Near Term Space Exploration

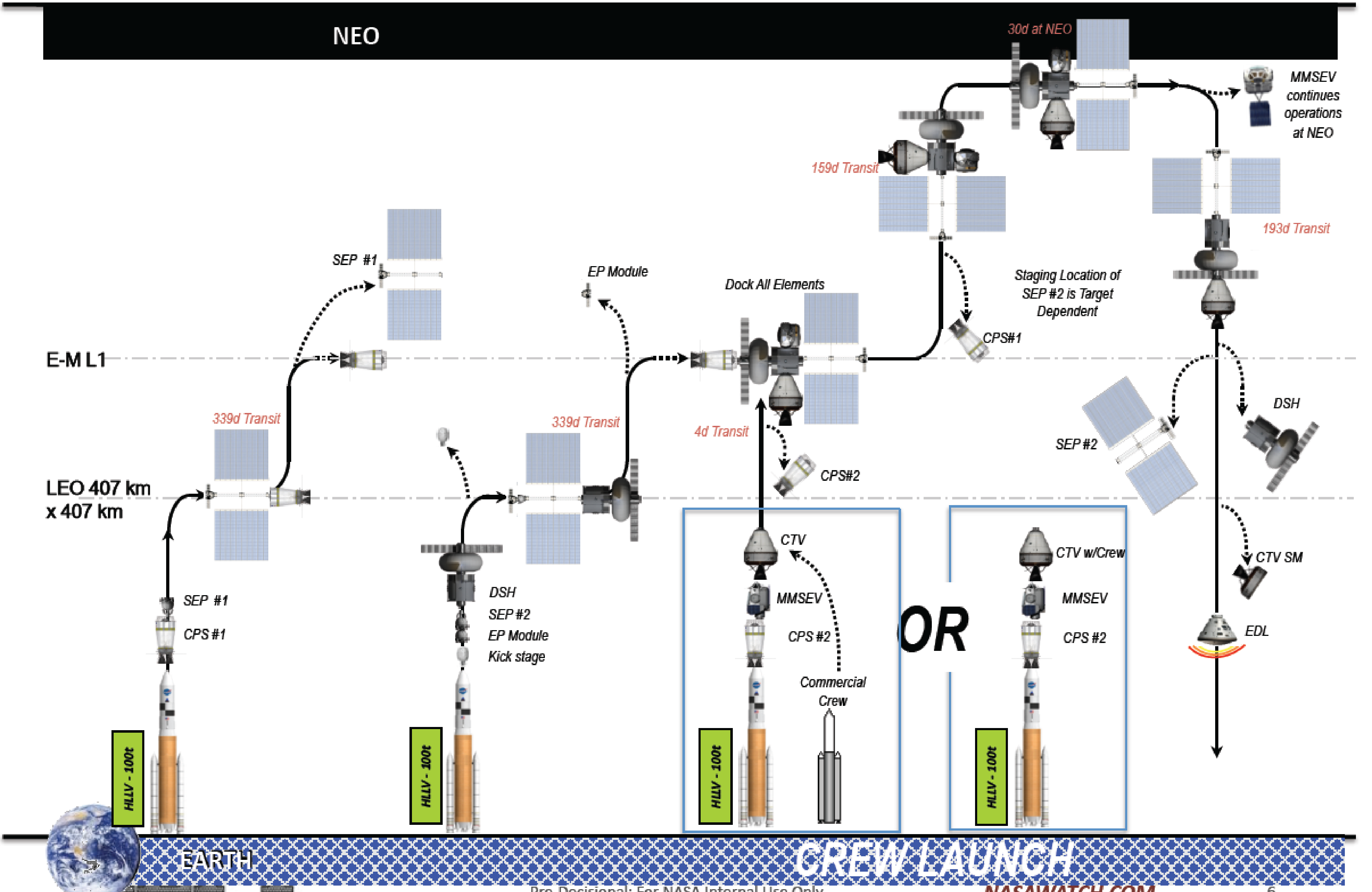
with

Commercial Launch Vehicles
Plus
Propellant Depot

Dr. Alan Wilhite and Dr. Douglas Stanley
Dale Arney and Chris Jones, GRAs
Georgia Institute of Technology/
National Institute of Aerospace
wilhite@nianet.org
757.870.5673

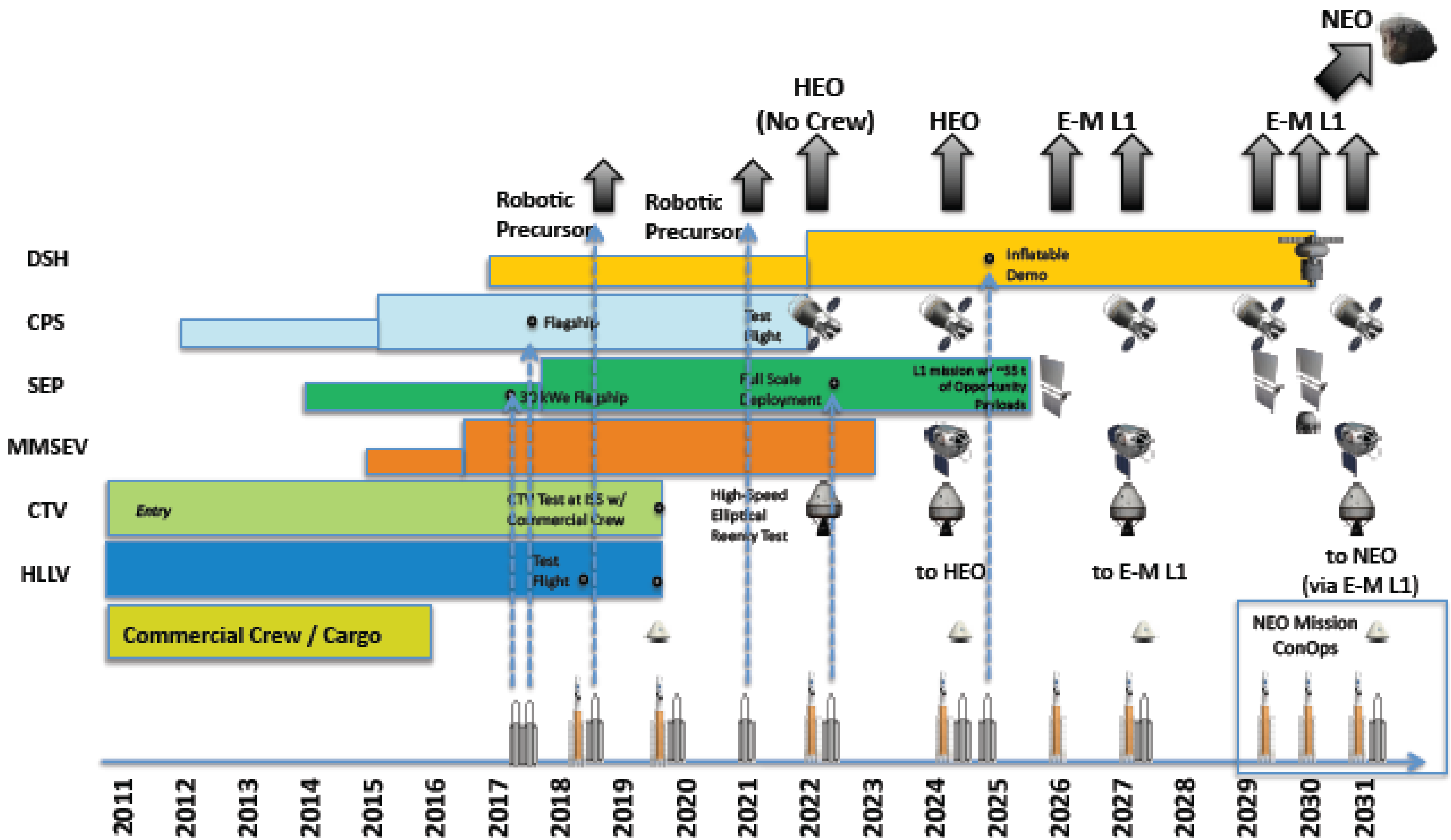
NASA’s Near-Earth Object (NEO) Campaign Plans
Human Exploration Framework Team
9/2/2010

Concept of Operations (NEO Crewed Missions, 100 t HLLV)



