



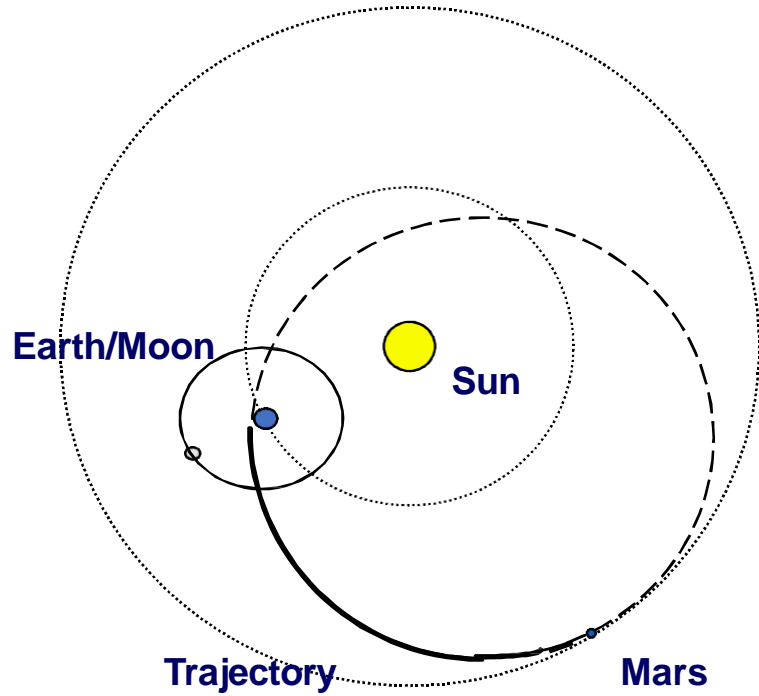
Hydrogen Applications for Space Transportation

Presented at the 2019 CEC/ICMC
July 24, 2019

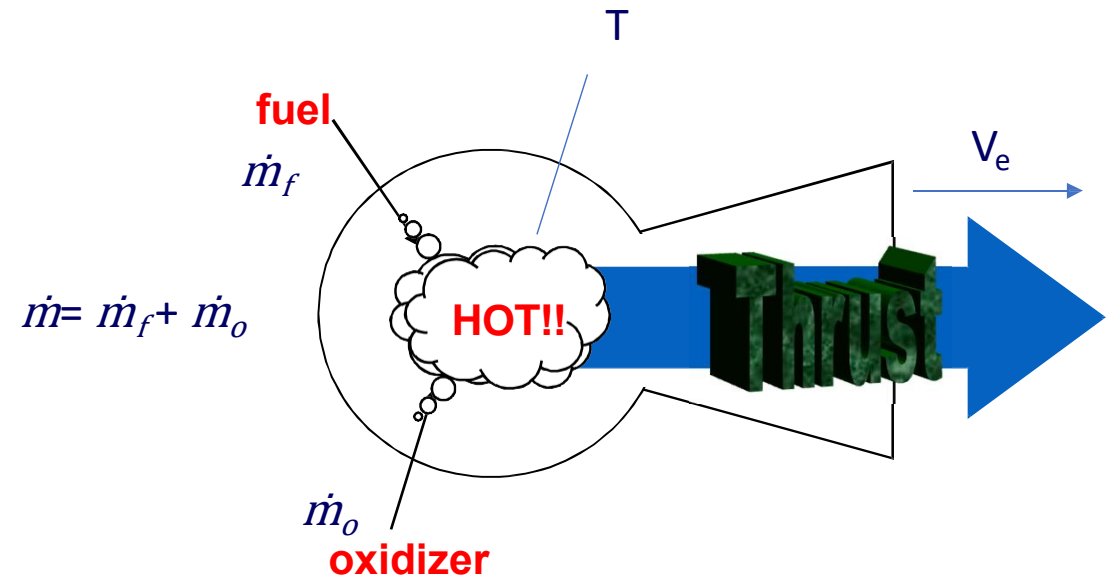
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How do we get around in space?



$$I_{sp} \equiv \frac{T}{\dot{m} g_0} = \frac{V_e}{g_0}$$



Rocket Thrust: $T = m \times a = M \times \Delta V/t$
 $T = \dot{m} \times V_e$
 $T = \dot{m} g \times I_{sp}$

- T = force (N or lbf)
- \dot{m} = mass flow rate (kg/s or lbfm/s)
- V_e = exhaust velocity (m/s or ft/s)
- g_0 = 9.8 m/s² or 32.17 ft/s²

Isp = specific impulse (s) ~ analogous to miles per gallon (or km/liter)

Why is Hydrogen a Good Rocket Propellant?

$$I_{sp} \equiv \frac{T}{\dot{m} g_0} = \frac{V_e}{g_0}$$

V_e is proportional to the combustion chamber temperature divided by average molecular weight of the exhaust products:

