Orbital Sciences Corporation Opinions on Launch vehicle Reusability

Presented to

Committee on Reusable Booster Systems NRC ASRB

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Orbital's Background on the Subject

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- Between 1987 and 2012 Orbital has Developed and Currently Operates Four Families of Launch Vehicles
  - One (Pegasus) Has a Reusable Component (Launch Aircraft)
  - Three are All-Solid (Pegasus, Taurus and Minotaur); One has a Large Liquid First Stage (Antares)
  - 62 Launches Since 1990 – 90% Success Rate (Including First Flights); 132 Satellites Orbited
  - Two (Pegasus, Antares) Were Developed Exclusively With Private Funding

- Orbital Carried Out Several In-Depth Studies Involving Launch Vehicle and/or Booster Reusability
  - Space Transportation Architecture Studies (STAS), 1998 – 2000
  - 2^{nd} Generation RLV System Engineering and Risk Reduction (2GRLV), 2000 – 2002

- Orbital Developed the X-34 Reusable Booster Test Bed In Cooperation With NASA
  - Two Airframes Built in the 1997 – 2000 Time Frame
  - NASA-Developed "Fastrac" Engine Not Available; Project Cancelled After Captive Carry Flights

- Orbital Has Studied the Possible Use of X-34 Airframes for Reusable Booster-Related Flight Experiments

Pegasus Flight 1 – April 5, 1990

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X-43 Reusable Booster Testbed

Booster Reusability Challenges

- Any Reusability Degrades the GLOW/Payload (G/P) Ratio
  - In Addition to the Obvious Size Consequences, Low G/P Greatly Reduces "Design Robustness": Small Misses in Structural Mass Fraction (SMF) and Specific Impulse (Isp) Has Large Payload Consequences

- This "Reusability Penalty" Depends on the Values of SMF and Isp Used
  - SMF and Isp Values at the 98% Limits of the "Laws of Physics" Since the 1950's (Atlas ICBM/SLV) and the 1970's (SSME), Respectively
  - No Significant Improvements In Sight Except Perhaps Nanotube Materials
  - Current SMF and Isp Make Single Stage to Orbit Architectures Unviable

- Any Reusability Increases System Complexity
  - Missions Success/Safety Becomes Harder
  - Development Cost Higher for the Same Launch Vehicle Mass

- 1971 Study by Mathematica, Inc.[1] Indicated a Minimum of 39 Flights/Year Needed to Justify a $12.8B (1975 $'s, $54B Today) Development Cost Shuttle Program
  - Later Work by Orbital 30 Years Later (Including Better Performance Cost Estimates) Raise This Estimate to 55-60 Flights/Year
  - Not Surprising, Since There Have Been No Major Improvements in SMF or Isp

- Time and Cost of Turnaround/Refurbishment Unclear
  - Space Shuttle Represents a Single "Data Point"

References:

1. "MATHEMATICA Economic Analysis of the Space Shuttle System" -- Heiss, AAS Science & Technology 1972/vol.30/p.233

