Vehicle Reusability

- The concept
- The promise
- The price
- When does it make sense?

Sir Arthur C. Clarke:

"We're moving from the 'beer can' philosophy of space travel towards the 'beer keg' approach."

- Discussion about recent Congressional approval of the Space Shuttle program (1972)

Wernher von Braun:

"The Apollo program is like building the Queen Elizabeth II ocean liner, sending three passengers on a trip from New York to London and back, and then sinking it."

“Common-Sense” Rationale:

- Launch vehicles are really, really expensive.
- If we could use them more than once, we could reduce the costs for each payload.
- Airplanes represent an “existence proof” that reusability provides lower costs
- If the costs become low enough, we can make space transportation a commercial endeavor like air transportation.

Airline Economics (from first lecture)

- Average economy ticket NY-Sydney round-round-trip (Travelocity 1/28/04) ~$1300
- Average passenger (+ luggage) ~100 kg
- Two round trips (same energy as getting to low Earth orbit = $26/kg
  - Factor of 60x electrical energy costs
  - Factor of 250x less than current launch costs
- So all we have to do is fly the launch vehicle 250 times and we're there?

Expendable --> Reusable?

What are the additional capabilities required to make a vehicle reusable?

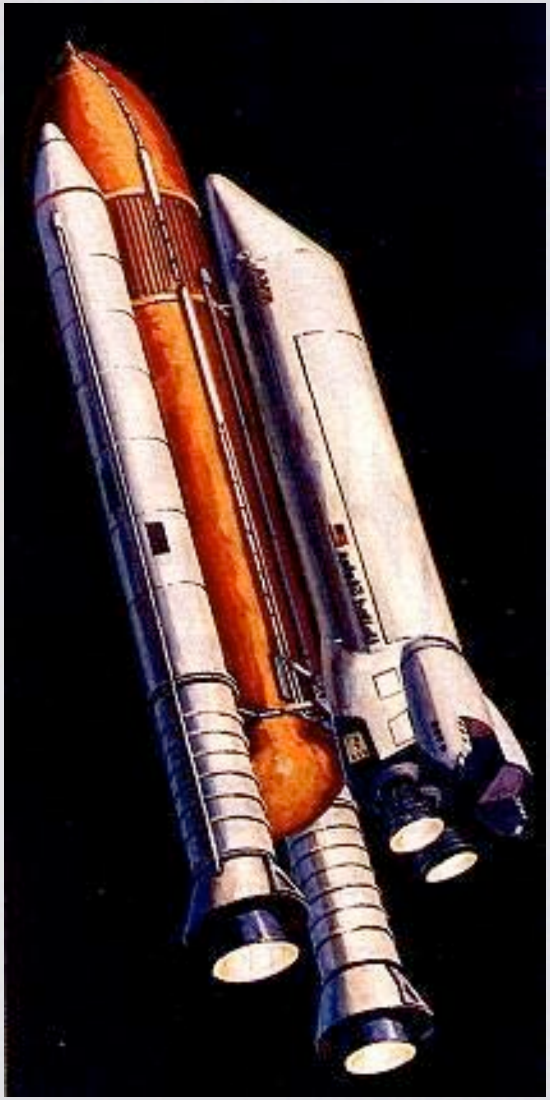
- Atmospheric entry and descent
  - Additional mass
- Targeting to desired landing point
  - Additional complexity
- Terminal deceleration and landing
  - Additional mass
- Robustness and Maintainability
  - Additional mass and complexity

Impact of Reusability

- ELV upper stage generally lighter than payload
  - Delta IV Heavy stage 2 inert mass 3490 kg
  - Delta IV Heavy payload mass 25,800 kg
- RLV upper stage generally much heavier than payload
  - Shuttle orbiter mass 99,300 kg
  - External tank mass 29,900 kg
  - Shuttle payload 24,400 kg

Side Issue - Heavy Lift to Orbit?

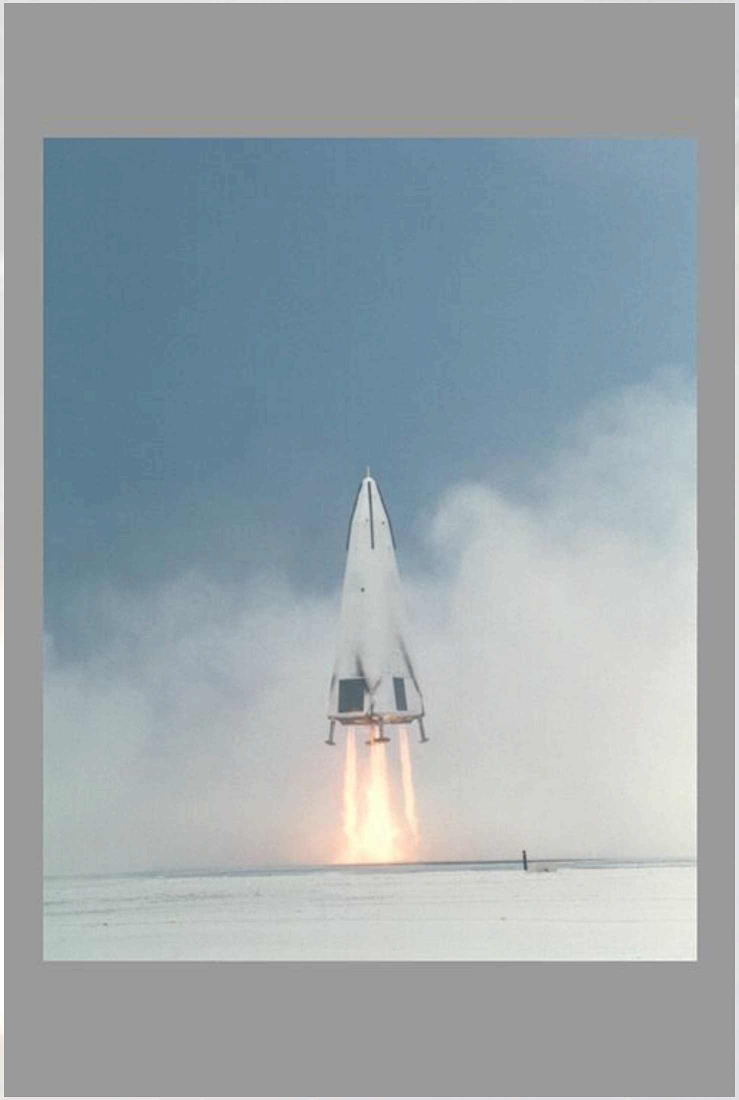
- Total Saturn V mass delivered to LEO = 131,300 kg (118,000 kg payload)
- Total Shuttle mass delivered to LEO = 153,600 kg (24,400 kg payload)
- Genesis of "Shuttle -C(argo)" concepts to eliminate orbiter in favor of payload

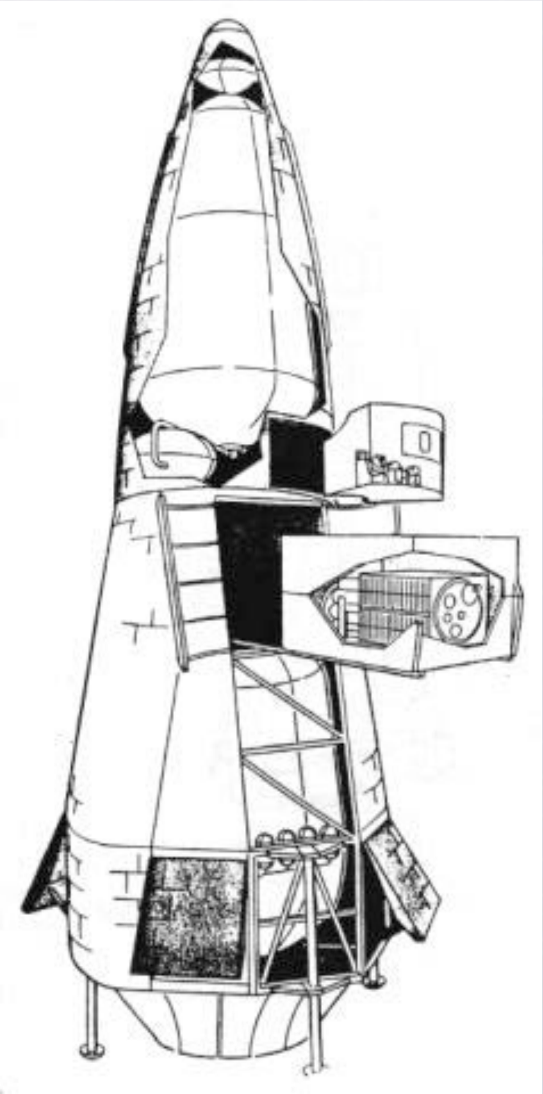


Performance Issues of RLVs

- Large ratios of orbited inert mass/payload mass degrades mission performance
- Atlas V payload capabilities
  - 27,550 lbs to 28° LEO
  - 23,700 lbs to polar orbit
- Shuttle payload capabilities
  - 53,800 lbs to 28° LEO
  - 19,000 lbs to polar (would have required augmentation)

Ballistic Vehicle (DC-X)





SSTO - Lifting Body (VTOHL)

SSTO - Winged (VTOHL)

Airbreathing SSTO

Airbreathing First Stage (HTOHL)

