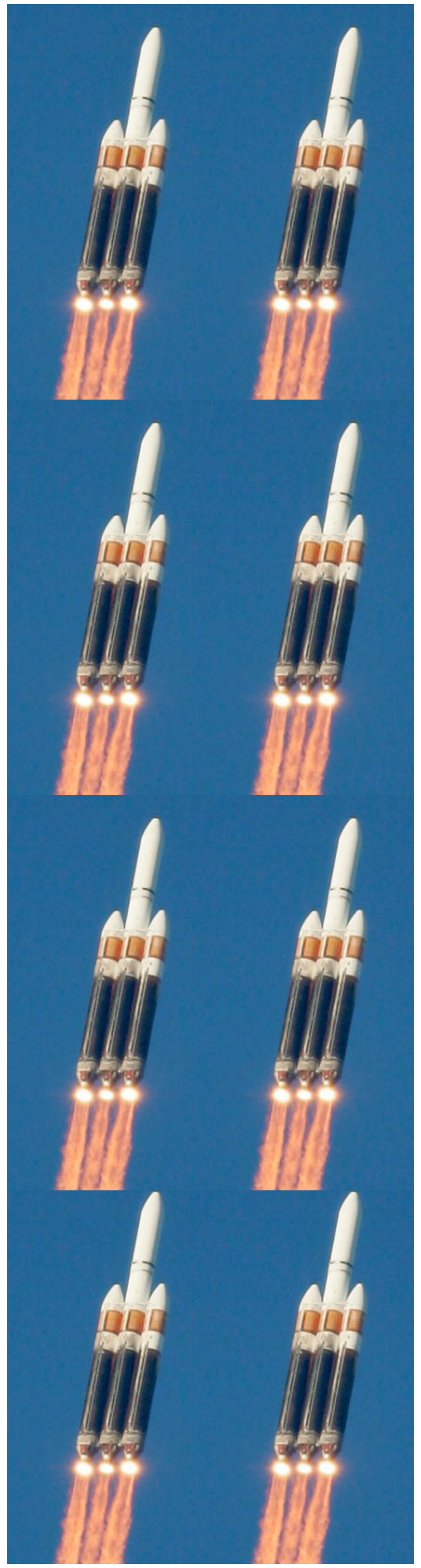
- Investors generally require specific minimum values of IRR
- Have to increase revenue stream to achieve IRR
- Saturn V launch case:
  - 10% IRR $11,480/lb
  - 25% IRR $17,580/lb
  - 50% IRR $32,700/lb
- Venture capitalists general look for 70-100% IRR with 18-month payback

