National Aeronautics and Space Administration

Refueling with In-Situ Produced Propellants

Presentation to

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By

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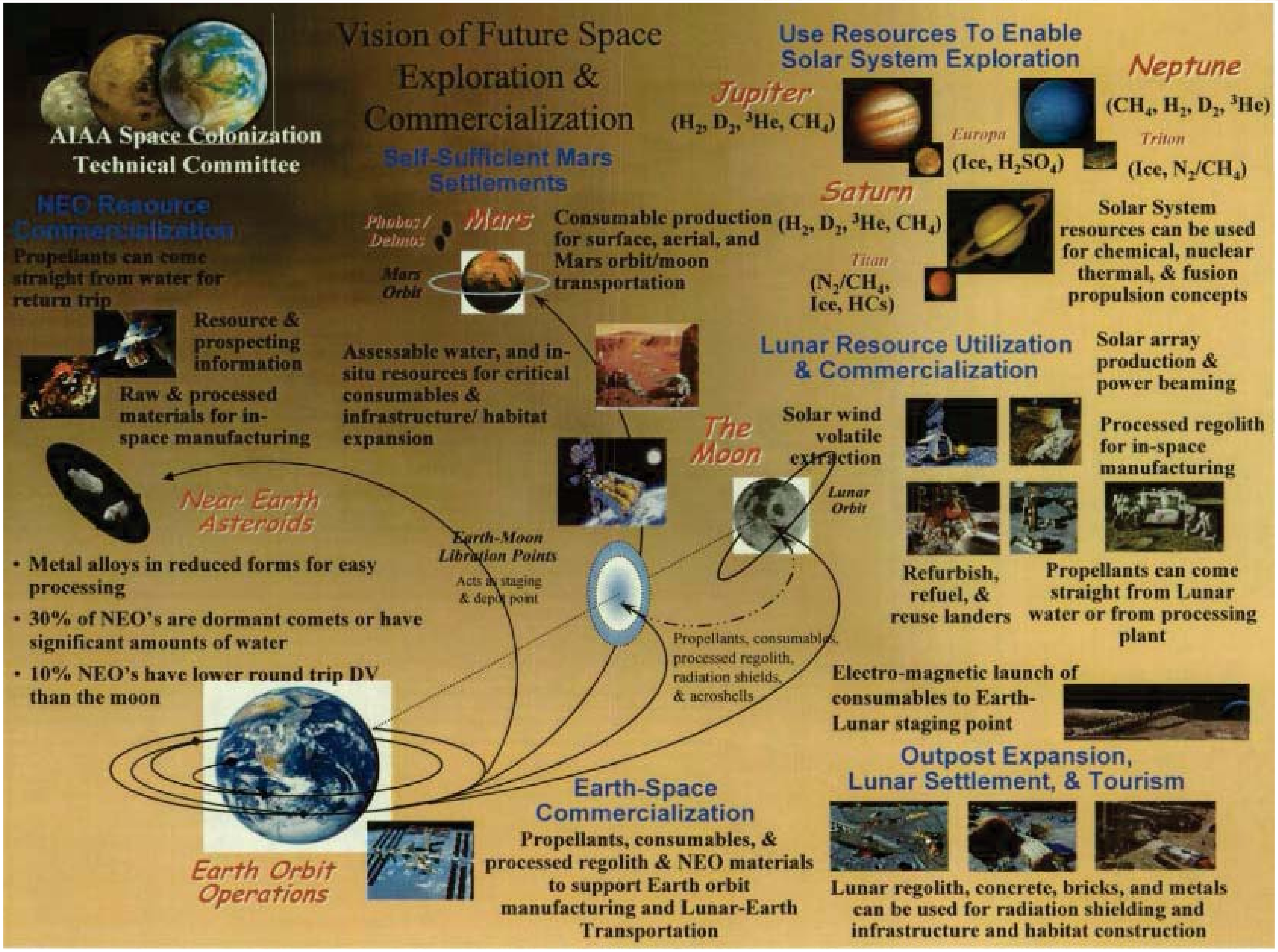
Introduction

- Speaker has been heavily involved with space cryogenics for a number of years
- In-situ resource utilization (ISRU) needs cryogenic technologies to be successful
- Cryogenic technologies being studied for advanced upper stages and propellant depots have significant overlap with ISRU
- Objectives of the talk
  - Familiarize the audience with ISRU propellant production
  - Show the need for cryogenic technologies in ISRU
  - Demonstrate the commonality with propellant depot work already underway
  - Suggest areas were ISRU specific research is required

