ULA Briefing to National Research Council

In-Space Propulsion Roadmap

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File no.

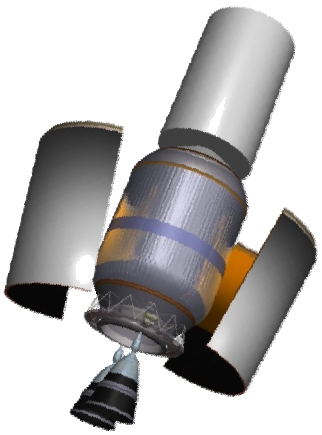
Key Transportation Technologies

- 3 most critical transportation technologies enabling beyond LEO Exploration:
  - Integrated Cryogenic Propulsion Stage (CPS) design
  - Efficient cryogenic storage
  - Cryogenic fluid transfer

- Lack of these 3 technologies negatively impacted Constellation
  - The time between Ares V and I launches was reduced from 3 months (ESAS) to 1 day
    - This short interval was the single largest risk to mission success
  - Use of a half full EDS for the Earth departure burn increased the initial mass in LEO (IMLEO) by >30% compared to a full EDS
    - On-orbit fueling and efficient CPS IMLEO could be reduced by >35%.
  - Orion's propulsion module was switched from LO2/LH2 to LO2/LCH4 and finally storable propulsion
    - The resulting increased lift requirement rippled through the entire launch system forcing significant redesign