# 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 |

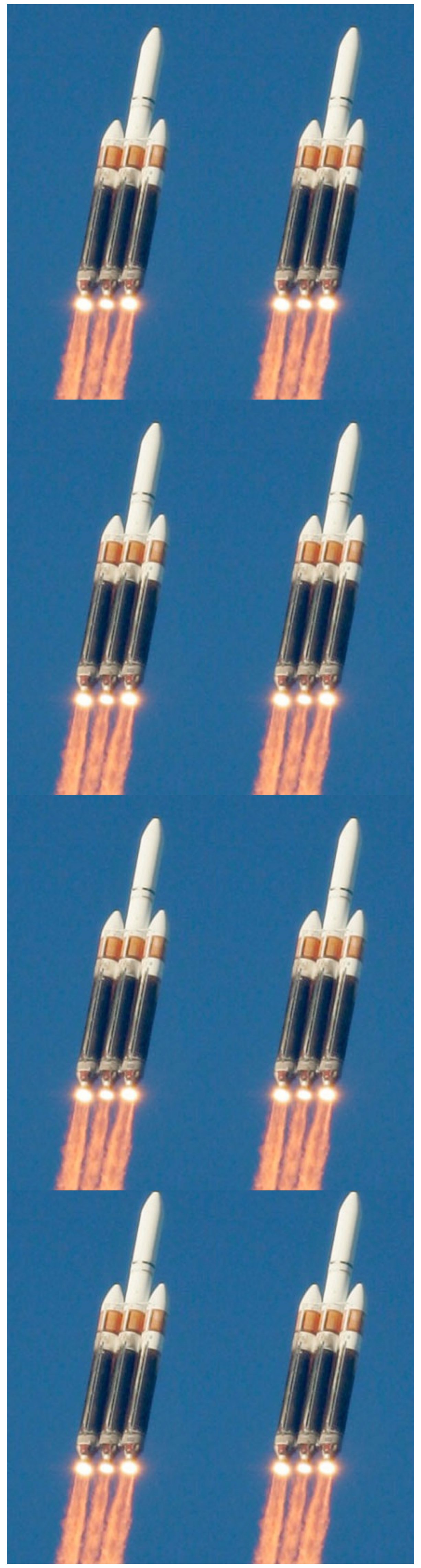
# Head-to-Head Launch Comparison



| | | |
|---|---|---|
| 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 |

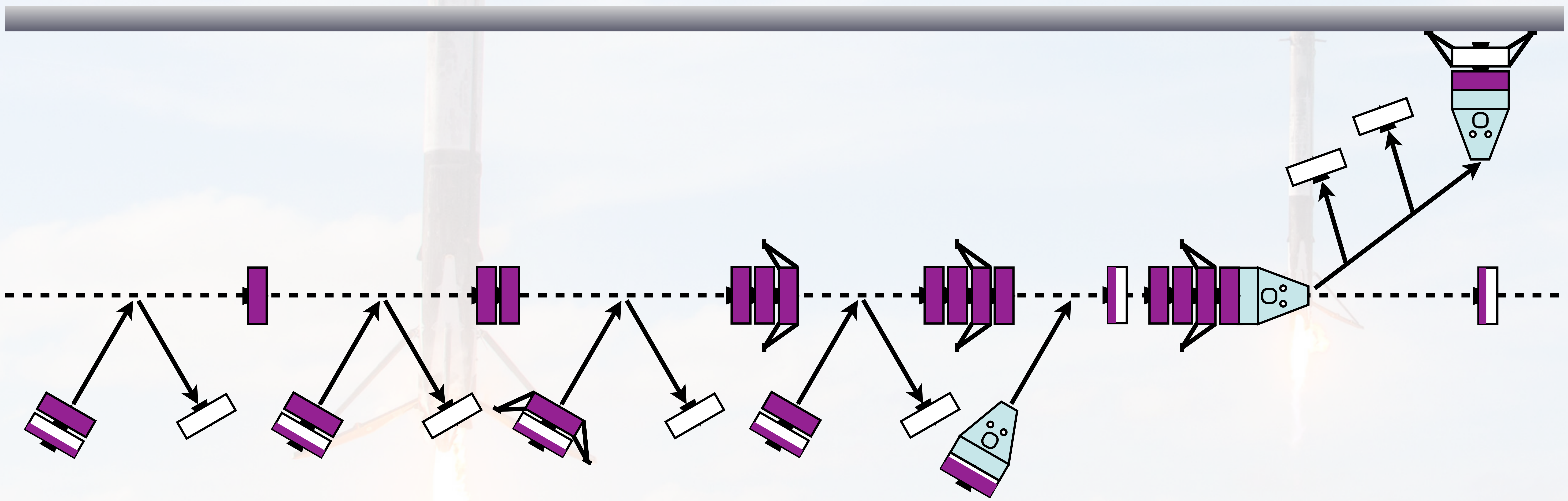
Low-Cost Return to the Moon

# 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 |

# Minimum Cost Lunar Architecture



# Vehicle Inert Masses

| Component | Direct Flight | Lunar Orbit Rend. |
|---|---|---|
| Boost Module | 2300 | 2300 |
| Descent Stage | 3450 | 3450 |
| Ascent Stage | 2159 | 1738 |
| Lunar Crew Mod | | 3849 |
| Mini-Boost Mod | | 1419 |
| TEI Stage | | 233 |
| Earth Return Mod | 3579 | 6000 |

*All masses in kg*

# Vehicle Nonrecurring Costs

| Component | Direct Flight | Lunar Orbit Rend. |
|---|---|---|
| Boost Module[1] | 611 | 611 |
| Descent Stage[1] | 765 | 765 |
| Ascent Stage[1] | 591 | 524 |
| Lunar Crew Mod[2] | | 2058 |
| Mini-Boost Mod[1] | | 469 |
| TEI Stage[1] | | 173 |
| Earth Return Mod[2] | 1977 | 2627 |
| *Totals* | *3944* | *7227* |

[1]Costed as LV stage

[2]Costed as manned S/C

All costs in $M2008

# Vehicle 1st Unit Production Costs

| Component | Direct Flight | Lunar Orbit Rend. |
|---|---|---|
| Boost Module[1] | 32.5 | 32.5 |
| Descent Stage[1] | 42.5 | 42.5 |
| Ascent Stage[1] | 31.2 | 27 |
| Lunar Crew Mod[2] | | 153.5 |
| Mini-Boost Mod[1] | | 23.6 |
| TEI Stage[1] | | 7.1 |
| Earth Return Mod[2] | 146.3 | 205.9 |
| *Totals* | *252.5* | *492.1* |