Vision of In-Situ Resource Utilization (circa 2005)



Vision of Future Space Exploration & Commercialization

AIAA Space Colonization Technical Committee

NEO Resource Commercialization

Propellants can come straight from water for return trip

Resource & prospecting information

Raw & processed materials for in-space manufacturing

Near Earth Asteroids

- Metal alloys in reduced forms for easy processing
- 30% of NEO's are dormant comets or have significant amounts of water
- 10% NEO's have lower round trip DV than the moon

Self-Sufficient Mars Settlements

Consumable production for surface, aerial, and Mars orbit/moon transportation

Assessable water, and in-situ resources for critical consumables & infrastructure/ habitat expansion

Use Resources To Enable Solar System Exploration

Jupiter (H_2, D_2, ^3He, CH_4)

Europa (Ice, H_2SO_4)

Neptune (CH_4, H_2, D_2, ^3He)

Triton (Ice, N_2/CH_4)

Saturn (H_2, D_2, ^3He, CH_4)

Titan (N_2/CH_4, Ice, HCs)

Solar System resources can be used for chemical, nuclear thermal, & fusion propulsion concepts

Lunar Resource Utilization & Commercialization

Solar array production & power beaming

Solar wind volatile extraction

Processed regolith for in-space manufacturing

Refurbish, refuel, & reuse landers

Propellants can come straight from Lunar water or from processing plant

Electro-magnetic launch of consumables to Earth-Lunar staging point

Outpost Expansion, Lunar Settlement, & Tourism

Lunar regolith, concrete, bricks, and metals can be used for radiation shielding and infrastructure and habitat construction

Earth-Space Commercialization

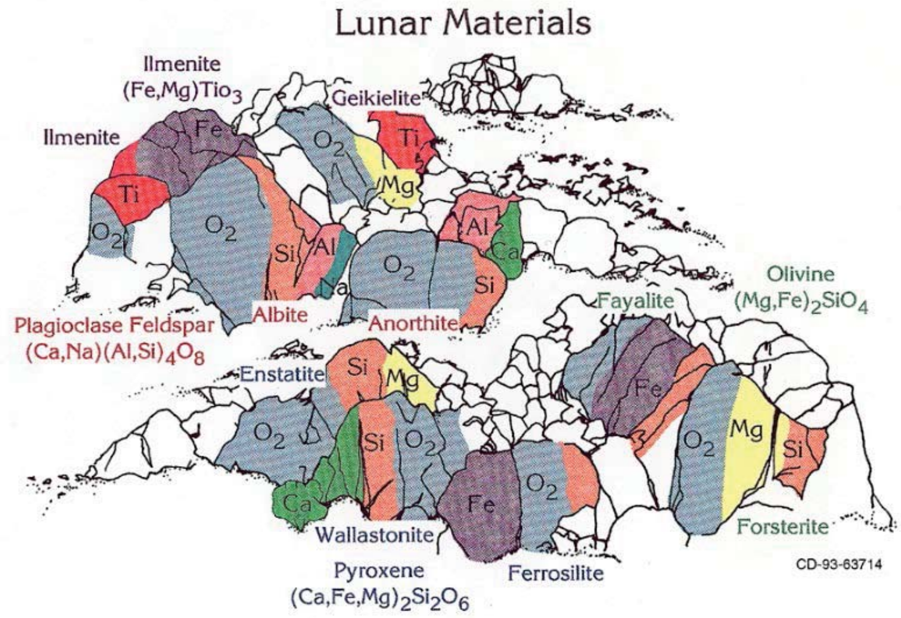
Propellants, consumables, & processed regolith & NEO materials to support Earth orbit manufacturing and Lunar-Earth Transportation

Mars Propulsion ISRU

- Design Reference Mission 5.0 (NASA baseline Mars mission)
  - Oxygen generated from Martian atmosphere using solid oxide CO_2 electrolyzers (SOCEs)
  - Rest of propellants brought from earth
  - Liquefier used to store liquid oxygen in tank, uses cryocooler
  - Cryocoolers also used to assist with storage of methane and hydrogen
- Alternates
  - Several alternate schemes for available breaking atmospheric CO_2
  - Electrolysis can be used on water to produce both hydrogen and oxygen (current studies show abundant ice in polar regions)
  - Methane propellant can be generated from either hydrogen brought from earth or hydrogen generated on Mars
  - Metal-oxide bearing rocks can be split apart for oxygen similar to lunar regolith