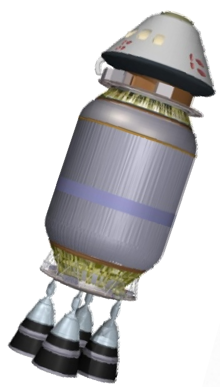
ULA
United Launch Alliance

CPS In-Space Applications

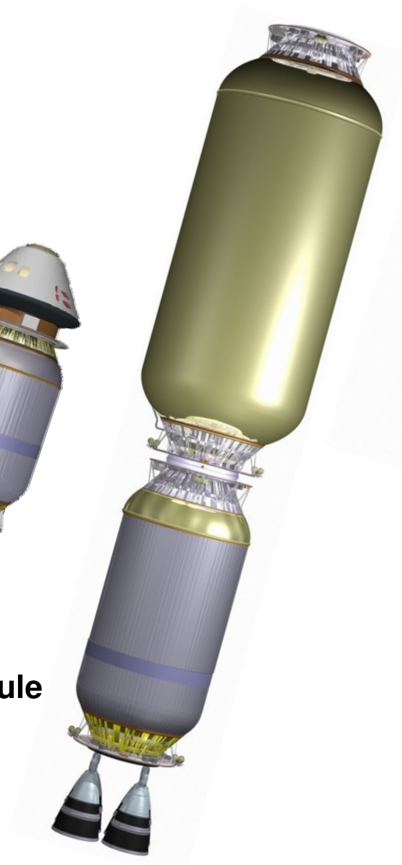


Satellite Launch

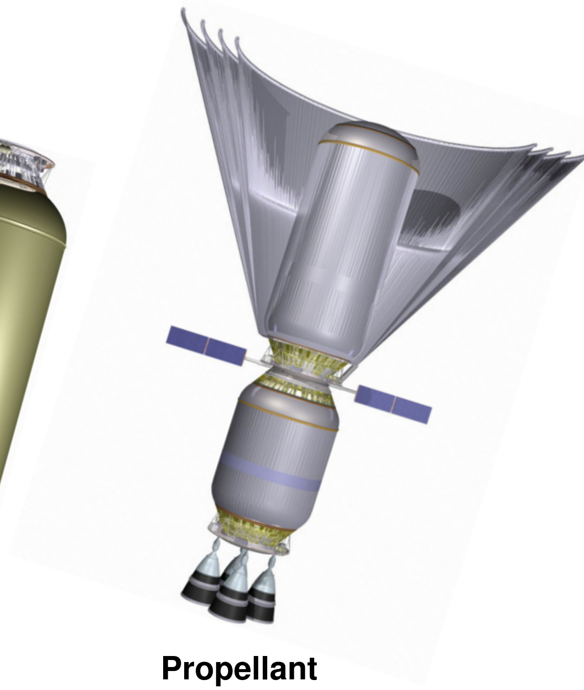
Propellant
Tanker



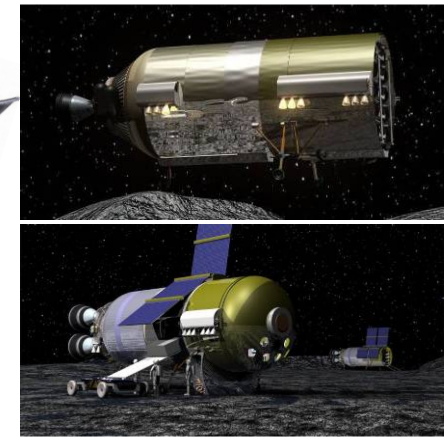
Orion
Service Module



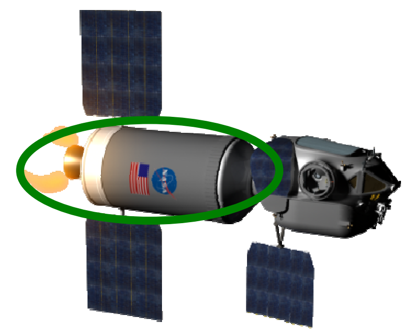
Multi-Year CPS



Propellant
Depot



Lunar Landers



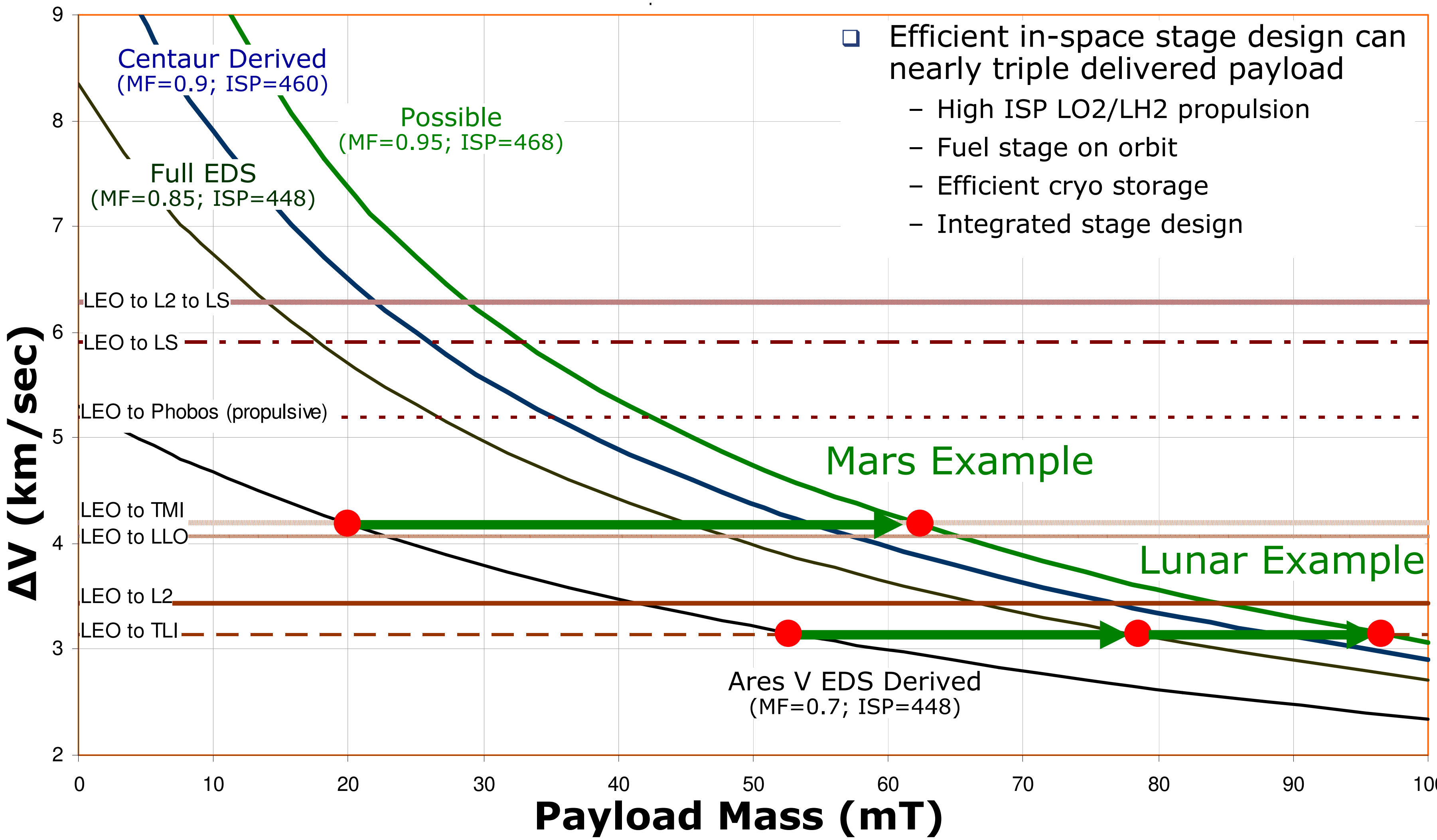
MMSEV CPS

Courtesy NASA

CPS Spans Entire Space Transportation Architecture

Integrated CPS Design is Critical

Example 100 mT Propellant Load



- Efficient in-space stage design can nearly triple delivered payload
  - High ISP LO2/LH2 propulsion
  - Fuel stage on orbit
  - Efficient cryo storage
  - Integrated stage design

CPS Design Drives Launch Requirements

HEFT Assumed CPS

United Launch Alliance

Cryo Propulsion Stage Characteristics: Long Duration Missions

Block 2

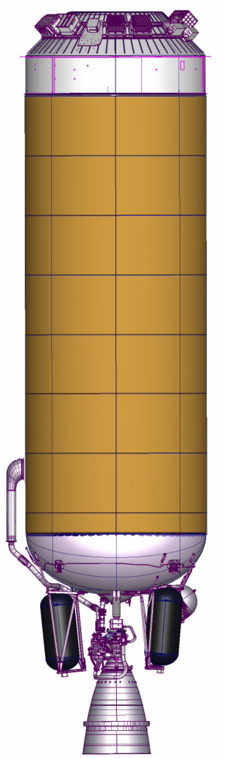
Design Characteristic	Value
Propellants	O2/H2
Approximate Stage PMF	0.75 – 0.825
Approximate Stage Maximum Diameter	7.5 m
Approximate Stage Maximum Length	15.0 m