Flyback Booster and Winged Upper Stage

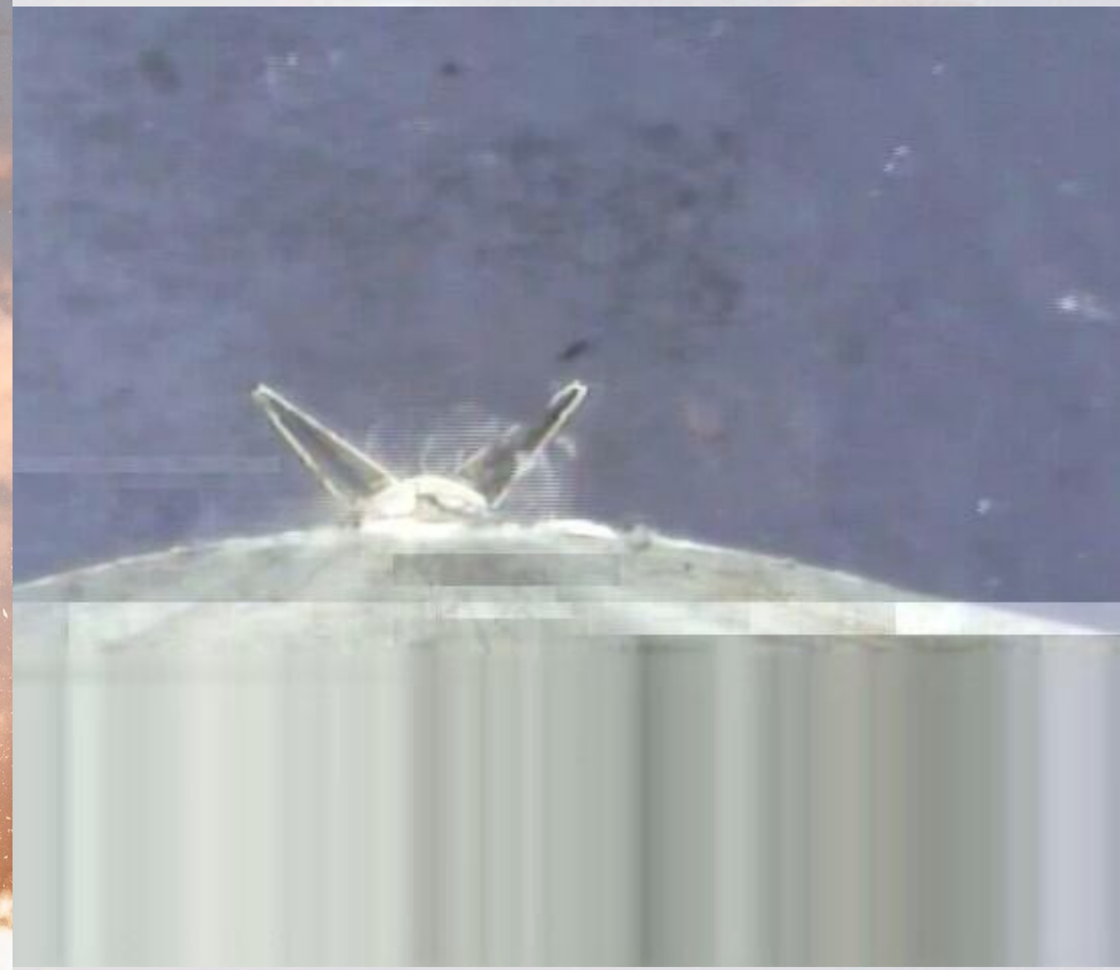
Flyback Booster and Winged Upper Stage

Flyback Booster and Winged Upper Stage

Air Launch and Winged Upper Stage

Air Launched and Winged Upper Stage

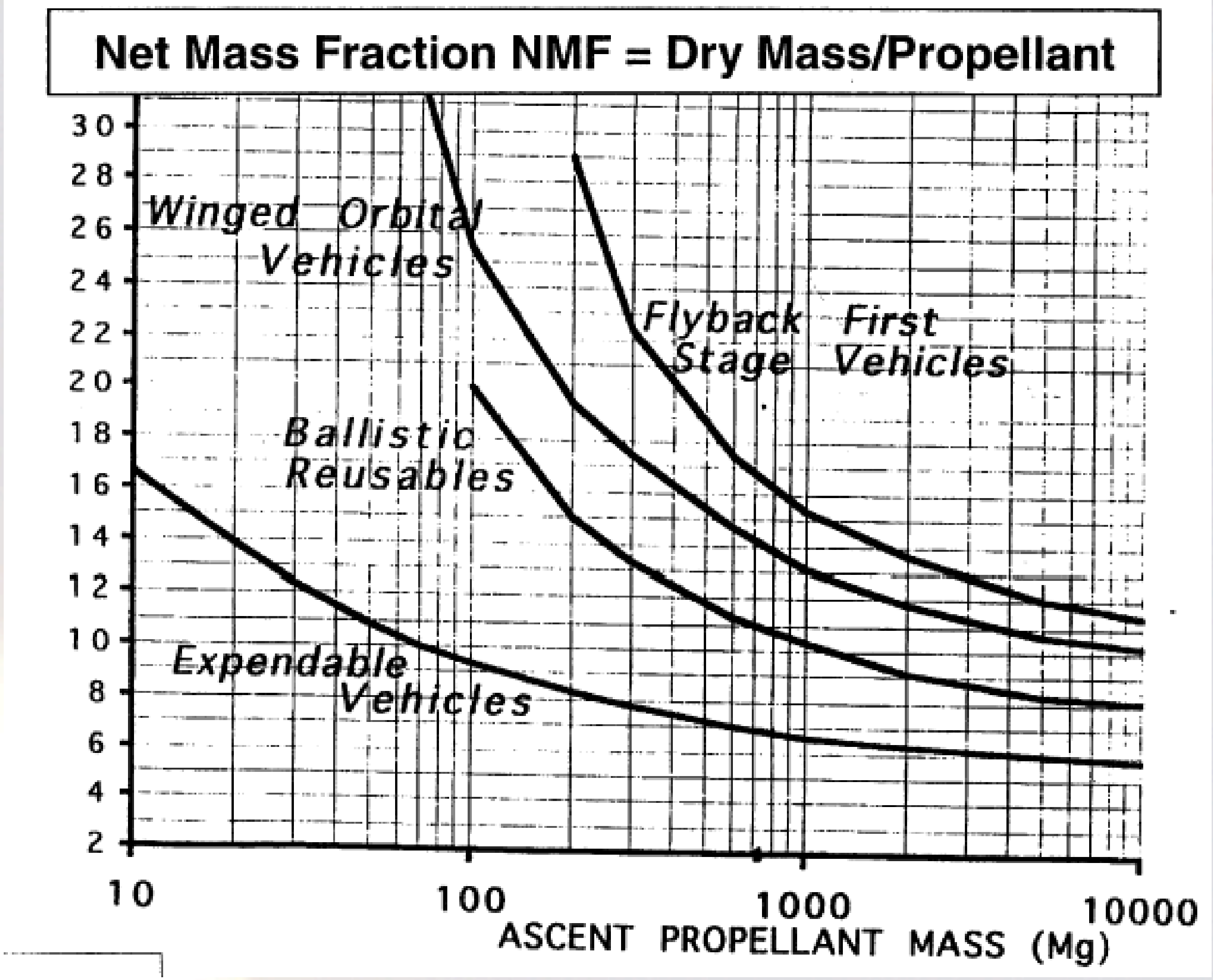
Falcon 9 CRS-3 Launch 4/14/14



Falcon 9 Reusability

- Current Falcon 9 price ~$80M
- Elon Musk:
  - "70% of cost is in first stage" (~$56M)
  - "Reuse saves 70% of first stage costs" (~$17M cost)
- F9 cost with "used" first stage ~$41M
- Elon again: "That doesn't mean tear the stage down between missions like shuttle." = return, refuel, refly
- Presupposes aircraft-like servicing

Mass Effects of Reusability



from Dietrich Koelle, Handbook of Cost Engineering (TRANSCOST v.7)

Orbital Entry (the Cliff's Notes version)

- Mass of thermal protection system ~ 20% of mass of vehicle protected
- Add ~300 m/sec (minimum) for maneuvering and deorbit
- Additional per-flight operating costs for maintaining orbital maneuvering system, thermal protection system

Landing Taxonomy

- Vertical landing
  - Rockets
  - Rotors
  - Parachutes
    - Land
    - Water
- Horizontal landing
  - Wings
  - Lifting body
  - Parafoils

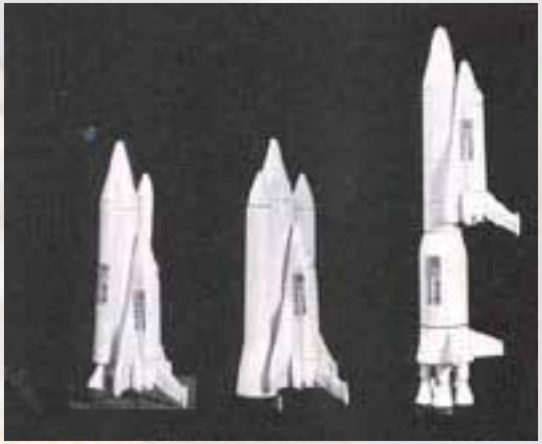
Landing (the Cliff's Notes version)

- Mass of wings ~20% of mass supported
- Mass of parachute/parafoil ~3% of mass supported
- Mass of landing gear ~ 5% of mass of vehicle landed
- Best landing velocity attenuation ~3-4 m/sec vertical impact velocity

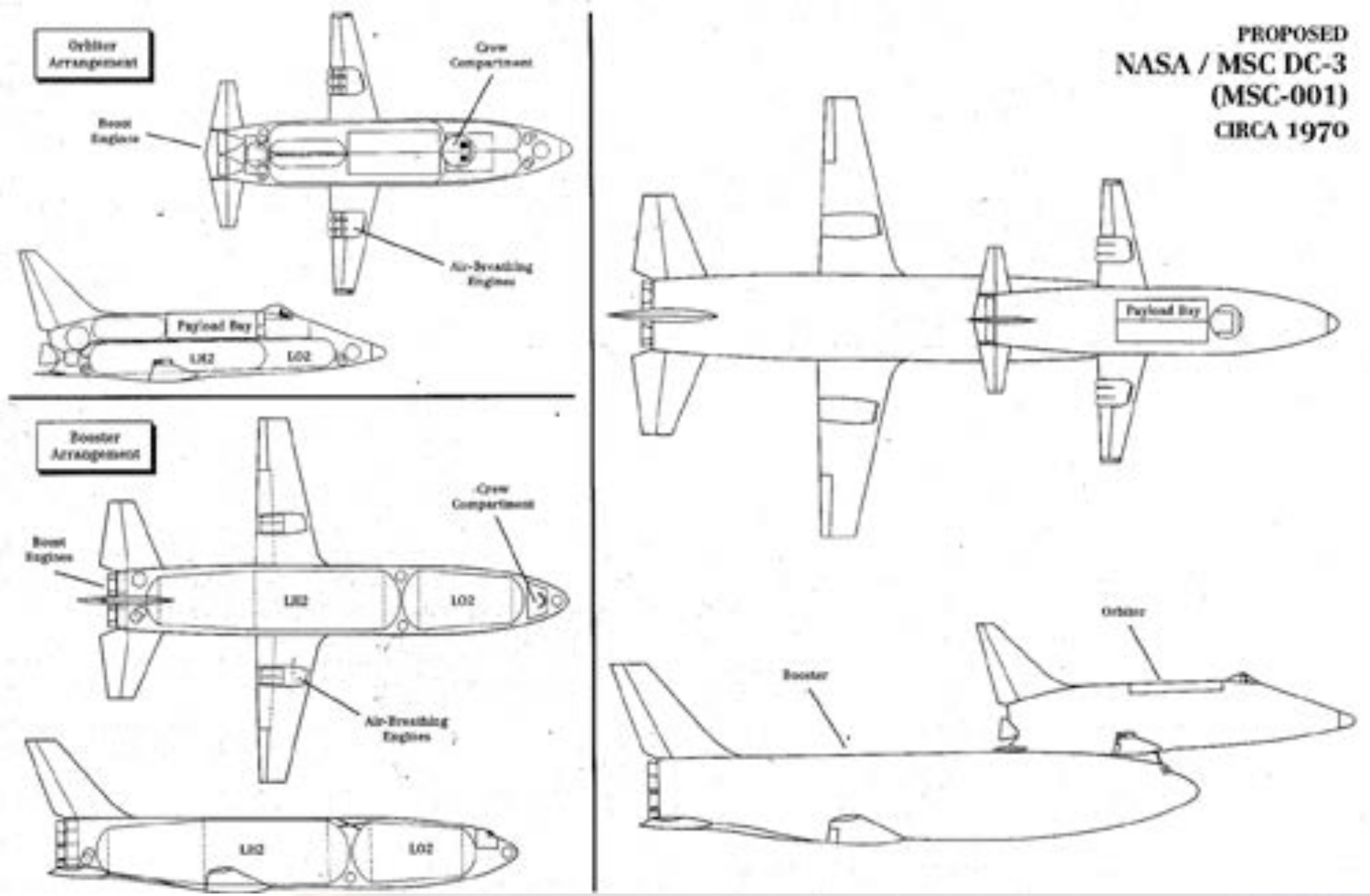
RLV and Cost Savings (Shuttle Version)

