SLS

Space Launch System

Launch Vehicle Production and Operations Cost Metrics

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SLS Space Launch System

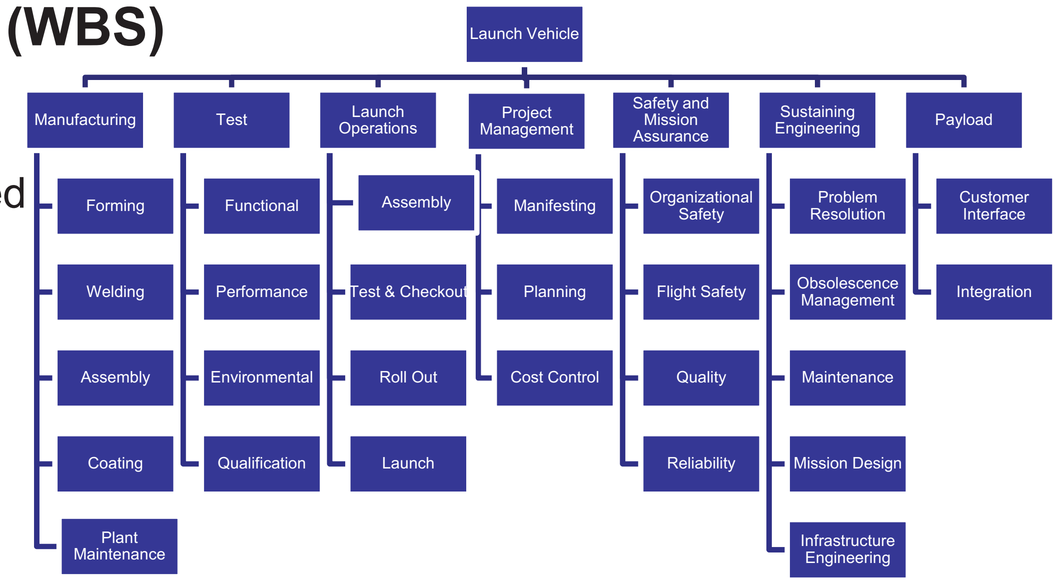
Introduction

♦ Traditional Cost Metrics

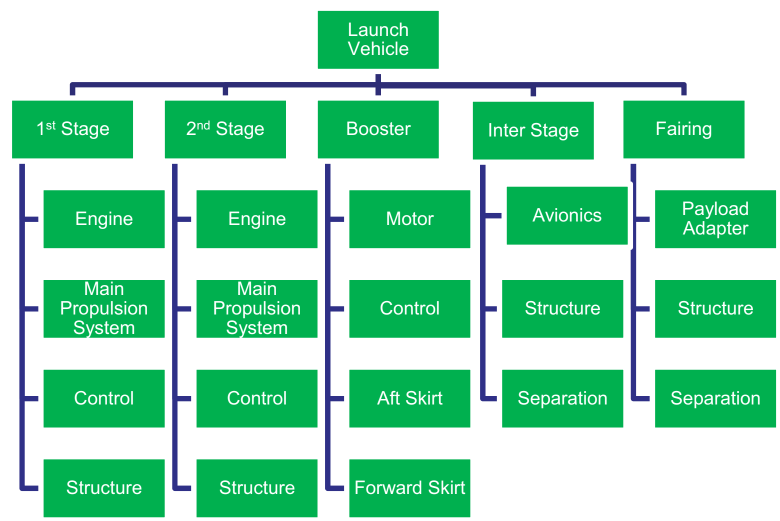
- Cost per Mass
  - Assumes 100% payload mass capacity utilized
  - Must have a common reference orbit
    - Altitude and Inclination
  - Examples:
    - Delta IV Medium
      - (1030 kg, GEO: 0 deg at 35,786 km circular)
      - (4210 kg, GTO: 27.0 deg at 35,786 km x 185 km)
      - (9190 kg, LEO: 28.7 deg at 200 km circular)
      - (8510 kg, LEO ISS: 51.6 deg at 407 km circular)
      - (7690 kg, LEO Polar: 90 deg at 200 km circular)
      - Reference: ULA Atlas and Delta Product Card, March 2013
    - Atlas V 501
      - (3780 kg, GTO: 27.0 deg at 35,786 km x 185 km)
      - (8210 kg, LEO: 28.7 deg at 200 km circular)
      - (7540 kg, LEO ISS: 51.6 deg at 407 km circular)
      - (6770 kg, LEO Polar: 90 deg at 200 km circular)
      - Reference: ULA Atlas and Delta Product Card, March 2013
    - Falcon 9
      - $4296/kg ($56.5M/13,150 kg, 28.5 deg inclination to LEO)
      - $11,649/kg ($56.5M/4,850 kg, 27.0 deg inclination to GEO)
      - Reference: http://www.spacex.com/about/capabilities, accessed 4/18/2014