# of Engines	2
Engine Thrust (100%)	125-135 kN
Engine Isp (100%)	445-455 sec
Inert Mass (Including RCS and Cyro Boiloff)	14550 - 17625 kg
Total Stage Wet Mass	67500 - 75000 kg
Active Lifetime (Launch through Disposal)	>400 days

In order to support long duration missions, a Cryogenic Propulsion Stage Block 2, maintains the responsibility for performing all orbital maneuvers, maintenance, and corrections for the integrated stack (including payload) after the initial orbital insertion by the SLS HLLV. Some combinations of CPS Block 2 characteristics and mission delta-V requirements will result in total integrated stack masses which exceed the HLLV lift capability of 100 tonnes. However, the parameters in this data package represent sufficient information to conduct a feasibility assessment of design options and trade offs that result in mission closure.

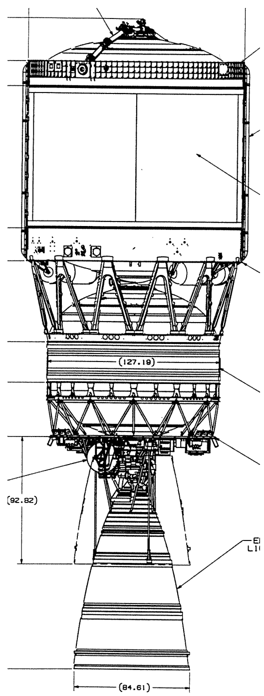
Inadequate CFM Technology Adversely Drives CPS Design

CPS Design Differences

- CPS design has huge impact on performance
  - Both stage mass and cryogenic storage