- Shuttle was intended to reduce payload costs from ~$5000/lb (Saturn V) to~$500/lb
- Cost savings predicated on high flight rates
  - Shuttle: 10 yr program, 550 flights
  - One flight/week; two-week turnaround between flights of individual orbiter
- Had to cancel all other launch systems (single-fleet approach)

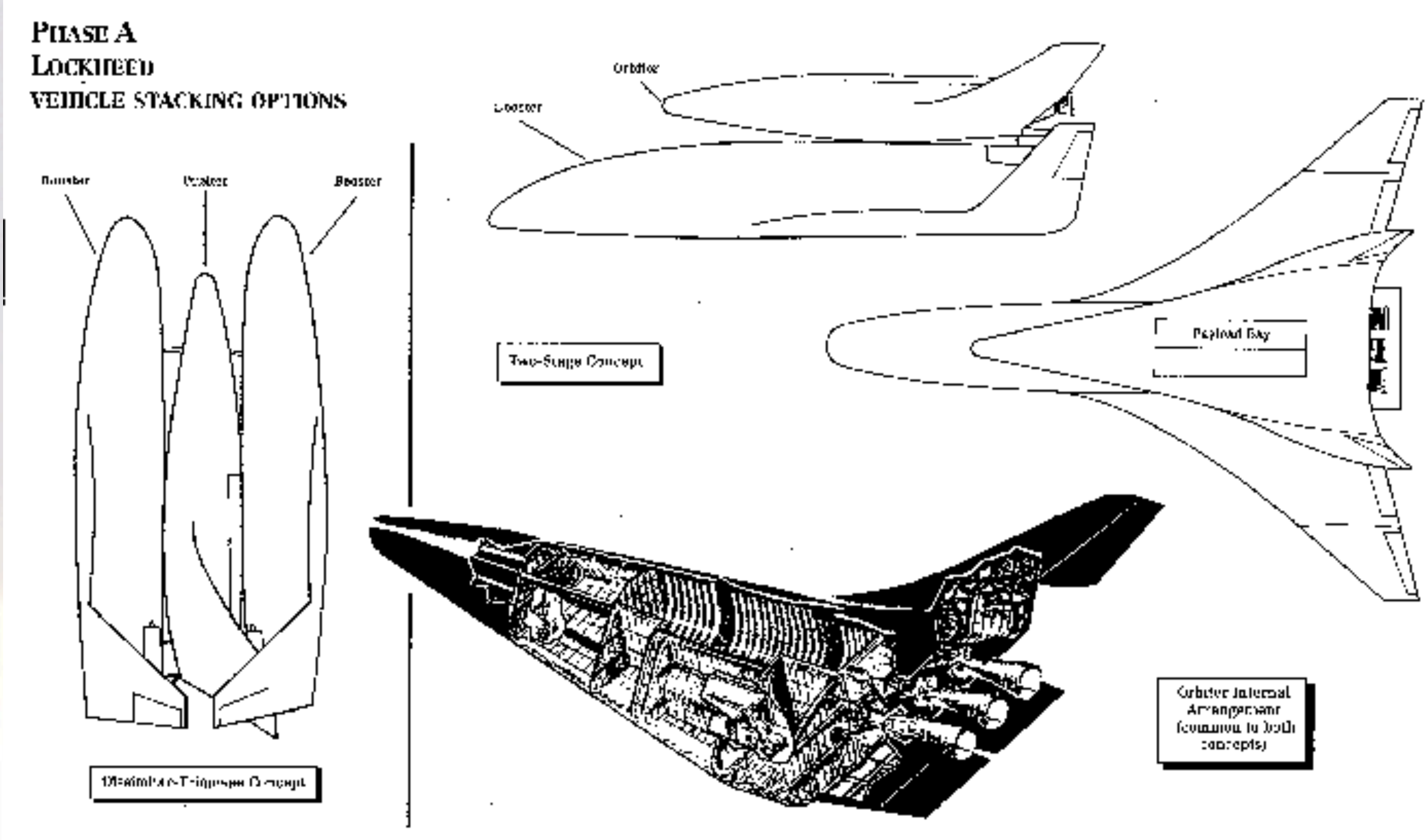
Shuttle Design Concepts



Early Shuttle Design Concept



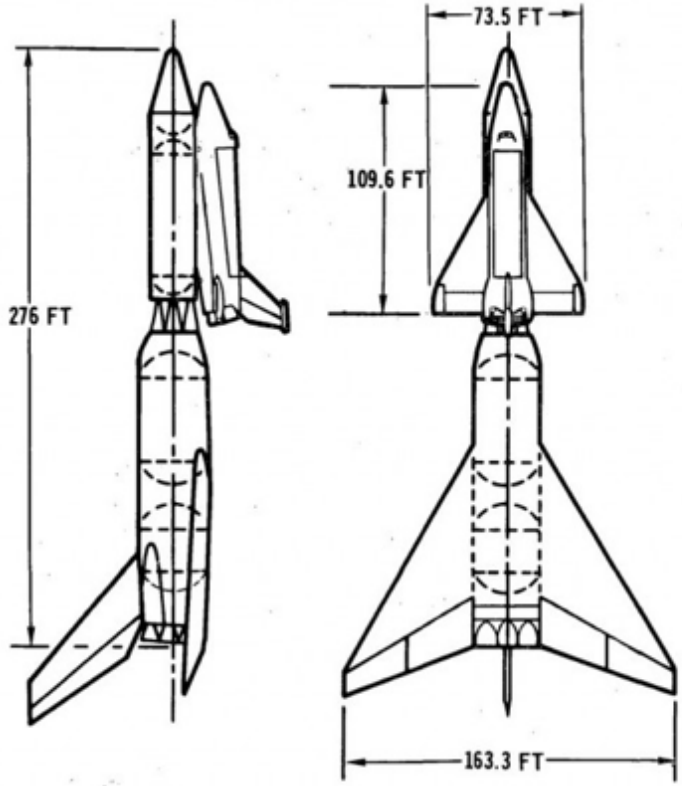
“Triamese”, “Biamese” Shuttle Concepts



Shuttle Concept with Flyback S1C

POGP
96-1071 B

BASELINE
WITH F-1 POWERED BOOSTER



GLOW (M LB)	5.626
STAGING VELOCITY (FPS)	7,000
MAXIMUM DYNAMIC PRESSURE (PSF)	650
DRY WEIGHT	
(BOOSTER/ORBITER – K LB)	628/130
PROPELLANT WEIGHT	
(BOOSTER/ORBITER – K LB)	3,900/704
TANK WEIGHT (K LB)	35.3
MAIN ENGINES	
BOOSTER	5 F–1
ORBITER (MARK II)	4 HiPc
ENGINE THRUST	
BOOSTER (K LB SL)	1,390
ORBITER (K LB VAC)	306
HO TANK	
(LENGTH/DIAMETER – FT)	116/24

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1–27

TRW

Reusable S1C First Stage Concept

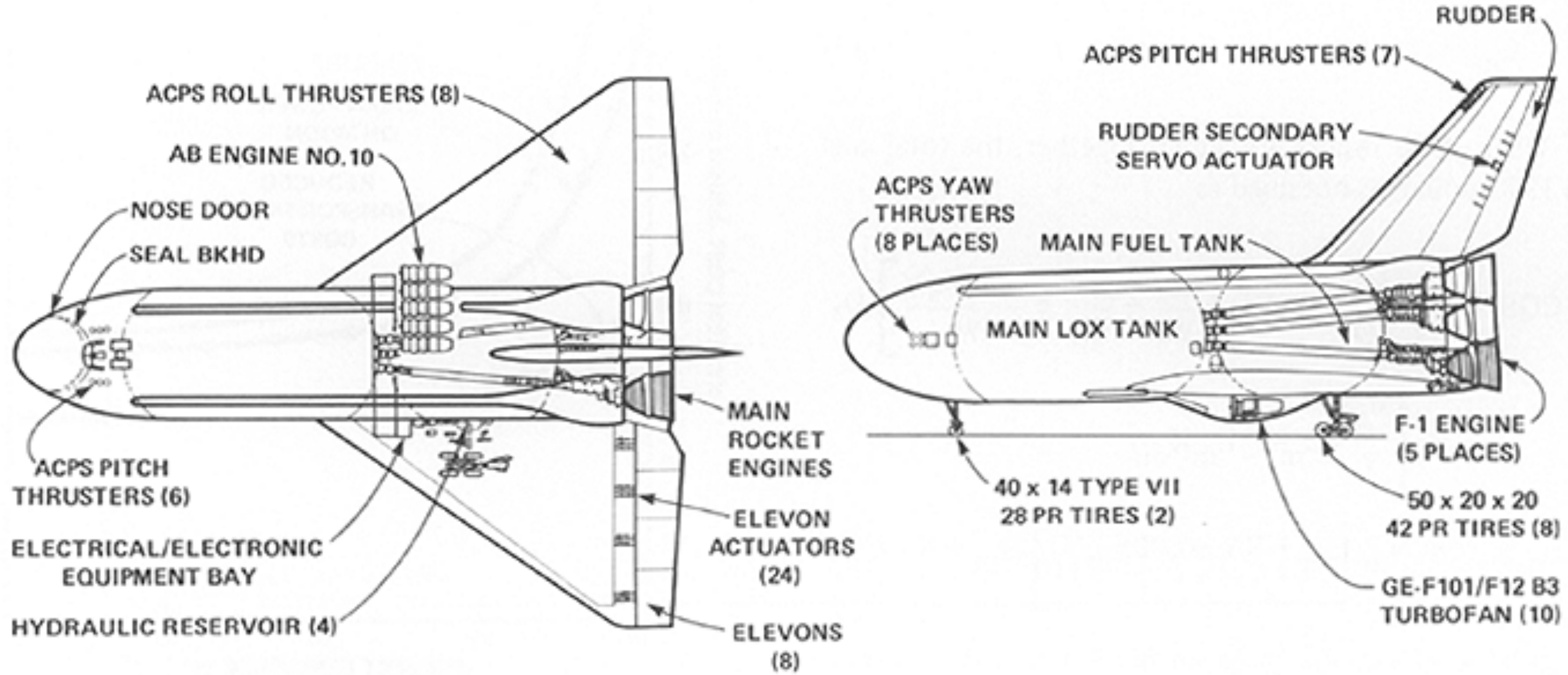
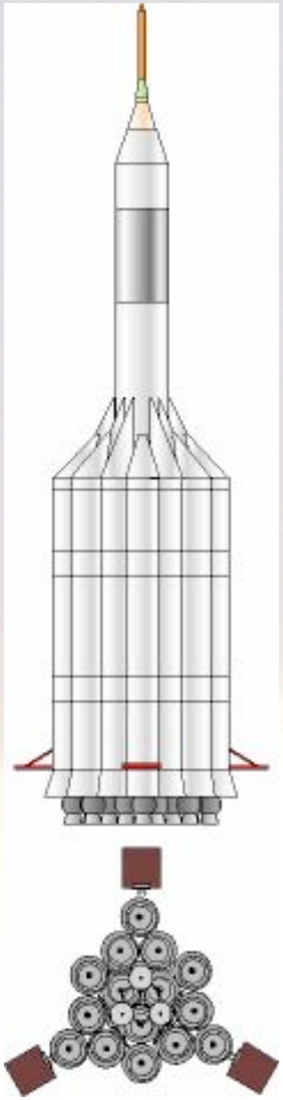