[1]Costed as LV stage

[2]Costed as manned S/C

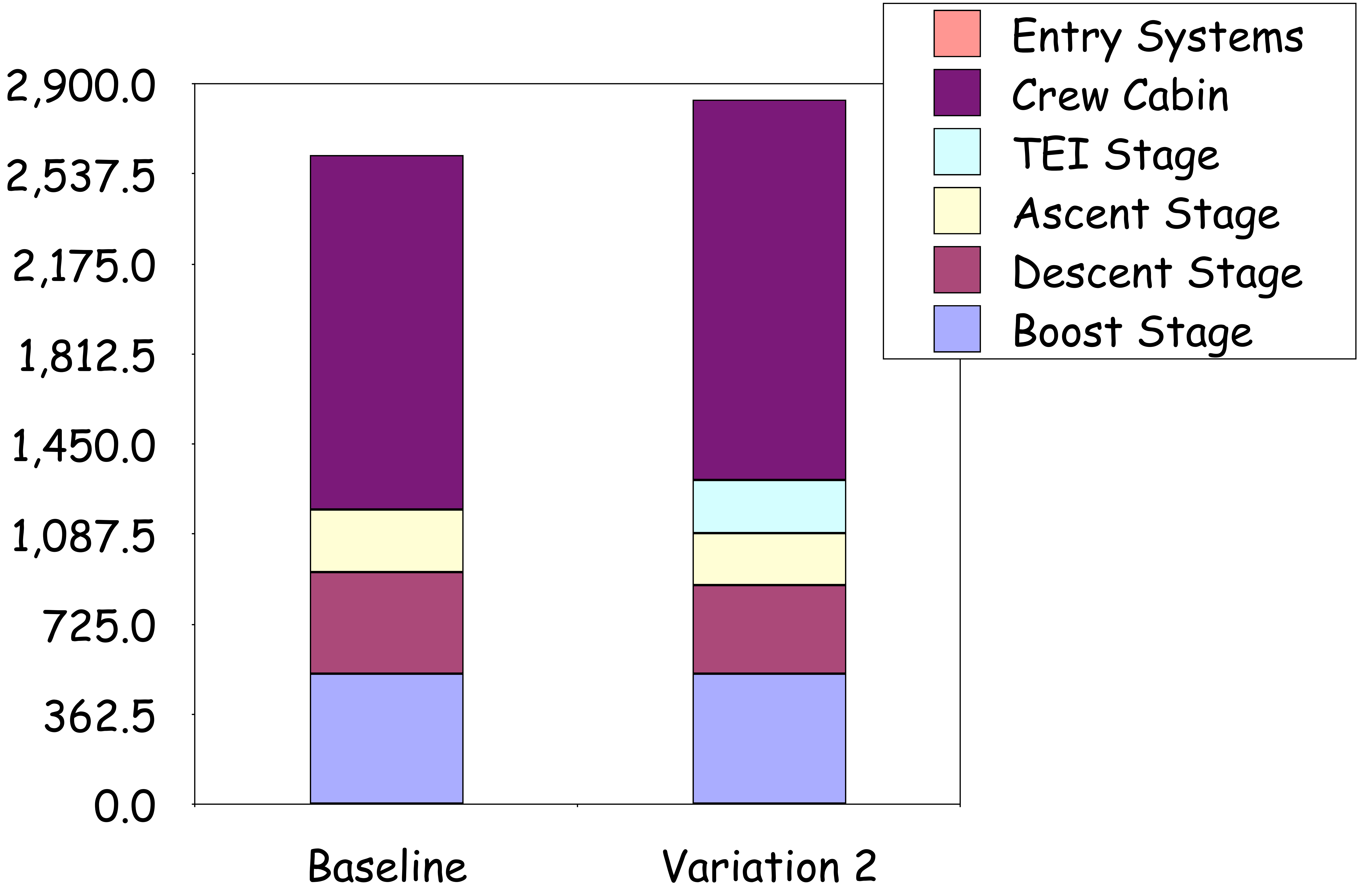
All costs in $M2005

# Nonrecurring Costs

| | Baseline | LLO Case |
|---|---|---|
| Boost Stage | 503.2 | 503.2 |
| Descent Stage | 549.6 | 526.0 |
| Ascent Stage | 332.7 | 317.0 |
| TEI Stage | | 244.2 |
| Crew Cabin | 1537 | 1756 |
| Entry Systems | | |
| Totals | 2923 | 3347 |

