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 \(\sim 20\%\) of mass of vehicle protected
- Add \(\sim 300\) 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

PROPOSED
NASA / MSC DC-3
(MSC-001)
CIRCA 1970
“Triamese”, “Biamese” Shuttle Concepts
Shuttle Concept with Flyback S1C

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

MDC E0497
15 November 1971

www.aerospaceprojectsreview.com

Vehicle Reusability
ENAE 791 - Launch and Entry Vehicle Design
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

![Graph showing the effect of refurbishment rate on payload cost and mass.]
Effect of Vehicle Lifetime

Payload Cost ($/kg to orbit) vs. Payload Mass (kg)

- Fits/vehicle=10
- 30
- 100
- 300
- 1000

The graph illustrates the effect of vehicle lifetime on payload cost. As the payload mass increases, the cost decreases significantly, especially for higher vehicle lifetimes.
Effect of Total Launch Mass

![Graph showing the effect of total launch mass on optimum payload mass and payload cost.](image-url)
Effect of Refurbishment Fraction

![Graph showing the effect of refurbishment fraction on optimum flights per vehicle and payload cost. The graph plots refurbishment fraction on the x-axis and optimum flights per vehicle, as well as payload cost, on the y-axis. The graph includes two lines: one for optimum flights per vehicle and another for payload cost.](image-url)
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

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<th>Reusable</th>
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Cost Elements for Two Stage Expendable

![Graph showing cost elements vs. payload mass](image)
Launch Cost Trends with Payload Size

![Graph showing launch cost trends with payload size. The x-axis represents payload mass in kg, ranging from 0 to 80,000. The y-axis represents $/kg Payload. Various lines represent different payload configurations, such as SS, EXP, CRYO or TS, EX/EX, CR/CR, among others. The graph illustrates how launch cost decreases as payload mass increases.](image)
Cost Elements for Test Cases

- **Series 1**: SS, EXP, CRYO
- **Series 2**: TS, EX/EX, CR/CR
- **Series 3**: TS, F1/EX, CR/CR
- **Series 4**: TS, F1/EX, ST/CT
- **Series 5**: TS, F1/FU, ST/CR
- **Series 6**: TS, F1/FU, AB/CR

Cost, $M

0  5000  10000  15000  20000  25000  30000  35000  40000  45000
“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

![Graph showing total achievable investment vs. cost per kg to LEO for different RoR values.]

- RoR = 10%
- RoR = 20%
- RoR = 30%
- RoR = 50%
- RoR = 75%

ENAE 791 - Launch and Entry Vehicle Design
Launch Costs and Total Market

![Graph showing launch costs and total market over ten-year payload mass. The graph compares Expendable TSTO Vehicle with Commercial Aviation. The boundary of commercial viability is marked as a shaded area. The timeline (1954 to 2003) for commercial aviation is highlighted.](image)
Solar Power Satellites?

~10Mkg/satellite

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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