Figure 6-8.– *Flyback F-1 schematic views.*

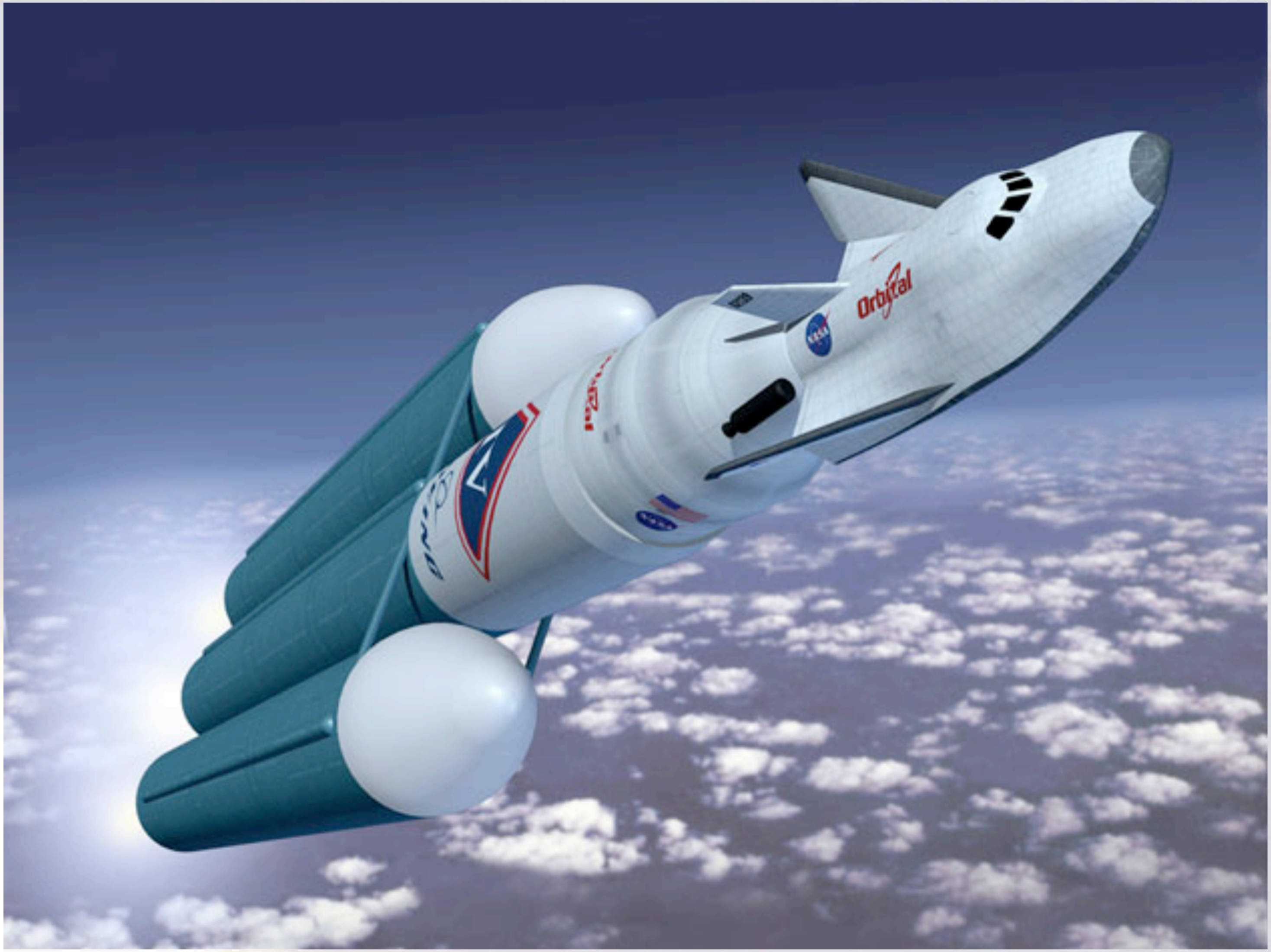
Shuttle Costs Savings: What Went Wrong?

- 160 hr turnaround --> 2000 hr turnaround
- 1% refurbishment --> 10-15% refurbishment
- Not everyone wants to be human-rated
- Why fly humans on missions where you don't need them?
- Why fly reusable stages on missions where nothing comes down?