All costs in $M

# Nonrecurring Cost Comparison

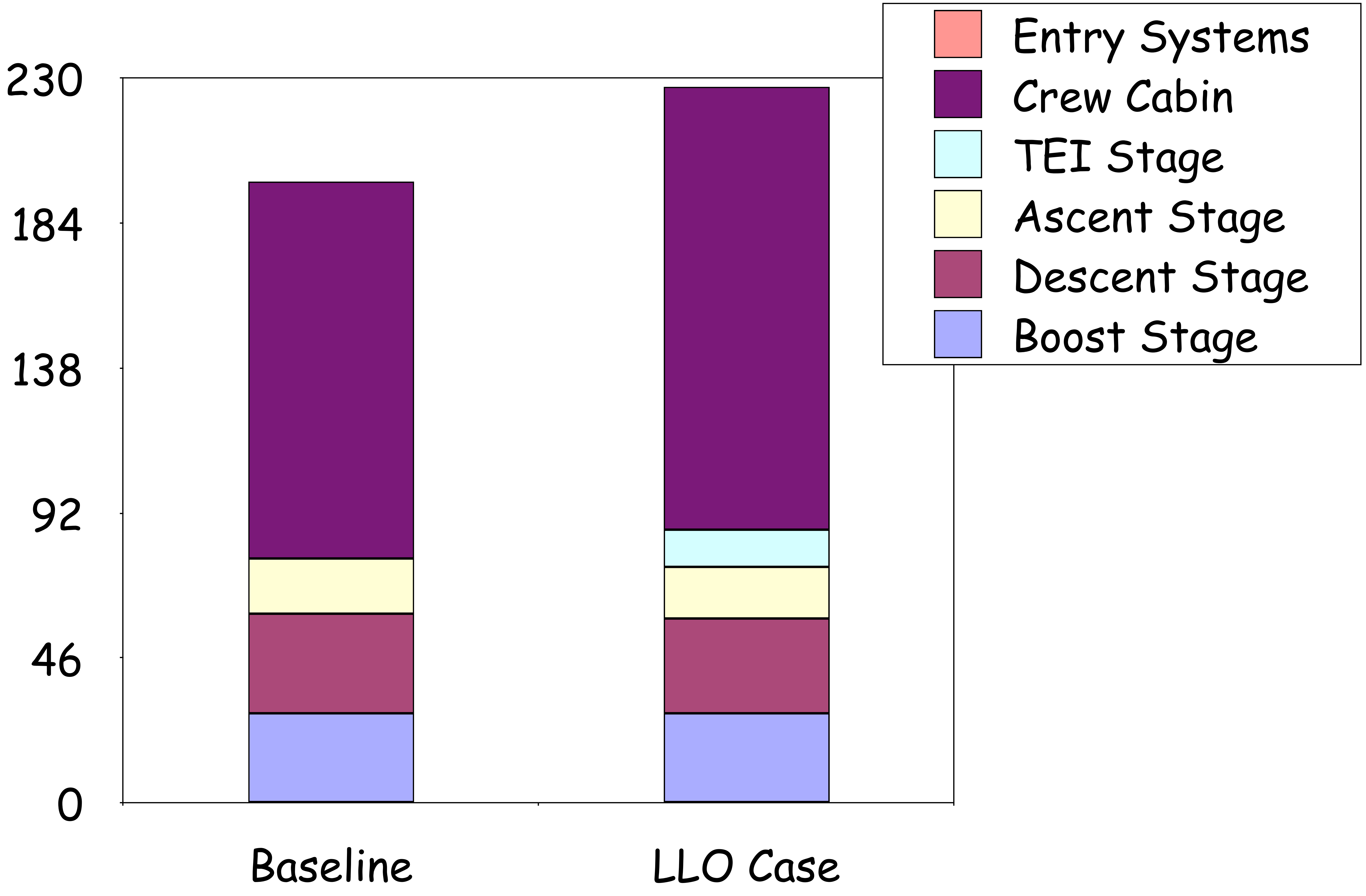


# First Unit Production Costs

| | Baseline | LLO Case |
|---|---|---|
| Shuttle Launch | 300 | 300 |
| Delta IVH | 150 | 150 |
| Boost Stage | 28.5 | 28.5 |
| Descent Stage | 31.6 | 30.0 |
| Ascent Stage | 17.3 | 16.3 |
| TEI Stage | | 11.9 |
| Crew Cabin | 119.6 | 140.4 |
| Totals | 647 | 677 |

All costs in $M

# First Unit Cost Comparison



# UMd EI Mission Models

- Single Mission Model
  - One all-up lunar flight
  - Single crew cabin, ascent/descent stages
  - Three boost stages, four launch vehicles
- Apollo Comparison Model
  - One orbital test flight (crew module, ascent/ descent stages)
  - One high orbital mission (above + one boost stage)
  - One lunar orbital rehearsal mission
  - Seven lunar landing missions

# Single Mission Model Cost Summary



## Baseline Case

| | Number | Nonrecurring Cost ($M) | First Unit Cost ($M) | Recurring Cost ($M) | Totals |
|---|---|---|---|---|---|
| Shuttle Launch | 1 | | 300 | 300 | 300 |
| Delta IVH | 4 | | 150 | 600 | 600 |
| Boost Stages | 4 | 503.2 | 28.45 | 71.26 | 574.5 |
| Descent Stage | 1 | 549.6 | 31.64 | 31.64 | 581.2 |
| Ascent Stage | 1 | 332.7 | 17.29 | 17.29 | 350 |
| TEI Stage | 1 | 0.0 | 0.00 | 0.00 | 0 |
| Crew Cabin | 1 | 1537 | 120 | 120 | 1657 |
| Totals | | 2923 | 647 | 1140 | 4062 |

