Heavy Lift Launch for Lunar Exploration

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Lunar Transportation Requirements

- > 50 tonnes on lunar transfer trajectory
  - Apollo: 40 tonnes @ TLI for 2 men, 3 days on lunar surface.
  - Unlikely to be reduced significantly; can miniaturize components but not crew.
  - Maybe less if lunar oxygen is used for return propellant.
  - Note: 50 tonnes @ TLI implies 100 tonnes in LEO for 450 sec I_{sp} LOX/LH_2 upper stage.
    - 70 tonnes if 850 sec nuclear thermal upper stage, but not likely in foreseeable political environment.
- Land anywhere on the Moon.
- Go any time of the month.
- Abort to Earth at any time.

Lunar Transportation System Architectures

- **Lunar Orbit Rendezvous (LOR)**
  - **Heritage from Apollo; “mother ship” waits in orbit while specialized lunar lander makes trip to surface. Avoids “cost” of fuel to carry robust Earth-return vehicle on entire round trip.**
  - **Probably minimum LEO mass for basic lunar round trip, but still many tens of tonnes for mission “critical mass”.**
  - **Can go twice every day.**
  - **Limited to low lunar latitudes w/o sacrificing abort-to-Earth.**
  - **Return vehicle left in lunar orbit represents inefficient use of mass in a developed transportation system.**
  - **Potentially lengthy storage times for return vehicle in lunar orbit will require low-efficiency space storable propellants, or new technology for long-term cryo storage.**
  - **Possible basis of future system if/when extensive lunar orbit infrastructure is ultimately developed.**

Transportation Architectures (cont.)

- **Earth Orbit Rendezvous (EOR)**
  - **Required LEO mass is built up with multiple launches to rendezvous in Earth orbit.**
  - **Minimum launch can be a few tonnes to LEO, but many launches!**
  - **Perceived as a good match to space station infrastructure, but subtle issues result in significant operational problems.**
    - **Cryogenic fuel storage during build-up is challenging, particularly in event of missed launch window.**
    - **Limited launch windows; Earth-centered plane of "station" (or rendezvous) orbit *must* point to lunar targeting position at TLI.**
      - **Happens only once every 9 days for due-East 28.5° maximum performance orbit from Canaveral; less for 51.6° ISS orbit.**
      - **Less frequent windows if particular landing times must be selected (e.g., dawn) or avoided (e.g., midnight) at the Moon.**
      - **Similar constraints limit aborts if must also *return* to ISS.**
  - **Will become a "must" if multiple RLV payload modules are ultimately used to construct a lunar mission.**

Transportation Architectures (cont.)

- **Lunar Surface Rendezvous (LSR)**
  - Required lunar mass attained with one or more launches to desired point(s) on lunar surface. Single mission must carry all essentials. ("Direct Ascent" in Apollo days.)
  - Ultimately necessary to build any sort of lunar base.
  - Can go twice per day, land anwhere , come home any time.
  - Minimum manned mission requires many tens of tonnes to maintain robust abort (propellant, heat shield), even assuming pre-deployment of surface assets.
    - Less if lunar-derived propellants available for return trip.
    - Cargo missions can be much smaller if economically favored.
    - Unavoidable penalties for carrying heat shield to lunar surface.
  - Obviously usable in concert with other methods, at cost of additional constraints.

Transportation Architectures (cont.)

- **Lagrange Point Rendezvous (LPR)**
  - **Build space infrastructure at stable Lagrange Points (L4, L5) instead of/in addition to LEO; deploy to/from Earth/Moon.**
    - **3 days from Earth, 2(?) days from Moon.**
    - **"Small" ΔV penalty for use of staging point.**
    - **Plenty of sunlight for power, plenty of shade for fuel storage.**
    - **Possibly best spot in cislunar space for "marshalling yard".**
  - **Can come and go at any time to any place on either planetary surface.**
  - **Abort may not always be to Earth.**
    - **Potential problem in solar flare seasons.**
  - **Minimum manned mission from Earth still several tens of tonnes.**
  - **Probably more suitable for use as part of a well-developed cislunar infrastructure, rather than as an initial lunar return.**

Lunar Transportation Costs

- **Benchmarks**

Vehicle	Cost($97)	LEO Payload (kg)	Cost/kg
Saturn V	$600 M*	140,000	4,300
Shuttle	$500 M**	23,000	22,000
Titan IV	$300 M	16,000	18,000
Atlas II-AS	$130 M	8,600	15,000
Delta 7920	$50 M	5,000	10,000

- **Goals**

RLV	$20 M	10,000	2,000
Magnum	$160 M	80,000	2,000

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* $100 M FY70$ for launch vehicle ($300 M for full Apollo mission).