Campaign Profile

DRM 4: 100 t HLLV w/ Commercial Crew

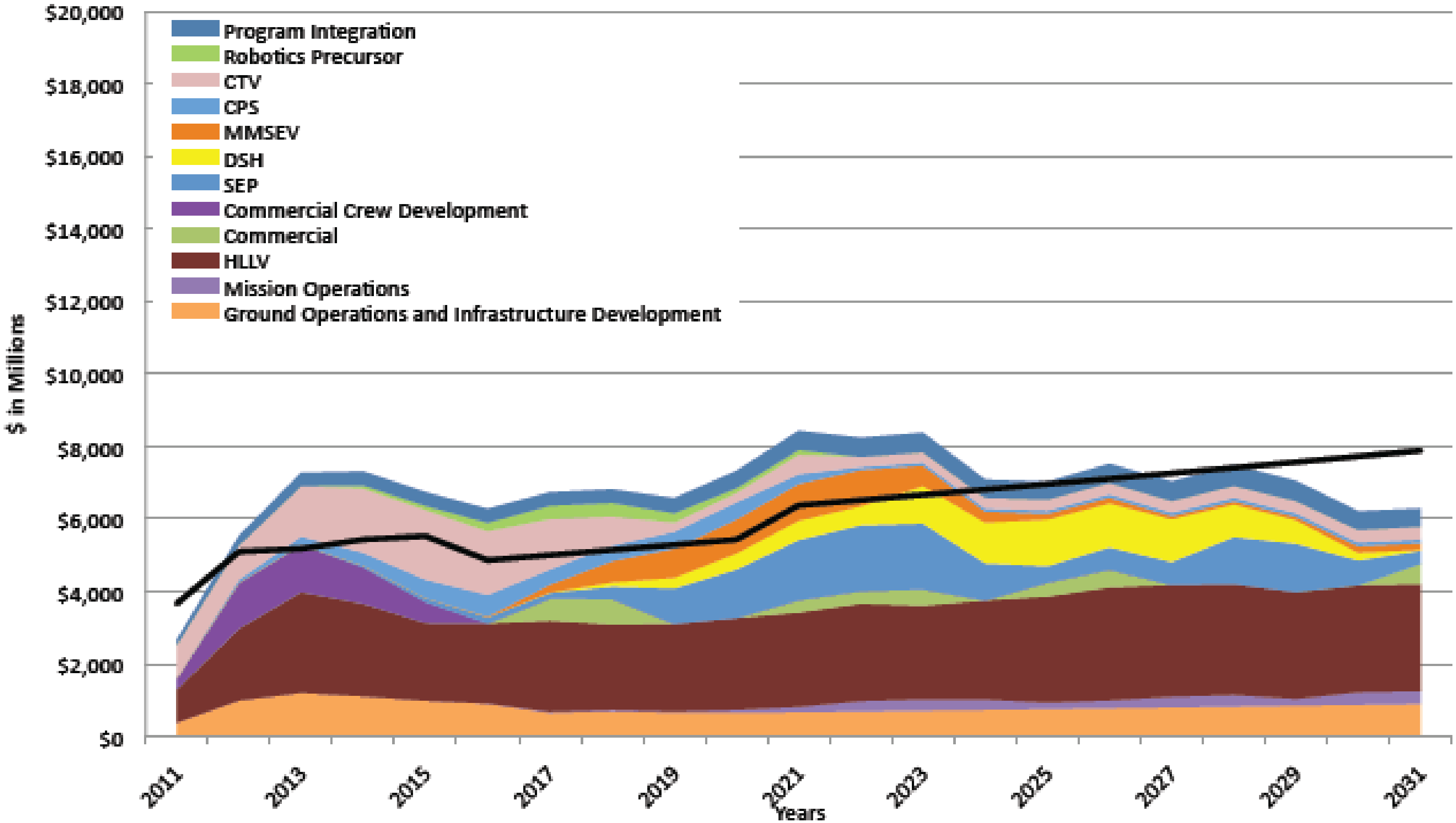


* Indicates flight to LEO

9 10

Integrated Cost Estimates

DRM 4: 100 t HLLV w/ Commercial Crew & CTV-E Prime to Representative NEO



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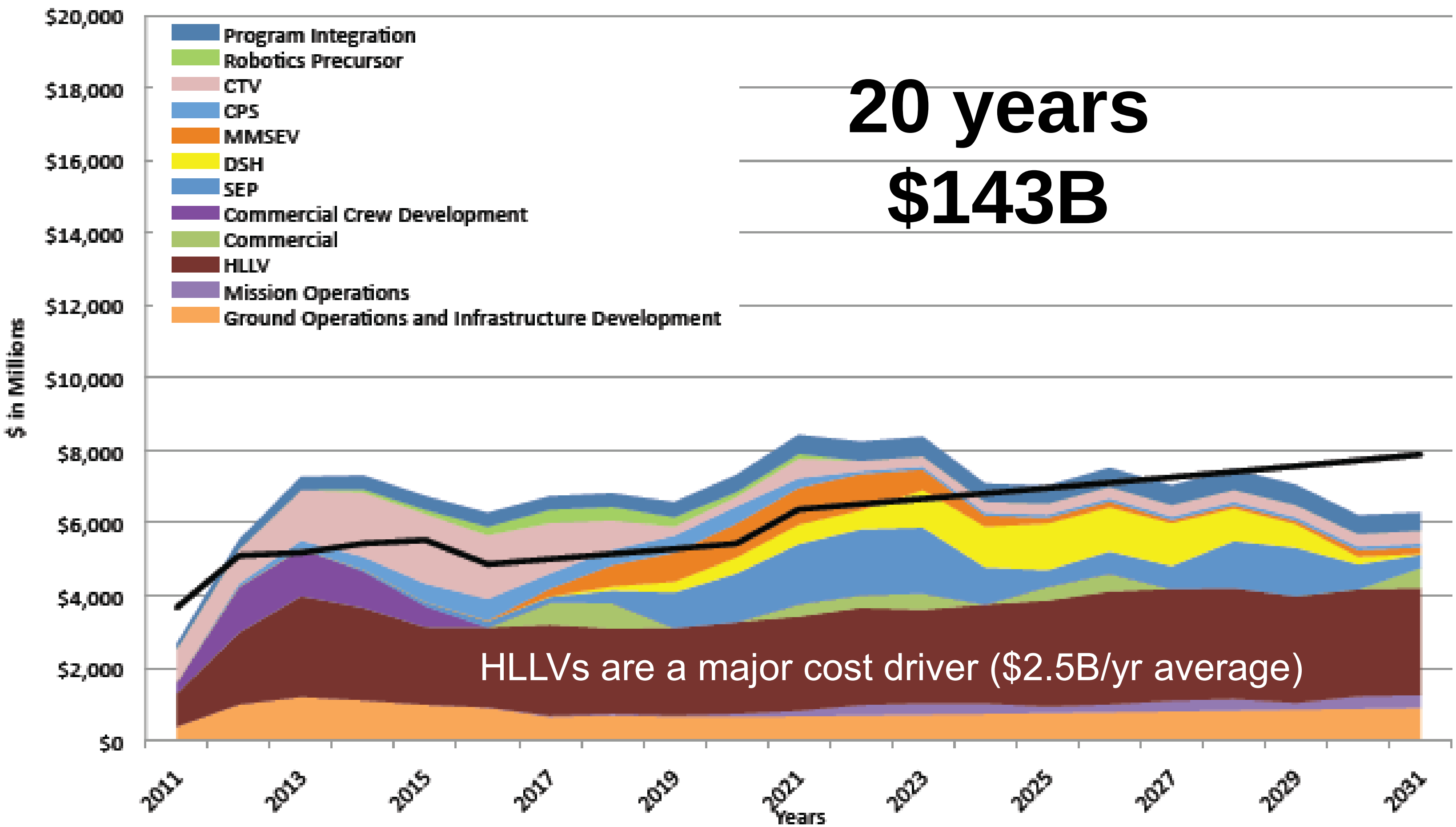

The Propellant Depot Hypotheses

- Large in-space mission elements (inert) can be lifted to LEO in increments on several medium-lift commercial launch vehicles (CLVs) rather than on one Heavy Lift Launch Vehicles (HLLVs)
- The heavy in-space transportation mission elements are beyond the payload capability of medium-lift CLVs; however, 80 to 90 percent of their mass is propellant that can be delivered in increments to a **Propellant Depot** and transferred to the in-space stages
- Saves DDT&E costs of HLLV
- Low-flight-rate HLLV dominated by high unique fixed costs. Use of CLVs eliminates these costs and spreads lower fixed costs over more flights and other customers.
- Use of large re-fueled cryo stages save DDT&E/ops costs for advanced propulsion stages (e.g., SEP)

Present Propellant Depot study follows Augustine and NRC recommendations

Present Propellant Depot Study Assumptions

- Advanced Technology (Also required for HEFT missions, except cryo transfer)
  - Cryo Zero Boiloff (Cryo Coolers)
  - Zero g automated propellant line docking and cryo transfer
  - (Semi) Automated in-space assembly of payloads
  - Automated Rendezvous and Docking
  - In-space IVHM and launch control
- State of the Practice Technology
  - Falcon 9 Heavy
  - Aluminum structure and tanks
  - RL10 propulsion
- Sources of Costs
  - NASA's Human Exploration Framework Team briefing (9/2/2010)
  - NASA's Exploration Systems Architecture Study (NASA TM-2005-214062)
  - Space X + large margins for Falcon 9 Heavy commercial launch vehicle
  - NASA Air Force Cost Model (NAFCOM)

DRM 2B Cost Summary

Constant FY10 Dollars

Capability	IOC costs $ in Million	Unit Cost $ in Million	% Applied for Uncertainty
Commercial Crew Development	$4,100	N/A	N/A
Commercial Crew Launch Vehicle	N/A	$313	25%
Commercial Cargo Launch Vehicle Atlas AV501 Moderate	N/A	$200	25%
Commercial Cargo Launch Vehicle Delta IV	N/A	$424	25%
100 mt HLLV 27.5 ' SSP Derived In line w/out Upper Stage with 5 SSME	$17,400	$1,860	25%
Ground Infrastructure	$7,000	$500	25%
70 mt HLLV 27.5 ' SSP Derived In line w/out Upper Stage with 3 SSME	$14,300	$1,600	25%
HLLV 33 ' RP Core*	[illegible]	[illegible]	[illegible]
Cryo Propulsion Stage (CPS) Medium	[illegible]	[illegible]	[illegible]
CPS Heavy (if built in parallel with CPS Medium)	$2,500	$316	35%
LEO Tug*	$1,800	$450	35%
Propellant Resupply Module (PRM)	$191	$191	35%
Solar Electric Propulsion (SEP)	$7,000	$1,500	25%
Nuclear Electric Propulsion (NEP)*	$11,100	N/A	N/A
Nuclear Thermal Propulsion (NTP)*	$19,000	N/A	35%
MMSEV In House	$3,800	$210	50%
Crew Transfer Vehicle (CTV)-Entry	$6,200	$400	25%
CTV-Entry Prime	$7,900	$597	25%
CTV-Ascent/Entry	$10,200	$840	25%
Deep Space Habitat (DSH)	$6,400	N/A	25%
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HLLV $18,600/kg payload

BACK

*lower fidelity estimates

Falcon 9 Launch Vehicle Family

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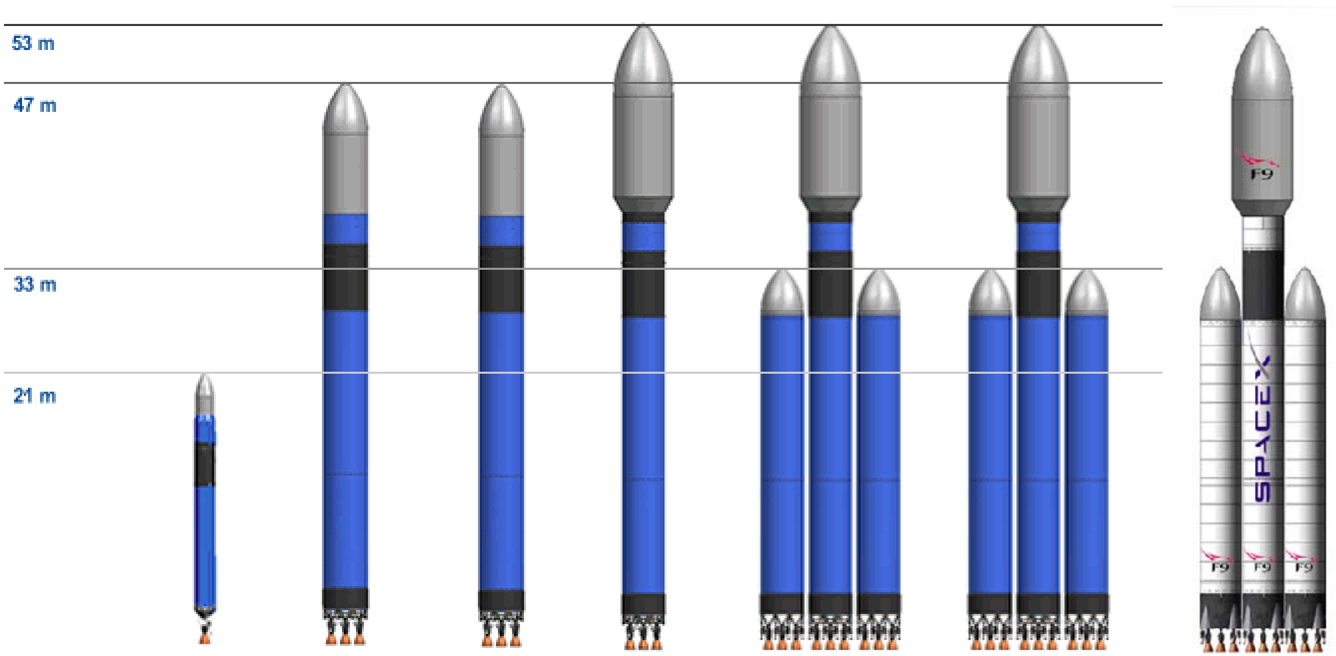


	Falcon 1	Falcon 5	Falcon 9	Falcon 9	Falcon 9 - S5	Falcon 9 - S9	Falcon 9 Heavy (Merlin 1C+)
LEO	570 kg	4,100 kg	9,300 kg	8,700 kg	16,500 kg	24,750 kg	32,000 kg
GTO	--	1,050 kg	3,400 kg	3,100 kg	6,400 kg	9,650 kg	15,010 kg
Fairing diameter	1.5 m	3.6 m	3.6 m	5.2 m	5.2 m	5.2 m	5.2 m
Price in millions *	$6.7	$18	$27	$35	$51	$78	$95

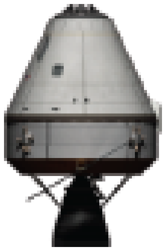
* Prices are all inclusive of launch range, third party insurance and standard payload integration costs.

$3000/kg

Falcon 9H has 6x lower $/kg but 3x lower payload capability

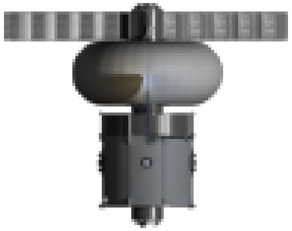
In-Space Mission Elements for DRM 4

Crew Transfer Vehicle (CTV)

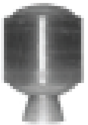


Multi Mission Space Exploration Vehicle (MMSEV)

Deep Space Habitat (DSH)

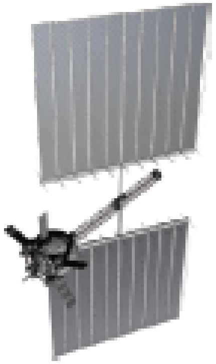


Kick Stage

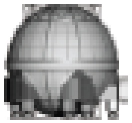


Cryogenic Propulsion Stage (CPS)

Solar Electric Propulsion (SEP)



Electric Propulsion Module (EPM)



Mission Element	*CTV-ERV*	*MMSEV*	*DSH*	*Kick Stage*	*CPS*	*SEP*	*EPM*
Mass (kg) **	13,500	6,700	23,600	6,300	12,600	10,600	2,900
Diameter (m)	5.2	4.5	4.57 (max stowed)	1.9	7.5	5.75 (stowed)	5.75 (stowed)
Length (m)	4.2	6.8	7.7*	3	12.3	9	5.1
Pressurized Vol. (m3)	18.4	12	115	n/a	n/a	n/a	n/a

NOTES:

- *Elements Not To Scale*
- ** Habitat length with adapters: 9.8 m*
- *** Inert mass shown for CPS, SEP and EPM*

In-Space Mission Elements for DRM 4

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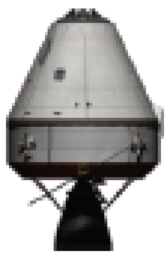

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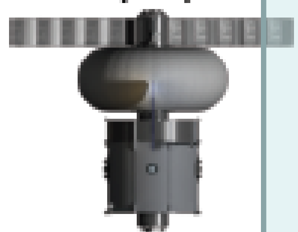
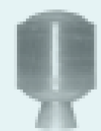


Not Required if Depot and Large CPS used

Kick Stage



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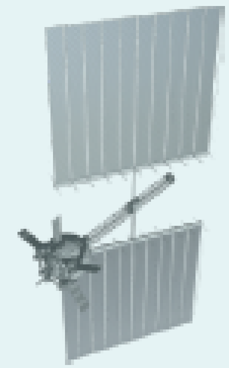
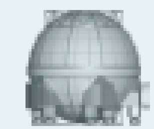


Electric Propulsion Module (EPM)



