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)

    • 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)

    • 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)
♦ 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
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
**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

- Includes fixed costs (Manufacturing Base and Launch Site Base Operations)
  - Separately identifiable
  - Fixed costs are generally independent of flight rate with the following 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

100% efficient variable cost

Fixed Cost

75% efficient variable cost

Fixed Cost
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
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 Inflation causes unit cost to be a variable
    - Must be accommodated for when using unit cost
$/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
    - LEO Polar: 90 deg at 200 km circular
  - Reference: ULA Atlas and Delta Product Card, March 2013

- 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
$/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

<table>
<thead>
<tr>
<th></th>
<th>1 Budget Baseline vs P&amp;O Cost Model</th>
<th>2 Unit Cost Goal vs Model Unit Cost</th>
<th>3 $/# to LEO</th>
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## Comparison Sensitivities

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<tr>
<th>Sensitivity</th>
<th>1 Budget Baseline vs P&amp;O Cost Model</th>
<th>2 Unit Cost Goal vs Model Unit Cost</th>
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<td>- Manufacturing/Oper.</td>
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<td>Weakly Sensitive</td>
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<td>- Learning Curve</td>
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<td>Based on Total Mass to Orbit Capability</td>
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<td>Big Changes on Cost Make Small Changes in Metric</td>
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</tbody>
</table>
◆ **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