Centaur



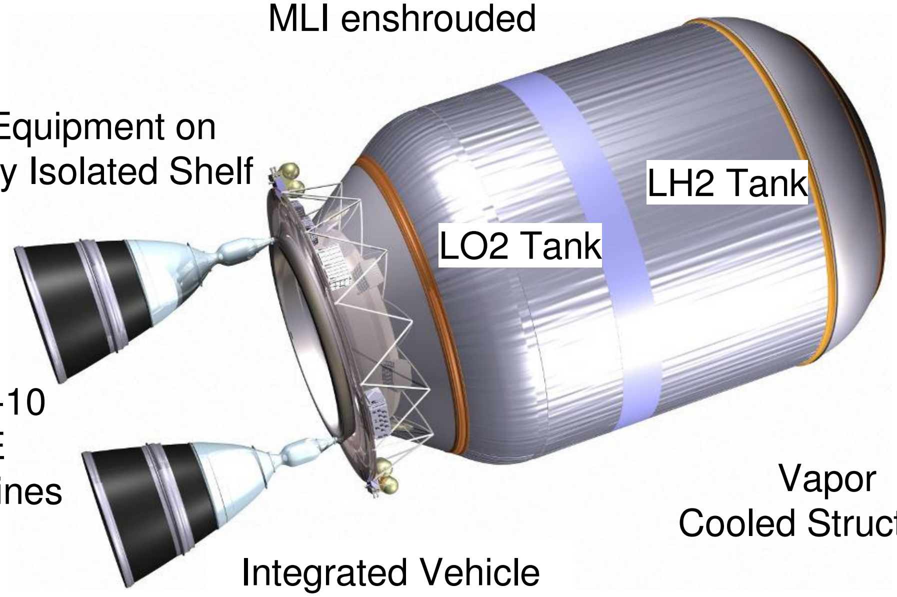
4m Delta IV

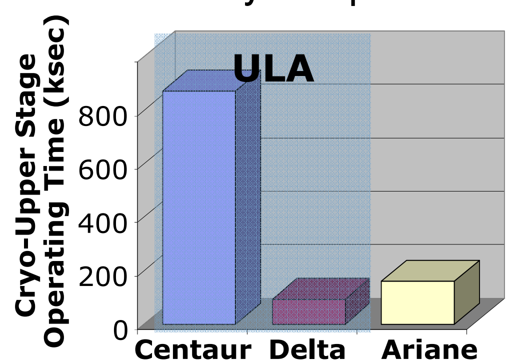
Centaur	Delta	
46 klb	46 klb	LO2 & LH2
5 klb	7 klb	Stage Dry Mass
2 klb	**4 klb**	**Structure**
90%	87%	Mass Fraction

Integrated CPS Design Improves System Capability

Integrated CPS Design
Advanced Common Evolved Stage (ACES)