Cost Model

- **Work Breakdown Structure (WBS)**
  - Labor Cost View
    - Tasks across all vehicles
    - Manufacturing Base embedded
    - Unit Cost not visible



- **Product Breakdown Structure (PBS)**
  - Unit Cost View
    - Cost per unit
    - Manufacturing Base Separate
    - Labor tasks may span multiple products

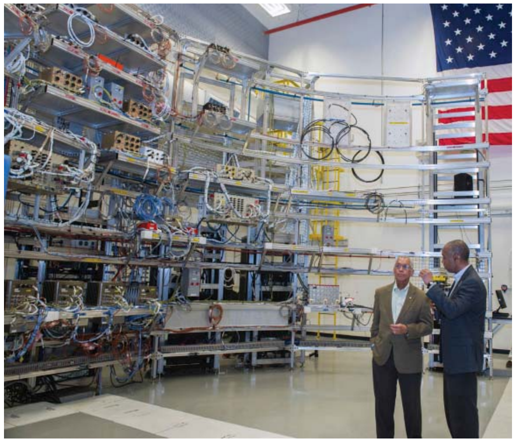


Cost Model

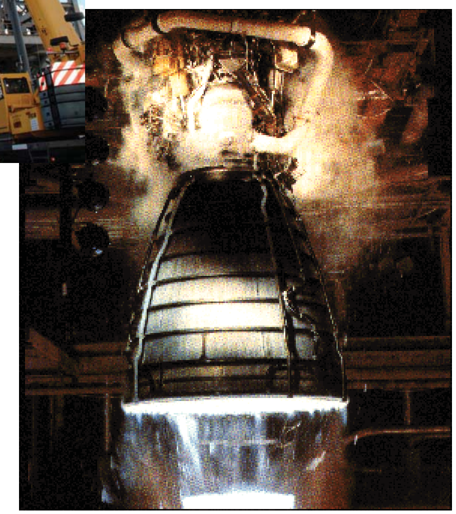
Life Cycle Costs

- Add costs of Development Phase and Production and Operations Phase

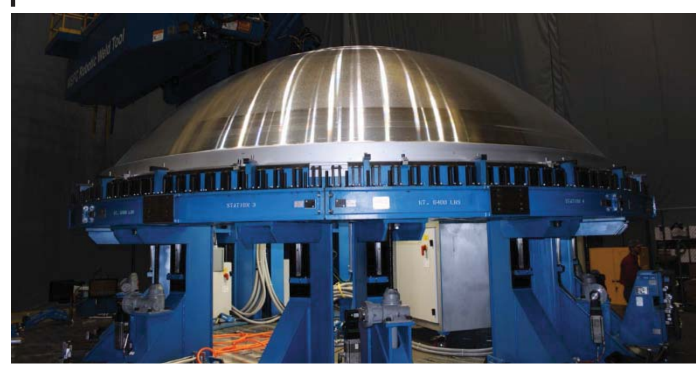
- Advantages
  - Full life of the program view
- Limitations
  - Must assume program duration
    - P&O costs are weighted more heavily the longer the program duration extends after development
      - Shuttle anticipated 10 years of operations, achieved 30 years
      - B-52 projected to be operational for almost 100 years at end of life
      - Greatly skews results
  - Funding is done on annual basis, not on a lifetime basis
    - U.S. Government Space programs are funded annually
    - Corporations report annual earnings, not life cycle earnings