# Production for Apollo Case

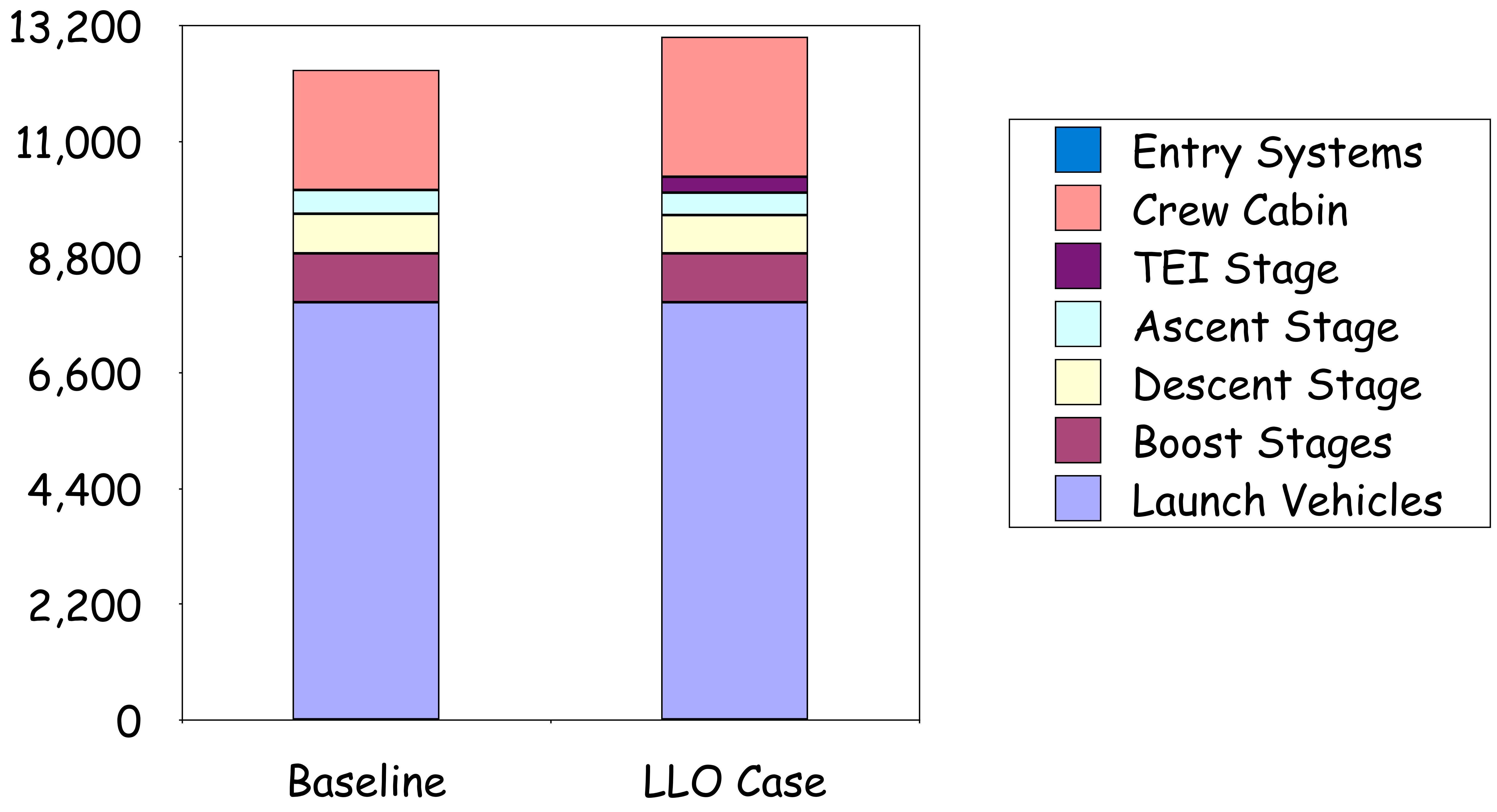
| | Earth Orbit | High Orbit | Lunar Orbit | Lunar Landing | Totals |
|---|---|---|---|---|---|
| Shuttle Launch | 1 | 1 | 1 | 7 | 10 |
| Delta IVH | 0 | 1 | 4 | 28 | 33 |
| Boost Stages | 0 | 1 | 4 | 28 | 33 |
| Descent Stage | 1 | 1 | 1 | 7 | 10 |
| Ascent Stage | 1 | 1 | 1 | 7 | 10 |
| TEI Stage | 1 | 1 | 1 | 7 | 10 |
| Crew Cabin | 1 | 1 | 1 | 7 | 10 |

# Apollo Mission Model Cost Summary

## Baseline Case

| | Number | Nonrecurring Cost ($M) | First Unit Cost ($M) | Recurring Cost ($M) | Totals |
|---|---|---|---|---|---|
| Shuttle Launch | 10 | | 300 | 3000 | 3000 |
| Delta IVH | 33 | | 150 | 4950 | 4950 |
| Boost Stages | 33 | 503.2 | 28.45 | 428.8 | 932 |
| Descent Stage | 10 | 549.6 | 31.64 | 200.3 | 750 |
| Ascent Stage | 10 | 332.7 | 17.29 | 109.5 | 442 |
| TEI Stage | 0 | 0.0 | 0.00 | 0.0 | 0 |
| Crew Cabin | 10 | 1537 | 119.6 | 757.4 | 2295 |
| Totals | | 2923 | 647 | 9446 | 12369 |