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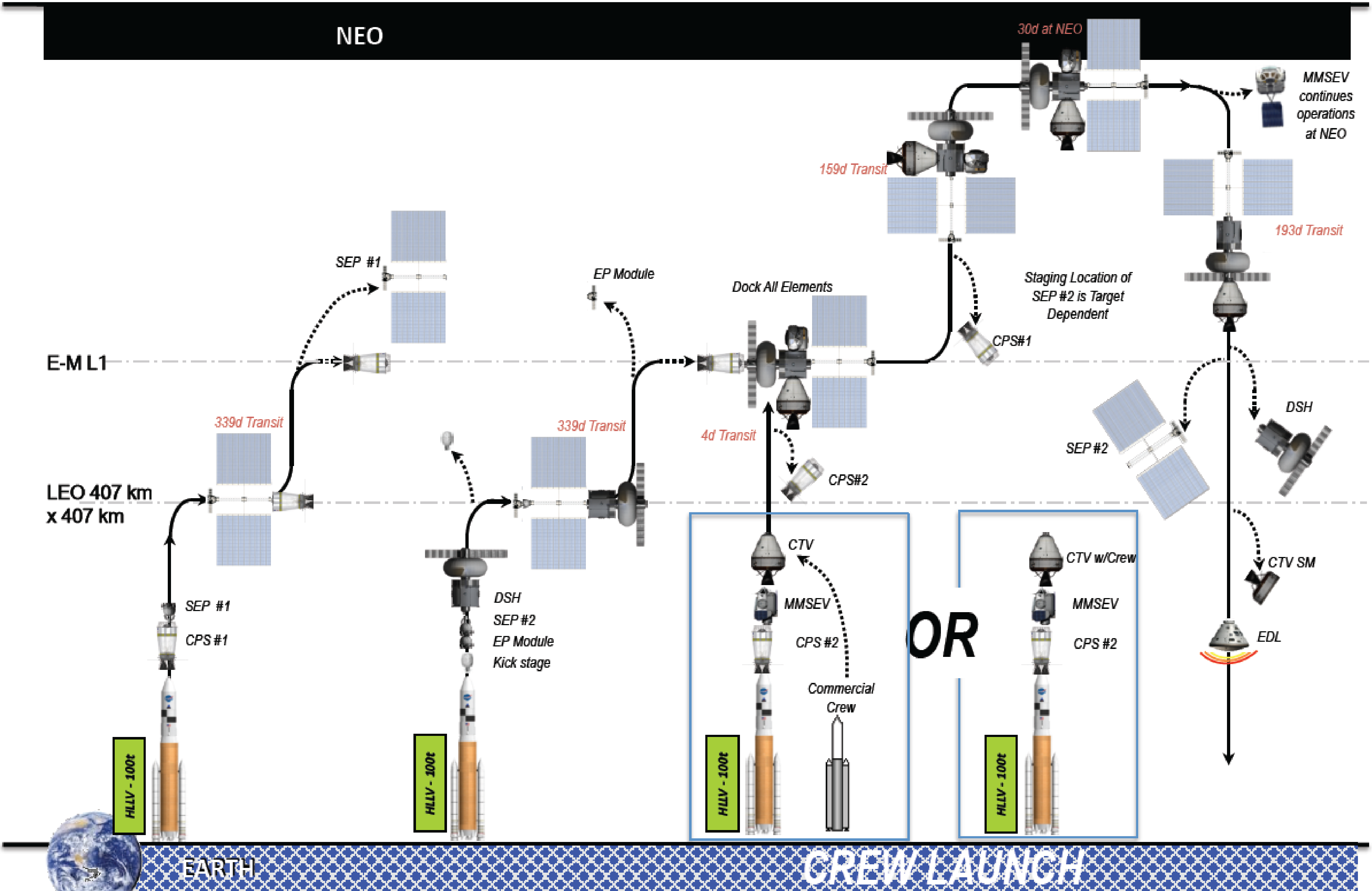
Diameter (m)	5.2	4.5	4.57 (max stowed)	1.9	7.5	5.75 (stowed)	5.75 (stowed)
Length							5.1
Pressu							n/a

1) Falcon 9 Heavy payload is 32,000 kg; all element inerts are less
2) F9H shroud diameter is 5.2m; only CPS will not fit.
3) Depot and large CPS require larger shroud diameters

- *Elements not to scale*
- ** Habitat length with adapters: 9.8 m*
- *** Inert mass shown for CPS, SEP and EPM*

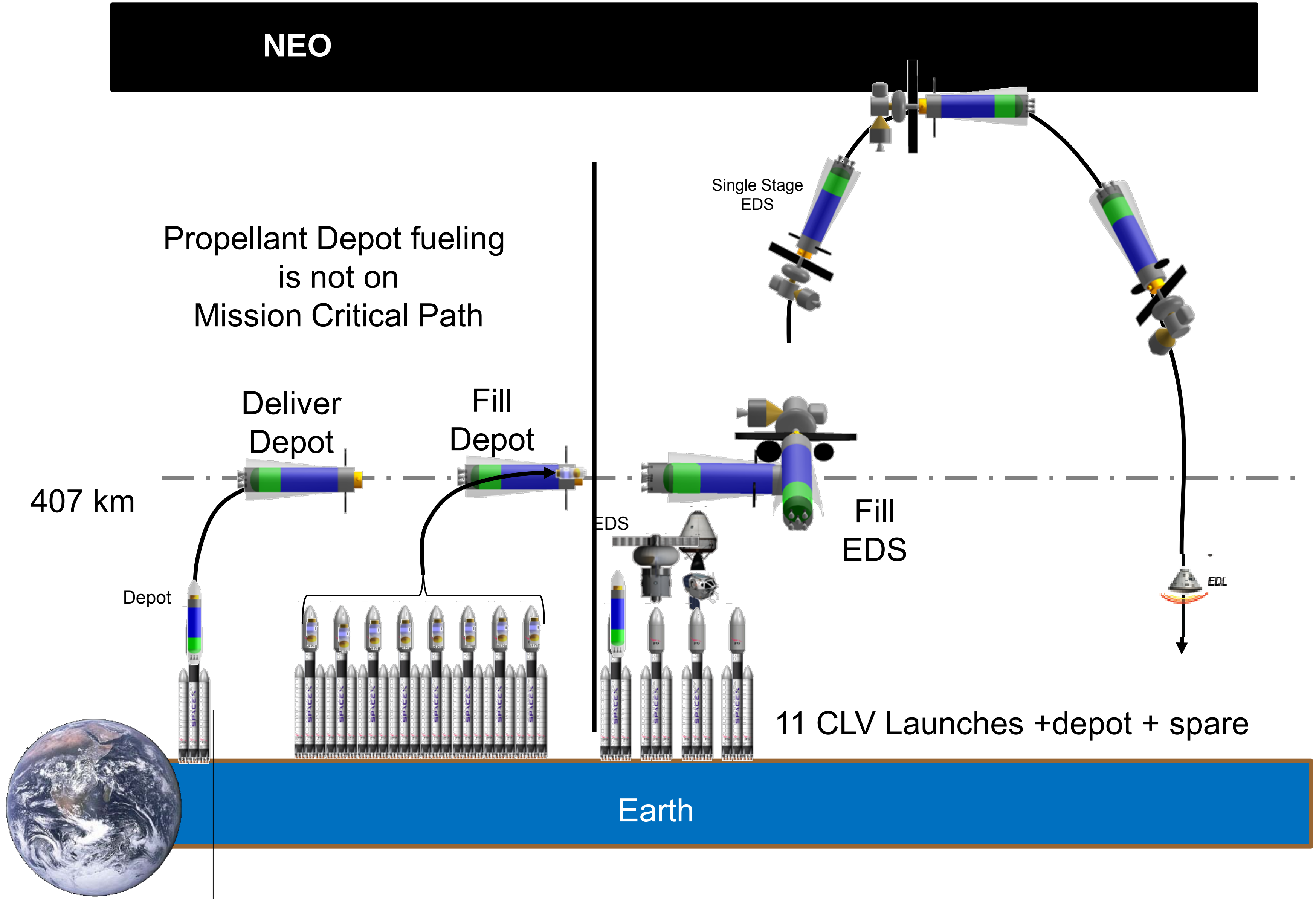
Concept of Operations (NEO Crewed Missions, 100 t HLLV)



A CLV and Depot ConOp Methodology (no trades, no optimization, for initial cost comparisons only)

- Depot
  - Sized for transfer of total mission propellant
  - Derivative Earth Departure Stage (EDS) to reduce costs
    - > 5 engines to transfer to 407km orbit
    - > Only one engine required for orbit keeping (could use OMS)
  - Like EDS, carries suborbital propellant to reach 407km circular orbit
  - Decouples in-space transportation from multiple refills like other architectures
    - > Only one prop line coupling required for propellant transfer
    - > Short stay time for critical in-space elements
- Earth Departure Stage (EDS)
  - Sized for NEO, lunar, and Mars flexible path mission (delivers 2x payload as ESAS/Constellation EDS for lunar mission)
  - Suborbital/TransInjection T/Ws compatible between empty suborbital and full for transinjection
  - Used 464.5 for RL10B-2 Delta IV second stage
- Multiple CLVs could be used
  - Competition for propellant delivery (reduced costs?)
  - Not on critical mission path with multiple delivery sources if one has catastrophic failure

ConOps with Falcon 9 Heavy + Earth Departure Stage/Depot



Campaign Profile

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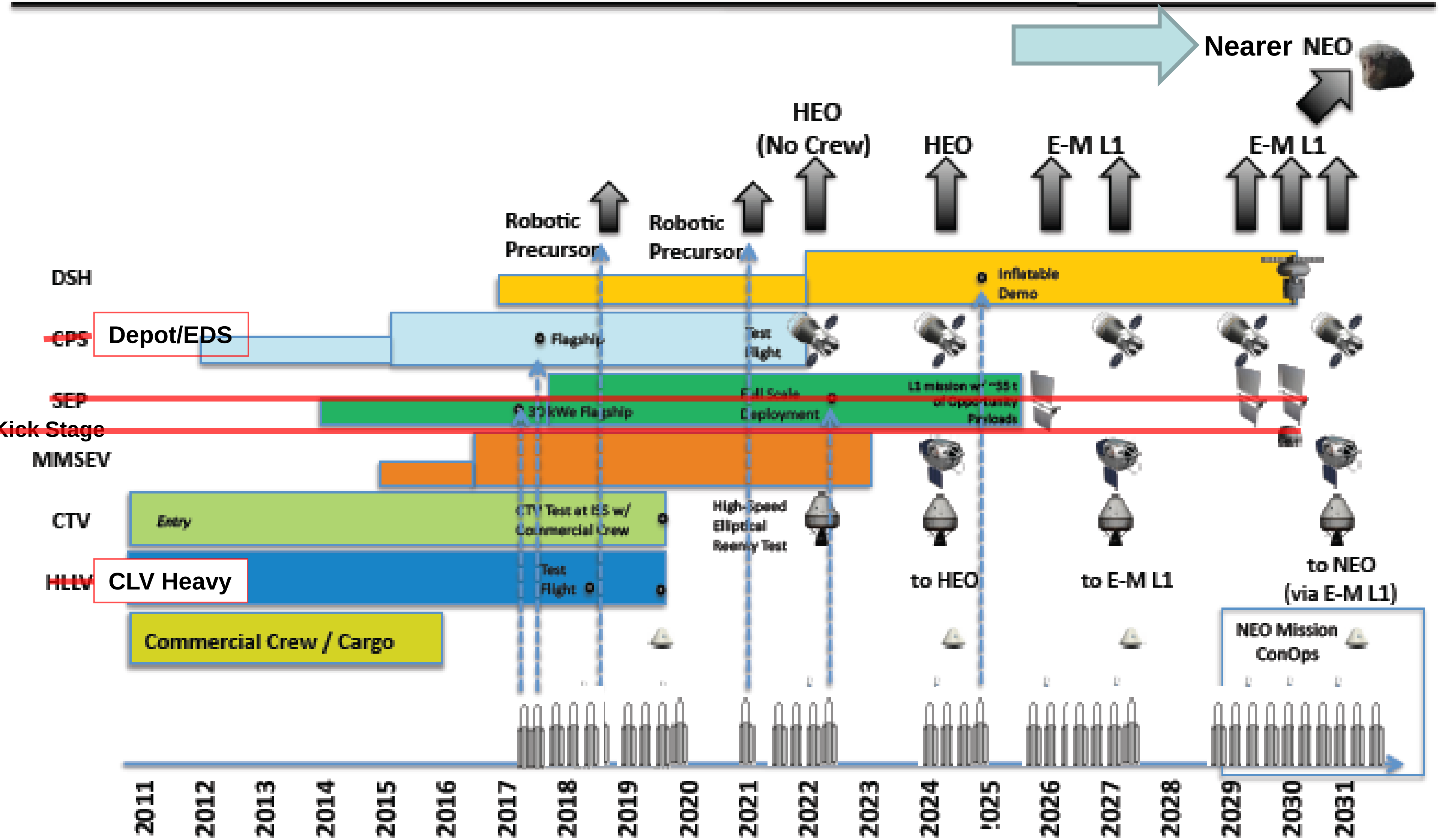