Ratio of Gross Lift-Off Weight to Payload

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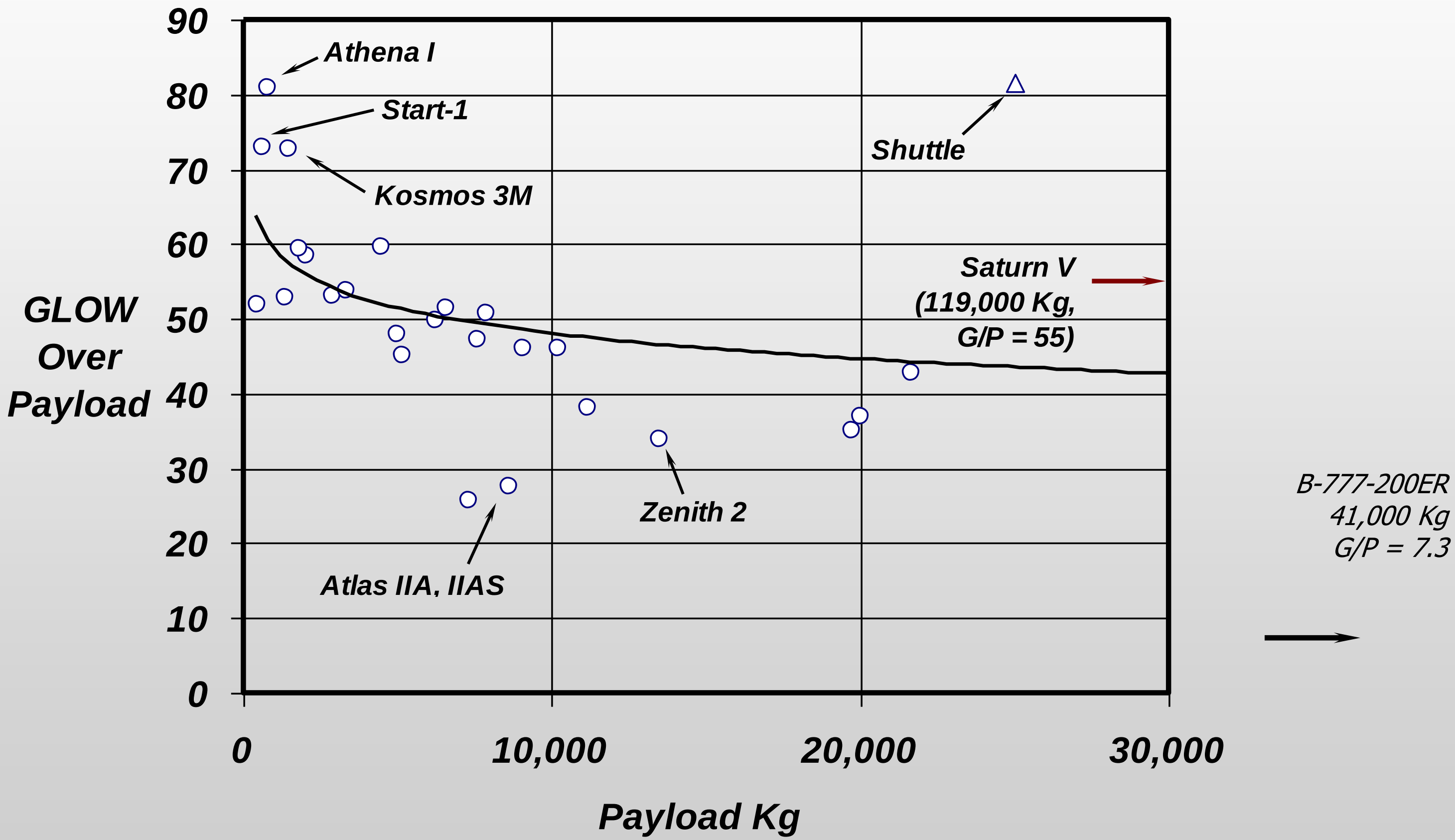
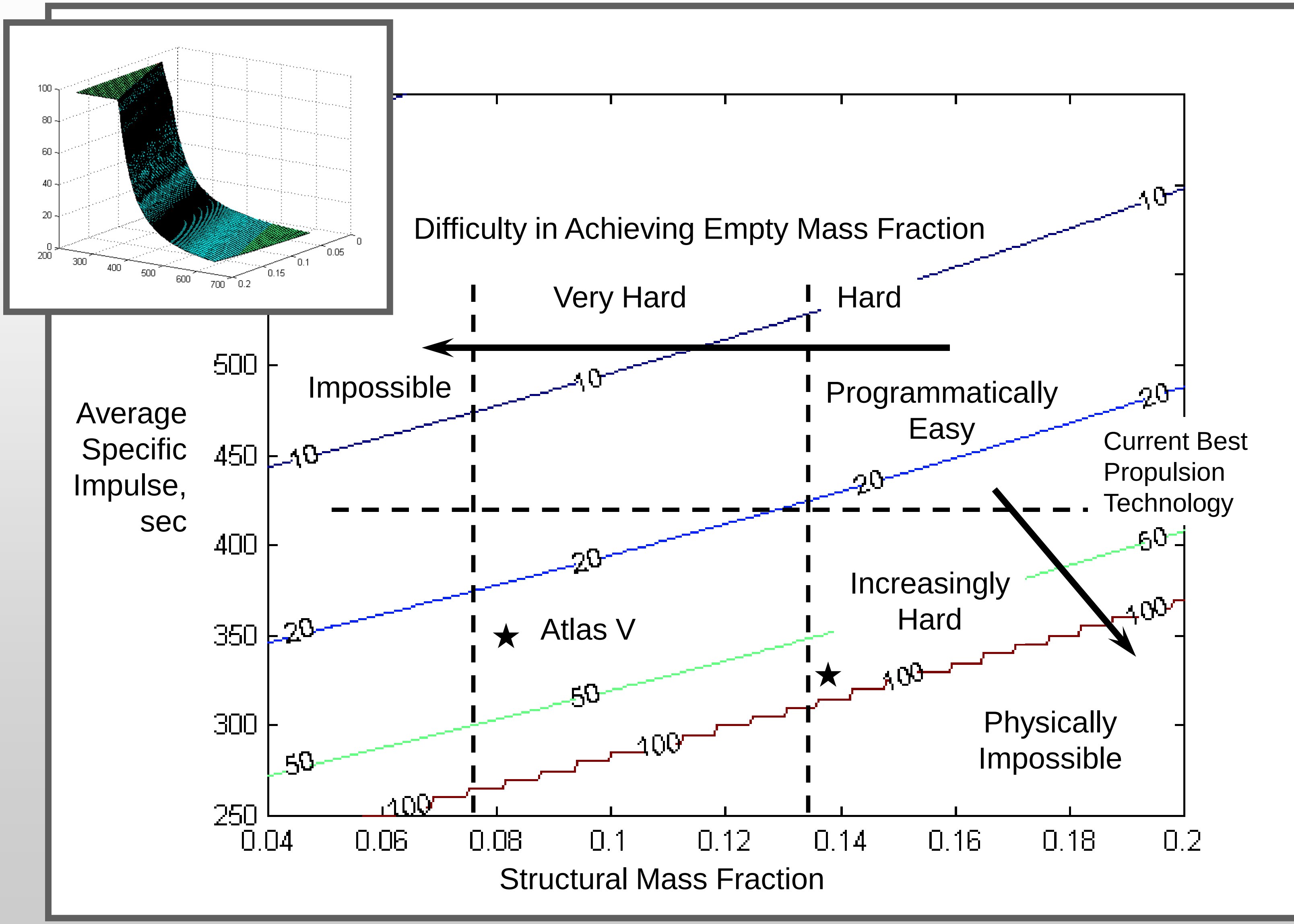
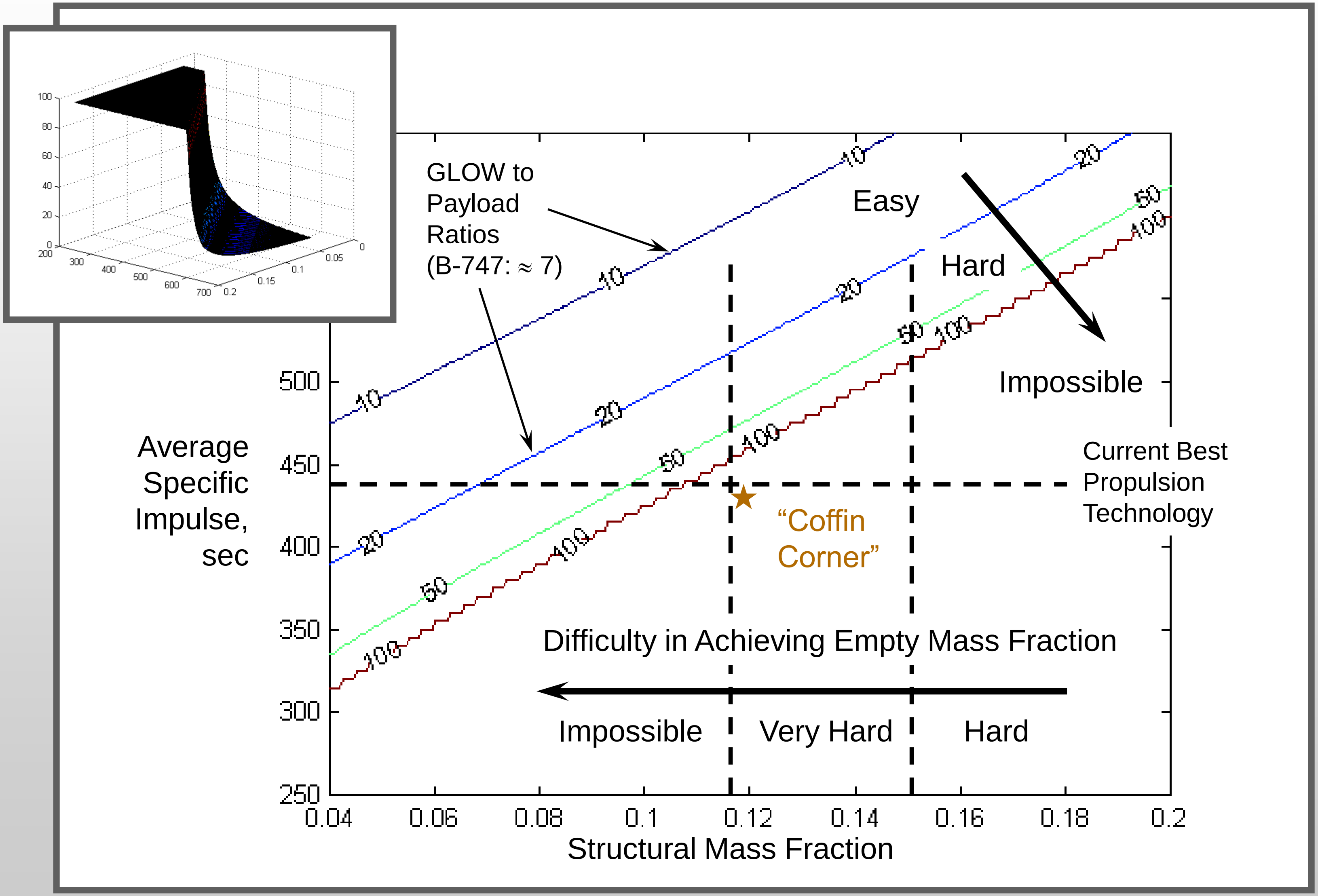