# Apollo Model Cost Comparisons



# 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

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

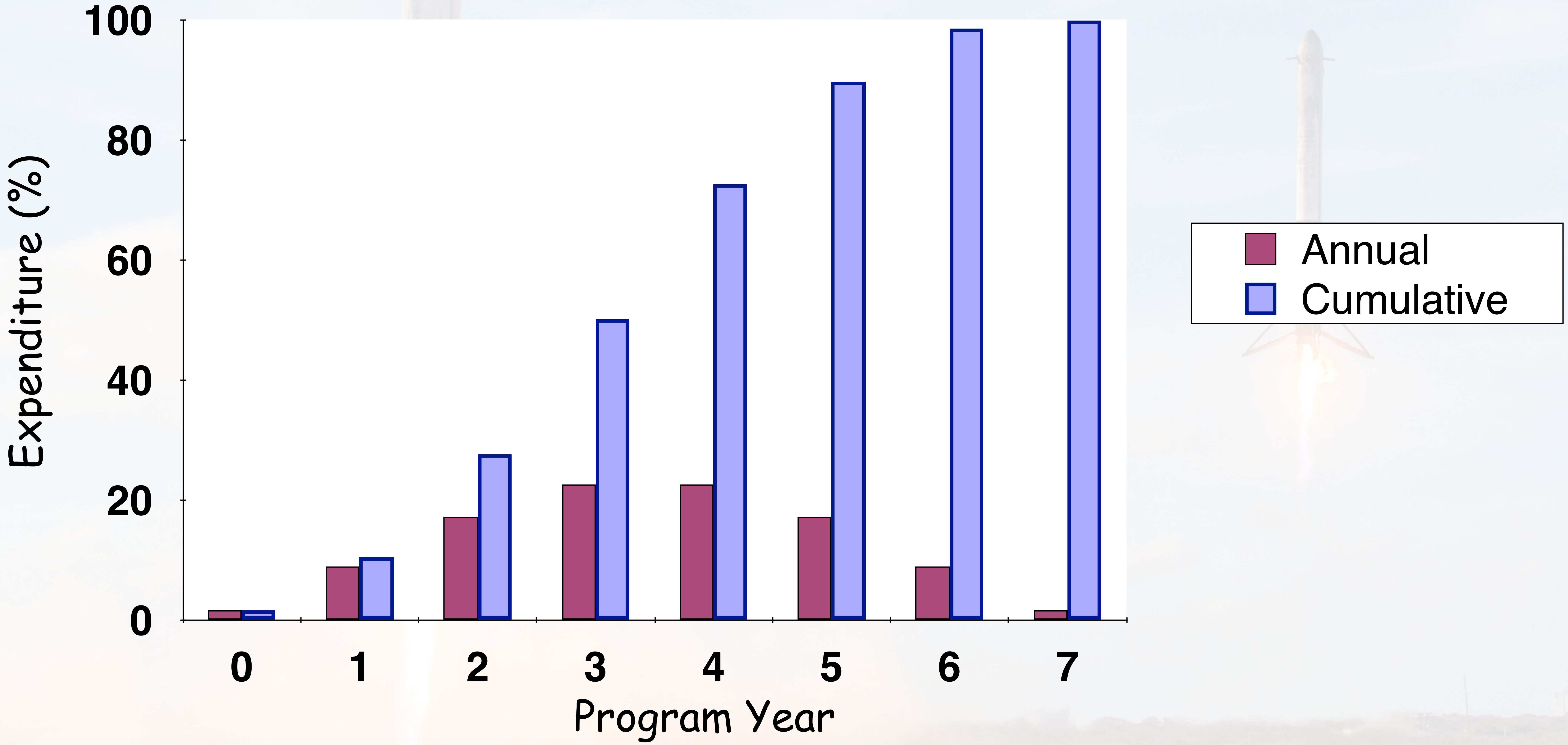
where

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

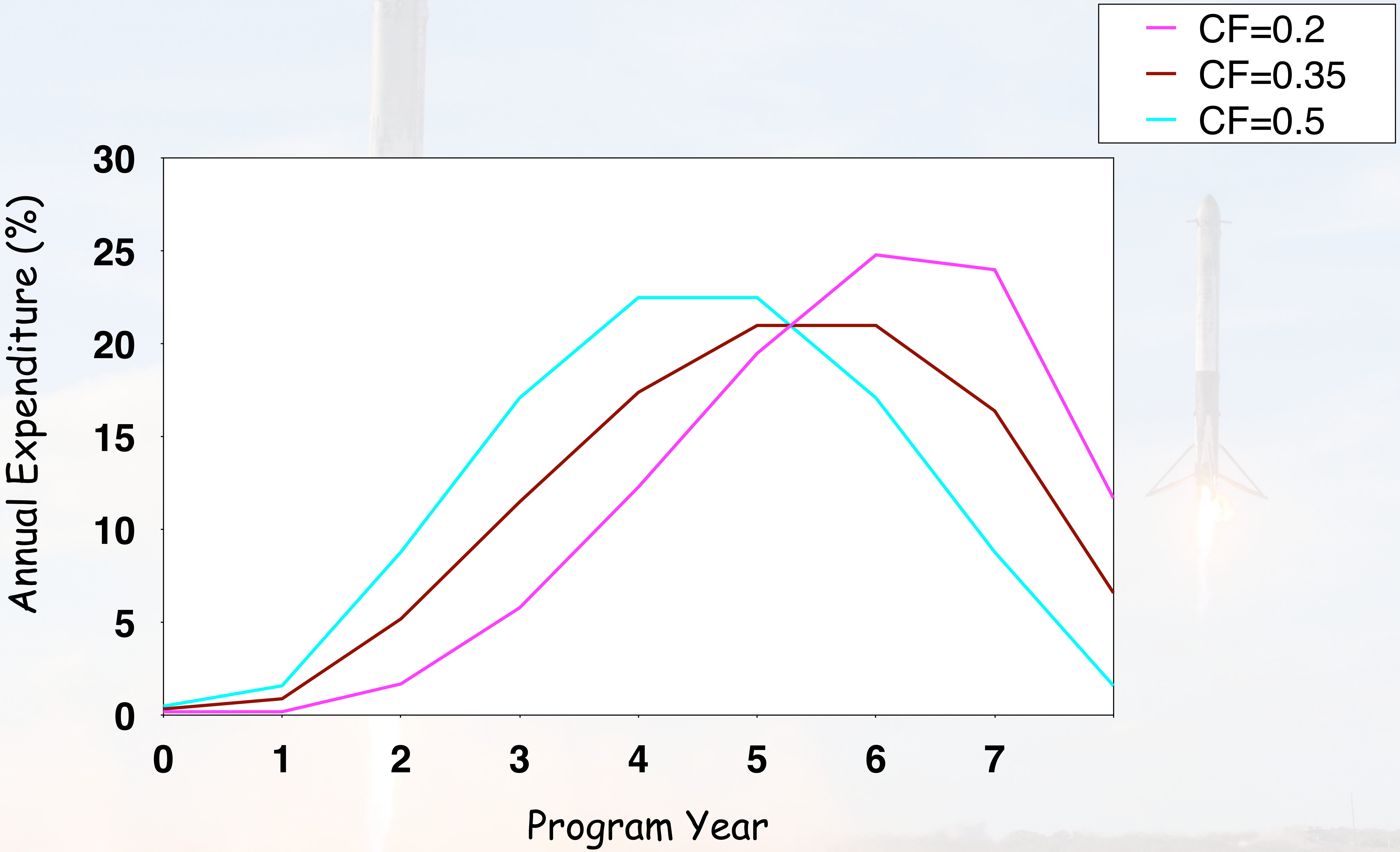
$$c_f < 0.5 : A = \frac{(1-P)(c_f - 0.1875)}{0.625}; B = P\frac{c_f - 0.1875}{0.3125}$$