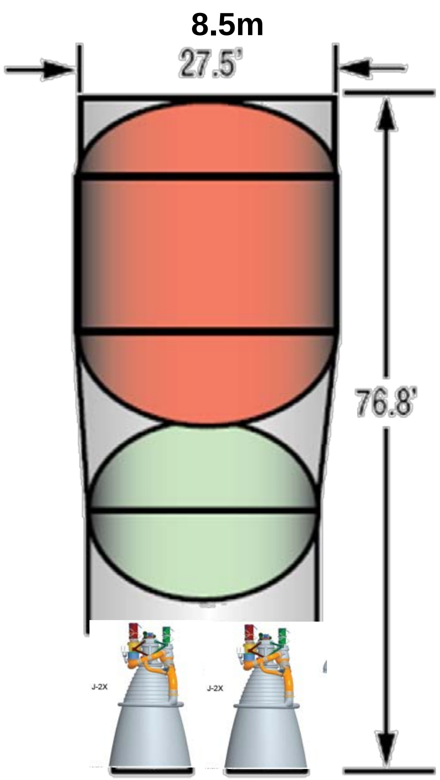
• Indicates flight to LEO

38 + 4 reserve

Falcon 9 Heavy EDS

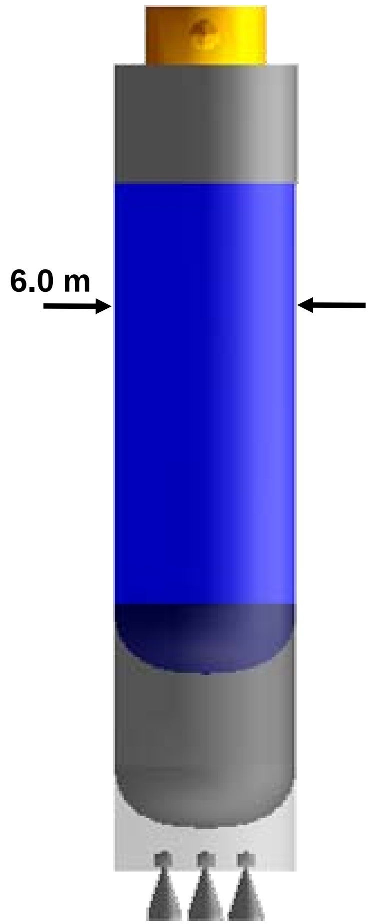
Earth Departure Stage

ESAS



2xJ-2X
Isp = 451 s

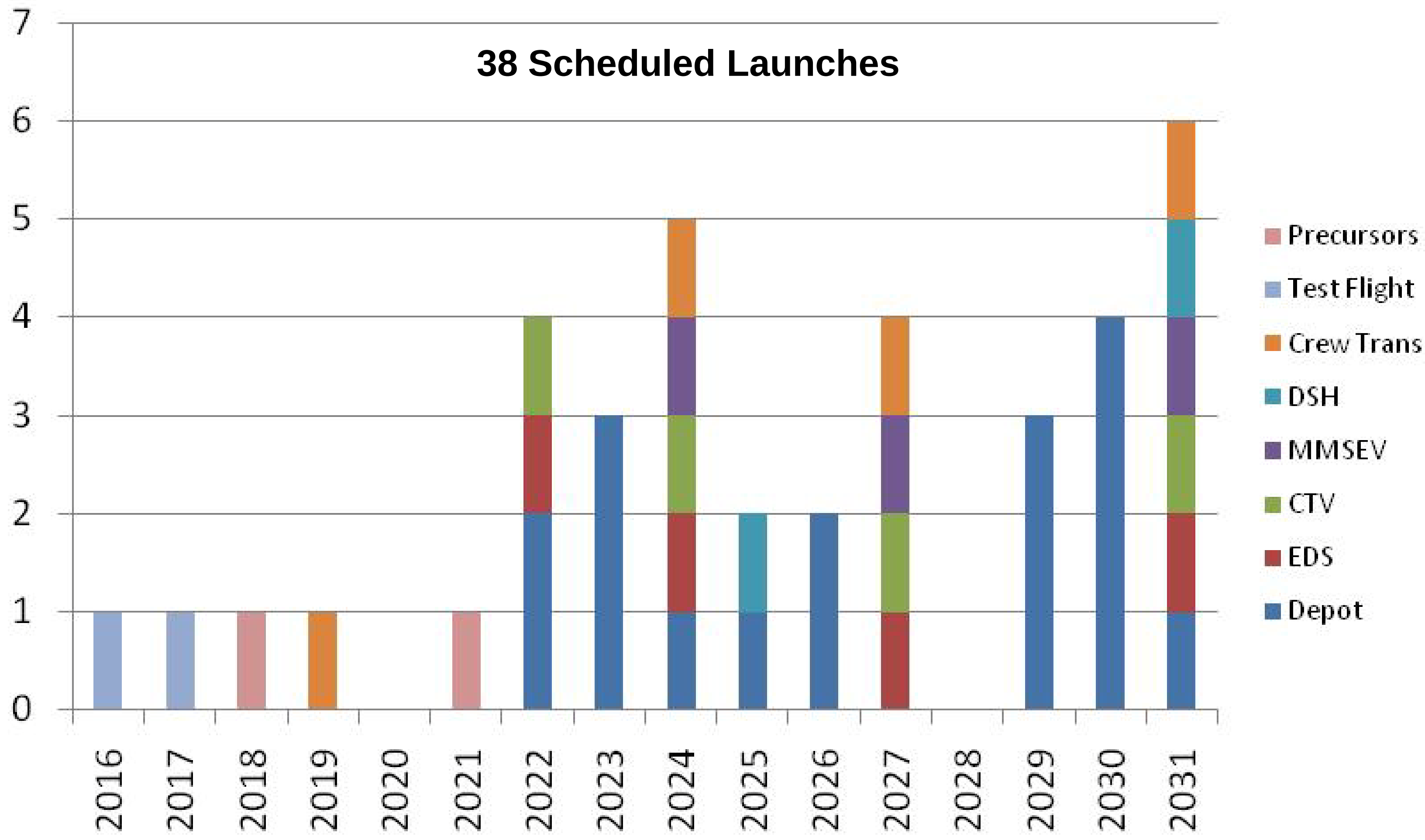
Falcon 9H
2nd Stage/EDS



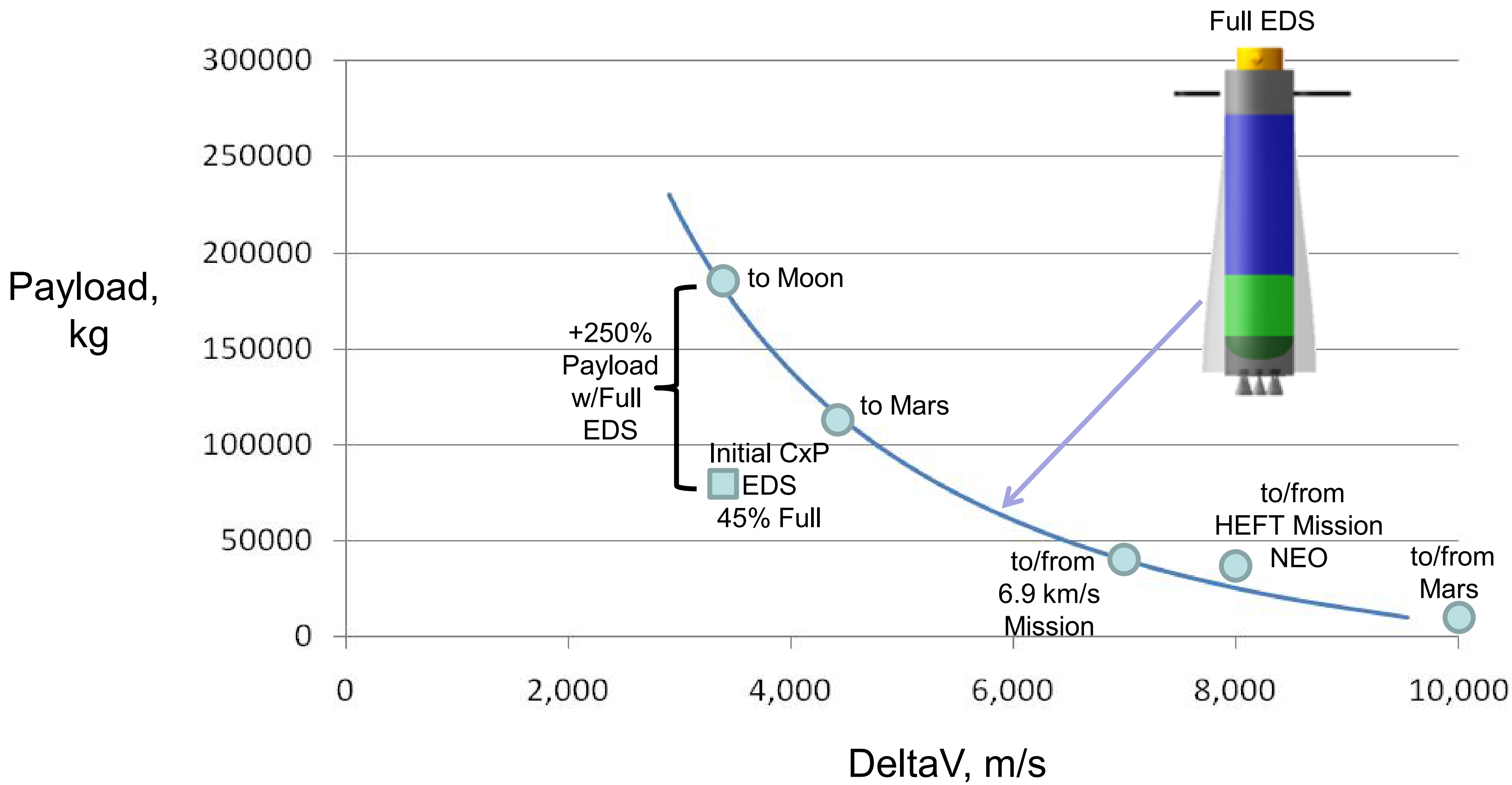
5xRL10B-2
Isp = 464 s

	ESAS EDS	F9H EDS
Primary Body Structure	8,887	8,950
Secondary Structures	1,105	1,214
Separation Systems	90	120
Thermal Protection System	144	291
Thermal Control System	672	672
Main Propulsion System	5,734	1,541 *
Power (electrical)	641	641
Power (Hydraulic)	183	89
Avionics	195	195
Cryocooler		3,639 *
Misc.	59	59
Shroud and Adapters		7,100
Dry	**17,711**	**24,511**
Growth	1,632	2,259
Dry w/Growth	**19,343**	**26,770**
Residuals	2,408	2,408
Reserves	285	285
In-flight Losses	27	27
Shroud and Adapters		(7,100)
Burnout Mass	**22,063**	**22,390**
Propellant to LEO/from Depot	123,061	39,349
Engine Purge Helium	24	24
Payload delivered to LEO	42,800	0
Additional Margin or Propellant	101,526	16,037
Suborbital Gross Mass (kg)	**289,474**	**77,800**
Empty Mass	22,063	22,390
IMLEO Payload	76,000	43,800
Propellant Left	123,061	16,037
Additional Depot Propellant		208,549
Total Propellant	123,061	224,586
Propellant Transfer Hwd		-3000
Orbital Gross Mass (kg)	221,124	287,776
DeltaV Capability, m/s	3,596	6,906