Two-Stage to Orbit G/P vs. Isp and SMF



Single Stage to Orbit G/P vs. Isp and SMF



Space Shuttle Programmatic Assumptions, 1971

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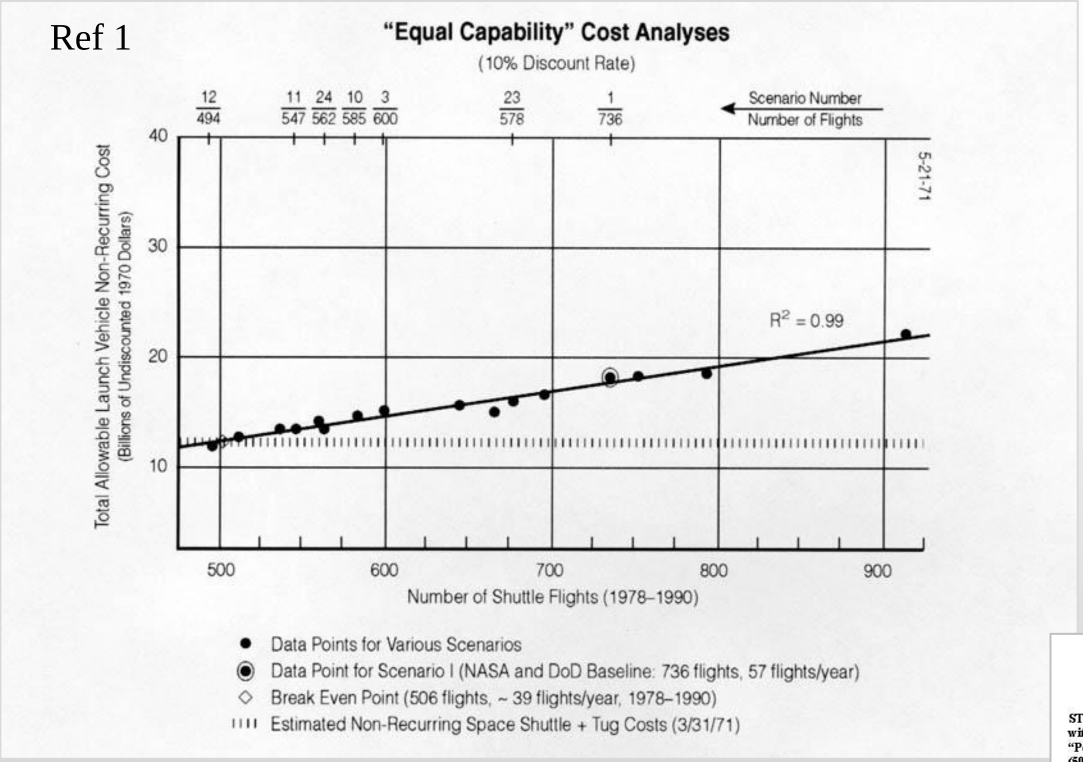
Ref 1