$$V_e \propto \sqrt{\frac{T_{comb}}{MW_{avg}}}$$

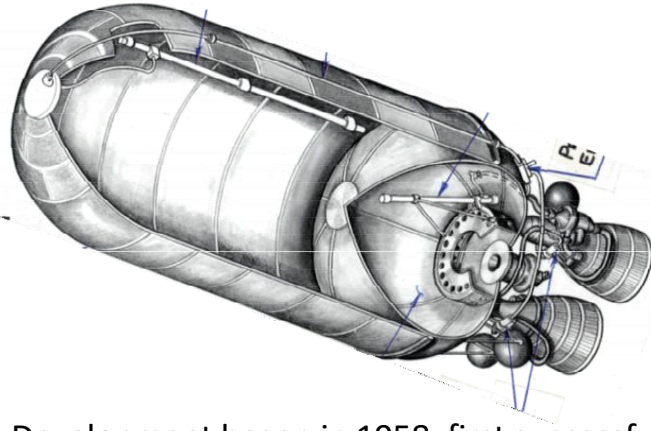
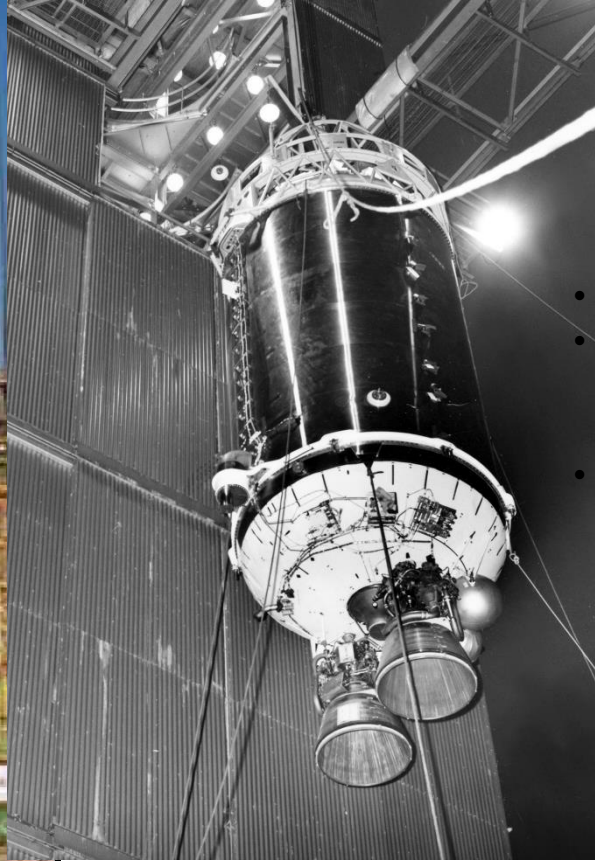
Hydrogen-oxygen propellant produces lower average molecular weight exhaust (H_2O) than other fuels and therefore higher I_{sp} . The I_{sp} optimizes at a fuel rich mixture ratio, which further lowers the exhaust average molecular weight with OH, H, and H_2 molecules.

Representative comparison of several engine I_{sp} values

| Engine | Space Shuttle OMS | F-1 (Saturn V) | RD-180 (Atlas V) | Space Shuttle Main Engine | RL-10B-2 Delta IV U.S. |
|----------------------|-------------------|----------------|------------------|---------------------------|------------------------|
| Propellant | MMH/N2O4 | LO2/Kerosine | LO2/Kerosine | LO2/LH2 | LO2/LH2 |
| Approx. I_{sp} (s) | 316 | 304* | 338 | 452* | 465 |

*Engine not optimized for vacuum operation

Centaur - The First Hydrogen Rocket Stage



Some Key NASA Missions Launched

- Surveyor Lunar Probes
- Viking 1 & 2 Mars Landers
- Voyager 1 & 2 Outer Planet Grand Tour
- Cassini Huygens

- Development began in 1958, first successful flight in 1963
- Evolutions of Centaur continue to fly today (>55 years)
 - General Dynamics -> Lockheed Martin -> United Launch Alliance
- Many Challenges Addressed
 - Lightweight tank: Hydrogen tank is pressure stabilized (“balloon tank”) and has a common bulkhead with LO2 tank
 - Tank pressure control
 - RL-10 engine was first flight engine to use LH2
 - LH2 turbopump
 - LH2 cools the combustion chamber and nozzle picking up heat to drive the expander cycle engine
 - Microgravity fluid behavior
- Early program had numerous failures, often minor changes having unintended consequences
 - Good reliability achieved over its history



Progression of LH2 Use for Space Transportation

1960



Atlas/Centaur

Saturn V



Space Shuttle



DC-X (experimental)



H II (Japan)



Ariane 5 (Europe)



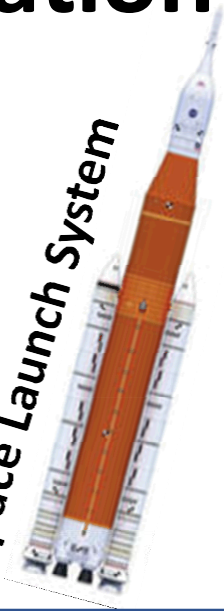
Delta IV



New Shepherd (Blue Origin)



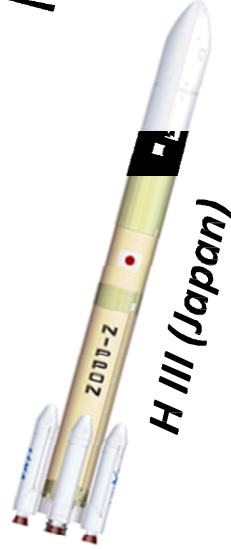
Space Launch System



Ariane 6 (Europe)



H III (Japan)



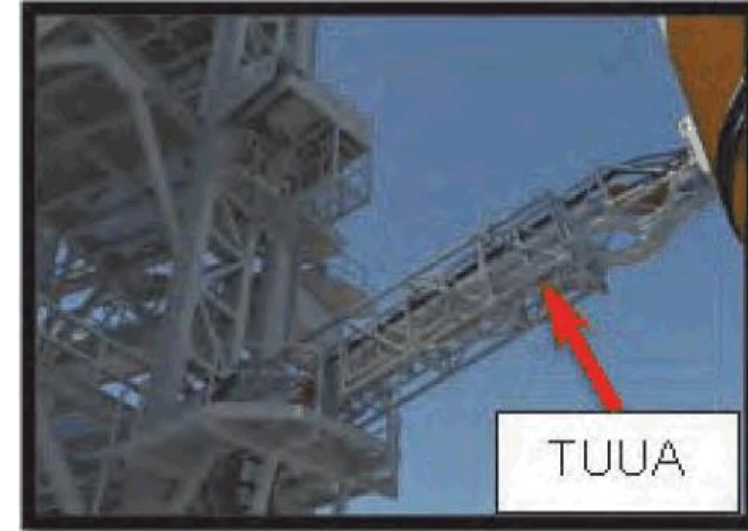
New Glenn (Blue Origin)