** Very difficult to determine accurately; minimum $3 B to support a nominal 6 launches/year.

Transportation Architecture Summary

- **All modes except EOR require a minimum manned mission of several tens of tonnes to TLI.**
- **EOR imposes numerous scheduling and operational constraints, and eliminates the economies of scale which are possible with larger payload envelopes.**
- **Robust lunar base development will require LSR no matter what else is done.**
- **History indicates that economies of scale produce significant cost/kg advantages for a heavy lifter.**
- **Conclusion: A heavy-lift launch vehicle is, if not strictly mandatory, highly desirable for lunar operations.**

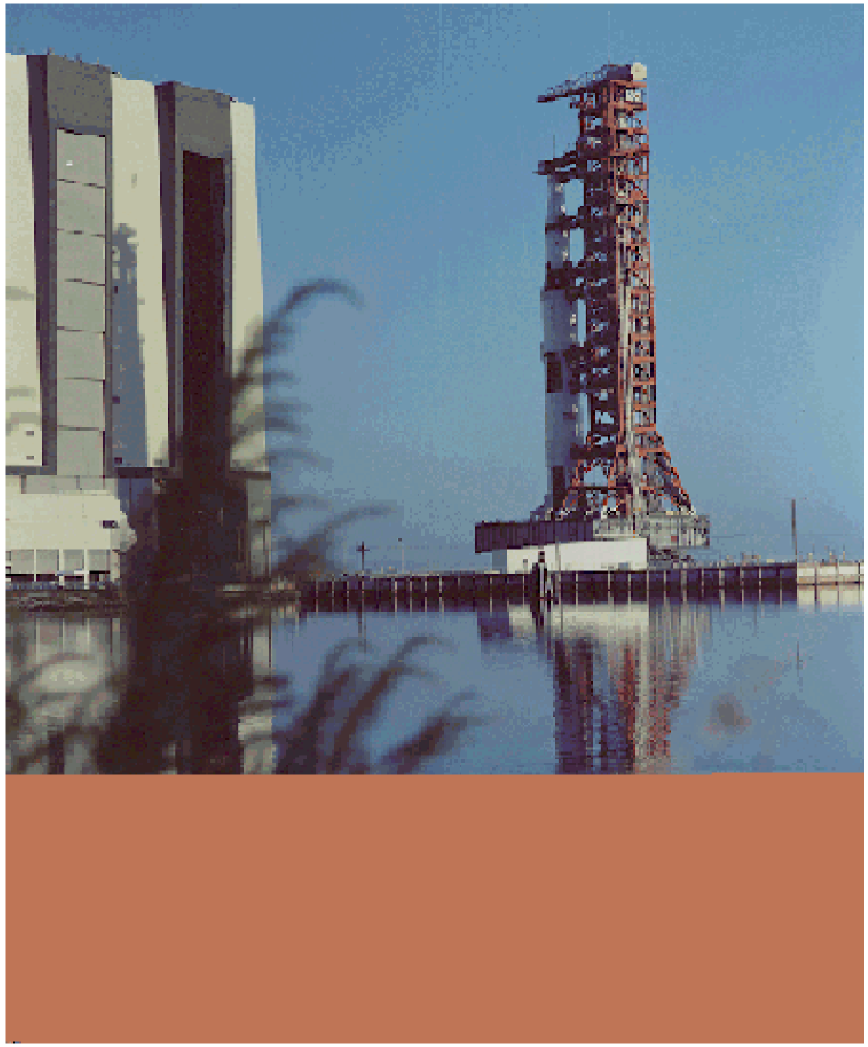
Heavy-Lift Launch Vehicle Concepts

- **Numerous HLLV concept designs have been studied by NASA/DoD/ Contractor teams for application to Lunar Return, Mars Exploration, and Ballistic Missile Defense applications.***