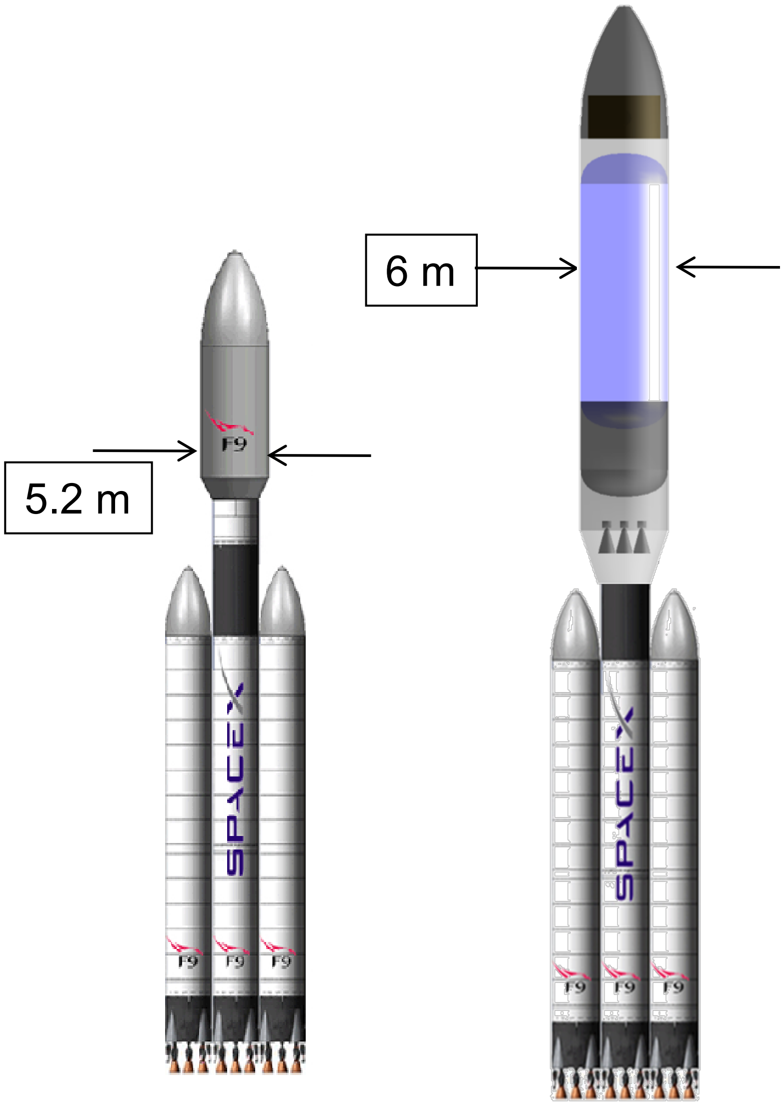
Falcon 9 Heavy Launch Schedule



Earth Departure Stage Performance Map



Earth Departure Stage for Falcon 9 Heavy



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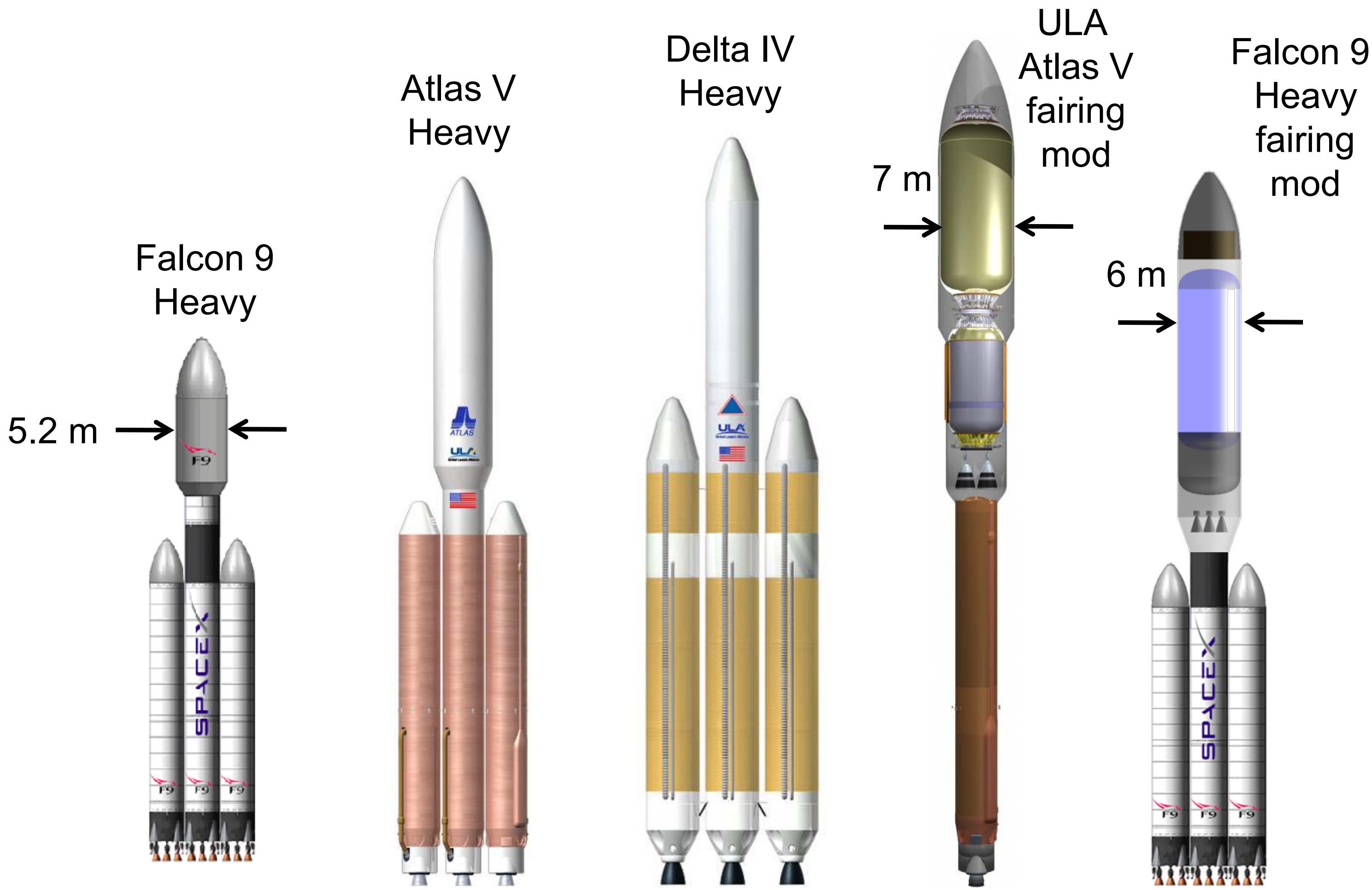
Falcon 9 Heavy

- 3 Falcon 9's using Merlin 1C+ engines
- 32t payload versus 100t HLLV

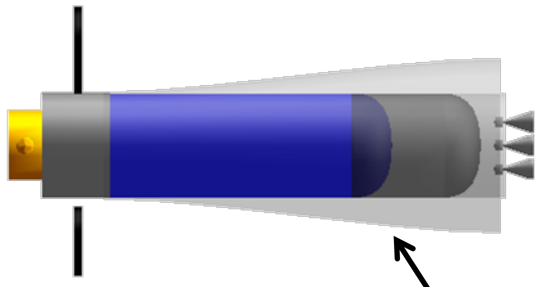
Earth Departure Stage (EDS)

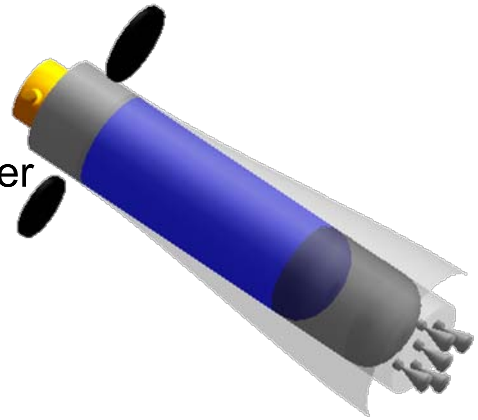
- Same propellant as Initial CxP EDS
- EDS fineness ratio increased for F9H integration
- Replaces Falcon 9 Heavy 2nd stage
- Same suborbital deltaV as 2nd stage + circ to 407 km
- Delivered to 407 km empty and fueled by Depot
- Lightly loaded - mostly inert EDS
- 5xRL10B-2 engines (Delta III and IV stage)
  - $T/W_{suborbital}$ = 0.72 (Falcon 9 2nd stage=0.6)
  - $T/W_{Orbital}$ = 0.15 (when full + payload)
- 4,100 m/s and 100t payload (Mars Injection)
- Replaces SEP, EPM, CPS, Kick Stage



	Falcon 9 Heavy	Atlas V Heavy	Delta IV Heavy	ULA Atlas V fairing mod	Falcon 9 Heavy fairing mod
Fairing dia	5.2 m	5.4 m	5.0 m	7m	6 m
Payload	32t	29.4t	25.8t		

LOX LH2 Propellant Depot





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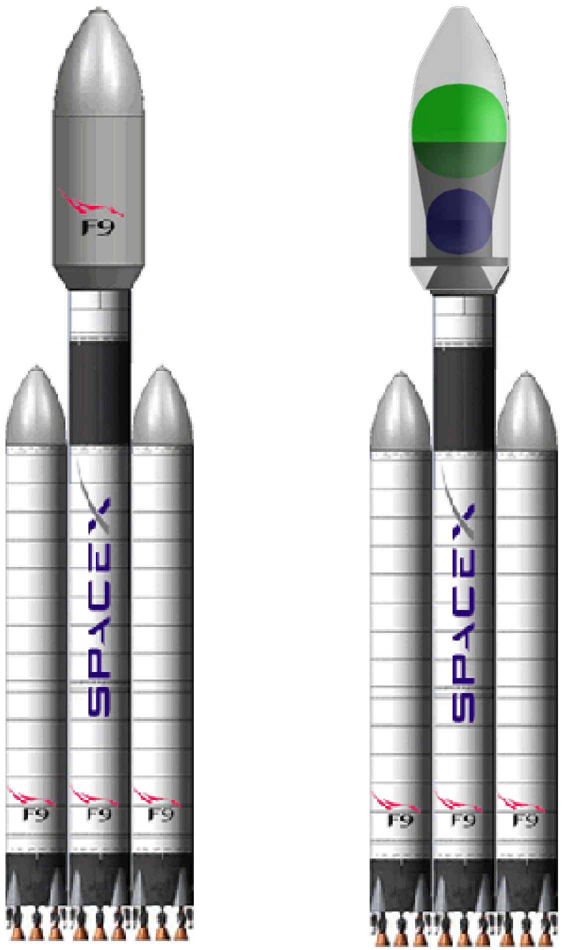
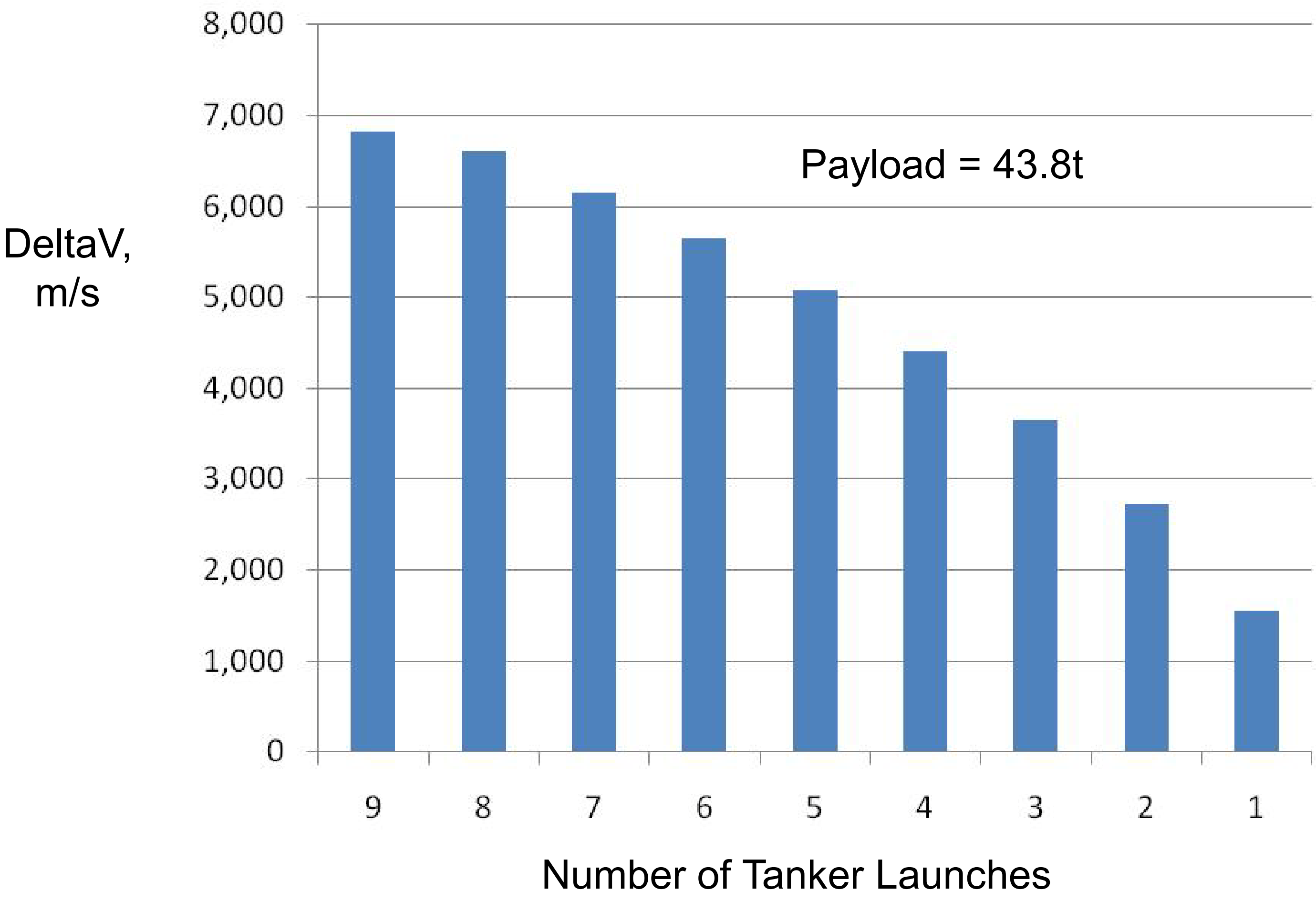
F9 Heavy Propellant Delivery



Falcon 9 Heavy	
Altitude	407 km
AR&D DV	30 m/s
Payload to 407km	29.4 t
Tanker	
Propellant Del.	26.5 t
Inert	2.9 t
PMF	0.9

8 flights + spare to fill up depot/EDS
For 6.9 km/s mission

EDS Capability



Cost Analysis

- Program Baseline
  - HEFT/NEO program study 9/2/2010

- Sources of Cost from Internet and NAFCOM
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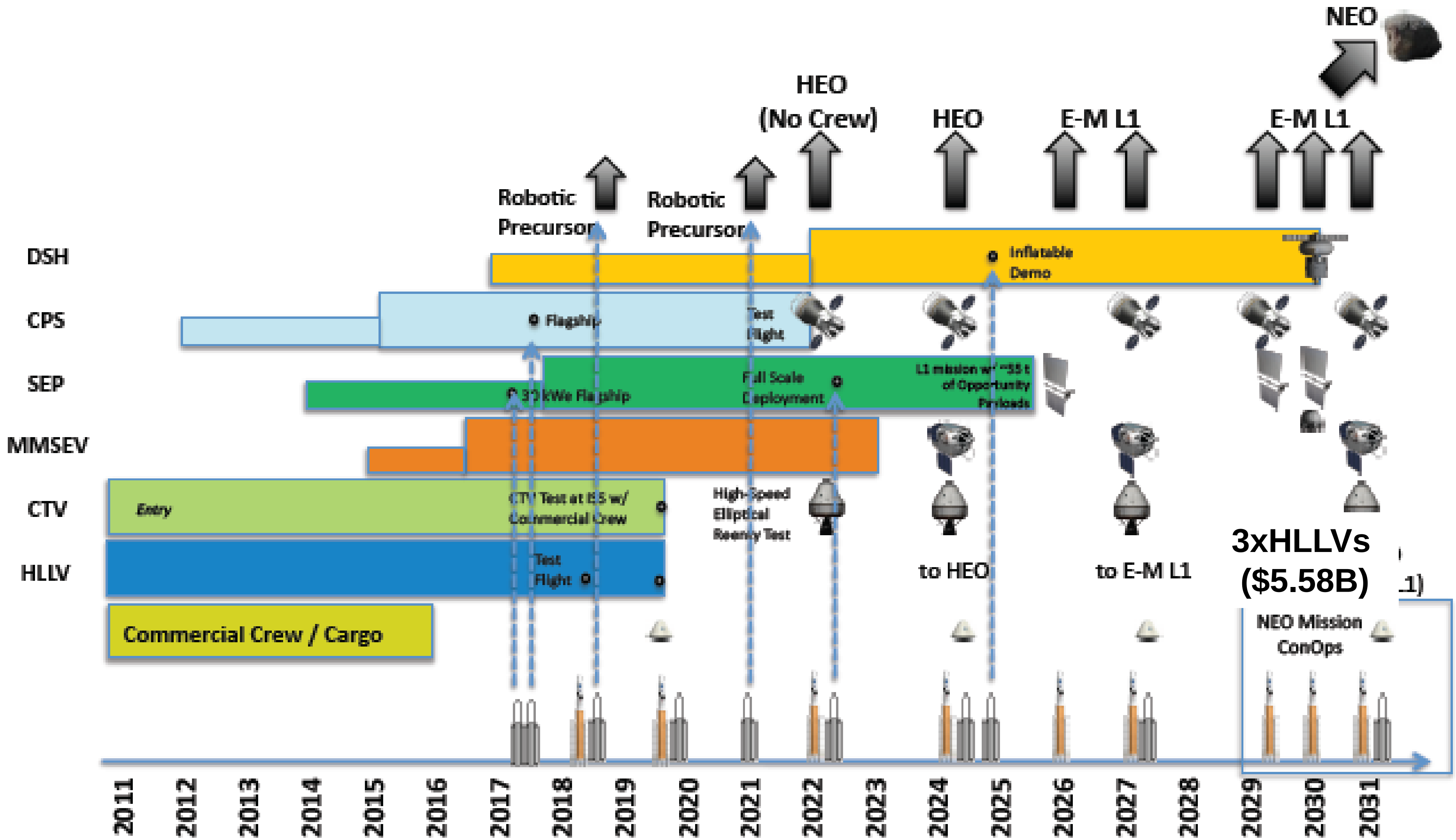