- Mass Fraction > 0.90
- Long duration
- Mission Flexibility

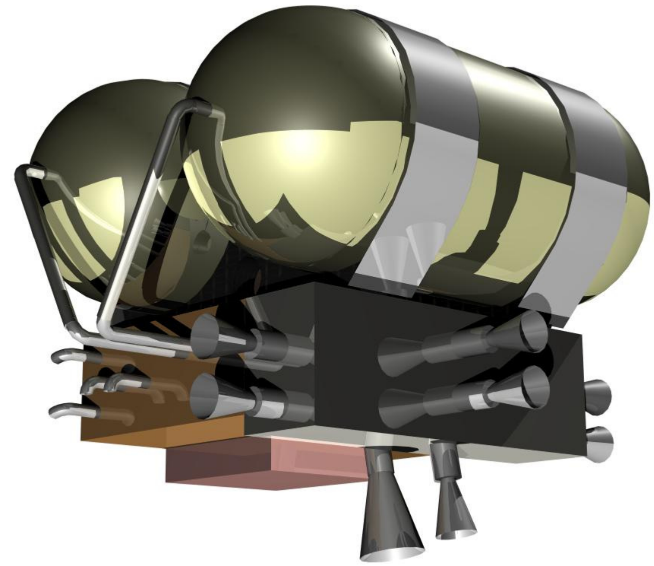




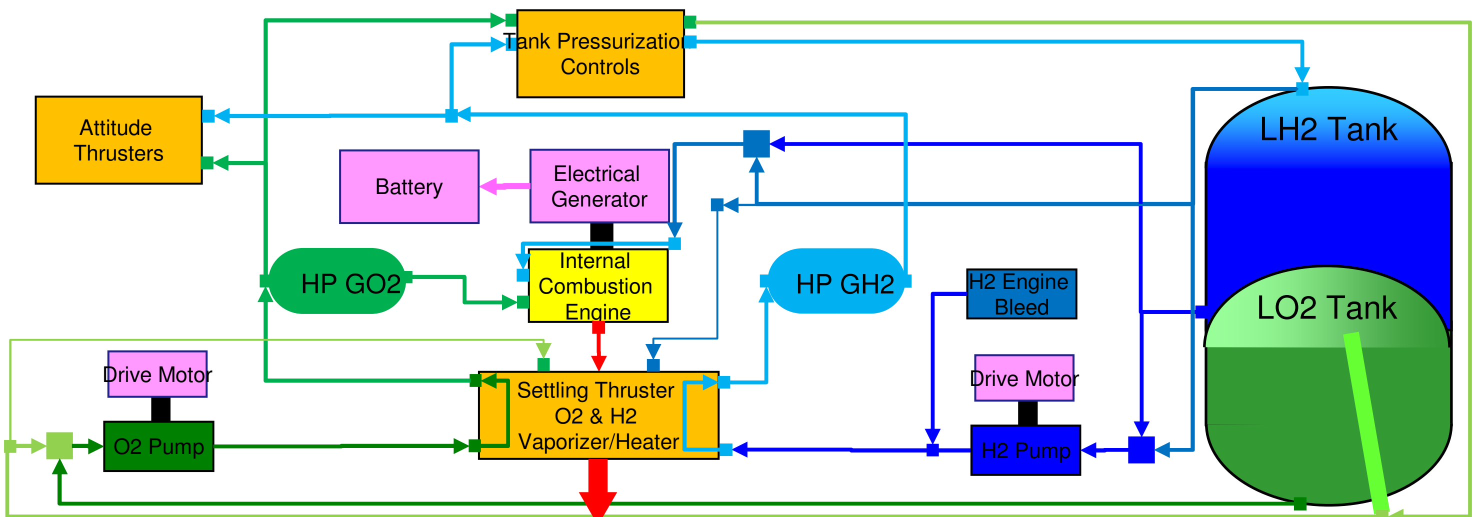
Integration of Individual Technologies into Effective System is Technical Challenge

Integrated Vehicle Fluids (IVF)

- Utilize Hydrogen and Oxygen to replace:
  - Hydrazine for attitude control
  - Helium for pressurization
  - Large Vehicle Batteries Power
- Provides mission flexibility
  - Unlimited Tank Pressurization Cycles
  - Numerous Main Engine Burns
  - Reaction control for attitude and translation
  - Long mission durations
  - Eases stage refueling and reuse