Future



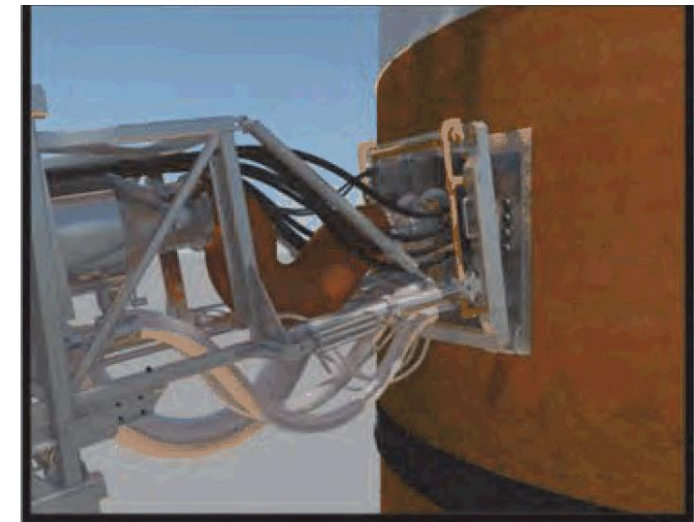
Fueling Space Transportation Vehicles



Ares I Umbilical Arm and Plate



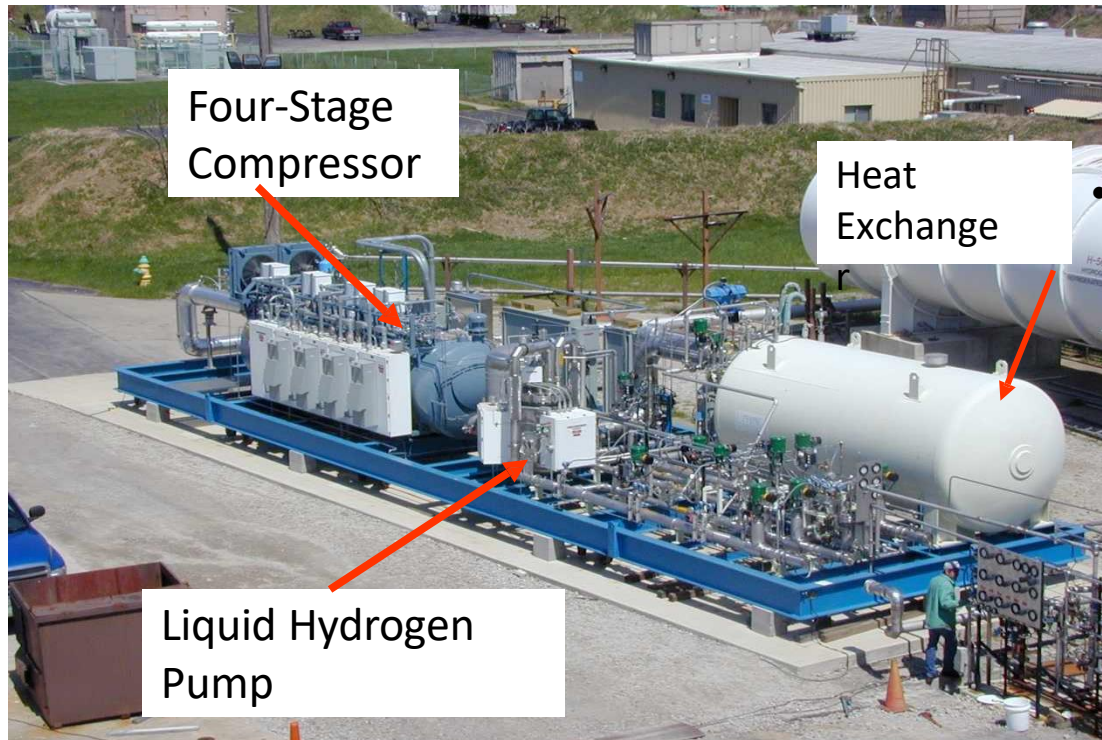
- 850,000 gal capacity LH2
- 304 SST inner vessel;
- Carbon steel outer vessel
- 95 psi design pressure
- Dual vaporizer system for pressurization
- Perlite powder / vacuum insulation system
- 450 m transfer line
- 90 m tall tower for Saturn V