Lunar Propulsion ISRU

- Oxygen extraction from lunar regolith
  - Lunar highland regolith ~40% oxygen but breaking silicate bonds require high temperature (as much as 2500 C)
  - Lunar mare regolith on average 14% iron oxide compounds such as ilmenite, olivine, and pyroxene: can have oxygen extracted at lower temperatures with hydrogen feed stock
- Water and volatile extraction from lunar polar regolith
  - Lunar Prospector indicates the possibility of water ice at both poles
  - Water can be electrolyzed
- Refueling for trans-Mars injection from near lunar way-point
  - ~60% of LEO trans-Mars injection mass is hydrogen and oxygen
  - Stages fueled with lunar ISRU only 40% of the LEO launch weight of LEO fueled systems



Phobos/Deimos Propulsion ISRU

- First proposed by O'Leary (1984)
- More recent work in Lee (2009)
- Significantly less delta-v than landing on Martian surface
- Resource potential
  - Regolith for oxygen production
  - Electrolysis of water if water can be found
- Recent observation suggest a good potential for water
- Questions to be answered for an ISRU design
  - What are the properties of the regolith?
  - What volatiles are near the surface?
  - How deep is the water (ice or hydrates) located?
  - Can ISRU operations in very low-g be performed efficiently?

ISRU "Gear" Ratios

Propulsion "Gear" ratio = amount of mass in low Earth orbit (LEO) required to transfer a unit of mass to the desired destination

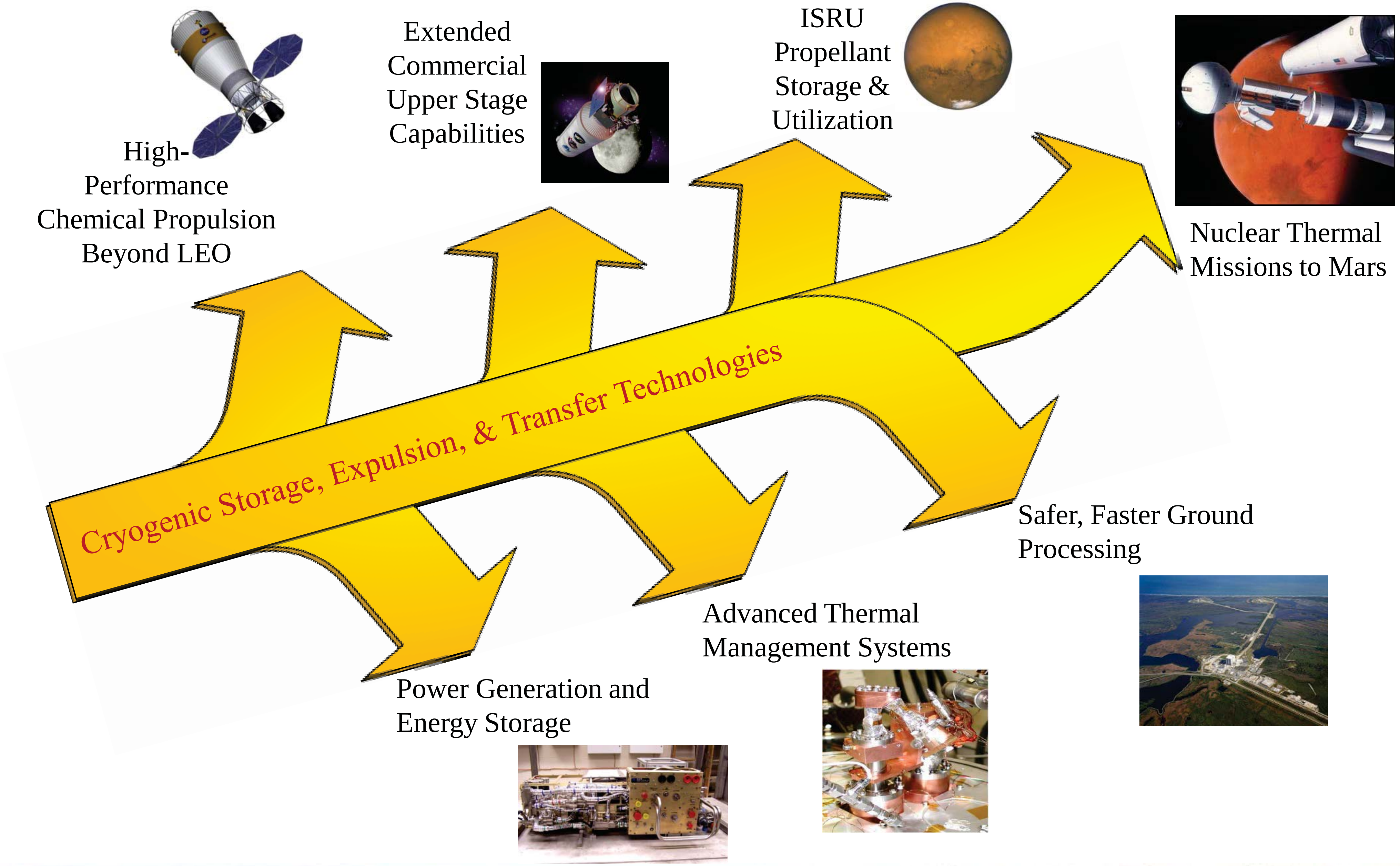
- (Mass in LEO/Mass payload landed on Moon) ~4 for cargo at lunar south pole
- (Mass in LEO without lunar fueling/Mass in LEO with lunar refueling) ~2.5 for Mars Mission
- (Mass in LEO/Mass in Mars orbit) ~5 similar to mass landed on Phobos/Deimos
- (Mass in LEO/Mass landed on Mars surface) ~10.5 aerobraked -- ~17.2 all propulsive