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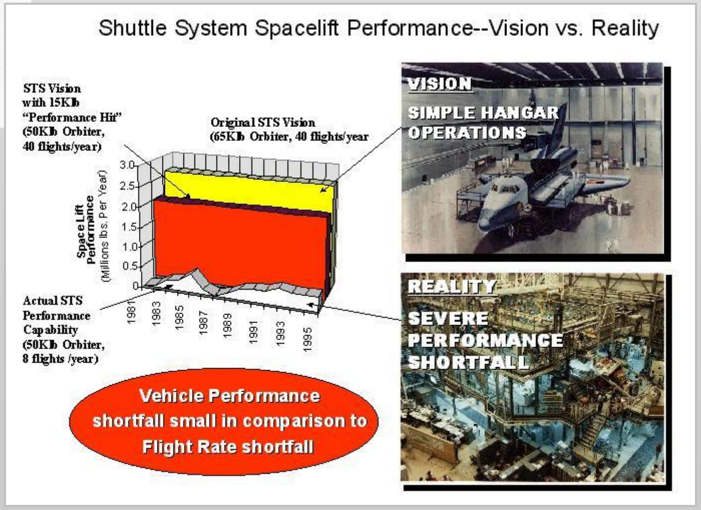


References:

1. Morgenstern and Heiss, Analysis, May 31, 1971; Astronautics & Aeronautics, October 1971, pp. 50-62

2. McCleskey, Carey M. and Zapata, Edgar, "DESIGNING FOR ANNUAL SPACELIFT PERFORMANCE" 49th International Astronautical Congress Melbourne, Australia, September 30, 1998 IAF-98-U.2.05

Other Reusability Issues

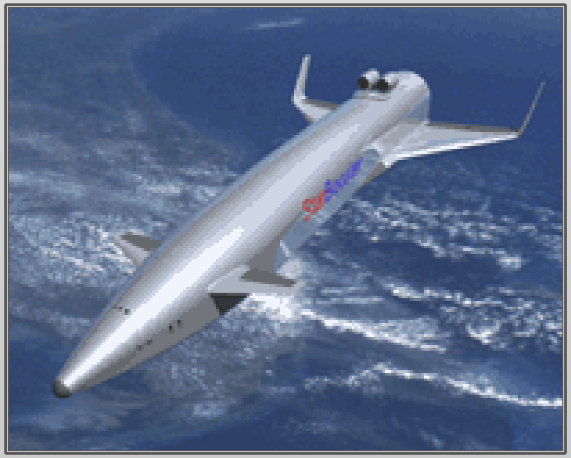
- Partial Reusability Is a Reasonable Compromise
  - Space Shuttle Was Partially Reusable (Orbiter), Partially Expendable (ET), Partially "Recyclable" (SRMs)

- Reusable First Stage Has:
  - Lowest Payload Mass Fraction Penalty
  - Highest Hardware Recurring Cost Advantage Over an Expendable Stage
  - High Development and Procurement Costs (Large Thrust Levels Required)
  - Nearly-insurmountable Recovery Problems Unless Limited in Burnout Velocity
  - Air-launch Is a Very Mild Form of First Stage Reusability