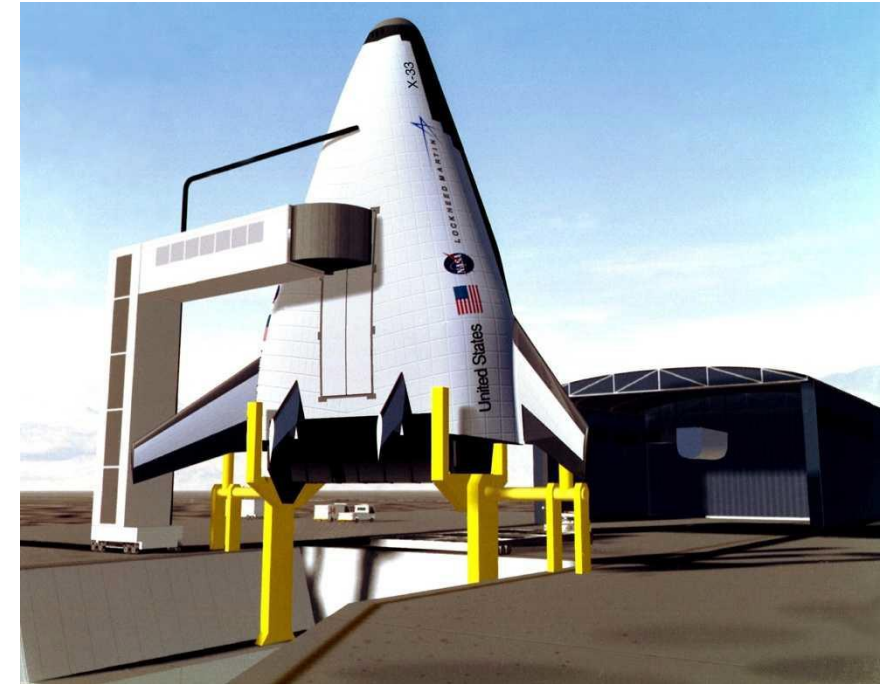
Lower Temperature Hydrogen

Why is lower temperature “densified” LH2 of interest for Space Transportation?

- Smaller vehicles or increased payload to orbit
- Additional heat capacity before H2 boils off
 - Ground operations, loading, and in flight
- X33 reusable Earth-to-orbit transportation looked to implement near triple point LH2
 - Program cancelled before it flew



- **8 lbm/sec (3.6 kg/sec) LH2 densifier developed for X33**



- **X33 Vehicle Concept**

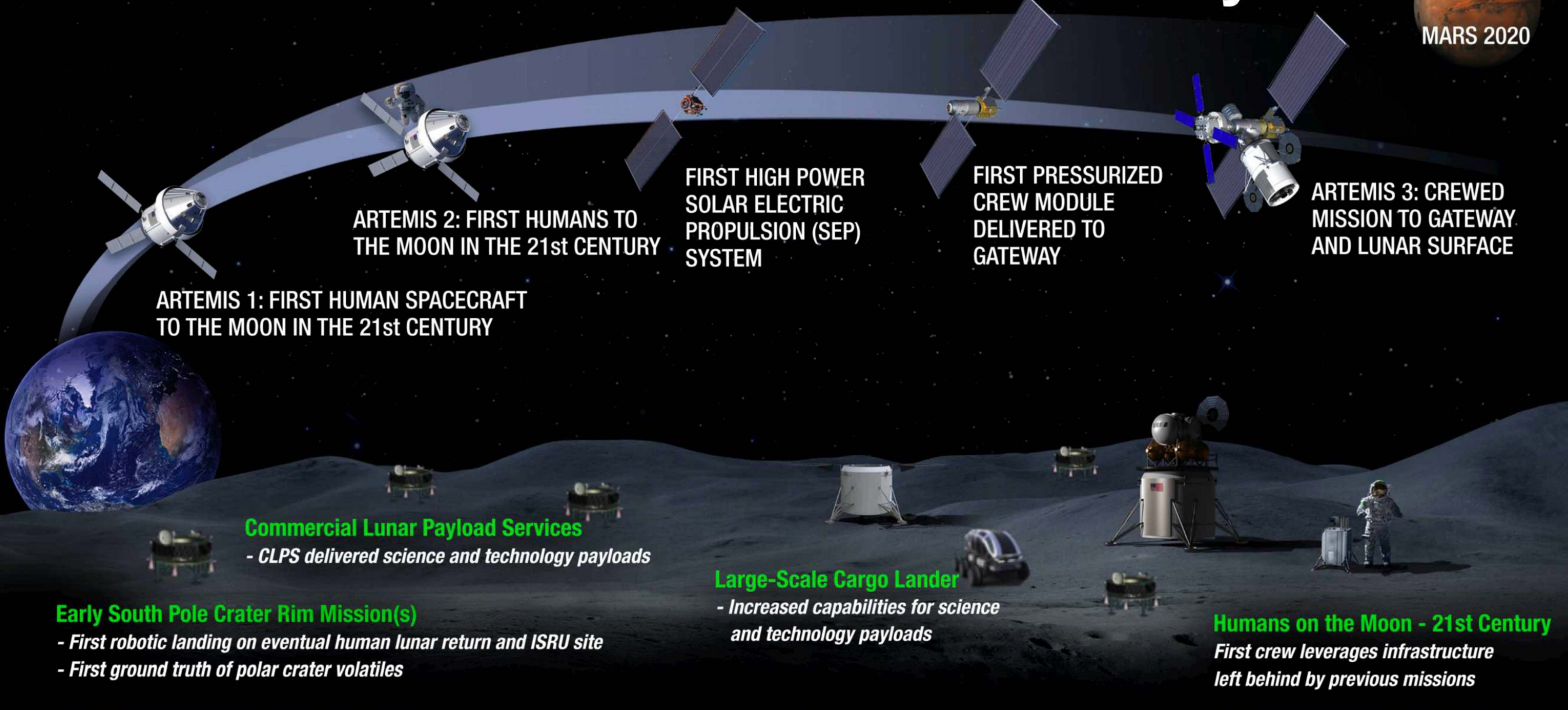
New LH2 Storage Sphere Pad 39B:

- 1,250,000 gal capacity LH2
- Glass Bubbles / vacuum insulation system (~50% less boiloff losses compared to the same tank with perlite)
- Internal cooling coil (heat exchanger) for Integrated Refrigeration & Storage (IRaS) capability

Artemis Phase 1: To the Lunar Surface by 2024



MARS 2020



ARTEMIS 1: FIRST HUMAN SPACECRAFT TO THE MOON IN THE 21st CENTURY

ARTEMIS 2: FIRST HUMANS TO THE MOON IN THE 21st CENTURY

FIRST HIGH POWER SOLAR ELECTRIC PROPULSION (SEP) SYSTEM

FIRST PRESSURIZED CREW MODULE DELIVERED TO GATEWAY

ARTEMIS 3: CREWED MISSION TO GATEWAY AND LUNAR SURFACE

Commercial Lunar Payload Services
- CLPS delivered science and technology payloads