Vehicle/Heritage	**LEO Payload**
Rebuilt/Uprated Saturn V:	**140+ tonnes**
Saturn V derived:	**240 tonnes**
Shuttle-derived inline:	**85 tonnes**
Shuttle-derived sidemount:	**80 tonnes**

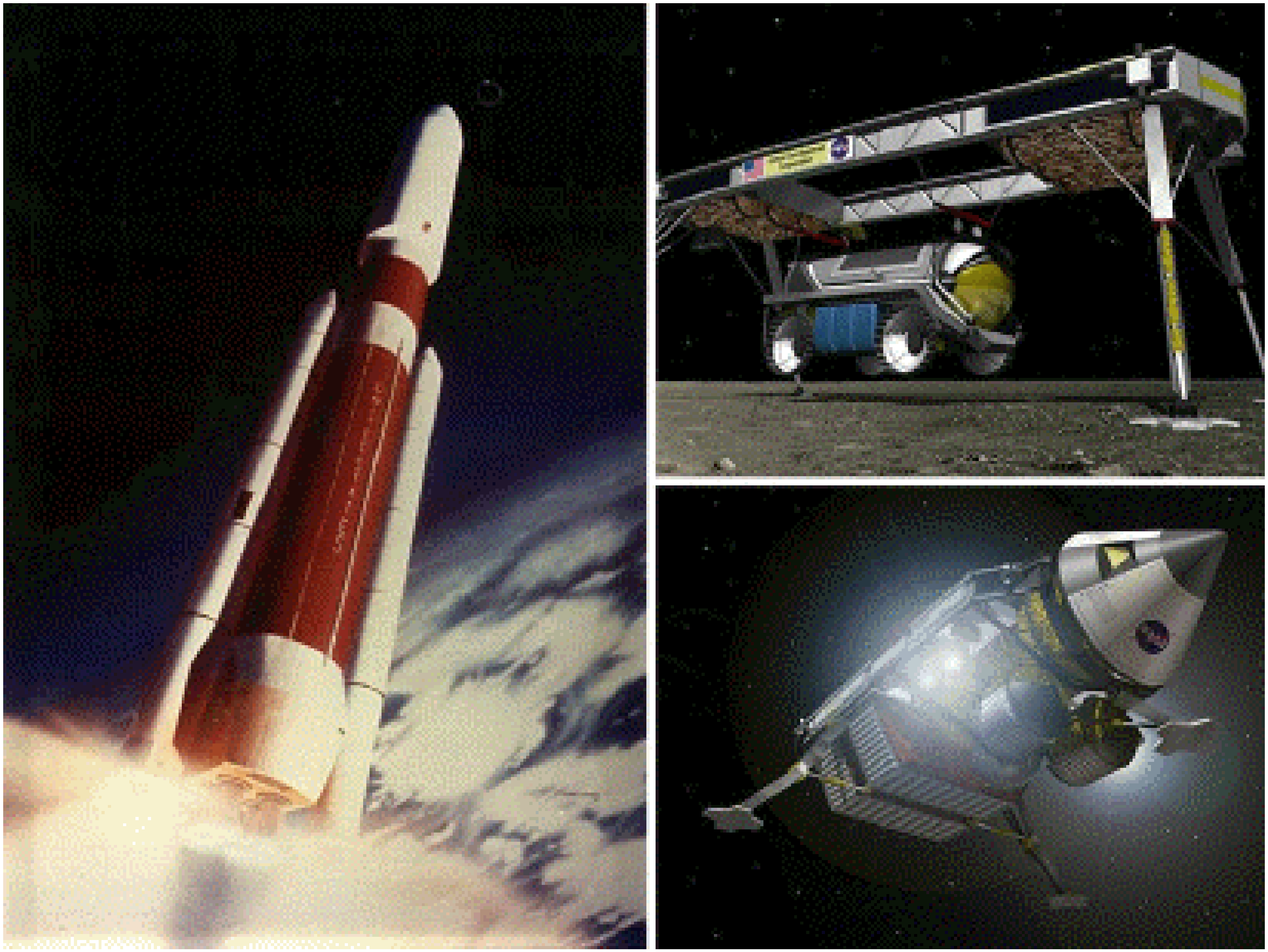
*** Refer to: http://exploration.jsc.nasa.gov/EXPLORE/explore.htm**