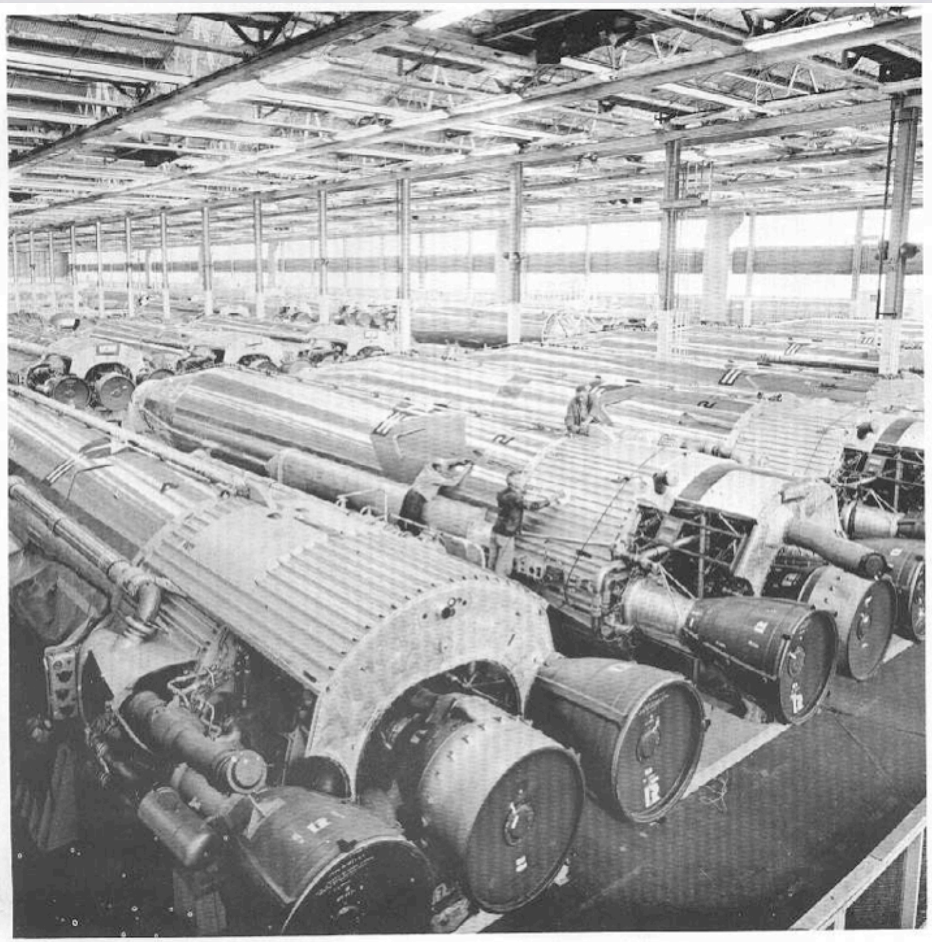
Cost Reduction: Modular Launch Vehicles



Crew Rotation Vehicle on Delta IV Heavy



Cost Reduction: Mass Production



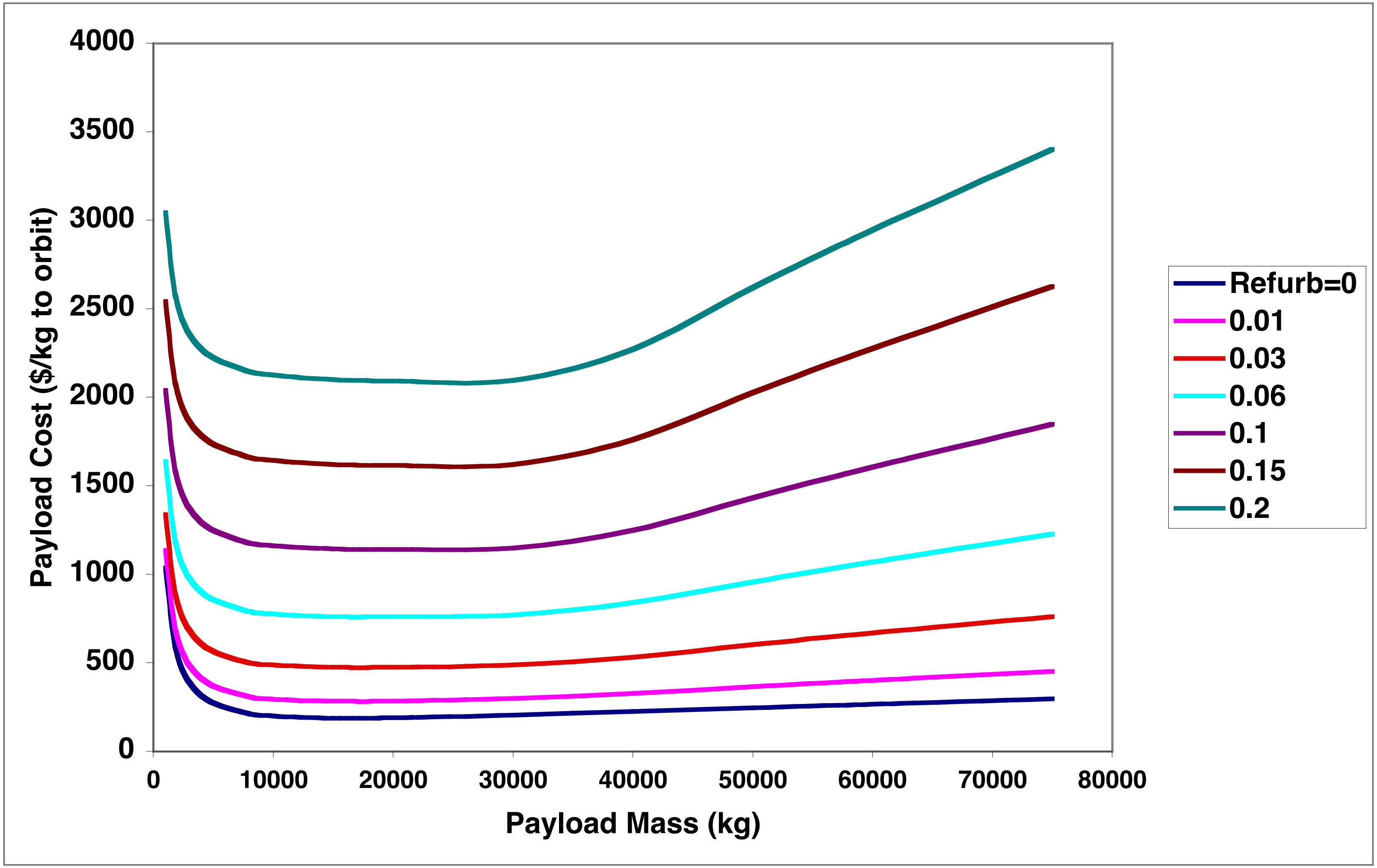
OUT OF RETIREMENT - Atlas ICBMs in storage are slated for refurbishment and launch for ABRES (Advanced Ballistic Re-Entry Systems) and Nike Target program launches for the U.S. Air Force. Twenty-three Atlas series E and F ICBMs will be updated under a contract awarded to the Convair division of General Dynamics by the Air Force Ballistic Systems Division. Fifteen of the twenty-three are shown here in storage at San Diego. The other eight of the twenty-three to be refurbished are in storage at Norton AFB, Calif. and will be taken to the Convair division's Kearny Mesa plant at San Diego for the updating work. The "retired" missiles were produced originally for service in the strategic missile deterrent force at eleven Air Force bases across the nation. (General Dynamics photo)

Why Launch Vehicles are Expensive

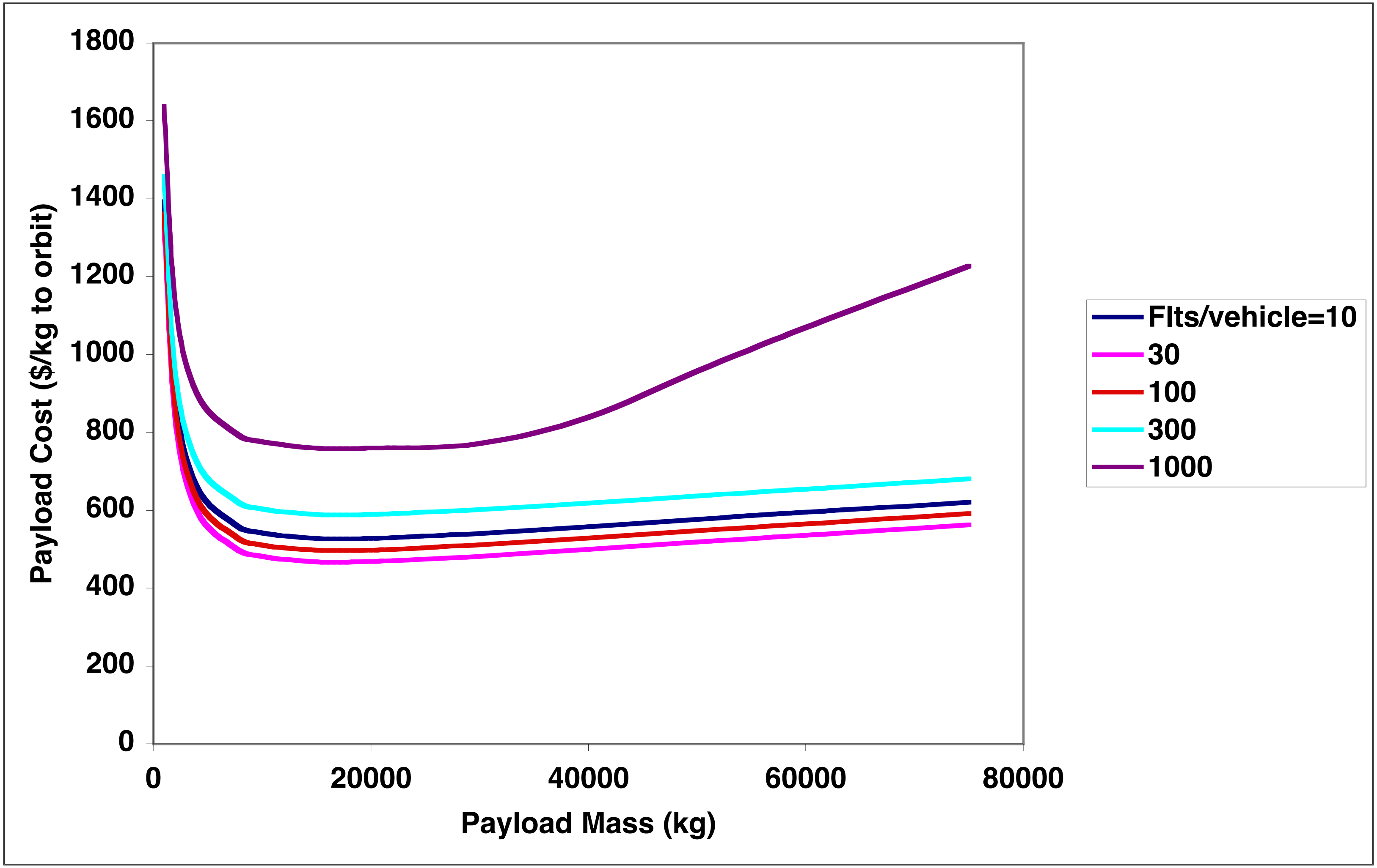
Parametric Cost Analysis

- 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.)