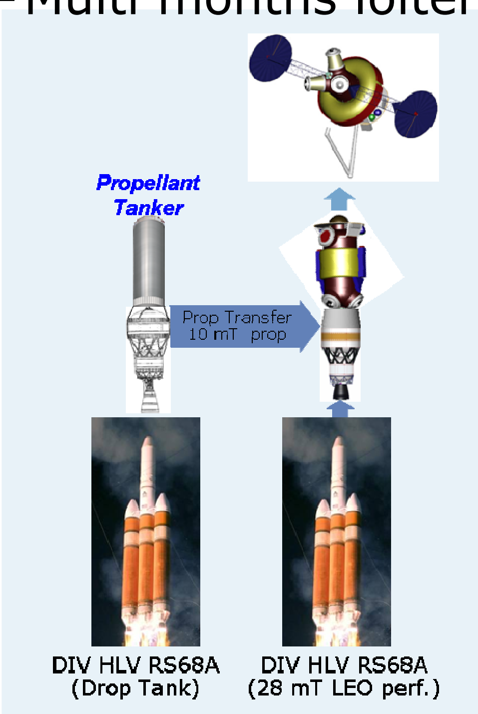


H2/O2 Thruster

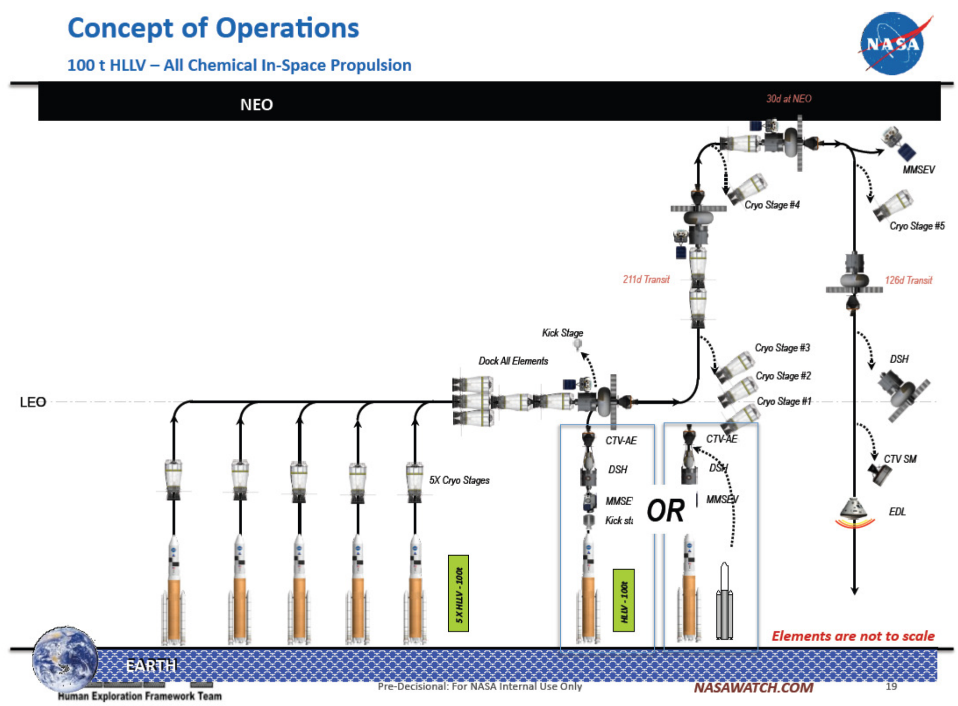


Mission Architectures

- All exploration missions require multi-launch aggregation
  - 2 or more launches
  - Transfer/Assembly of: Payloads, CPS, and/or propellant
  - Multi months loiter



Dual Launch L1 Gateway Mission



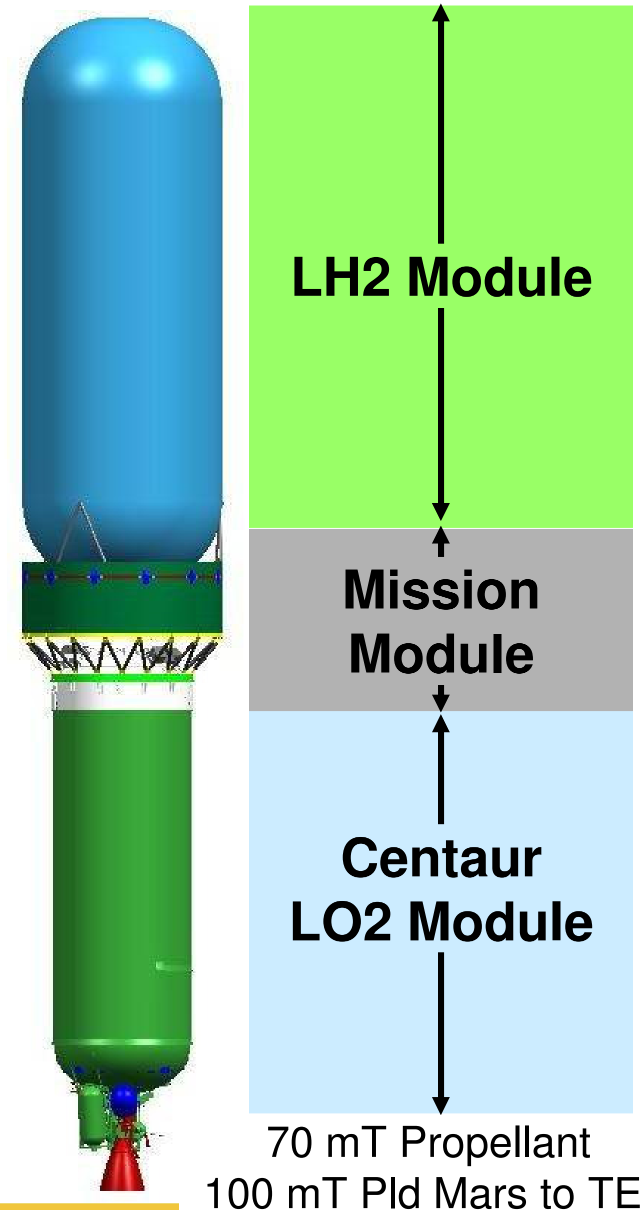
HEFT NEO Mission

Courtesy NASA

Multi-Launch Requires Long Duration Cryo Storage and Significantly Benefits from Cryogenic Propellant Transfer