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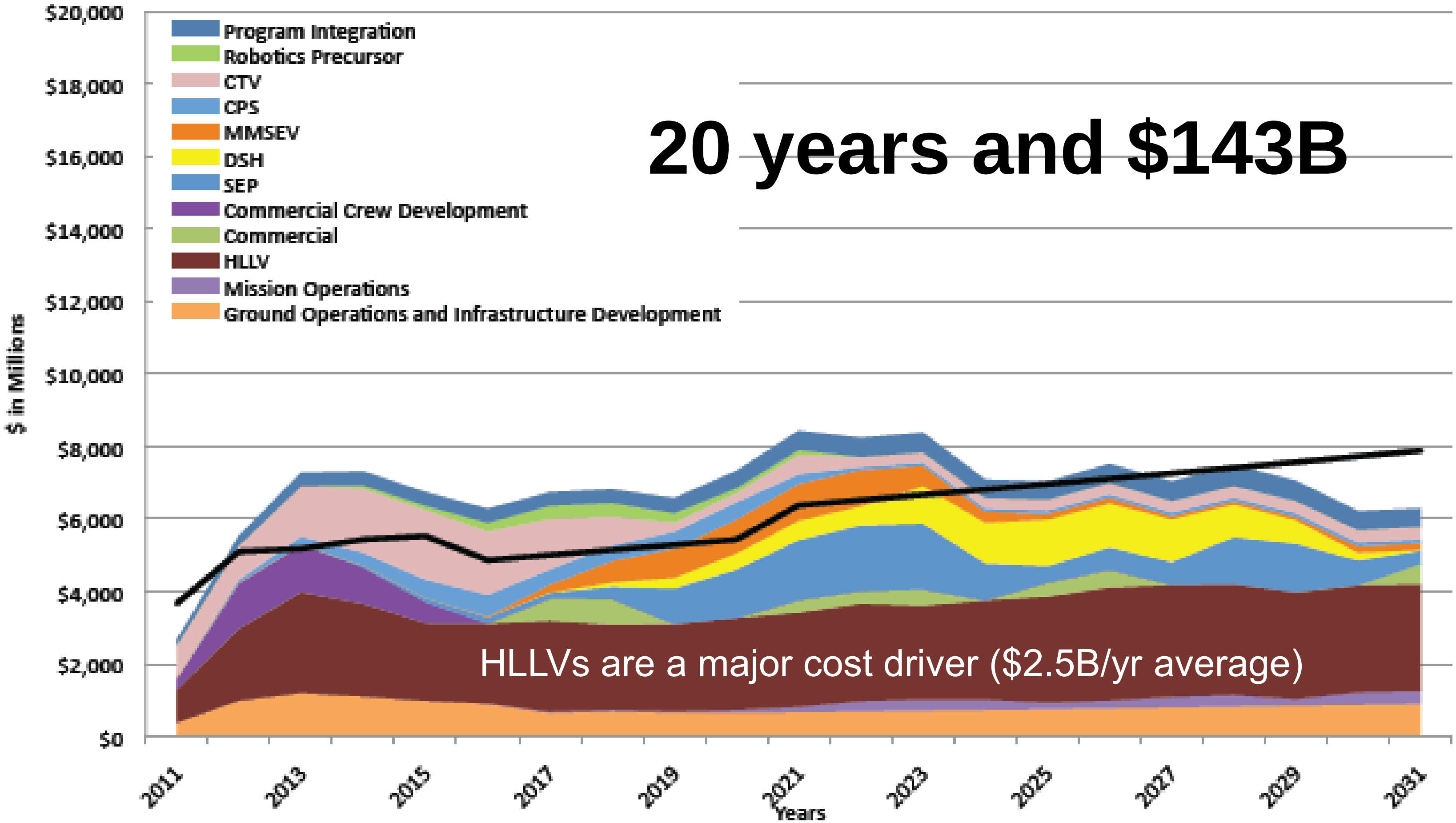
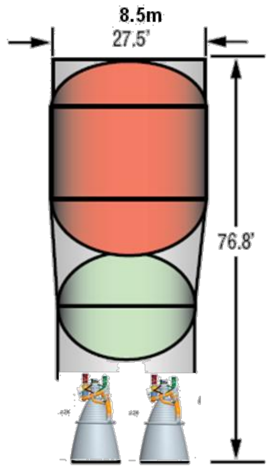


EDS/Propellant Depot Costs

ESAS
EDS

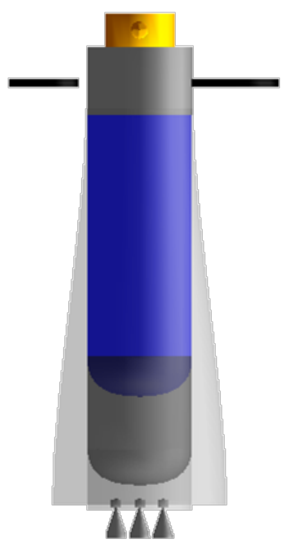


2xJ-2s

EDS configuration	Suborbital Burn	Suborbital Burn	Suborbital Burn	EDS Used as Upper Stage with 2 J-2Ss
Heritage Vehicle	13.1	7.4	15	13.1
DDT&E	$1,353 M	$1,118 M	$700 M	$1,782 M
Production (fixed $/yr)	$152 M*	$56 M**	$152 M*$152 M***	
Production (var $/flt)	$56 M	$59 M	$56 M	$56 M***

Ref. NASA TM-2005-214062

Present Study
EDS
&
Propellant Depot



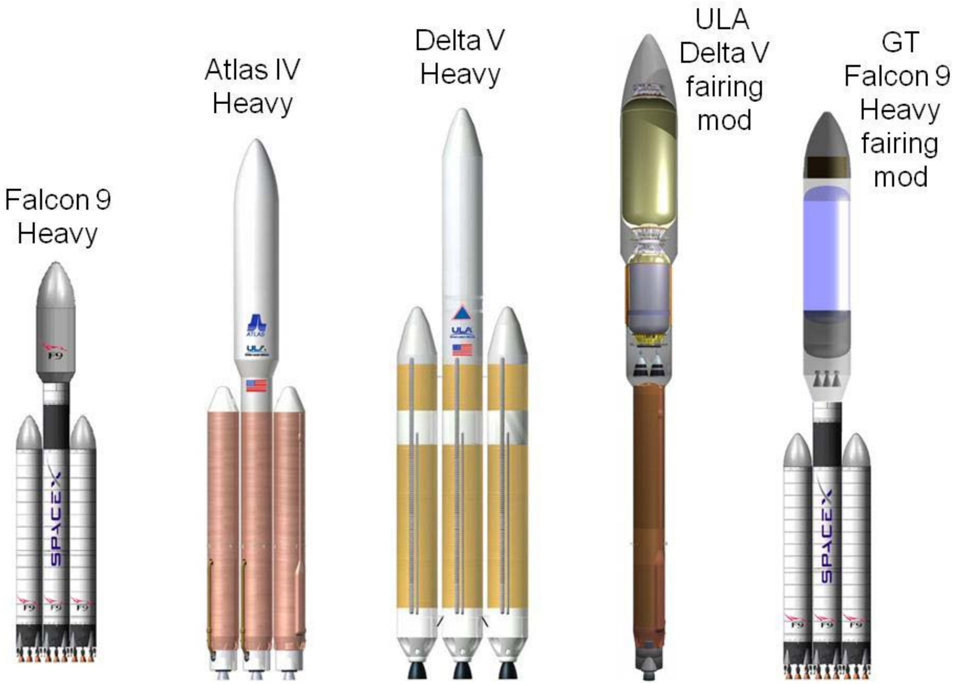
5xRL10s

Present Study

- 2xNASA ESAS EDS DDT&E and recurring costs
- J-2s do not have to be developed; DDT&E not reduced
-Thus, approximately 4xESAS EDS DDT&E

DDT&E	$3,564M
Production (fixed $/yr)	$302M
Production (var $/yr)	$118M

Falcon 9 Heavy Costs

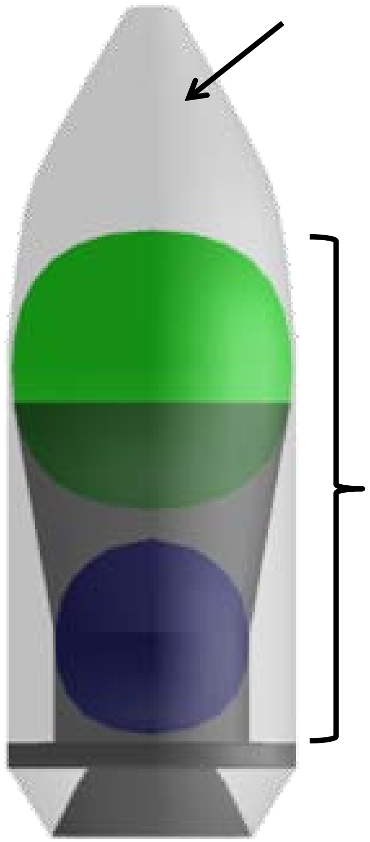


Falcon 9 DDT&E total cost = Ares I mobile launch tower cost
= NAFCOM cost/8

	DDT&E, $M	$M/launch	Payload, kg	$/kg
Falcon 9	$450	$50	8,700	$5,747
Falcon 9 Heavy	$335	$95	32,000	$2,969

Tripled quoted Falcon 9 Heavy DDT&E/pad upgrade costs and Doubled Falcon 9 Heavy Launch costs for analysis!!

Propellant Tanker Costs



Falcon 9 Heavy 2nd Stage	
Altitude	407 km
AR&D DV	30 m/s
Payload	29.4 t

Propelant Tanker		
Propellant Del.	23.5 t	
Inert	4.9 t	
PMF	0.8	
DDT&E	$931.1M	Costs from NAFCOM 2004 “manned”
Flt Unit Cost	$98.2M	

Note: These NAFCOM costs are a factor of 3 to 6 higher than actual costs for ISS Cygnus and Dragon DDT&E