Cost Drivers



- **Development Testing**
  - Primary cost driver in the Development phase
    - Driven by prototype production
    - Test facility costs
- **Manufacturing Base**
  - Maintenance of
    - equipment and facilities
    - training and retention of the workforce
    - retained viability during any low launch periods
- **Manufacturing processes**
  - labor required to operate and maintain the equipment
  - Material costs are not generally substantial compared to labor cost



Cost Drivers

- **Launch Site Base Operations**
  - Maintenance of
    - servicing facilities
    - launch pad services
    - launch towers
    - consumables (i.e., fuel and oxidizer)
    - control center
  - 20 – 35% of the annual launch vehicle program costs

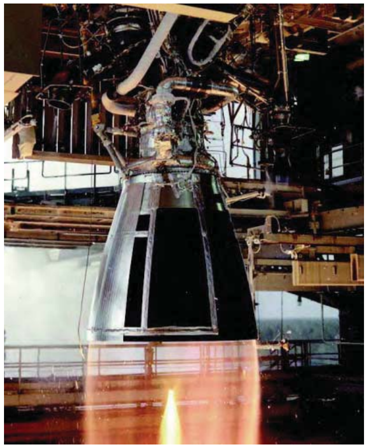
- **Learning Curve**
  - Reduction in production and launch site operation costs as experience gained in production, assembly, launch of launch vehicle

- **Inflation Rate**
  - Varies with economy
  - Significant over time

Cost Metrics

♦ Annual Production and Operations Cost

- Provides the annual cost of all production costs and operations costs
- Based on unit cost
  - – Constant cost independent of payload mass or orbit achieved
- Production
  - – Manufacturing costs for each unit leading to unit delivery
- Operations
  - – Post manufacturing unit costs
    - Green run testing
    - Shipping
    - Assembly
    - Launch



- Learning curve sources are visible in production and operations
- Inflation rate is visible on P&O costs, manufacturing base, and launch site base operations