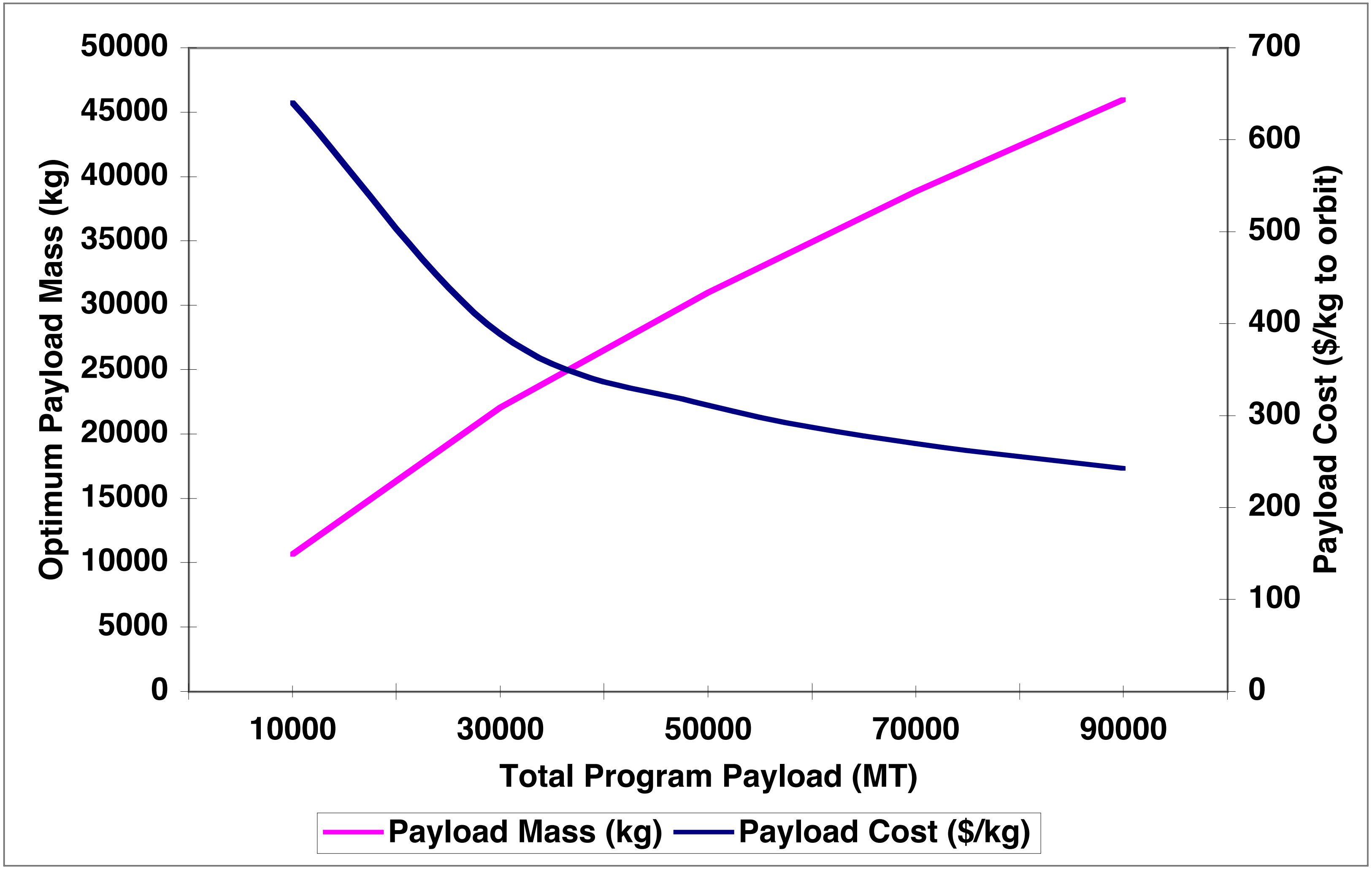
Effect of Refurbishment Rate



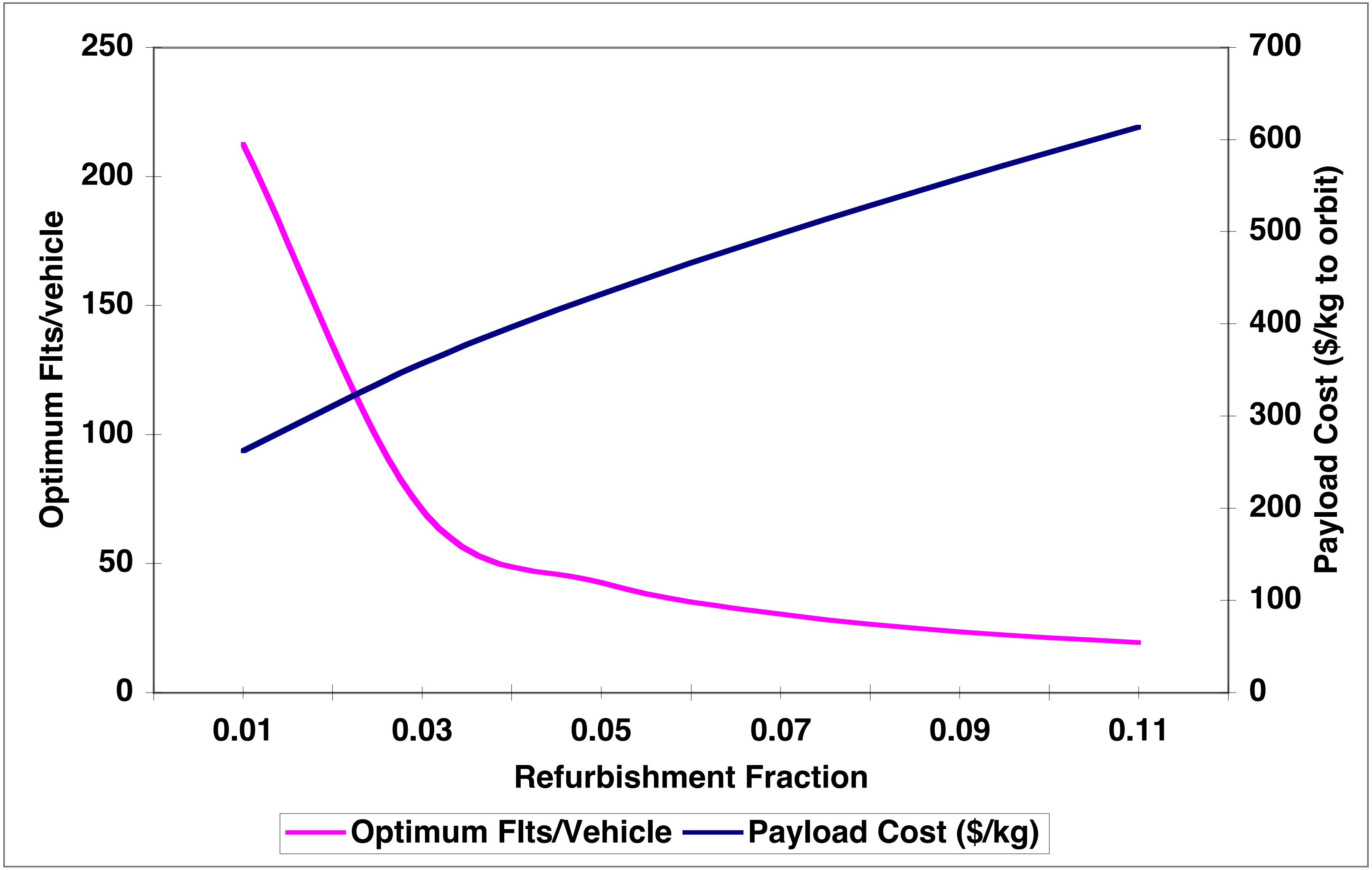
Effect of Vehicle Lifetime



Effect of Total Launch Mass



Effect of Refurbishment Fraction



Costing Conclusions

- 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!)

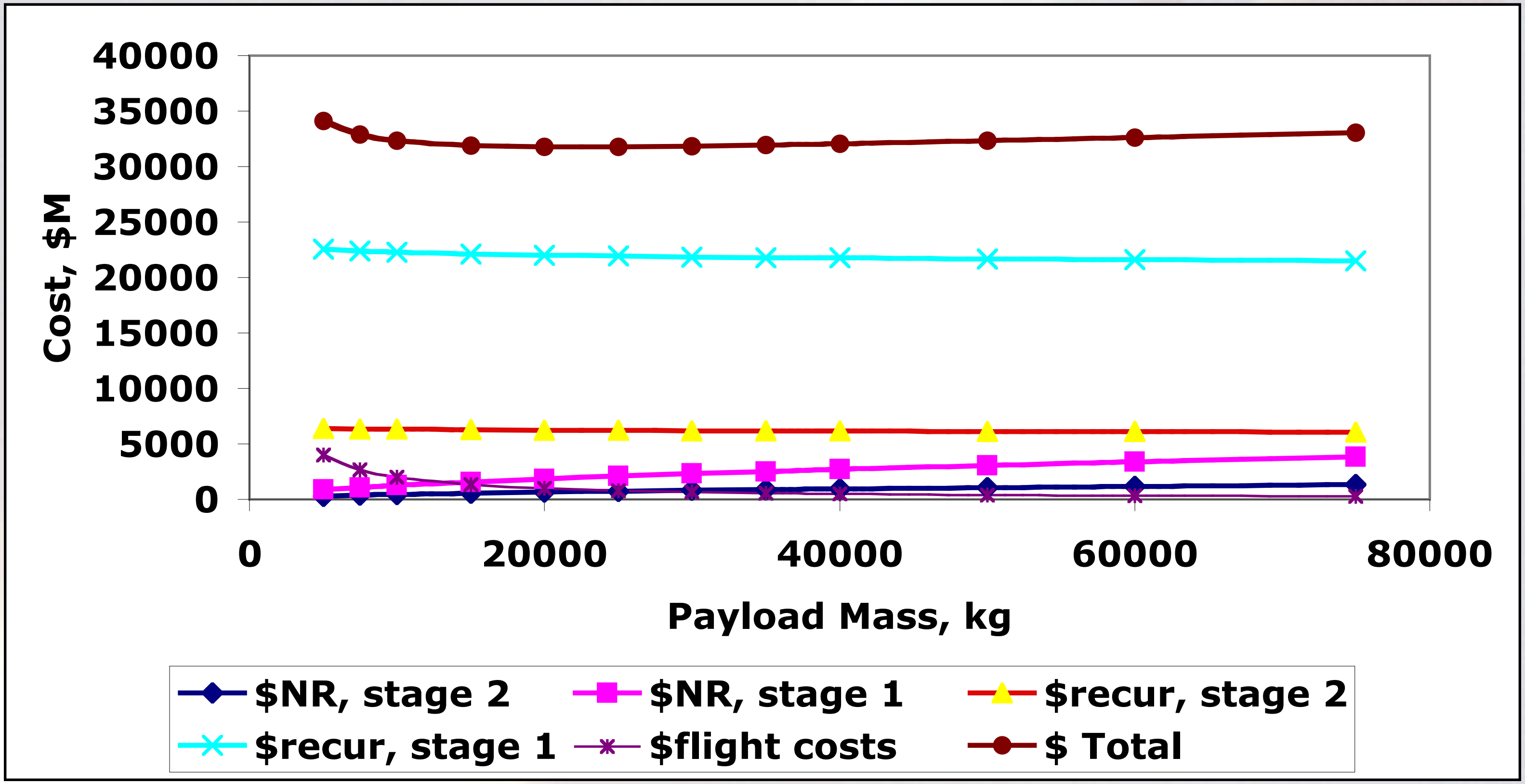
Architecture Study Basic Assumptions

- Market of 20,000,000 kg to LEO over 10 years
- Reusable vehicles have a 5% refurbishment fraction
- Reusable vehicles have a 50-flight lifetime