*Numbers estimated from Rapp (2008)

Why Cryogenics for ISRU?

- Easily produced ISRU propellants are gases at room temperature with low densities
- High pressure and metal hydride storage have mass to storage volume ratios unsuitable for rocketry
  - Rocket equation contains two major terms: isp and mass ratio -- low numbers in either produce low performance
- Cryogenic storage is mandatory for high performance rockets

Cross-Cutting Benefits of Space Cryogenics



Cryogenic Storage, Expulsion, & Transfer Technologies

High-Performance Chemical Propulsion Beyond LEO

Extended Commercial Upper Stage Capabilities

ISRU Propellant Storage & Utilization

Nuclear Thermal Missions to Mars

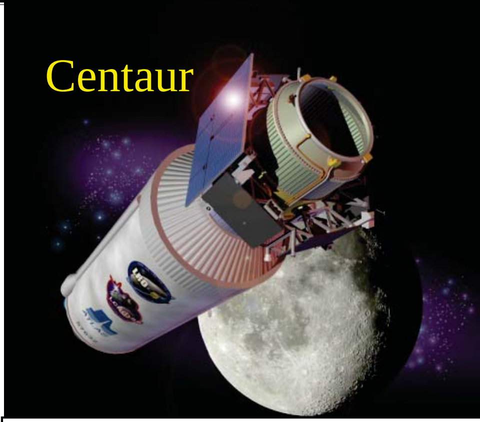
Power Generation and Energy Storage

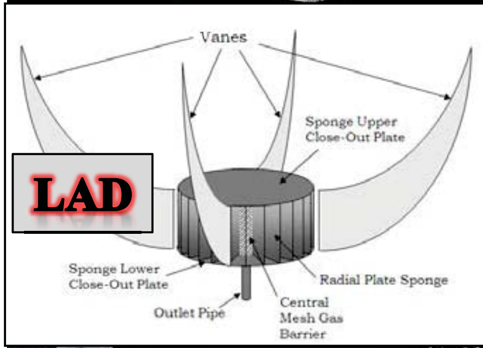
Advanced Thermal Management Systems

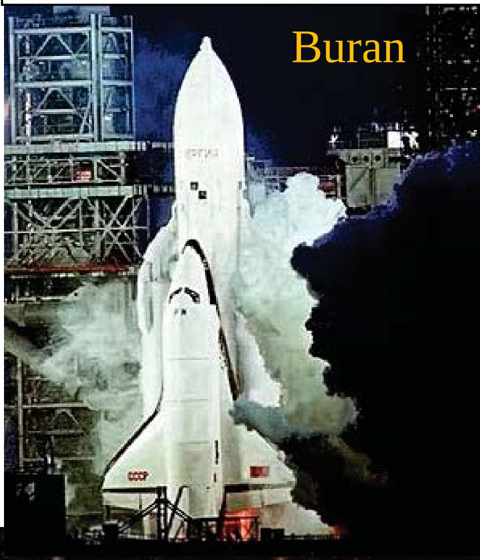
Safer, Faster Ground Processing

Present Challenges for In-Space Cryogenic Systems

- We have no demonstrated capability to store cryogenic propellants in space for more than a few hours
  - SOA is Centaur’s 9 hours with boil-off rates on the order of 30% per day
- We have no demonstrated, flight-proven method to gauge cryogenic propellant quantities accurately in microgravity
  - Need to prove methods for use with both settled and unsettled propellants
- We have no proven way to guarantee we can get gas-free liquid cryogens out of a tank in microgravity
  - Gas-free liquid is required for safe operation of a cryo propulsion system
  - Need robust surface-tension liquid acquisition device (LAD) analogous to those in SOA storable propulsion systems
  - Only known experience in the world is the single flight of the Russian Buran (liquid oxygen reaction control system)
- We have no demonstrated ability to move cryogenic liquids from one tank (or vehicle) to another in space