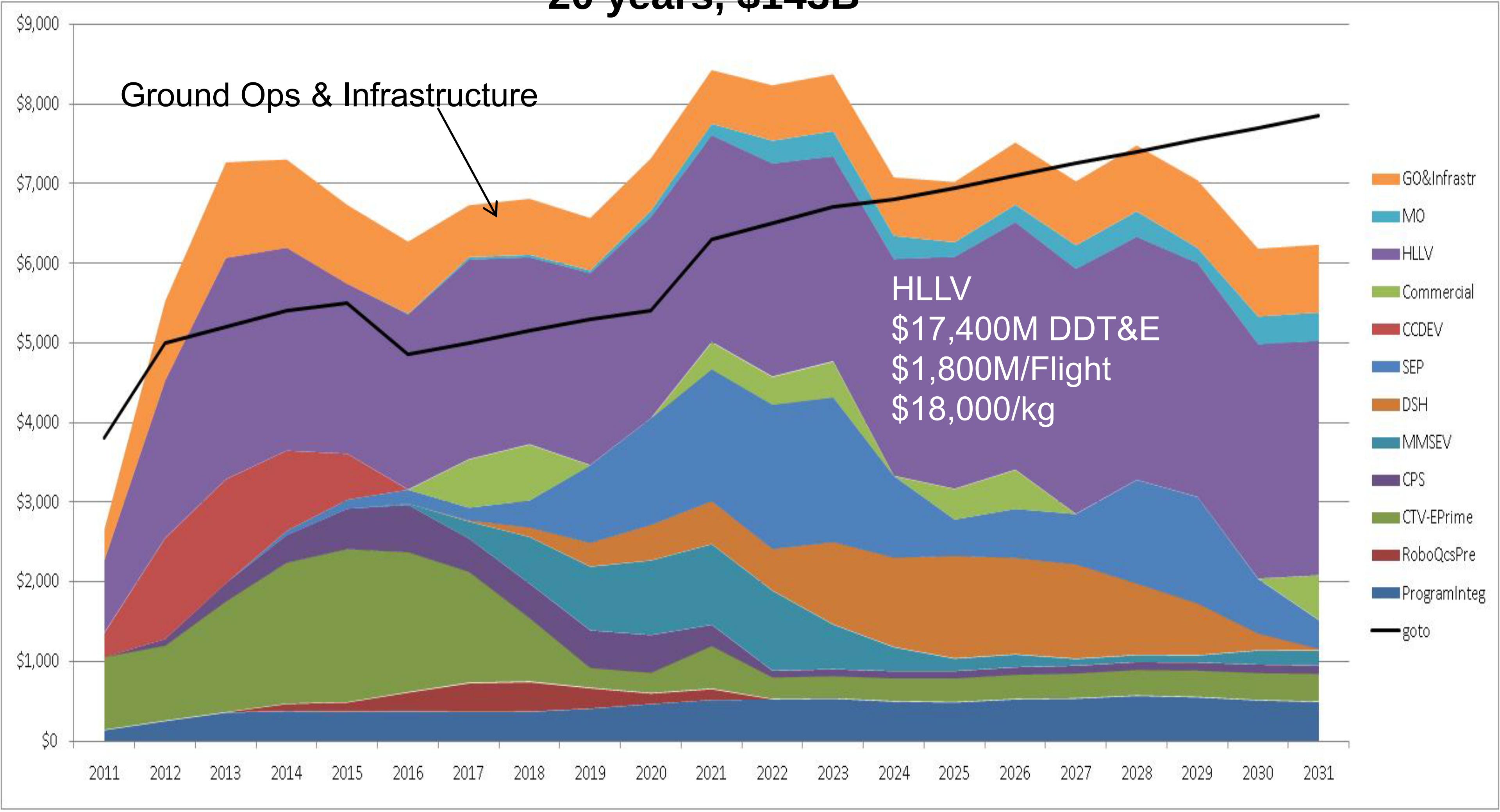
Summary of Cost Assumptions

- Used NASA cost estimates, NASA/Air Force Cost Model, and Space X estimates with very large margins
- Deleted DDT&E and recurring cost from HEFT:
  - HLLV, SEP, CPS, Kick Stage
- Did not modify costs of
  - Ground Ops and infrastructure ($7B!! In non-recurring and $1B/year in recurring – need to know how much related to HLLV)
  - Mission Operations (but have three less mission elements to operate)
  - Commercial launch (HEFT assumed EELV instead of F9H)
  - Commercial crew development
  - DSH, MMSEV, CTV space elements
  - Initial robotic missions
  - Program Integration (but should be function of program costs and number of elements)
  - Did not reduce program schedule for test flights of elements not included
    - Could potentially save two years at about $4B/year fixed/carrying costs

Summary of Cost Assumptions (cont.)

- EDS and Prop Depot: ~ 4 x NASA ESAS initial DDT&E and recurring cost for EDS to account for
  - Development differences between Prop Depot and EDS
  - Unknown cost of cryocoolers
  - But used existing RL10s rather than new engines
- Falcon 9 Heavy
  - 3 x SpaceX DDT&E/pad estimate (even though Space-X says they are paying the DDT&E cost to compete with EELV)
  - 2 x SpaceX recurring cost of $95M
  - One Falcon 9 Heavy launch added for every 9 flights for reliability and/or management reserve
- Propellant Tanker – used NAFCOM "manned" costs rather than lower "unmanned" cost (significantly higher than Cygnus and Dragon DDT&E)
- Depot life of 10 years maximum

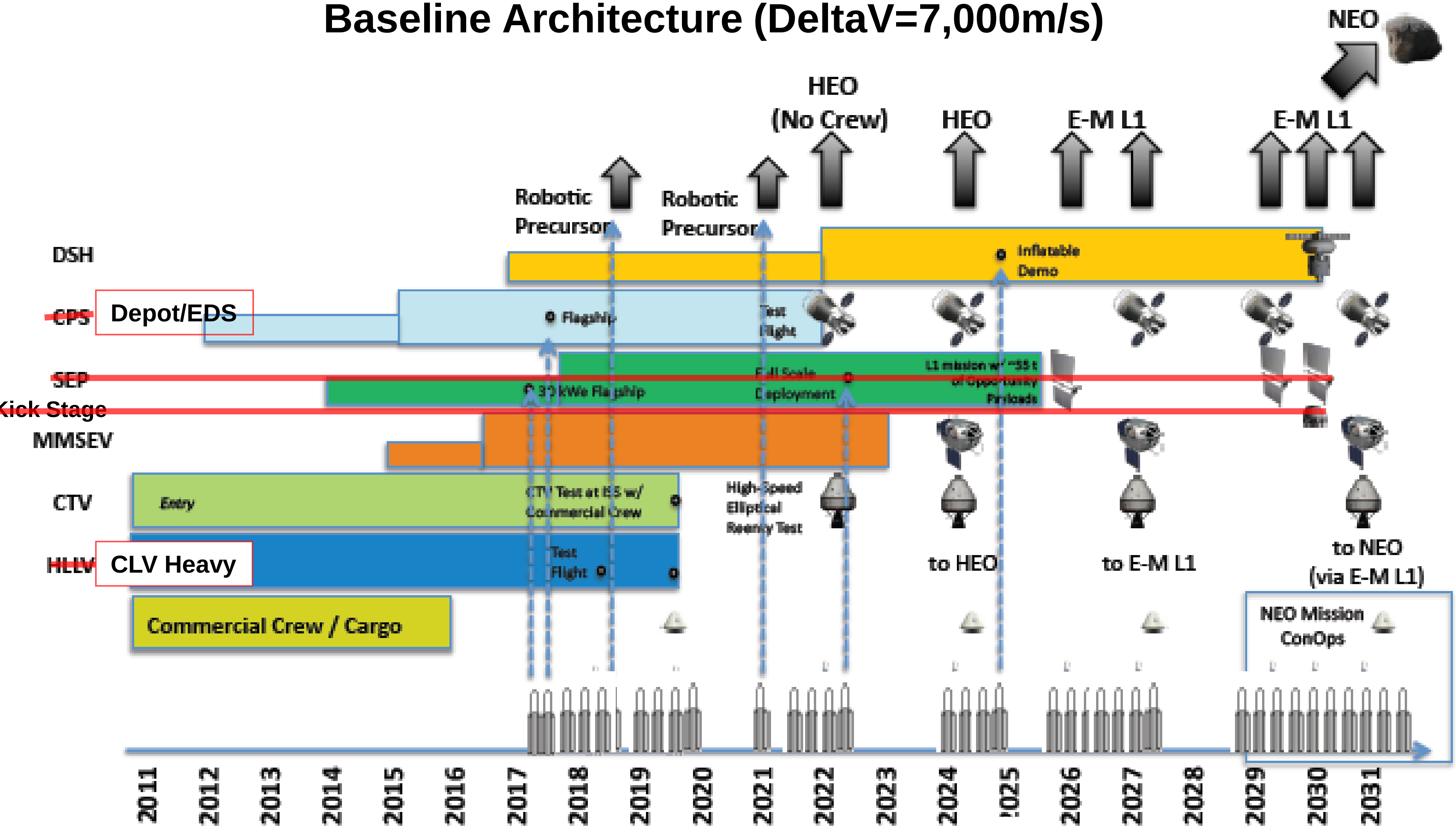
Human Exploration Framework Team - Sept 2010
20 years, $143B



Campaign Profile

DRM 4: 32t Falcon 9 w/ Depot and Commercial Crew

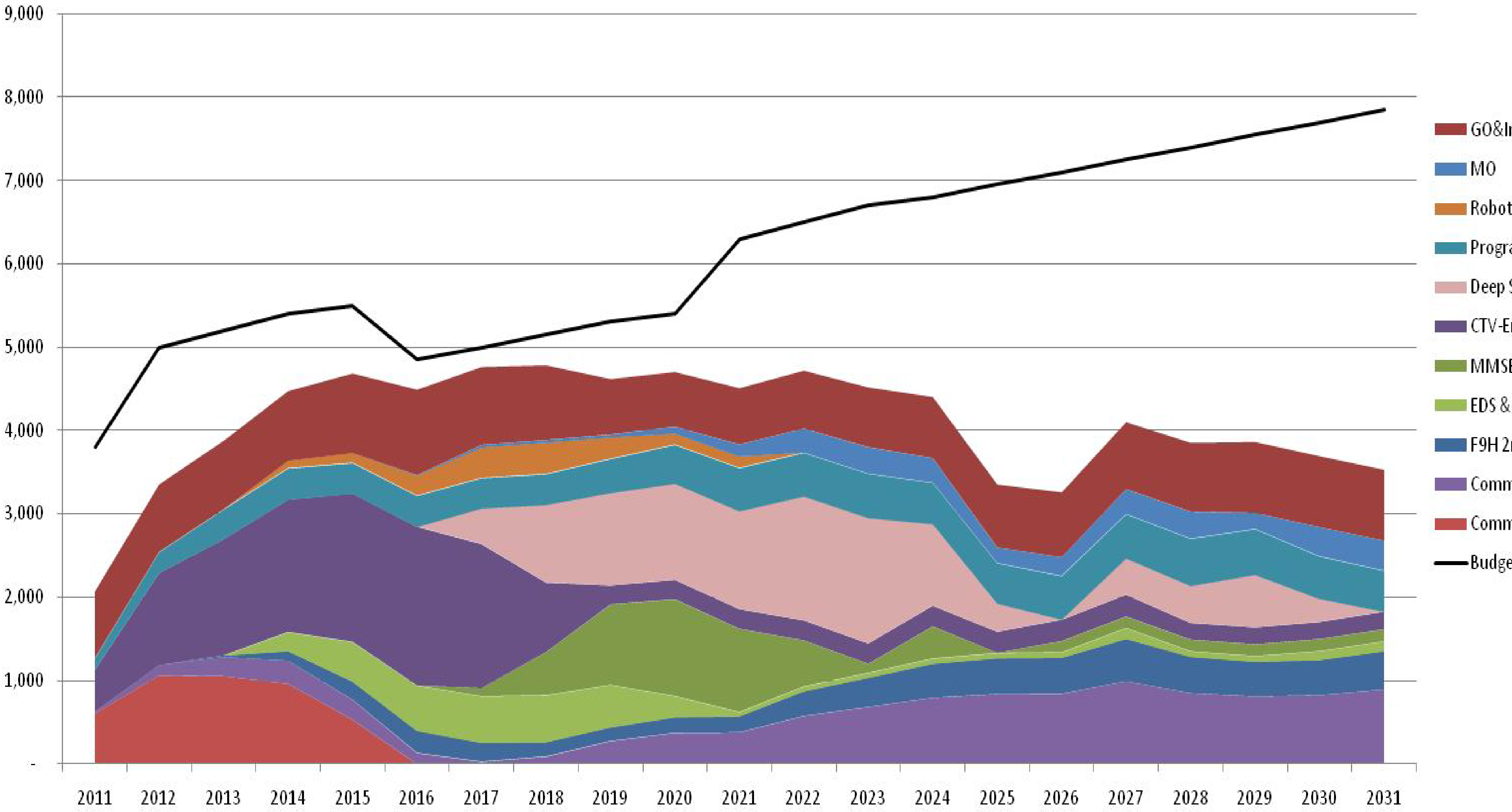
Baseline Architecture (DeltaV=7,000m/s)