Early South Pole Crater Rim Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles

Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions

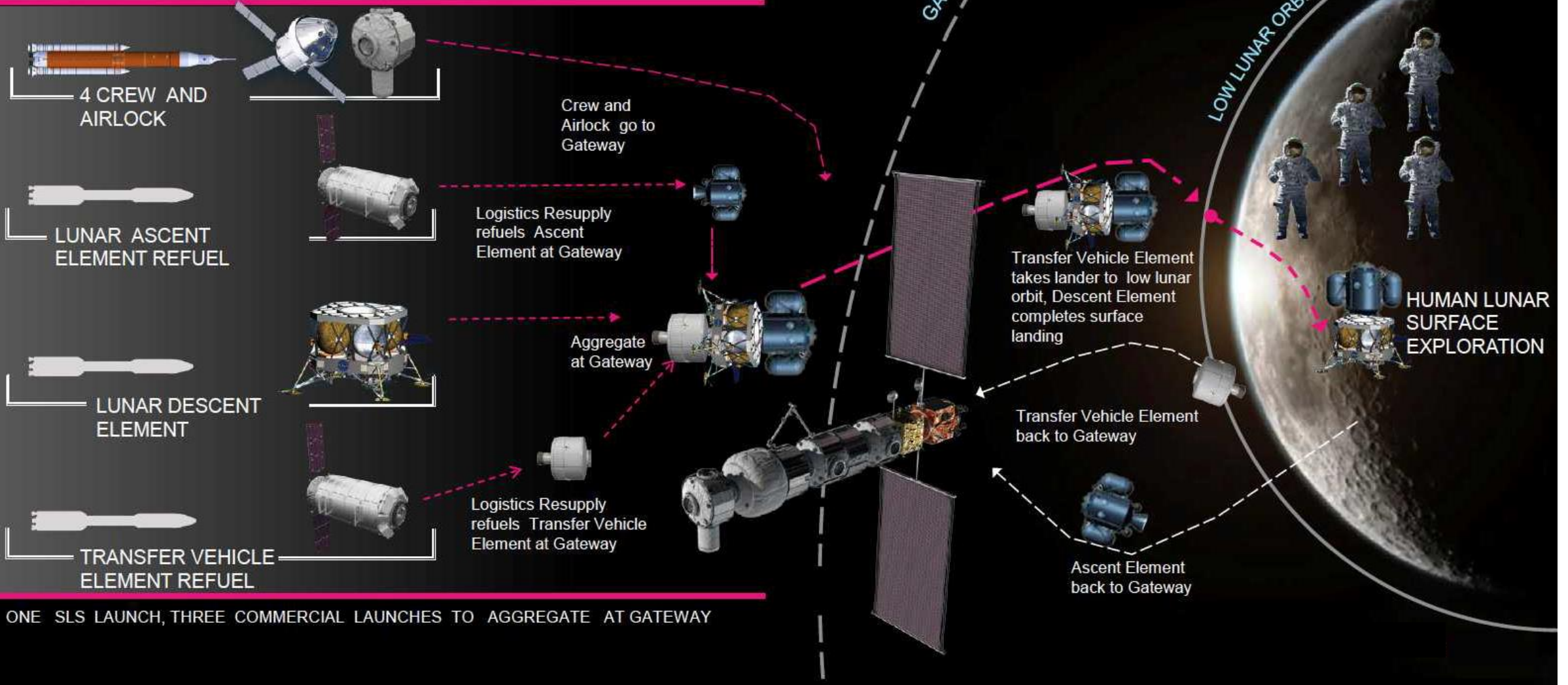
LUNAR SOUTH POLE CRATER TARGET SITE

2019

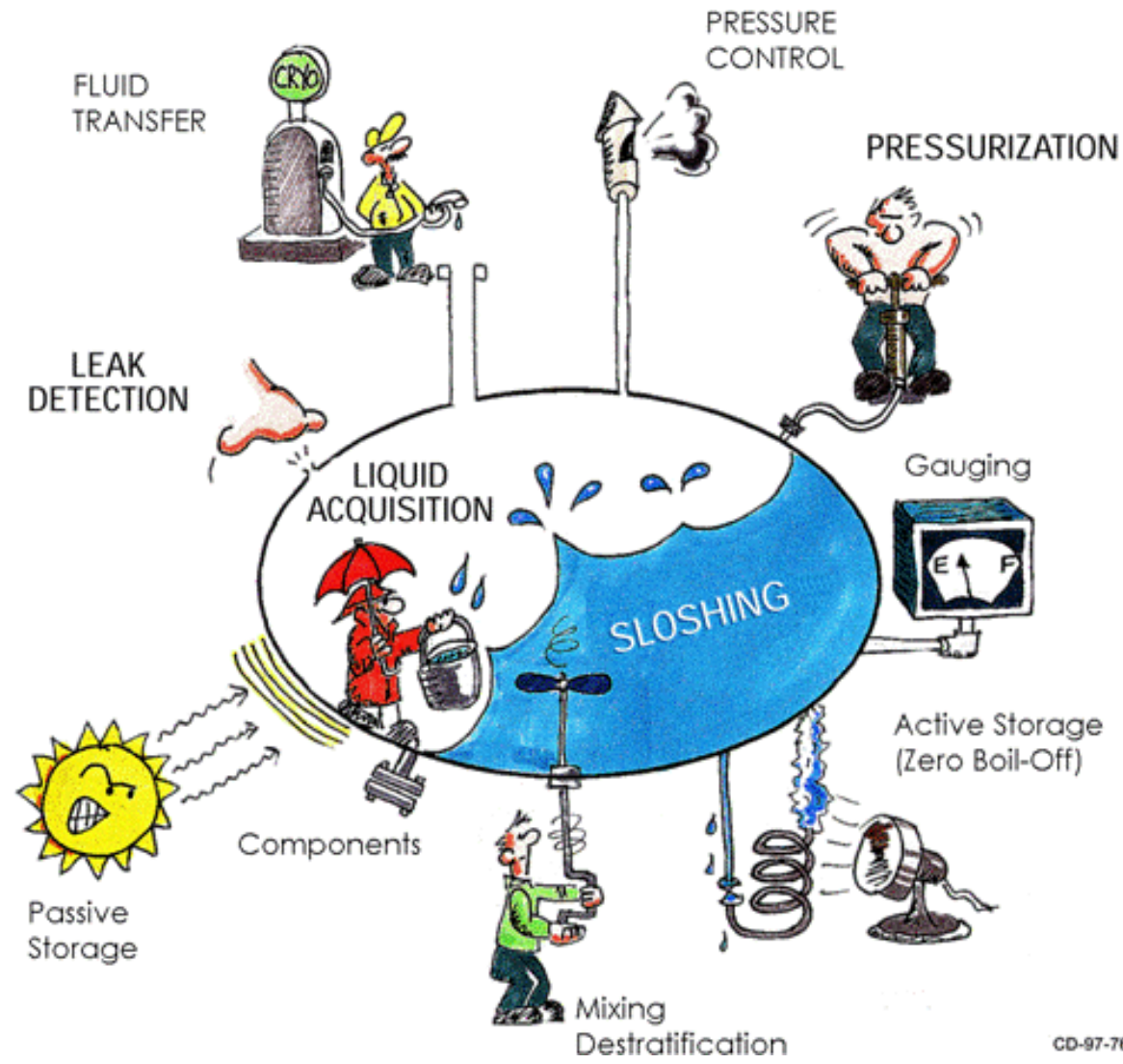
2024

Buildup of Notional Human Landing System Reference Architecture

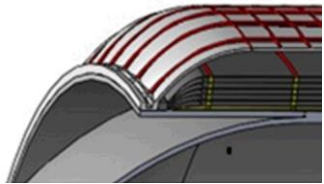
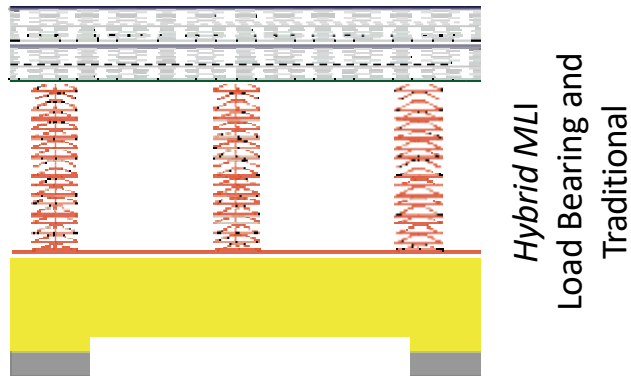
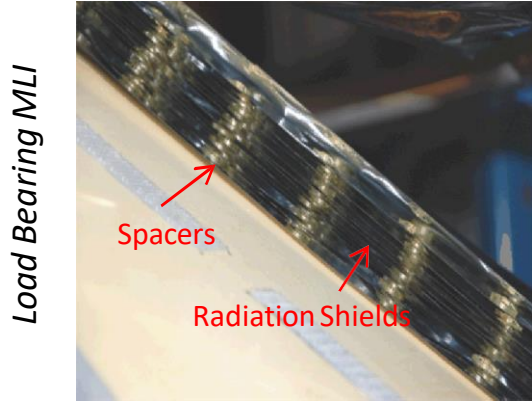
2028



Capabilities for In-Space Cryogenic Propellant Management



Reducing Heat Load and Mass for Storing LH2



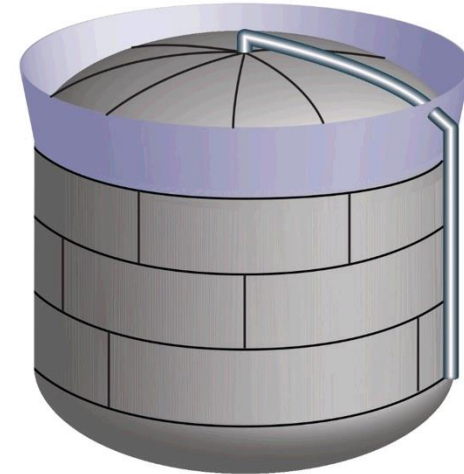
Cryogenic Encapsulating Launch Shroud and Insulated Upper Stage (CELSIUS)

Insulation

- Spray On Foam Insulation (SOFI) – new formulations
- Multi Layer Insulation
 - Thick Traditional
 - Novel construction MLI
- Aerogels (loose fill, composite blankets)
- Insulation Penetrations and Seams

Advanced Structures

- Composite Tanks
- Low conductivity structural interfaces
- Additive Manufactured Structures



MLI seaming concept for a large LH2 tank



5 m diameter composite LH2 tank (Boeing/NASA)

Tank Pressurization, Venting, Slosh and Expulsion

- Autogenous pressurization vs. non-condensable (Helium)
 - Pressure-fed engines (higher tank pressures)
 - Pump-fed engines - NPSP, pump cavitation
- Slosh - Ullage Pressure collapse & momentum impacts on Guidance, Navigation & Control
 - Baffles



Slosh visualization experiment on the International Space Station

- Venting and Expulsion in microgravity
 - Antivortex Baffles
 - Settling thrust
 - Surface tension based Liquid Acquisition Devices (LAD) / Propellant Management Devices (PMD)