Centaur


LAD


Buran

Orbital Aggregation & Space Infrastructure Systems (OASIS)

Objectives:

- **Develop robust and cost effective concepts in support of future space commercialization and exploration missions assuming inexpensive launch of propellant and logistics payloads.**
- **Infrastructure costs would be shared by Industry, NASA and other users.**

Accomplishments:

- **A reusable in-space transportation architecture composed of modular fuel depots, chemical/solar electric stages and crew transportation elements has been developed.**

Hybrid Propellant Module

Infrastructure Elements:

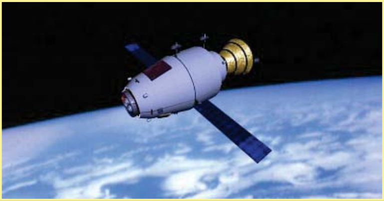
Lunar Gateway

Space Station

Crew Transfer Vehicle

Solar Electric Propulsion

Chemical Transfer Module



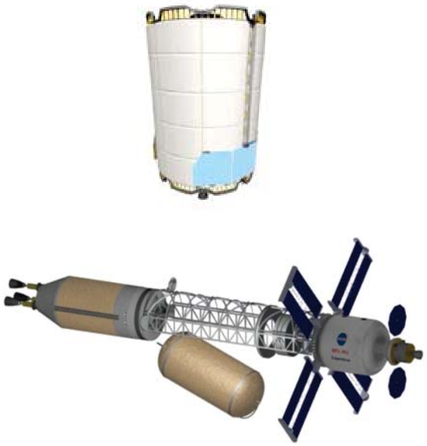
Propellant Transfer and Depots

Different types of depots for space exploration architectures (provided to Augustine Commission "Beyond Earth Orbit" Subcommittee 2009)

Pre Deployed Stage

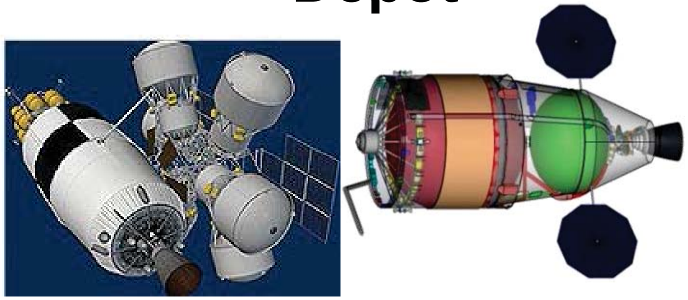
Features:
- Advanced CFM
- Long term loiter
- Rendezvous & Docking

Tanker



Features:
- Advanced CFM
- Long term loiter
- Rendezvous &Docking
- Low G Fluid Transfer

Semi-Permanent Depot



Features:
- Advanced CFM
- Long term loiter
- Rendezvous &Docking
- Robust MMOD Protection
- Dedicated Power System

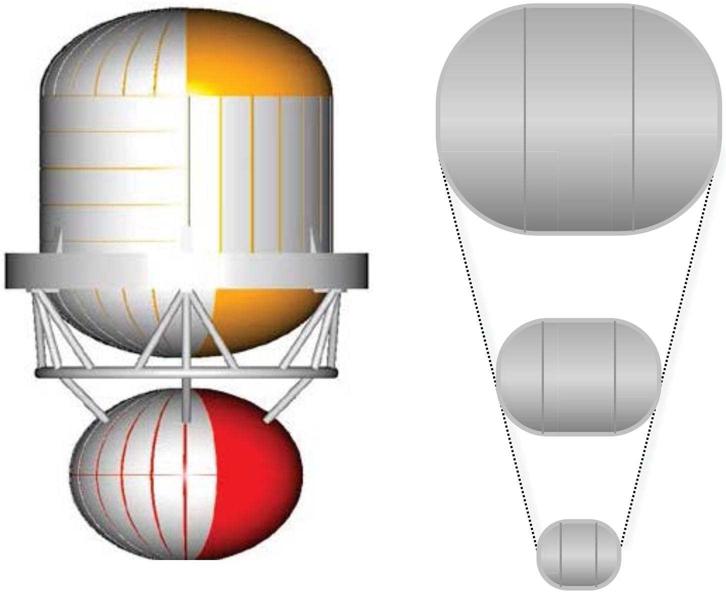
Recent Technology Maturation in Pictures