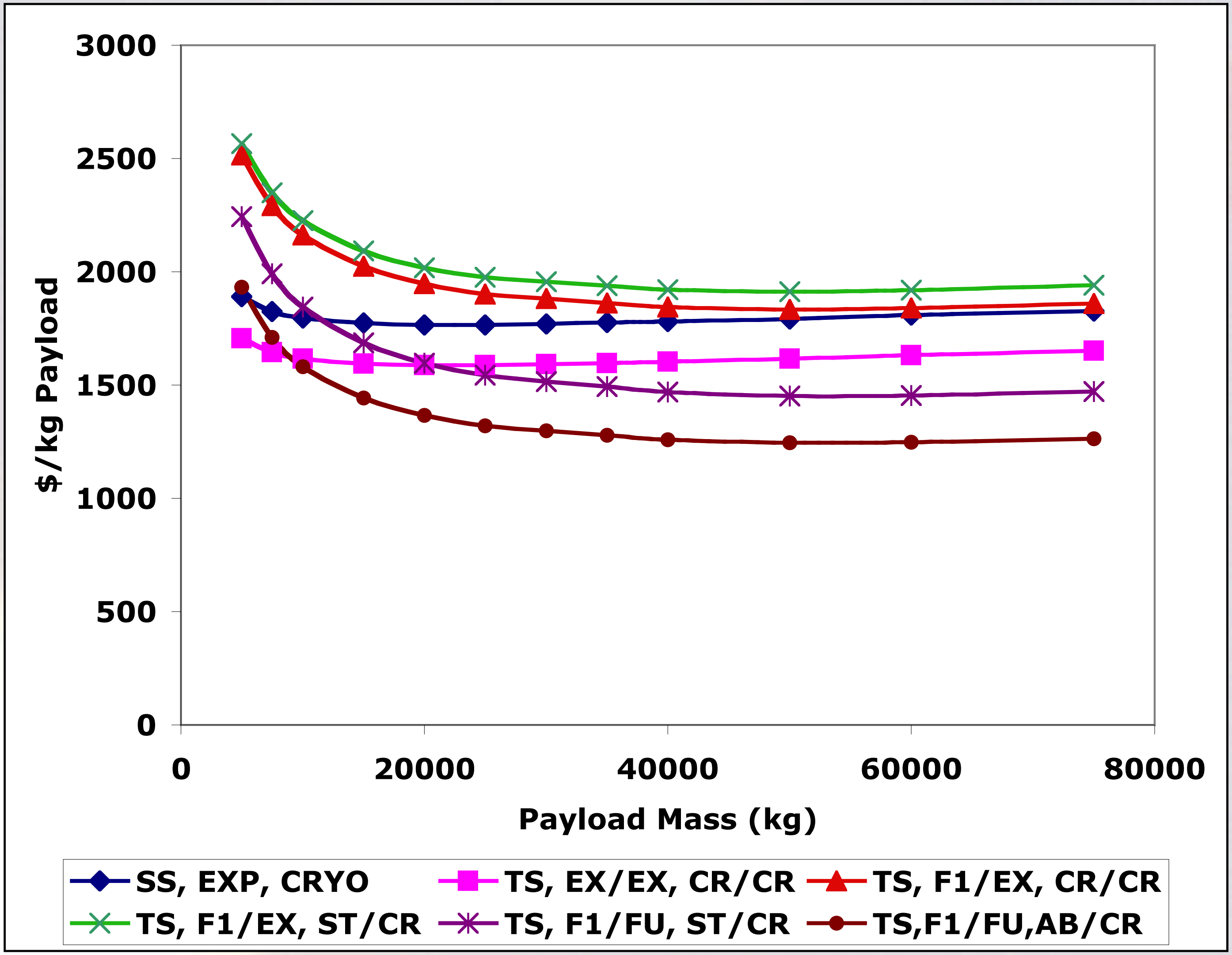
Assumed Isp's and Inert Mass Fractions

Propellants	Specific Impulse	Expendable	Reusable		
			Ballistic Reusable	Winged Orbital	Winged First Stage
Cryogenic	433	0.078	0.125	0.156	0.215
Storables	312	0.061	0.098	0.122	0.168
Solids	283	0.087	0.139	0.174	0.239
Airbreathing	2000				0.323