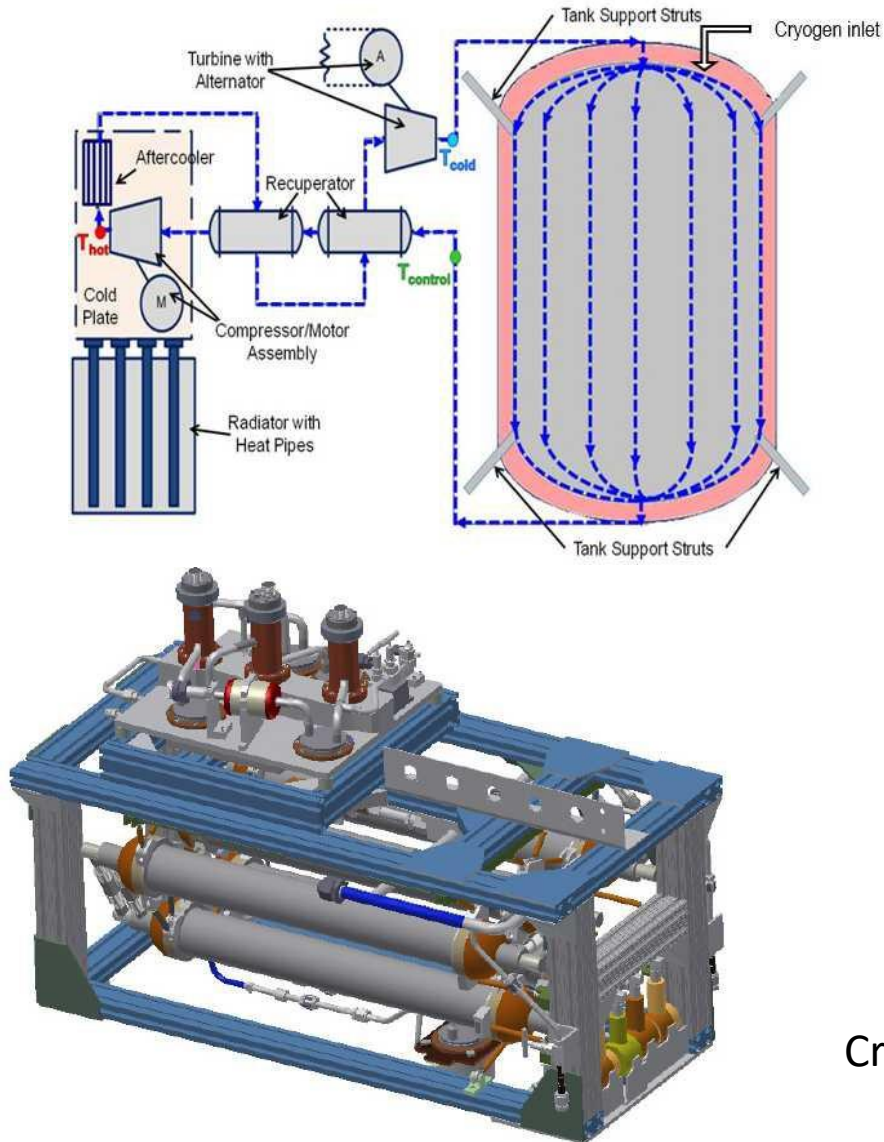


Vane Type PMD



*Space Shuttle Reaction Control System
Screen Gallery LAD*

Zero Boil-Off (ZBO) LH2 Storage

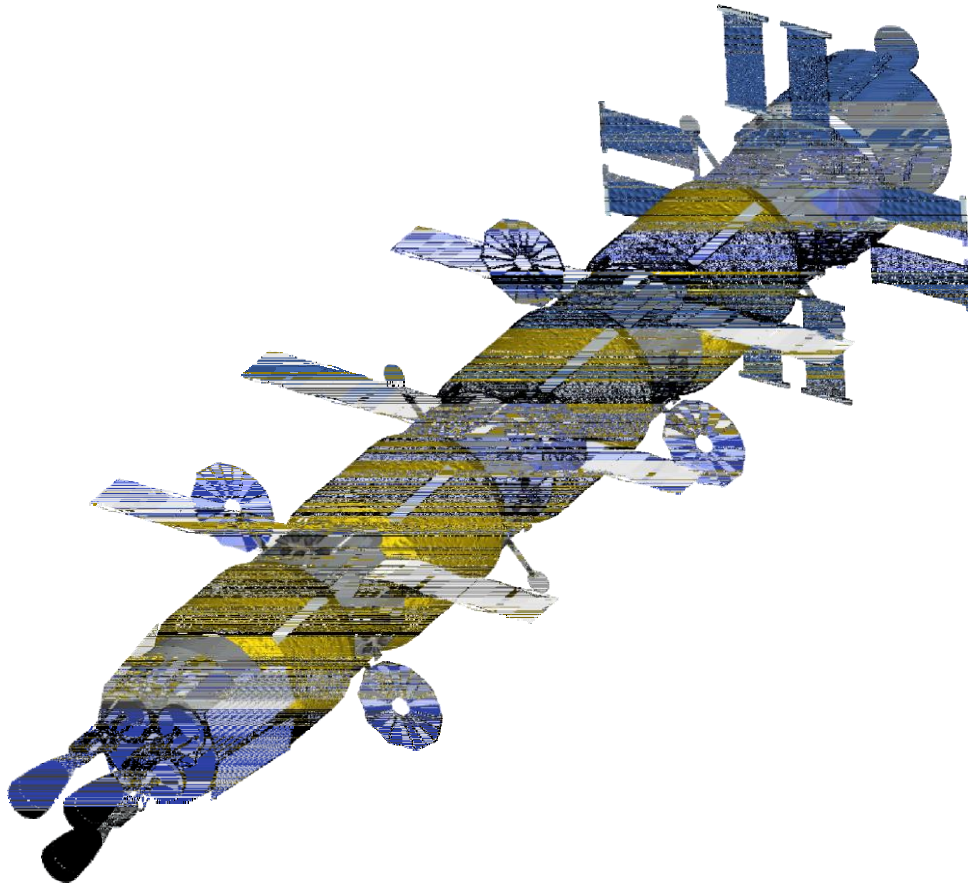


| Key Performance Parameters | | | | | |
|---|------------------|-----------------|--------------|-------------------------|-------------------------|
| Cryocooler | | | | | |
| Performance Parameter | State of the Art | Threshold Value | Project Goal | Estimated Current Value | Projected Flight Design |
| Cooling Capacity (W) | 1 | 17 | 20 | 19.1 | 20 |
| Specific Power (W/W) | 370 | 80 | 60 | 95 | 71 |
| Specific Mass (kg/W) | 18.7 | 5.5 | 4.4 | 5.3 | 5.3 |
| <i>Notes:</i> Performance Parameters for Cooling Capacity @ 20K At 23.2K, 20-20 lift is 26.6 W at 53 W/W (1400W input power) | | | | | |

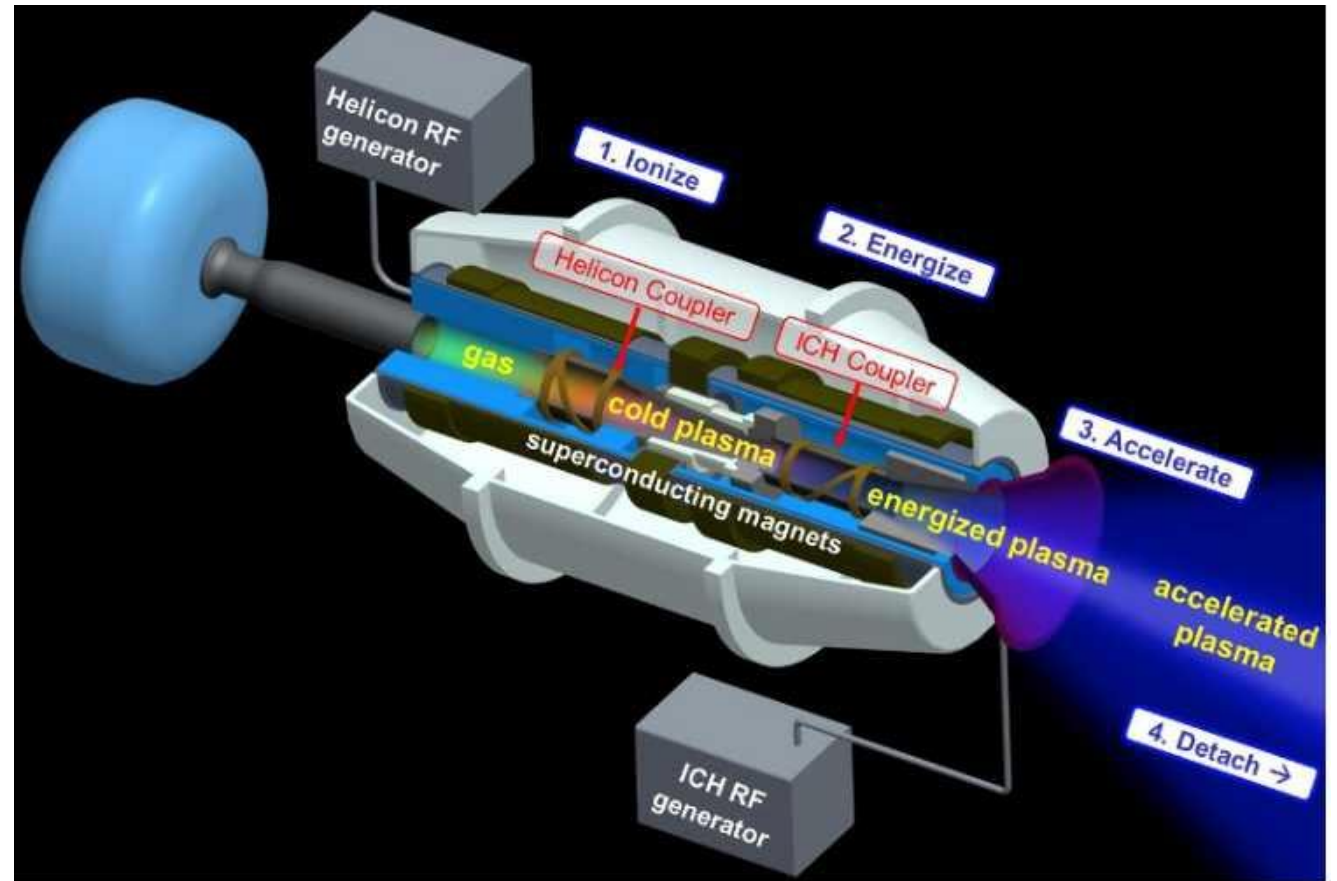
Create brassboard Reverse-Turbo-Brayton cycle cryocooler

Future Potential Space Transportation Applications of Hydrogen

Nuclear Thermal Propulsion Vehicle Concept



Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) Engine



- <http://www.adastrarocket.com/aarc/VASIMR>

Citations

- https://www.nasa.gov/audience/foreducators/rocketry/imagegallery/rpd_Japan.jpg.html#.XR-YP5NJHUI
- <http://www.adastrarocket.com/aarc/VASIMR>
- <https://gameon.nasa.gov/projects-2/archived-projects-2/composite-cryogenic-propellant-tank/>
- Wesley Johnson¹, Juan Valenzuela², Jeff Feller³, Dave Plachta¹, “Tank Applied Testing of Load-Bearing Multilayer Insulation (LB-MLI),” 2014 Propulsion and Energy Forum
- Wesley Johnson and David Chato, “Performance of MLI Seams between 293 K and 20 K”, 2019 Cryogenic Engineering Conference.