LH2 Active Cooling – Thermal Test (RBO) and Acoustic Test (VATA)

LAD Outflow Test

Sight Glass during Line Chilldown

RF Mass Gauging



Scaling Studies – MLI and Active Thermal Control

(MLI) Penetration Heat Leak Study

Composite Strut Study

Cryogenic Storage Control Technology Approach

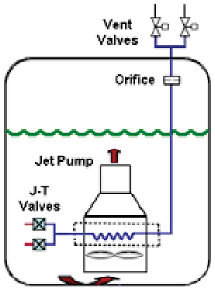
Efficient Low-g Venting

- Thermodynamic Vent System (TVS) ensures that only gas phase is vented in low gravity without using settling thrusters.
- De-stratifies propellant tank contents, with mixer

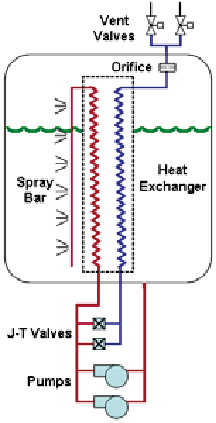
Reduced Boil-off Technologies

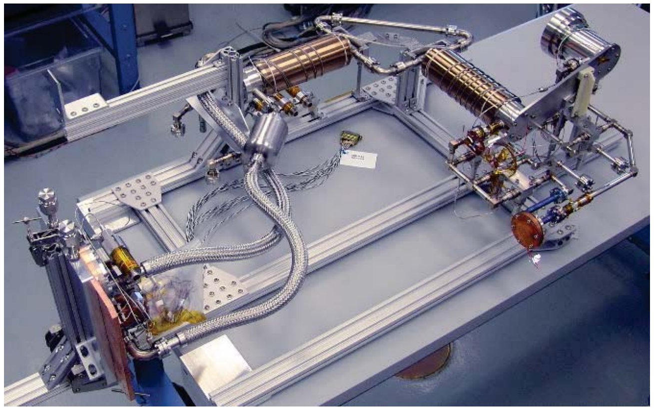
- Eliminate heat leak into the storage tank, re-condense vapor, or potentially sub-cool propellant
- 90 K cryocoolers to achieve reduced boil off for hydrogen storage
- Demonstrated capability of ~50% reduction in tank heat load

Axial Jet



Spray Bar

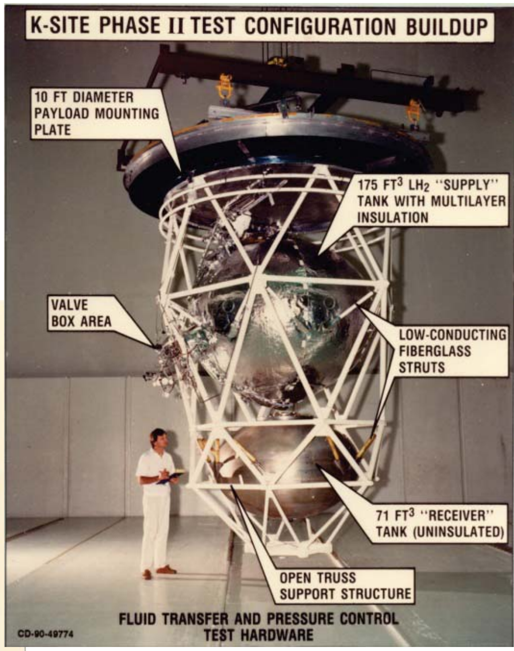




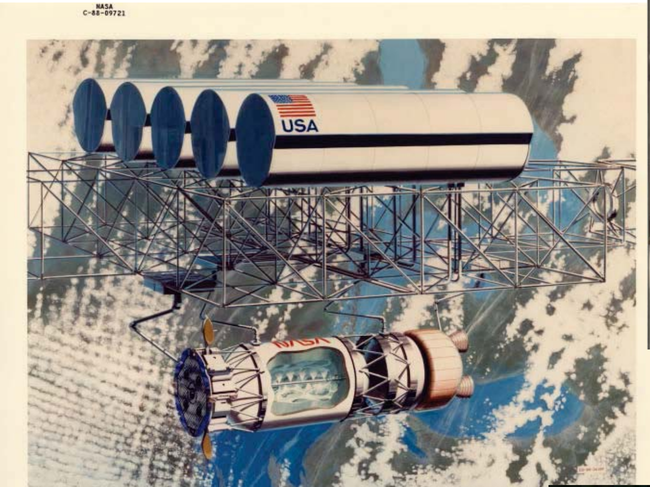
Flight representative Turbo-Brayton Cryocooler used in technology maturation