Variable Costs vs Efficiency

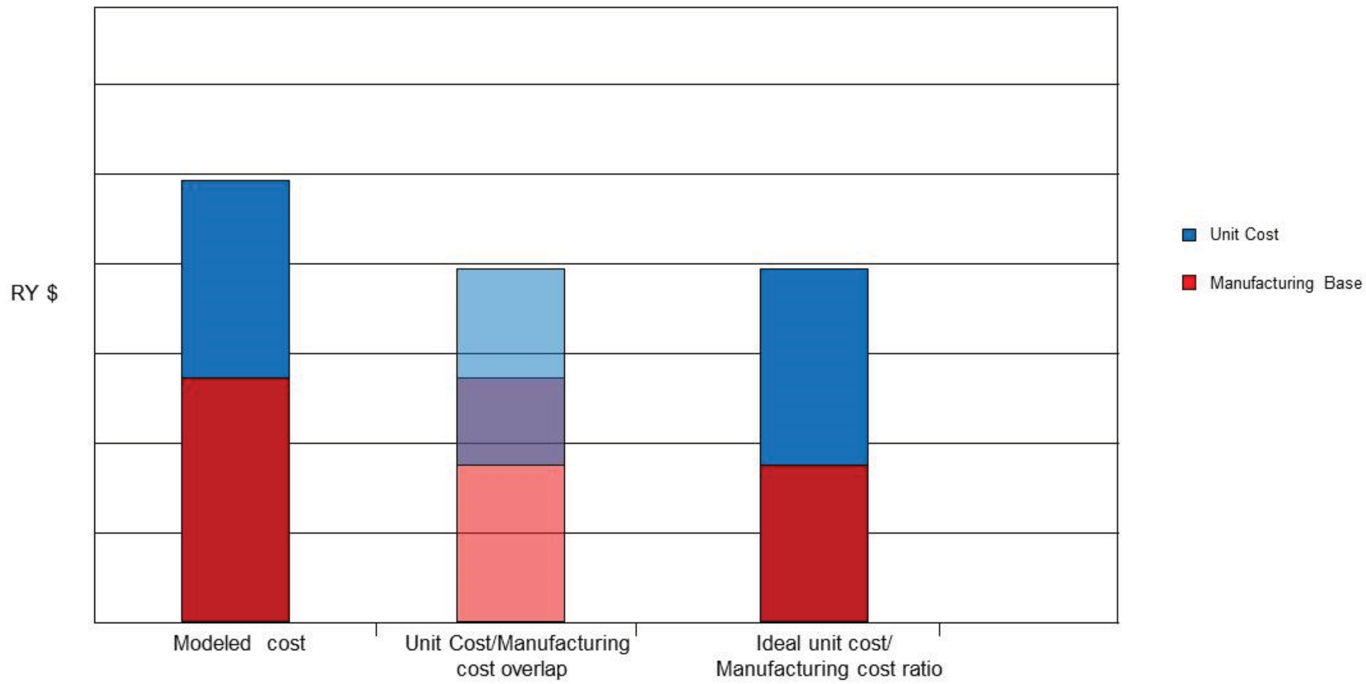
100% efficient variable cost
Fixed Cost

- Includes fixed costs (Manufacturing Base and Launch Site Base Operations)
  - Separately identifiable
  - Fixed costs are generally independent of flight rate with the follow exceptions
    - Flight rate << production/operations capacity leads to higher fixed costs to maintain unused facilities and equipment
      - Idle systems experience freeze up, lose calibration, increased corrosion, and soft goods expiration
      - Failures due to these cases are not often detected until manufacturing and operations restart
      - If capacity is leased out, the leased uses affect machine wear and life.
      - Low utilization of work force tends to lead to many continuous improvement ideas for production and operation performance
        - Increased cost of upgrade and modifications
    - Flight rate >> production/operations capacity leads to higher fixed costs to expand facilities and equipment to meet flight rate
      - Added production lines
      - Storage facilities to allow lower rate lines build ahead and store for higher flight rates

75% efficient variable cost
Fixed Cost

Unit Cost vs. Manufacturing Base

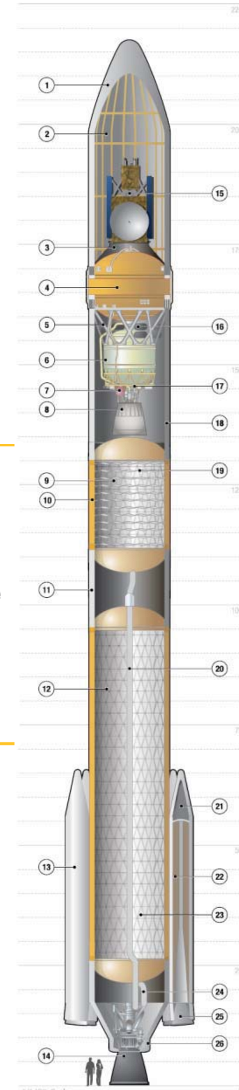
- **Manufacturing Base and Launch Operations maintenance costs provide partial unit cost capability**
  - Varies by manufacturing and launch site
  - Overlap defined by comparing unit cost to base cost
    - – Effort to produce unit assigned as part of unit cost
    - – Effort to maintain facilities and equipment assigned to base cost
    - – If a production lapse occurs, all costs revert to base case
      - Transition is accounted for as production stop and restart costs



Cost Metrics

♦ Unit Cost

- Advantages
  - – Calculates cost of a single unit
  - – Constant cost independent of payload mass or orbit achieved
  - – Metric compares actual unit cost to planned unit cost
  - – Includes all costs associated with vehicle production and launch
    - Production
      - – Manufacturing costs for each unit leading to unit delivery
    - Operations
      - – Post manufacturing unit costs
        - – Green run testing
        - – Shipping
        - – Assembly
        - – Launch
- Limitations
  - – Manufacturing base and launch site base operations are not accounted
  - – Can be amortized but varies greatly with launch rate fluxuations
    - Extreme low actual flight rates from planned flight rates eliminate this as a useful metric
      - – Shuttle had early estimates of 50-150 flights per year, and averaged 5
  - – Learning curve and Inflaction causes unit cost to be a variable
    - Must be accommodated for when using unit cost