Apollo 17/Saturn V Rollout

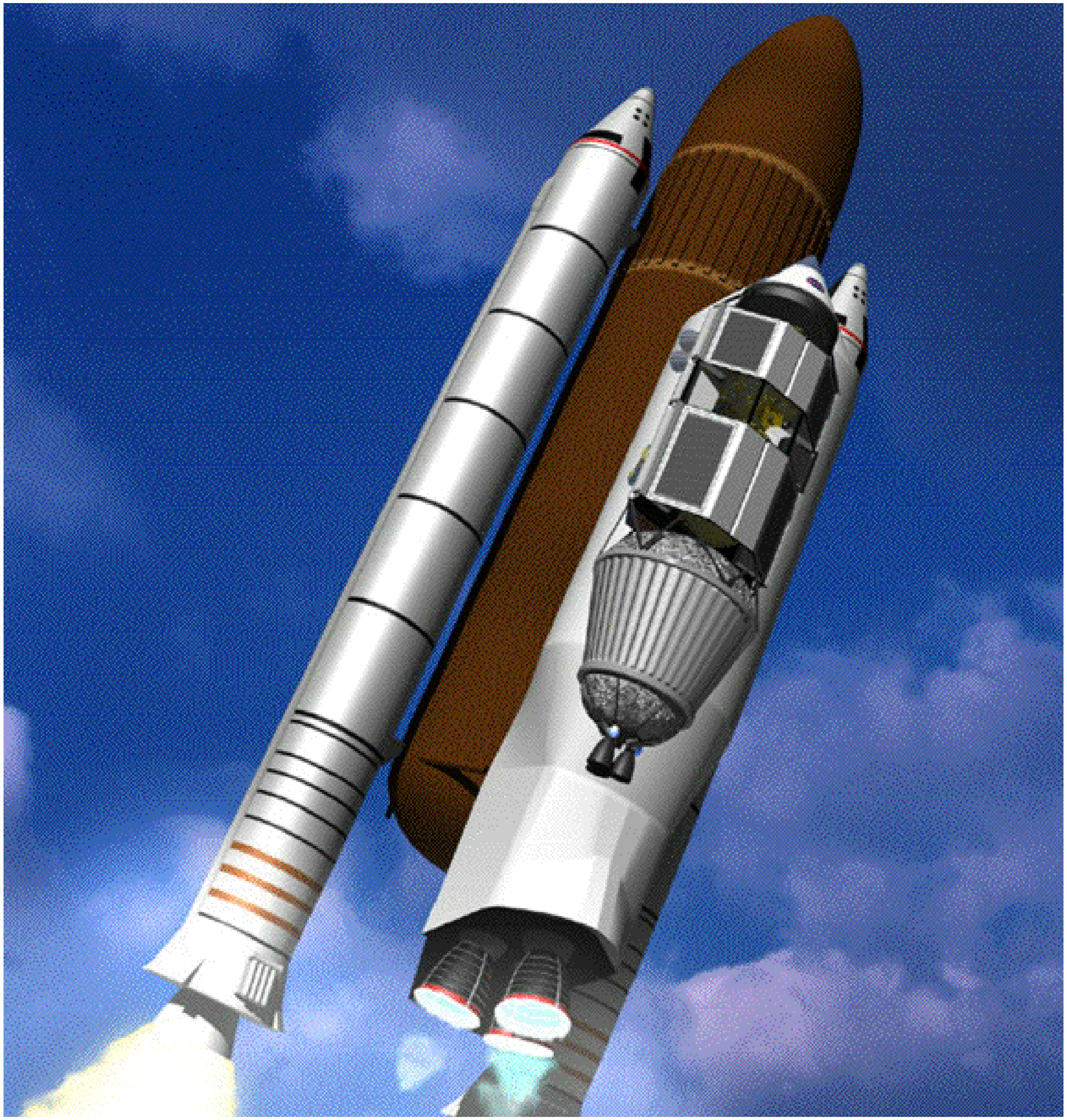


Saturn V-Derived HLLV and ISS-Derived Habitat Module

Shuttle-Derived Inline HLLV Concept and Lunar Landers



Shuttle-Derived Sidemount Heavy Lift Launch Vehicle



Magnum Launch Vehicle - Potential Vehicle Paths

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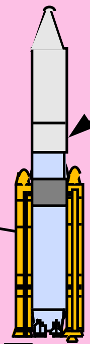
SDV Path