Tank Chill and Fill Technology Approach

- Current baseline approach is to use micro–g thruster settling to acquire propellants and a no-vent Fill procedure to transfer propellants.
- Recommended approach requires minimal additional hardware
- No-vent Fill
  - Uses evaporative cooling and sub-cooling to chill cryogenic tank and transfer fluid without venting
  - Demonstrated in 1990’s at NASA Glenn Plumbrook station vacuum chamber
- Both micro-g settling and no-vent fill will require proof of concept testing



Plumbrook Station Test Rig



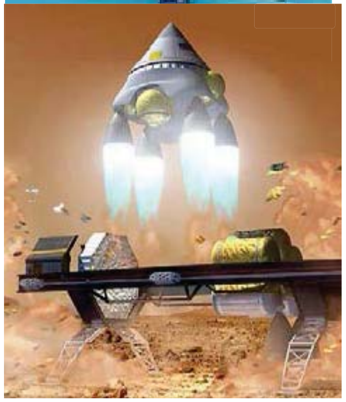
Artist's concept of transfer

Fluid Acquisition and Transfer Experiment (FARE)
on Space Shuttle

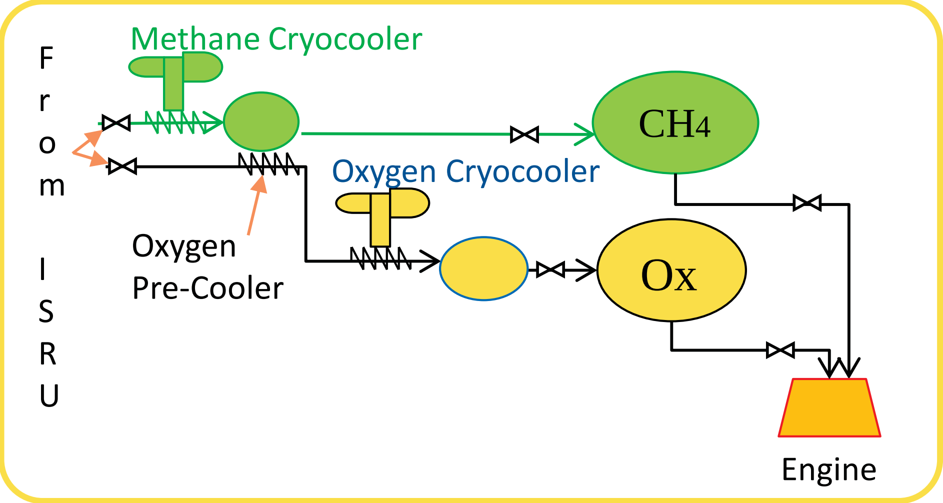
Mars Liquefier

- Liquefaction and Storage
  - Cryocoolers are used to cool the process stream and condense the gas to liquid
  - Liquid is transferred to insulated tanks for storage
- Assumptions
  - Process stream is purified prior to liquefaction
  - Liquid can be stored in ascent stage
- Tank insulation will have to trade poorer performing but non-vacuum jacket insulation with weight of vacuum jacket
- Current liquefier approach requires use of a catch tank for collection
  - Optional approach could liquefy in the storage tank, but may lower the process efficiency
- Prior work has used Pulse Tube Cryocoolers but recent Turbo-Bratyon Cryocoolers may be better for large scale