1. Payload Fairing	14. First-Stage Engine (RS-68)
2. Acoustic Blankets	15. Spacecraft
3. Payload Attach Fitting	16. High-Pressure Helium Bottle
4. Second-Stage Fuel (LH_2) Tank	17. Second-Stage Equipment Shelf
5. Second-Stage Intertank Truss Assembly	18. Interstage Adapter
6. Second-Stage Oxidizer (LO_2) Tank	19. Anti-slosh Baffle
7. Hydrazine Bottle	20. First-Stage Oxidizer (LO_2) Feedline
8. Second-Stage Engine (RL10)	21. Solid Rocket Motor Nosecone
9. First-Stage Oxidizer (LO_2) Tank	22. Solid Rocket Propellant
10. Common Booster Core	23. Isogrid Structure
11. Centerbody	24. First-Stage Fuel (LH_2) Feedline
12. First-Stage Fuel (LH_2) Tank	25. Solid Rocket Motor Nozzle
13. Solid Rocket Motor	26. Thermal Shield

Cost Metrics

- **$/lb, $/Kg, (€/Kg) to orbit**
  - Traditional Metric

  - Metric is an idealistic optimum
    - Rarely, if ever, do vehicles carry the maximum mass to orbit
    - Orbits very greatly with missions
      - GEO: 0 deg at 35,786 km circular
      - GTO: 27.0 deg at 35,786 km x 185 km
      - LEO: 28.7 deg at 200 km circular
      - LEO ISS: 51.6 deg at 407 km circular
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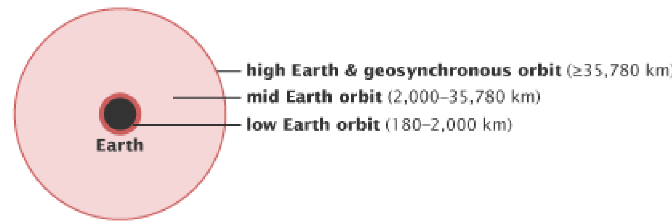
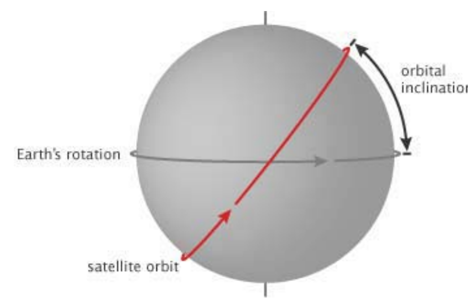
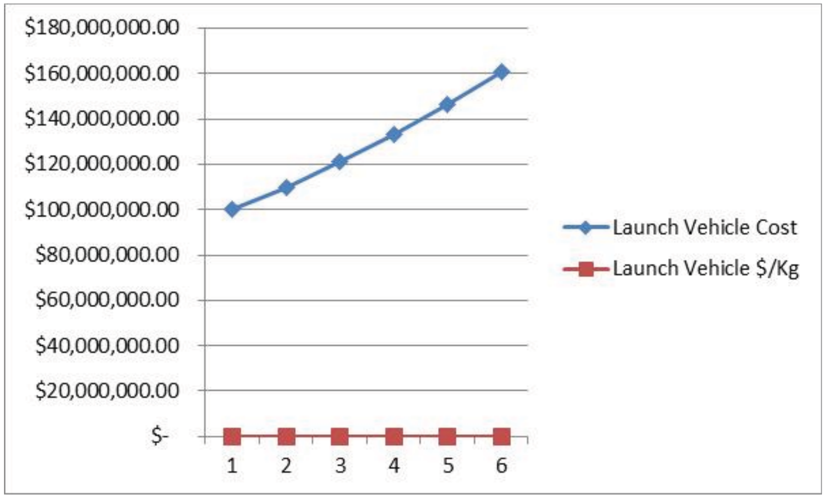


  - Launch Vehicle costs vary directly with launch vehicle mass between launch vehicle classes and inversely within a specific class of launch vehicle
    - Simpler manufacturing costs, more economic materials, are generally higher mass solutions at lower cost



Cost Metrics

- **$/lb, $/Kg, (€/Kg) to orbit**
  - Manufacturing base, launch site base operations are amortized (over an assumed program duration and flight rate) and are very uncertain
  - Learning curve and inflation rate are not visible (would need to be averaged over assumed program duration)
  - Scaling in the cost/mass calculation lead to a sensitivity reduction of 4 or 5 magnitudes
    - Very small variations represent significant cost changes
  - The large number of assumptions required make this metric very uncertain