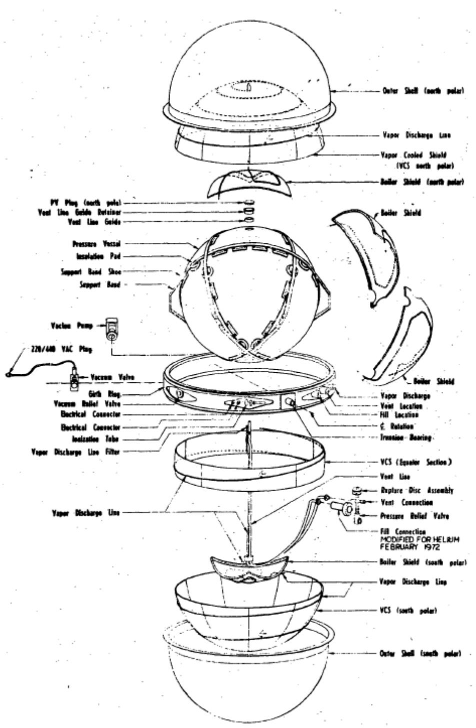
Long Duration CPS

- Earth Departure Stage
  - Mars or NEO return stage
  - Lunar lander
  - Propellant depot
- Return stage mission duration
  - Multi year mission with very low boil-off
    - 1 year: 0.027%/day
    - 2 year: 0.014%/day
    - 3 year: 0.009%/day
    - 4 year: 0.007%/day
- On orbit fueling allows:
  - Structure/insulation to not be driven by launch environment
  - Reduced structural heat leak paths
  - Very high mass fraction (>0.90)

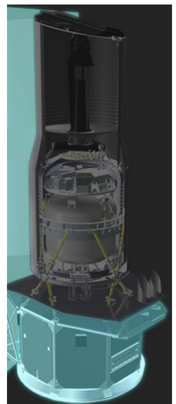


Cryo Storage Experience

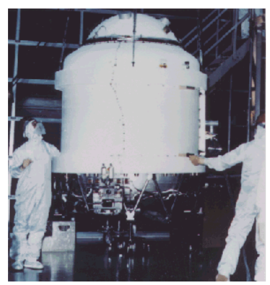
Cryo Dewar Experience: small scale, heavy, very efficient



Hydrogen Thermal Test Article
0.022%/day boil-off LH2
Courtesy NASA



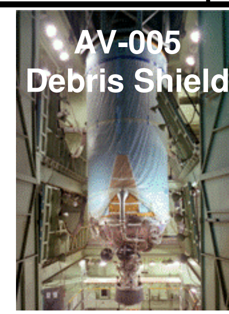
Spitzer
0.05%/day boil-off Solid He
Courtesy NASA/JPL-Caltech



COBE
0.07%/day boil-off SfHe
Courtesy NASA GSFC

Centaur Experience: large scale, light weight, modest efficiency

	TC-15		TC-11	
	(LO2)	(LH2)	(LO2)	(LH2)
Tank Heating (Btu/hr)	2100	2500	1300	3100
Boil-Off (%/day)	1.5	4.1	1.0	5.1
System B-O (%/day)	2.0		1.6	



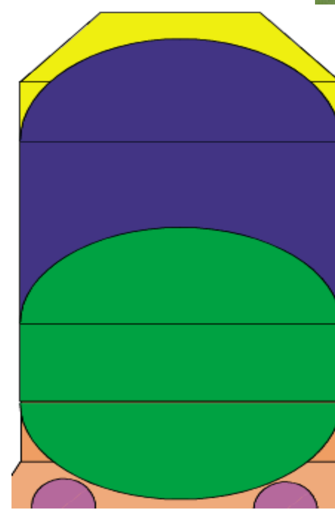
Need to Combine Dewar and CPS Technology to Enable Efficient, Light Weight Cryo Storage

Integrated Cryo Test

- Integrated ground cryo test
  - Demonstrate large scale, flight like systems
  - Use actual Centaur flight tank
- Demonstrate low boil-off storage
  - ~2%/day current flight demonstrated
  - ~0.25%/day with existing Centaur
  - Guide future vehicle design to support <0.1%/day boil-off

Courtesy NASA

Enhanced Thermal Protection



Technology Advancement Through Large Scale Ground Demonstration

CRYogenic Orbital TEstbed

- In-space laboratory for cryo fluid management (CFM) technologies
- Uses residual Centaur LH2 after primary payload separation