US Options
- Solid
- Liquid
  - Storable
  - LOX/RP
  - LOX/LH2
  - Other?
- Hybrid

ET Diameter Tankage
- Standard ET Fabrication
- Non-performance Driven ET Fab
- Extended Tank
- Composites

Engine Options
- RS-68
- SSME w/ PA Mod
- TRW Eng.
- RD-170
- RD-171
- RD-180

Booster Options
- RSRB's
- LRB's
  - Propellant Type
  - Engine Options
  - Pressure Fed
- Hybrids
- Titan IV Solids

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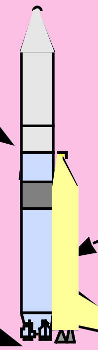
Flyback Booster Path



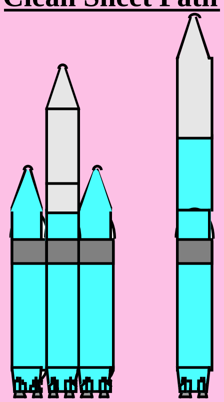
US Options
- Solid
- Liquid
  - Storable
  - LOX/RP
  - LOX/LH2
  - Other?
- Hybrid

Flyback Booster Options
- FBB Concept from Perkinson / Eudy Study

Engine Options
- RS-68
- SSME w/ PA Mod
- TRW Eng.
- RD-170
- RD-171
- RD-180

③

Clean Sheet Path



Configuration Selection
- Parallel or Series
- Propellant Selection
- Engine Size and Number

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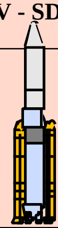
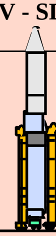
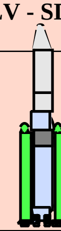
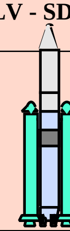
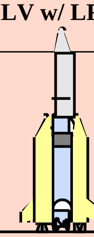
Other Contractor Path

- **Lockheed Martin -** ***Stellaris***
- **Microcosm -** ***Heavy Lift BMDO***
- **Truax Engineering -** ***Excalibur***
- **Thiokol - EELV, Atlas, Delta Core w/ Solids**

Magnum Launch Vehicle - Inhouse Concept Comparison

SDV and LFBB Pathway Concepts
(Note: Cost and Performance Data are Very Preliminary)

	MLV - SDV-1a 	MLV - SDV-1b 	MLV - SDV-2 	MLV - SDV-3 	MLV - SDV-4 	MLV w/ LFBB 	Program Metric
Concept Description	**• 2 RSRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	**• 4 RSRB's** • ET Dia. Core w/ 5 ft. Stretch • 3 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp • Core Airstart @ T+100 sec • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	**• 2 RSRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 P/A Modules - 2 SSME per P/A Module • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	**• 2 Pump Fed LRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp - LOX / RP - 3 - RD180 per LRB • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	**• 2 Pressure Fed LRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp - LOX / RP - 4 - 800K Pr-Fed Eng/LRB • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	**• 2 Liq. Flyback Boosters** • ET Dia. Core, no Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp - LOX / RP, 1.5Mlb each - RD180 type engs, 338s ISP • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	
Preliminary Performance (220 x 220 nmi @28°)	120 K	207 K	176 K	201 K	141 K	205 K	175 K
DDT&E Cost	$1.46B	$1.46B	$2.26B	$2.00B	$2.41B	$1.46B No LFBB DDTE	$1.9B
TFU	$279M	$359M	$294M	$494M	$669M	$225M	N/A
Average Unit Cost (over 25 flights)	$1917 / lb ($230M)	$1488 / lb ($308M)	$1347 / lb ($237M)	$1761 / lb ($354M)	$3553 / lb ($501M)	$849 / lb ($174M)	$995 / lb LEO ($176M / Flt.)
GLOW	4.62 Mlb	7.34 Mlb	4.70 Mlb	5.22 Mlb	7.11 Mlb	5.72 Mlb	N/A