Pulse Tube Cryocooler



Mars Ascent Stage Concept



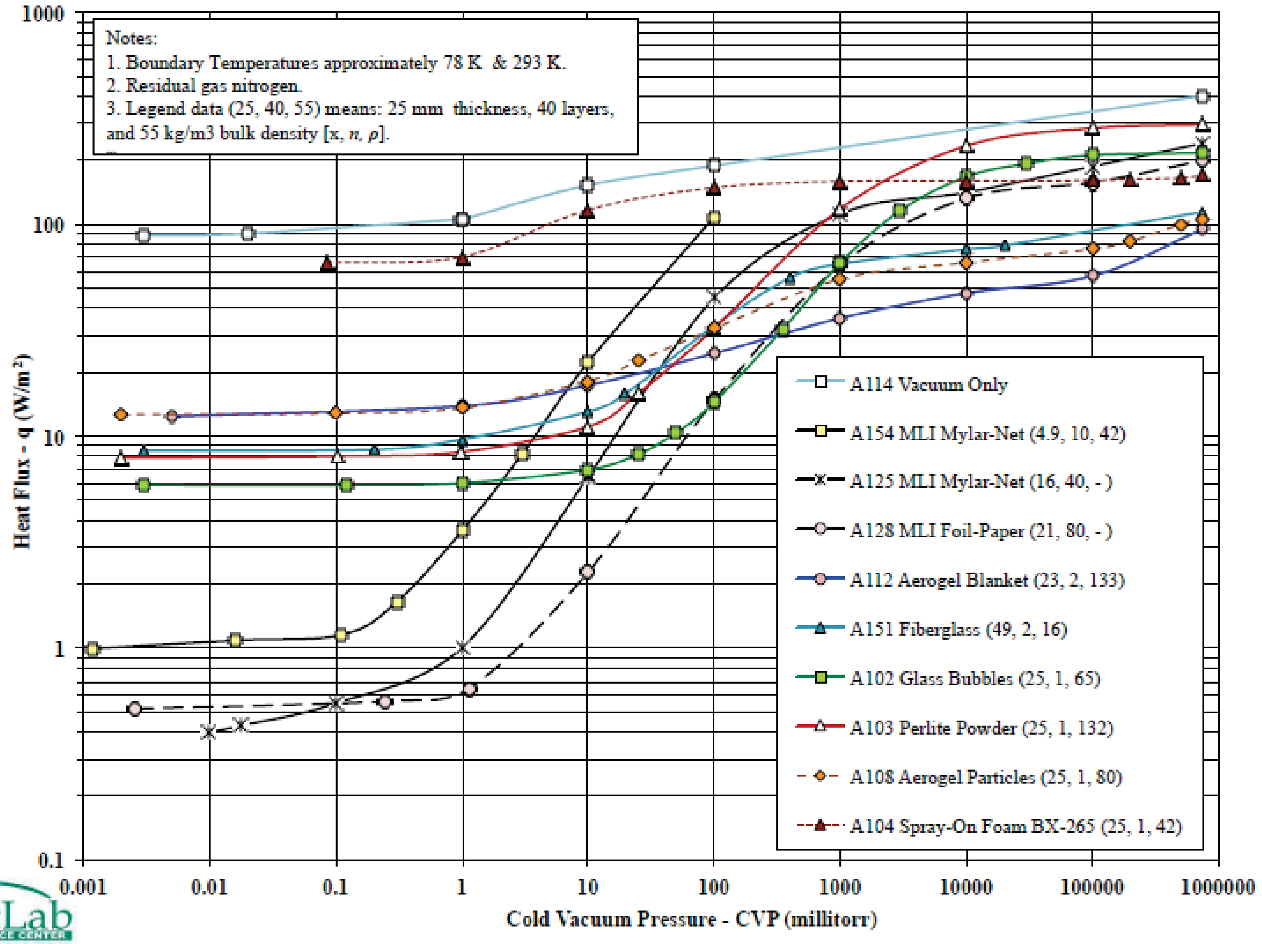
Liquefier Schematic

Mars Atmosphere Insulation

- Although low pressure, the Mars atmosphere is sufficient to significantly degrade MLI performance due to gas conduction
- Alternate insulation approaches include foam (worst performance), aerogel, aerogel/MLI, and MLI/vacuum jackets
- A vacuum jacket designed to only work on Mars can be significantly lighter
  - Only has to support the 5 torr Martian atmospheric pressure versus the 760 torr of Earth
  - Typical concepts launch with pad pressure in the vacuum jacket during launch which is then vented to space en route to Mars

Insulation Performance versus Pressure

Variation of heat flux (q) with CVP for different cryogenic insulation systems and materials.
Boundary temperatures: 78 K and 293 K. Residual gas is nitrogen.



Fesmire (2014)

Concluding Remarks

- ISRU is of significant advantage to human exploration
- Cryogenic technologies are required for ISRU success
- Cryogenic technologies from upper stages and depots for storage and transfer can be applied to ISRU
  - TVS systems for storage and venting
  - Reduced boil-off for long term storage
  - Large capacity space rated cryocoolers
  - Low loss transfer systems (all locations) and low-g transfer (Lunar, Phobos/Deimos)
- ISRU unique technologies need further development
  - Liquefier is unique to ISRU although cryocoolers used may not be
  - Mars surface insulation cannot use the space vented MLI of upper stages and depots without adding a vacuum jacket, but may still be able to take advantage of cryocoolers and boil-off reduction

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