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

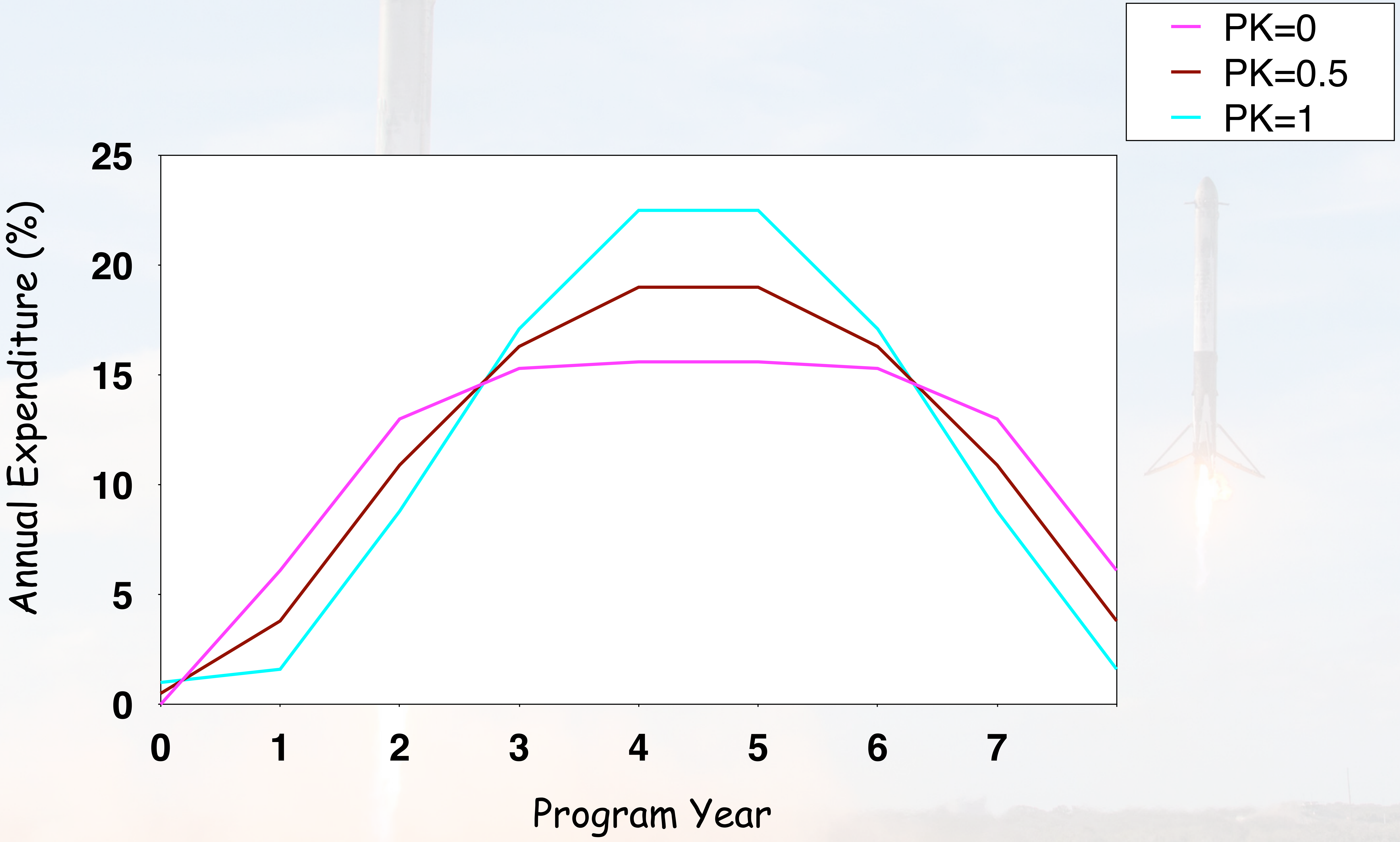
# Sample of Beta Function



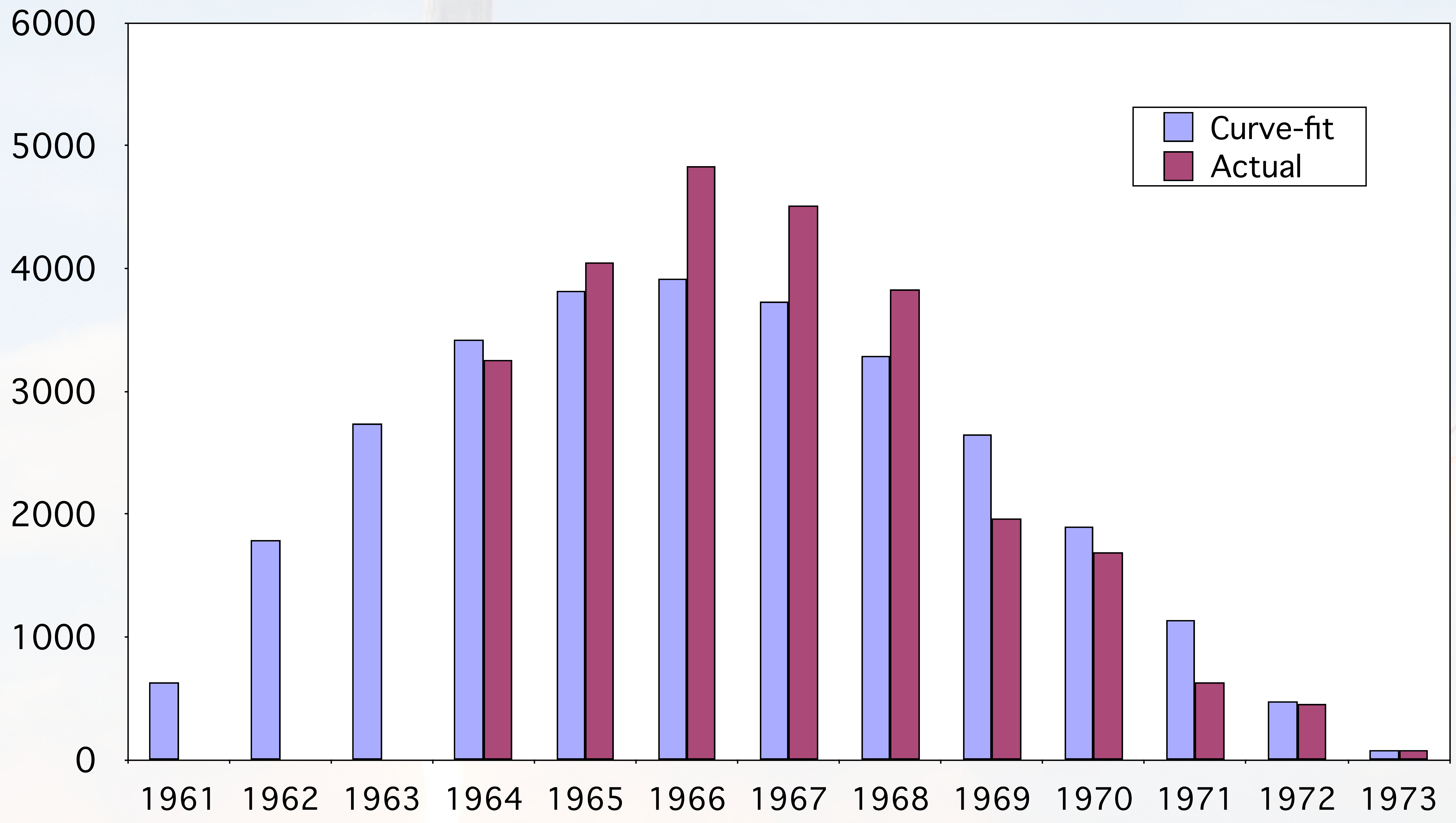
# Cost Fraction in Beta Function



# 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://cost.jsc.nasa.gov/index.htm
- Vehicle-Level Costing Models
  http://cost.jsc.nasa.gov/SVLCM.html
- Inflation Adjustment
  http://cost.jsc.nasa.gov/inflate.html
- Learning Curves
  http://cost.jsc.nasa.gov/learn.html