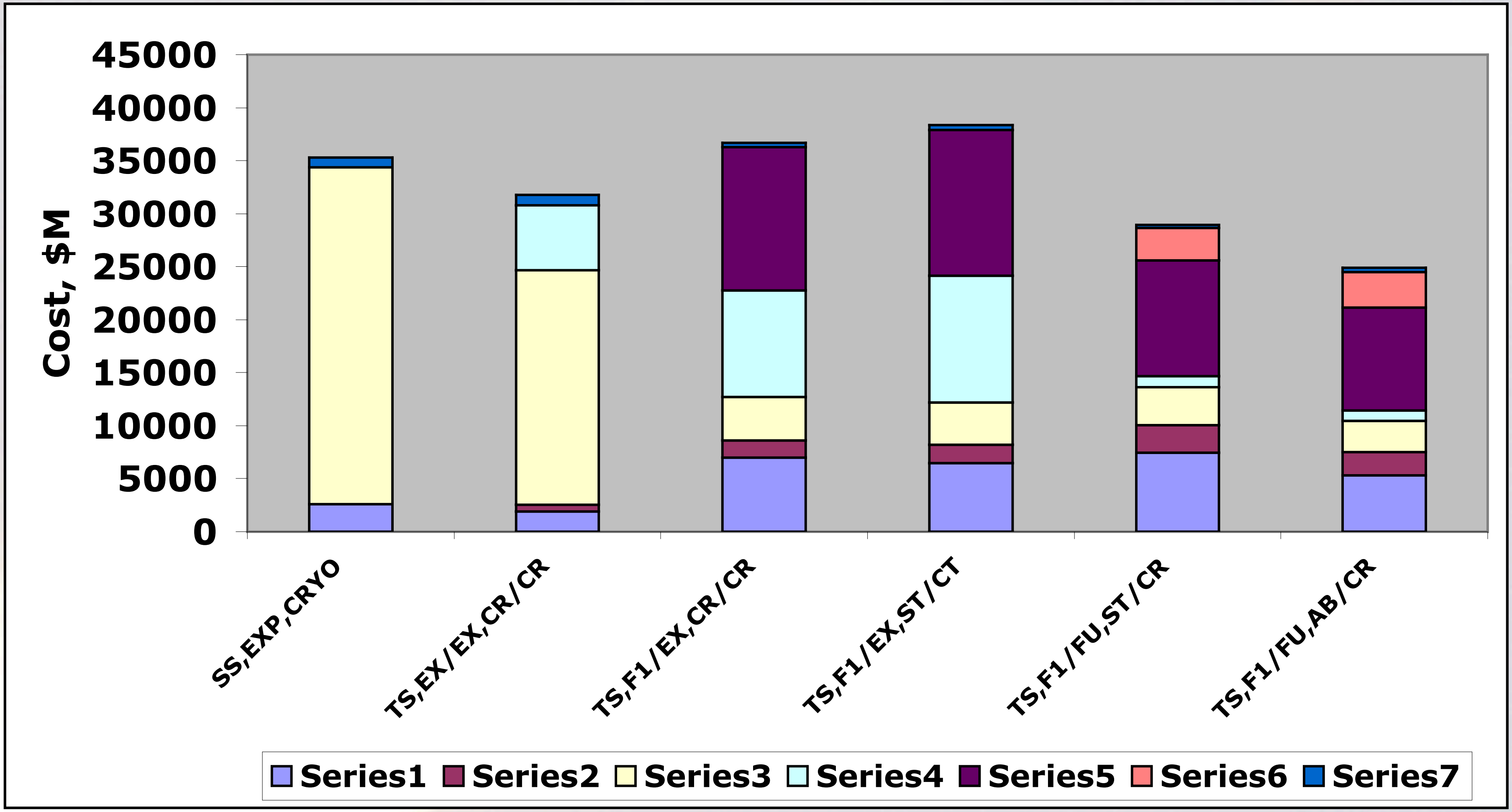
Cost Elements for Two Stage Expendable



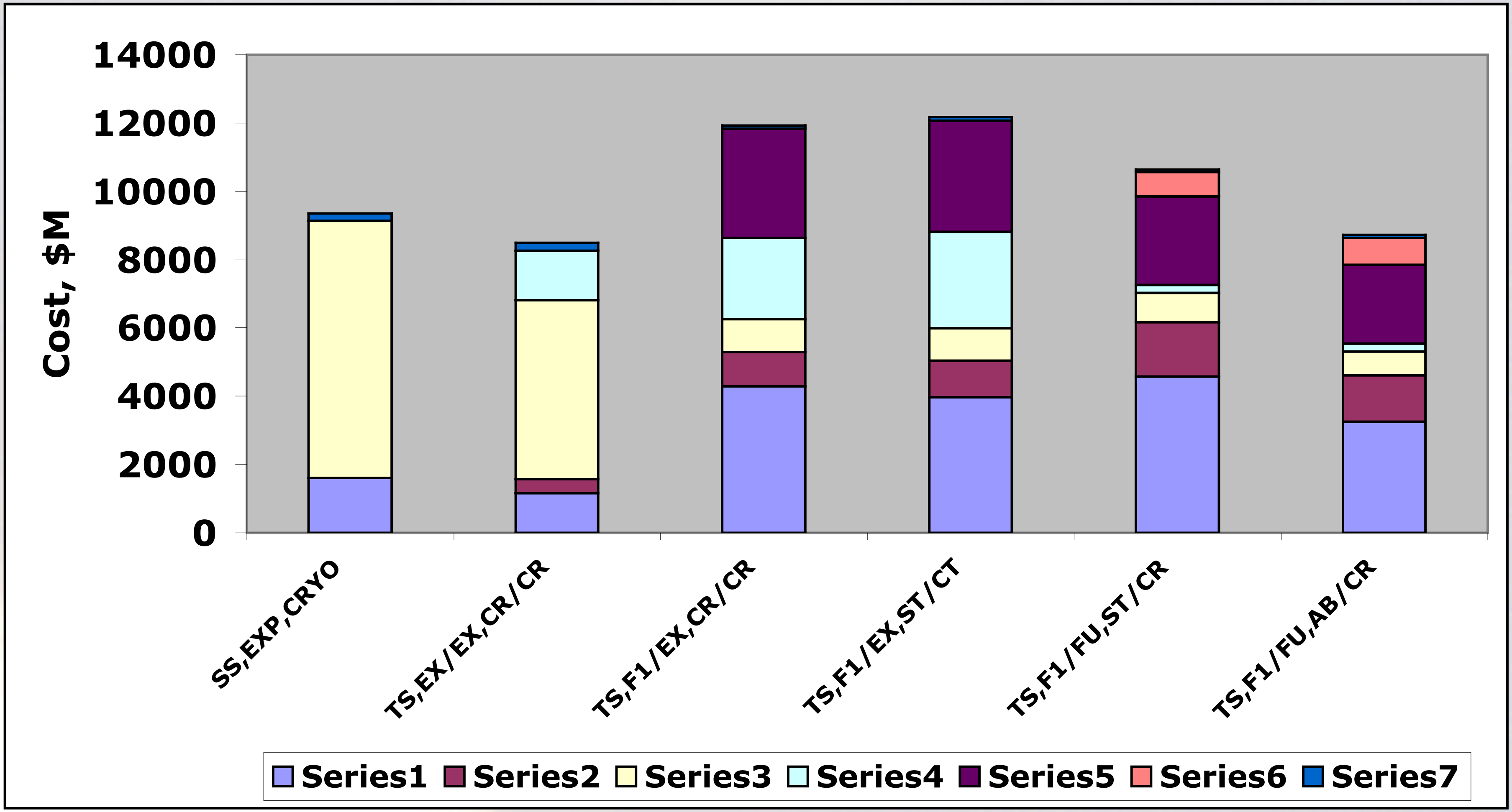
Launch Cost Trends with Payload Size



Cost Elements for Test Cases



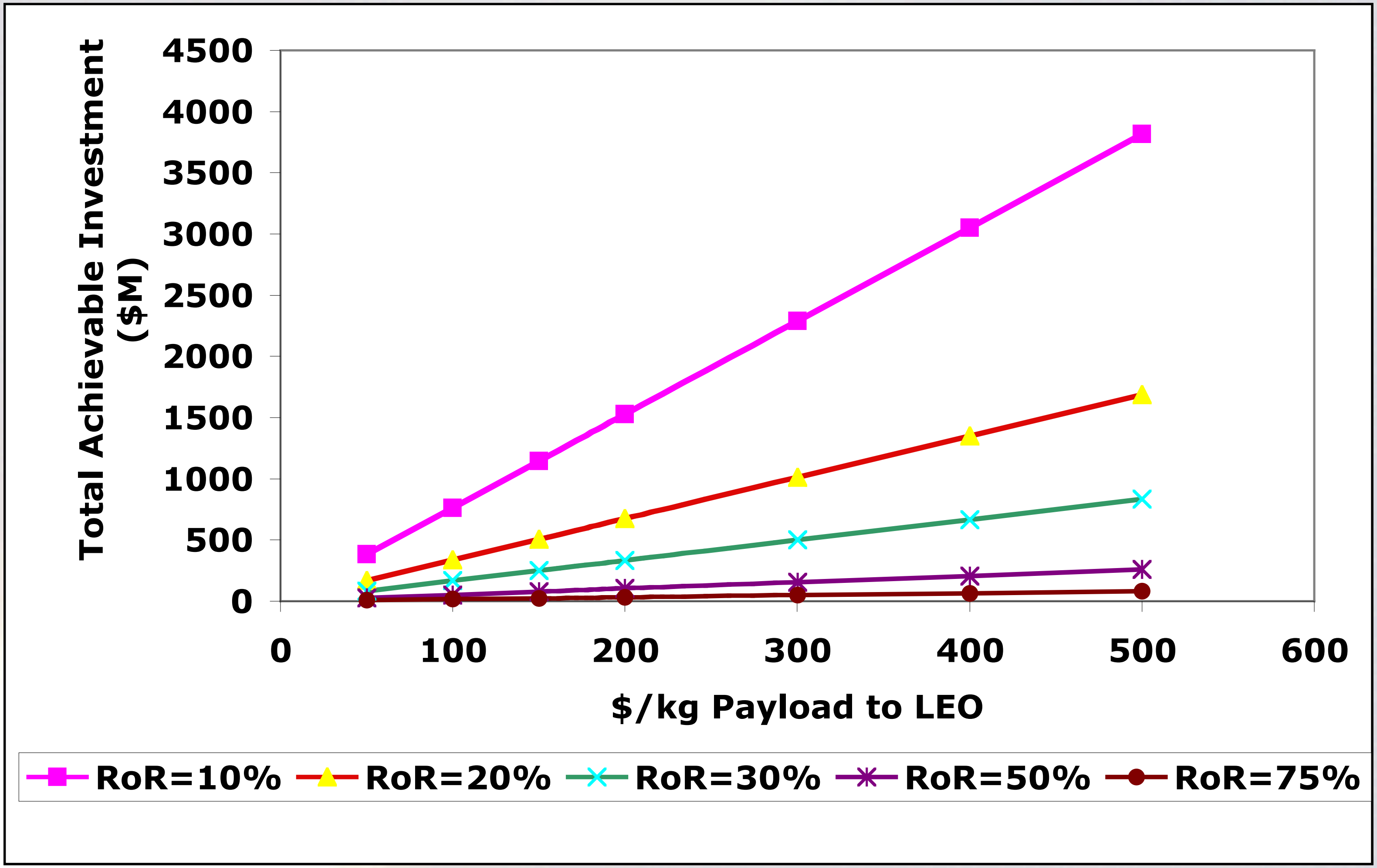
Cost Elements, 10% Cost Discounting



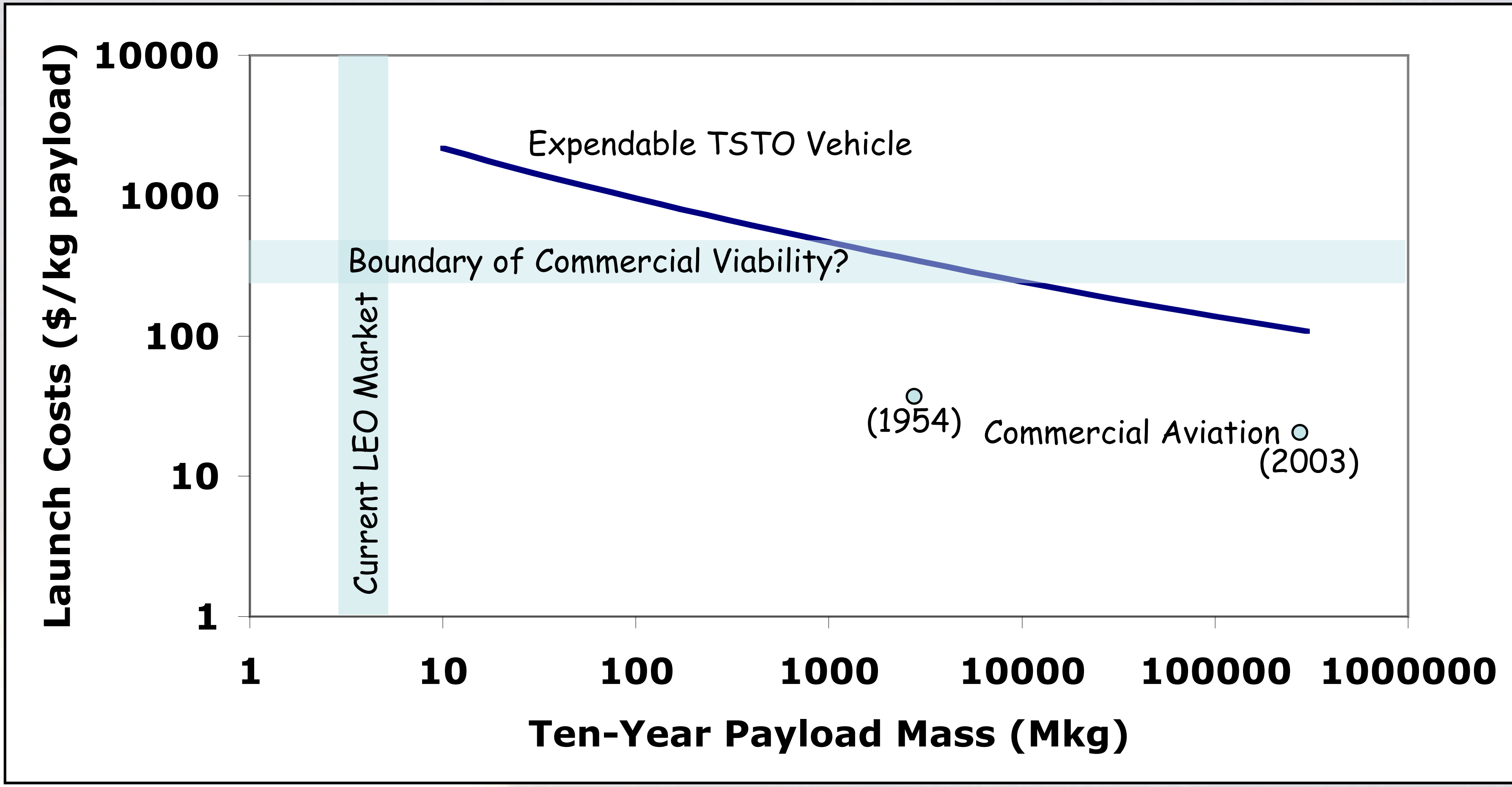
“Top-Down” Economic Analysis

- Assume five years of development (constant expenditures)
- Free flights!!!
- Charge enough over ten years of operations to amortize development costs
- Vary rate of return

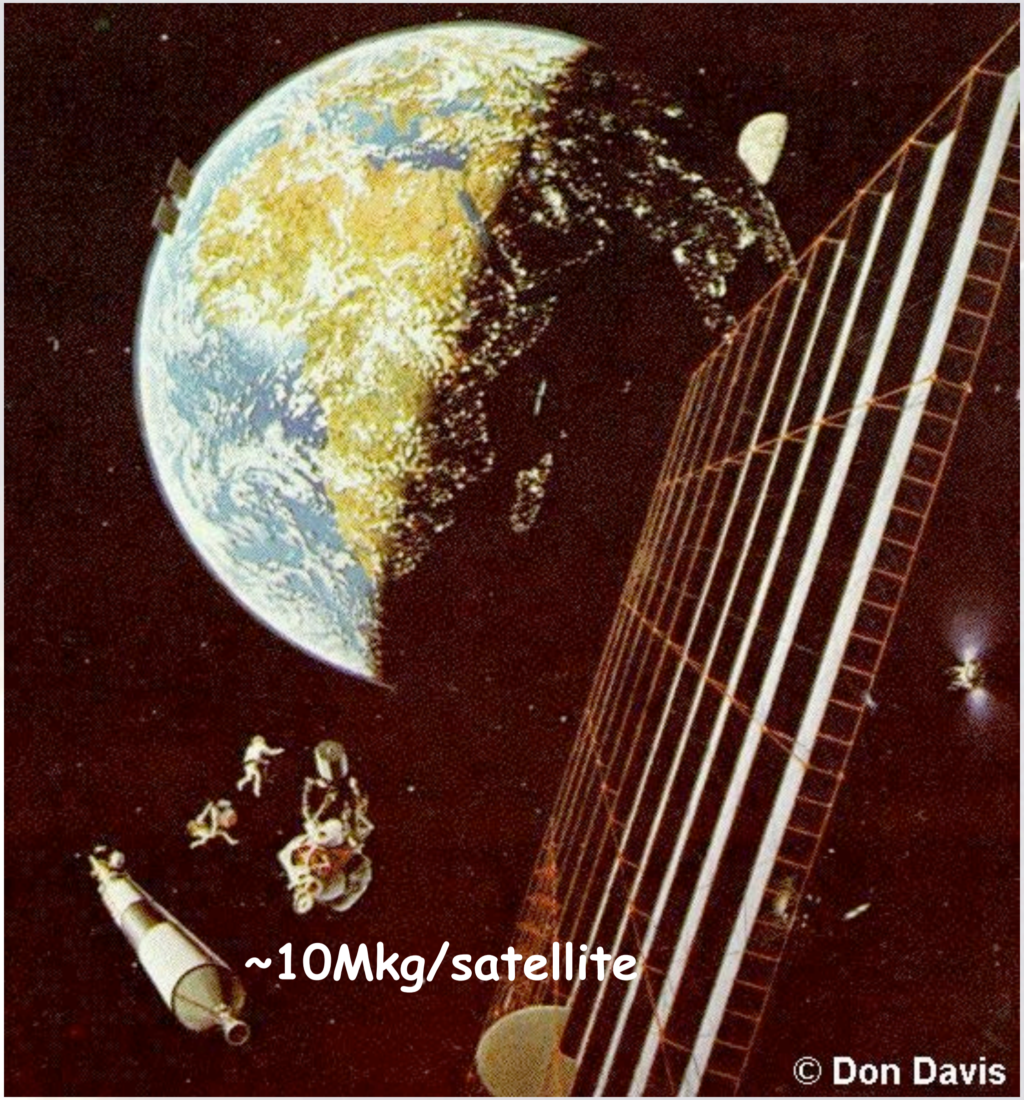
Allowable Investment in "Free" Launch



Launch Costs and Total Market



Solar Power Satellites?



Conclusions about Launch Costs

- Technology (reusability, airbreathing) will provide marginal improvements in cost, but requires large front-end investments
- There's no "magic bullet" that will make Earth launch economical
- Three most critical parameters
  - Flight rate
  - Flight rate
  - Flight rate