2010 Ground Test
Flight Article Design

Courtesy Ball

Courtesy NASA

Small Scale
Demonstrations
2013-2014

Leading to
Large Scale
Cryo-Sat
Flagship
Technology
Demonstrations
2015

Repeated Flight Opportunities
Enabling Technology Advancement

CFM Technologies TRL

Cryo Fluid Management Technology	Current TRL		TRL Post-CRYOTE Lite		TRL Post-CRYOTE Pup, Free Flier	
	0-g	Stld	0-g	Stld	0-g	10^{-4} g
Transfer System Operation	4	5	4	9	9	9
Pressure Control	4	9	6	9	9	9
Low Acceleration Settling	N/A	9	N/A	9	N/A	9
Tank fill operation	4	5	4	9	9	9
Thermodynamic Vent System	5	5	7	7	9	9
Multi-layer insulation (MLI)	9	9	9	9	9	9
Integrated MLI (MMOD)	6(2)	6(2)	9(7)	9(7)	9	9
Vapor Cooling (H_2 para-ortho)	9(4)	9(4)	9	9	9	9
Passive Broad Area Cooling (active)	9(4)	9(4)	9(4)	9(4)	9	9
Active cooling (20k)	4	4	4	4	9	9
Ullage and Liquid Stratification	3	9	9	9	9	9
Propellant acquisition	2	9	9	9	9	9
Mass Gauging	3	9	9	9	9	9
Propellant Expulsion Efficiency	3	9	9	9	9	9
System Chilldown	4	5	4	9	9	9
Subcooling P>1atm (P<1atm)	9(5)	9(5)	9(5)	9(5)	9(5)	9(5)
Fluid Coupling	3	3	3	3	9	9

In-Space Engine Development

- In-Space propulsion requirements
  - Reliable
  - Producible
  - Affordable
  - High ISP (>460 sec)
  - Light weight (~500 lb)
  - ~25 klb thrust
  - Low net positive suction pressure
  - Engine out

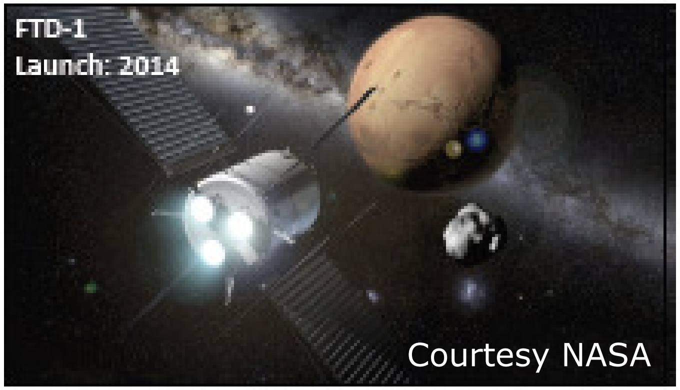
Courtesy PWR

Courtesy Xcor

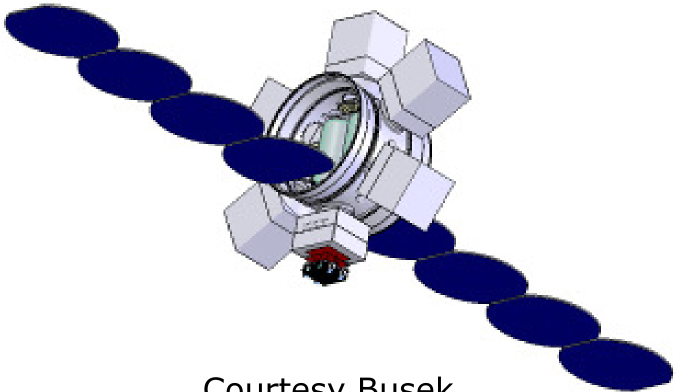
Continuous US Propulsion Investment

Solar Electric Propulsion

- Solar electric propulsion has potential to significantly reduce required launch mass
  - Typically large exploration class missions assume high power SEP
    - 50kW class vehicles such as FTD1
    - Ultimately 200 kW to multi MW class
  - At low mission tempo SEP cost may not be worth reduced launch mass
- Smaller SEP systems have broad application
  - xClass robotic exploration
  - Rideshare orbit delivery
  - Propellant scavenging and delivery to HEO
  - 5kW class vehicles such as ESPA OMS



Courtesy NASA



Courtesy Busek

Small SEP provides valuable experience

Summary

- Enhanced technologies supporting CPS design critical for Exploration
  - Integrated CPS design
  - Efficient cryogenic storage
  - Cryogenic fluid transfer
- Integrated Vehicle Fluids
  - Mission capability, reliability
- Integrated testing
  - Ground testing
  - Affordable in-space testing (CRYOTE)
- Continuous engine investment
- Affordable solar electric propulsion