- Reusable Last Stage Has:
  - Highest PMF Penalty
  - Lowest Recurring Cost Advantage (Especially With Modern Avionics)
  - Obvious Solution to the Recovery Problem (Re-entry from Orbit)
  - Matches Well a System With Independent Recovery Requirements (e.g. Human Spaceflight)

- Creative Vehicle Configurations Not Sufficient to Overcome the "Tyranny of SMF and ISP"

Vehicle Configuration as an Alternative to SMF and Isp Improvements



Final Thoughts and Recommendations

- Difficult to Justify Interest in Reusable Boosters Unless There Is a Solid "Business Case"

- The Business Case for Reusable Boosters Hinges on Launch Rate
  - But Launch Rate Also Has a Very Significant Impact on the Cost and Reliability of Expendable Boosters

- Additionally, There Are Two Key Obstacles
  - No Reliable Data Base of Refurbishment/Turnaround Costs and Schedules
  - The U.S. Has Abandoned the Key Technology of Launch-sized Liquid Rocket Engines

- "Best Use of Money Recommendations"
  - Flight Experiment to Gain Insight on Refurbishment/Turnaround Costs
  - Significant Government Investment on Launch Propulsion Engines
    - Could be Common to Reusable and Expendable Launch Vehicles Alike
  - Investigate Nanotube Technology to Improve Structural Mass Fraction
    - Significant Improvements in Isp at Launch Thrust Levels Does Not Appear Possible

Answers to Formal Questions

Q - *In developing a future Air Force space lift architecture, what factors should be considered in evaluating the trade-offs between a Reusable Booster System (RBS) and expendable launch vehicles?*

1. Realistic Launch Rate, Realistic Development Funding

Q - *What are the major technology risks associated with realization of a Reusable Booster System (RBS) for space lift?*

1. Lack of Fundamental Sea-level Liquid Propulsion Technical and Industrial Base
2. Recovery of Non-orbiting Stages
3. Uncertainty in Turnaround (Recovery/Refurbishment and Recertification) Conops and Technologies (e.g. Non-Destructive Testing)

Q - *What risk mitigation strategies should the Air Force pursue if it was to develop a RBS capability?*

1. Development of Dual-Use (Reusable/Expendable) Mid-Thrust-Level (500,000 – 1Mlbf) Sea Level Engines
2. Experiments (Preferably Flight) to Develop and Validate Turnaround Conops and Cost Models
3. Structural Mass Fraction Improvements (e.g. Large-scale Nanotube Structures)

Answers to Formal Questions (Cont'd)

Q - *What infrastructure investments (launch platforms, ground test facilities, etc.) are necessary in realization of an RBS capability?*

1. It would be Unwise to Speculate on What Kind of Infrastructure Investments to Make Before We Know What the Launch and Turnaround Conops Are

Q - *What are reasonable assumptions concerning workforce size and ground processing timelines associated with the steady-state use of an RBS system?*

1. The Only "Reasonable Assumption" At This Time Is That It Will Be More Onerous Than Expected, Based on the Single Data Point Available (Space Shuttle)

Q - *What commercial technology development activities should influence the Air Force strategy regarding future space lift capabilities?*

1. Large-scale Nanotube Structures

Backup Data

Simple Math for the G/P Analysis

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G = Gross Mass; S = Structure Mass; F = Propellant Mass; P = Payload Mass

$$G = S + F + P$$

For Each Stage:

$$m_s = \frac{S}{S+F}$$

m_S = 0.2 (Easy) to 0.1 (Hard)

$$r = \frac{S+P}{S+P+F} = e^{-\frac{\Delta V}{g_0 I_{sp}}}$$

I_{sp} =

Solids:	*295 sec*
Biprop/LOX-Kerosene:	*325 sec*
LOX-LH2:	*435 sec*

$$\boxed{\frac{G}{P} = \frac{1-m_s}{r-m_s}}$$

For an n-Stage Rocket:

$$\Delta V = \Delta V_1 + \Delta V_2 \cdots + \Delta V_n$$

$\Delta V \approx$ 9.3 Km/s (30500 f/s) Including Loses (e.g. Vacuum Isp)

$$\frac{G}{P} = \left(\frac{G}{P}\right)_1 \left(\frac{G}{P}\right)_2 \cdots \left(\frac{G}{P}\right)_n$$