COST METRICS

Options

	1 Budget Baseline vs P&O Cost Model	2 Unit Cost Goal vs Model Unit Cost	3 $/# to LEO
Learning Curve	✔	✔	✔
Inflation	✔		
Learning Curve & Inflation	✔	✔	✔
Mnfg/Ops Base	✔		
w/o Mnfg/Ops Base	✔	✔	✔

Comparison Sensitivities

Sensitive to all Cost Factors	Not Sensitive to - Budget Inflation - Mnfg/Ops Base	Based on Total Mass to Orbit Capability Not Sensitive to - Budget Inflation - Manufacturing/Oper. Weakly Sensitive - Learning Curve Big Changes on Cost Make Small Changes in Metric

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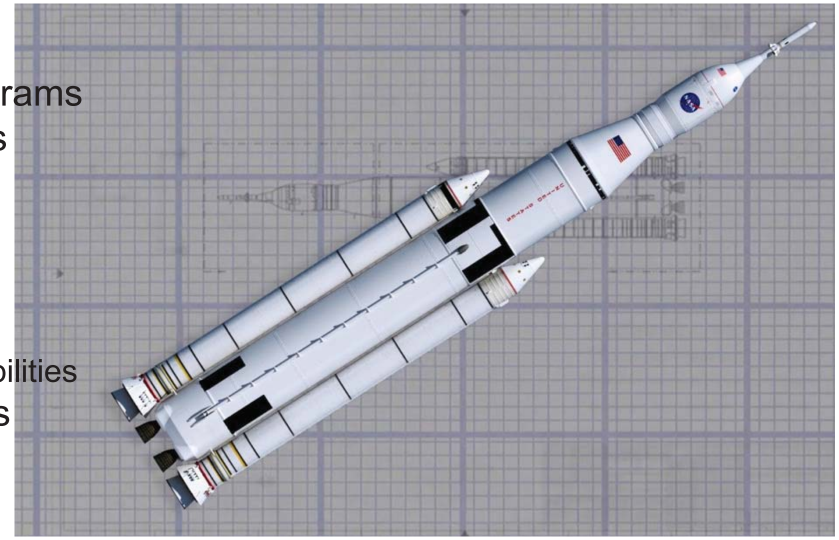
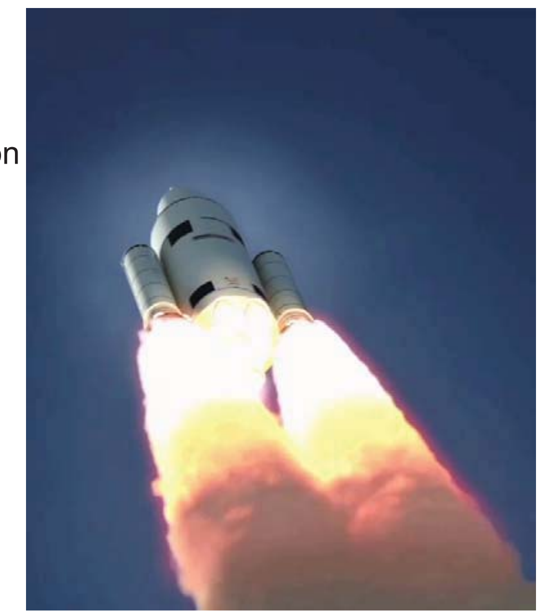
Summary



- **WBS vs. PBS**
  - Both breakdown structures are useful to manage programs
  - PBS provides basis for unit costs necessary in metrics
- **Life Cycle Costs**
  - Requires assumption on program duration
- **Cost Drivers**
  - Development Testing
    - Major cost during development relying on early P&O capabilities
  - Manufacturing Base and Launch Site Base Operations
    - Significant costs during P&O
  - Learning Curve
  - Inflation Rate



- **Cost Metrics**
  - Cost/Mass to orbit
    - Traditional
    - Requires assumptions on flight rate, 100% payload mass, orbit, program duration
    - Inherent scaling makes metric weakly sensitive to major changes
    - Large uncertainty
  - Unit Cost
    - Relative measure to planned cost
    - Insensitive to manufacturing base and launch site base operations costs
  - Annual Production and Operation Costs
    - Direct measure of actual costs
    - Not dependent on program duration assumptions
    - Sensitive to all major cost drivers