Indicates flight to LEO

38 + 4 reserve

Baseline Depot/EDS, 20years, $86B, 38 flights

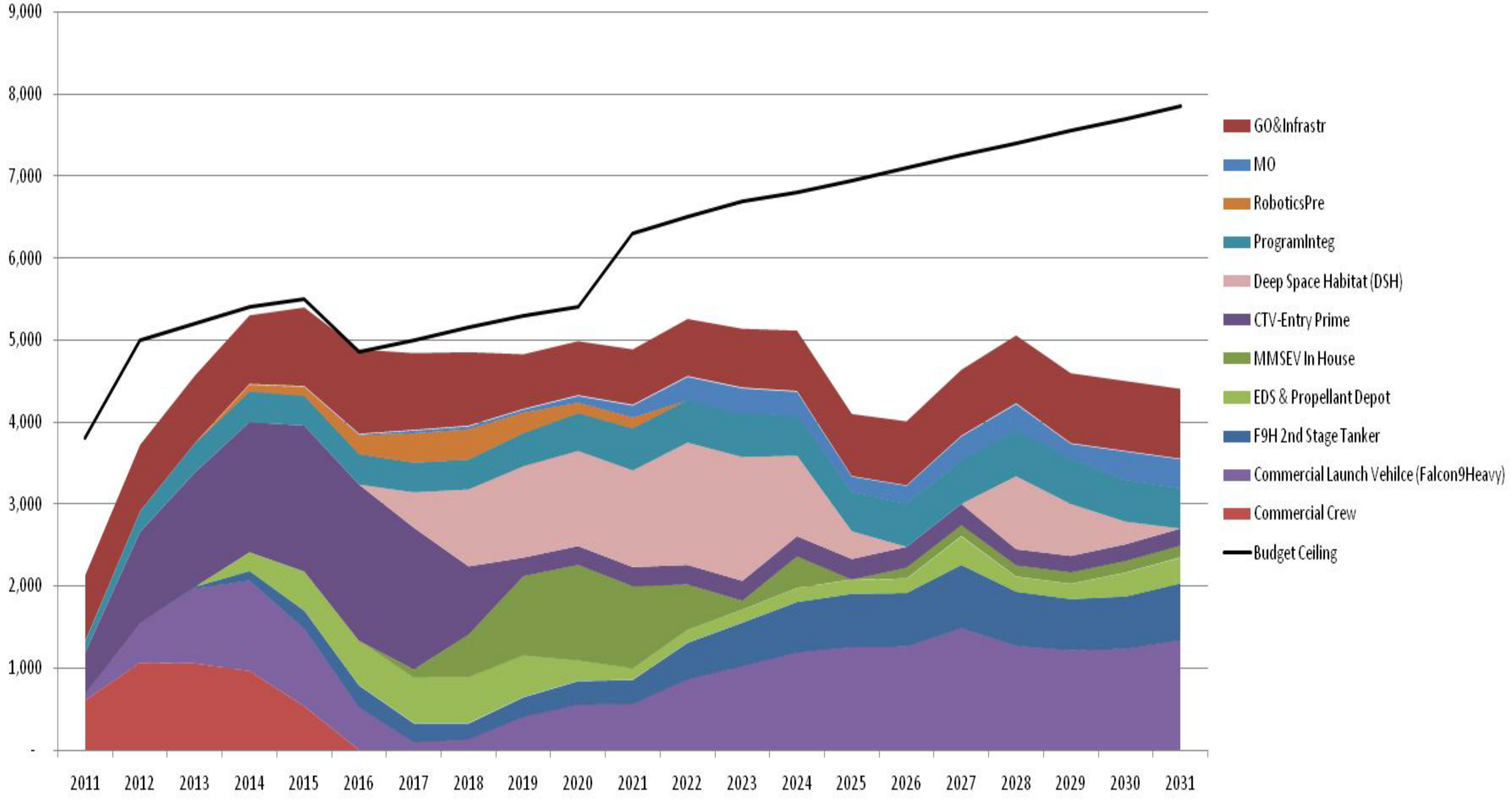


Georgia Tech

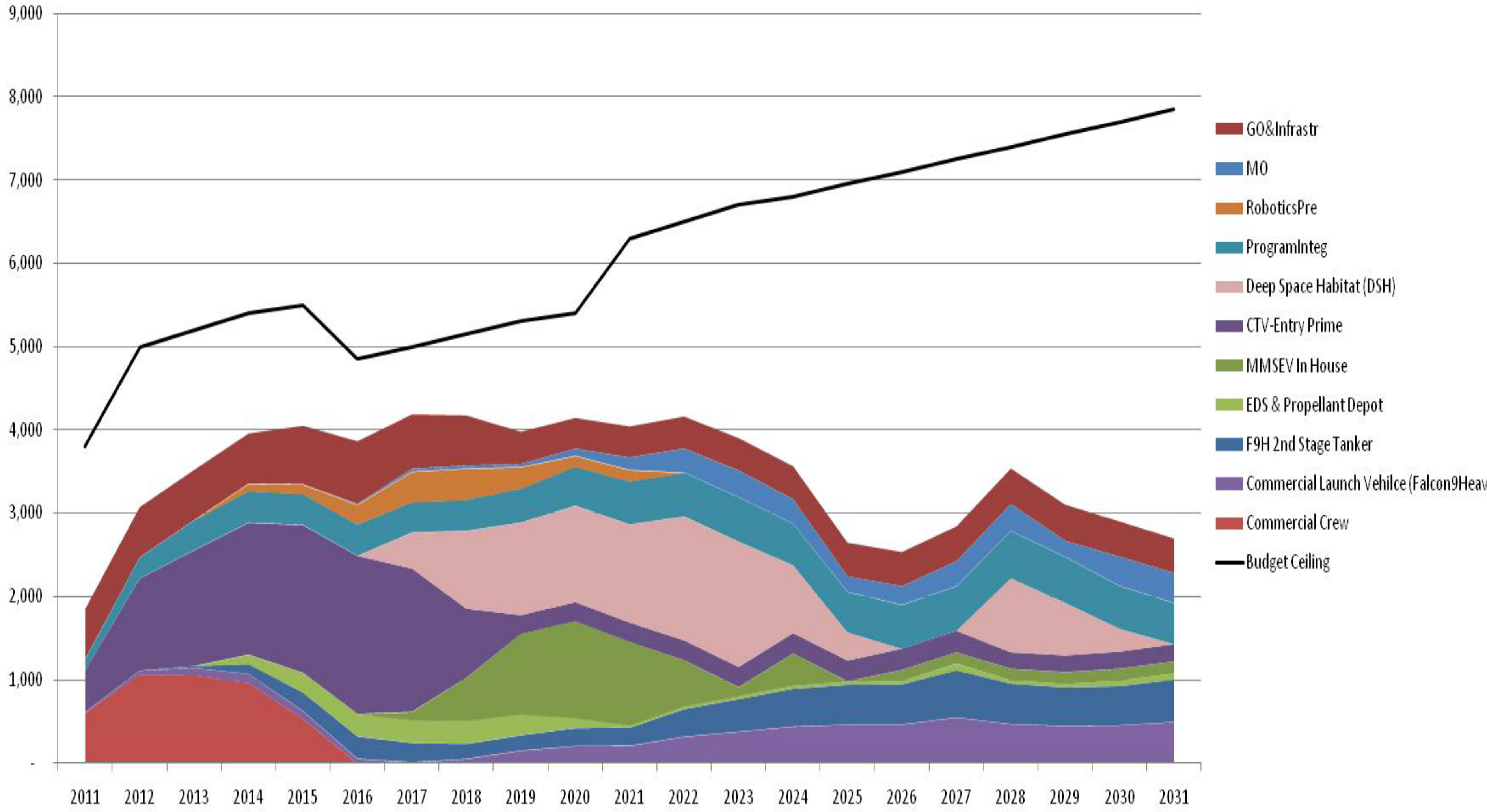
Daniel Guggenheim School of Aerospace Engineering

National Institute of Aerospace

Heavy Depot/EDS for Distant NEO Mission
20 Years, $97B, 51 flights



Baseline Depot/EDS w/SpaceX cost without margin 20years, $73B, 38 flights



Forward Work

- Refine current results
  - Validate cryocooler performance, mass, and power
  - Refine EDS/depot mass/performance
  - Validate F9H performance and masses with SpaceX
  - Refine RF9H “large” shroud mass with trajectory loads and structural analysis
  - Refine manifesting for latest HEFT 2 NEO mission with HAT Team
  - Validate number of launches/pad and capacity/cost assumptions with SpaceX
  - Refine costs with HAT Team and remove multiplication factors
    - Determine correct way to account for NASA indirect costs
  - Determine risk/LOM and compare with HEFT non-depot approach
  - Compare apples-to-apples cost/LOM/other FOMs with latest HEFT NEO mission and multi-mission non-depot approaches

Forward Work

- Additional trades
  - Determine “right-size” EDS/depot for multi-mission, capability driven architecture (balance lunar, L1, Mars, NEO requirements)
  - Trade single- vs. two-stage EDS
  - Add second supplier (e.g.,Orbital) and cost COTS-like procurement approach (also look at using EELVs and international partners)
  - Trade EDS with LOX/hydrocarbon engines
    - > Smaller launch volume
    - > Lower cryocooler requirements with hydrocarbons or storables
  - Compare baseline approach with Falcon-derived triple-core HLLV with single (32 mT) core developed first and used in conjunction with depot until need triple core for human Mars
    - > Provides phased HHLV capability to fit within budget
    - > Also examine use of EELV-derived triple core
    - > Uses large Merlin 2-like hydrocarbon engines
  - Trade benefits of depots for HLLV-based architectures (e.g., Stanley HEFT 2 white paper)

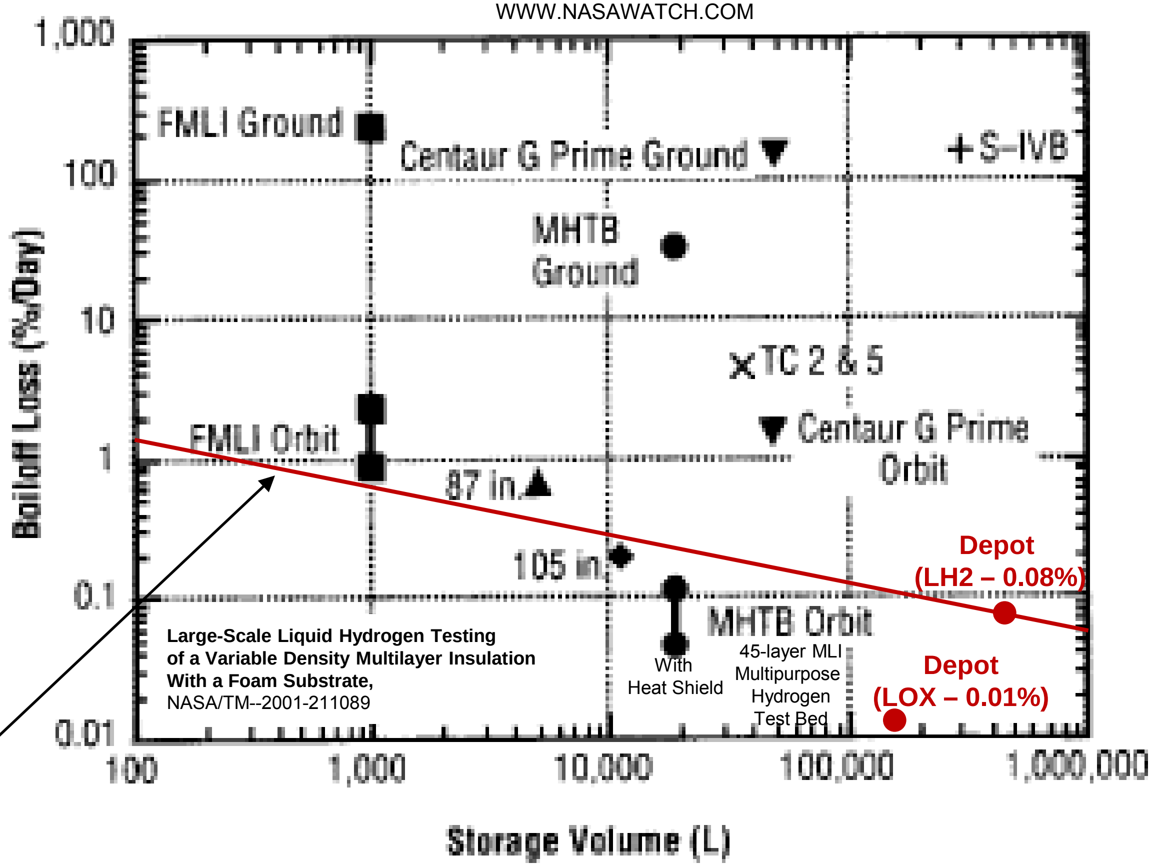
Issues

- Authorization Act language
- Requires longer storage of cryo propellants than alternatives and addition of zero-g transfer technologies
- Multiple launches statistically will result in more launch failures, but most launches are to the depot and not on critical mission path
- NASA loses some control/oversight
- Added complexity of depot

Pros

- Tens of billions of dollars of cost savings and lower up-front costs to fit within budget profile (no HLLV-based options fit within budget)
- Launch every 2 or 3 months rather than 1 every 18 months with HLLV
  - Provides experienced and focused workforce to improve safety
  - Operational learning for reduced costs and higher launch reliability.
- Allows multiple competitors for propellant delivery
  - Competition drives down costs
  - Alternatives available if critical launch failure occurs
  - Low-risk, hands-off way for international partners to contribute
- Reduced critical path mission complexity (AR&Ds, events, number of unique elements)
- Provides additional mission flexibility by altering propellant load
- Commonality with commercial crew/COTS vehicles will allow sharing of fixed costs between programs and “right-sized” vehicle for ISS
- Stimulate US commercial launch industry

Appendix



Variable Density 45 Layer MLI (GT DRAWW model)

LH2

$m_{boil\ off}$ = 2.584*(LH2 mass, kg)^(-1/3) percent LH2/day

m_{MLI} = 1.95 kg/m^2 (tank area, m^2)

LOX

$m_{boil\ off}$ = 0.6416*(LOX mass, kg)^(-1/3) percent LOX mass/day

m_{MLI} = 1.95 kg/m^2 (tank area)

Methane

$m_{boil\ off}$ = 0.4681*(CH_4 mass, kg)^(-1/3) percent CH_4 mass/day

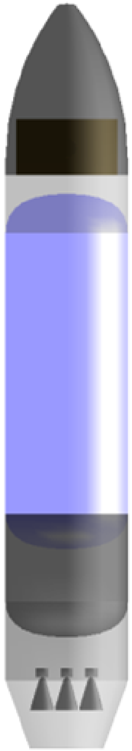
m_{MLI} = 1.95 kg/m^2 (tank area)

Falcon 9 Heavy
2nd Stage

Falcon 9H
2nd Stage

Replaced with

EDS
for
Depot
And
Space Missions



	F9H Stage 2	F9H EDS
Empty, kg	2,400	24,869
Propellant, kg	43,400	35,285
Payload, kg	29,610	(Propellant left) 15,256
Initial, kg	75,410	75,410
Engine	1xMerlin 1cVacuum	5xRL10B-2
Isp, s	342	465
Thrust, N	411,400	549,200
DV, m/s	2,874	2,874
T/W	0.556	0.743
IMF	0.052	

	HEFT	CLV+Depot
Commercial Crew Development	4,417	4,417
CLV (+ Tanker)	3,758	23,527
100 mt HLLV	54,089	
Cryo Propulsion Stage (CPS)	4,781	
LEO Tug*	1,881	
Solar Electric Propulsion (SEP)	14,822	
MMSEV In House	6,321	6,321
CTV-Entry Prime	15,197	15,197
Deep Space Habitat (DSH)	9,576	9,576
ProgramInteg	9,187	9,187
RoboticsPre	1,703	1,703
MO	3,165	3,165
GO&Infrastr	16,801	16,931
EDS/Depot		4,644
	145,698	94,667