Refueling with In-Situ Produced Propellants

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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)

- **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
- **Earth-Moon Libration Points**
  - Acts as staging & depot point
- **Earth-Space Commercialization**
  - Propellants, consumables, & processed regolith & NEO materials to support Earth orbit manufacturing and Lunar-Earth Transportation
- **Use Resources To Enable Solar System Exploration**
  - Jupiter
    - (H₂, D₂, ³He, CH₄)
  - Europa
  - Triton
    - Ice, N₂/CH₄
  - Saturn
    - Ice, H₂SO₄
  - Titan
    - (N₂/CH₄, Ice, HCs)
  - Neptune
    - (CH₄, H₂, D₂, ³He)
- **Lunar Resource Utilization & Commercialization**
  - Solar wind volatile extraction
  - Lunar Orbit
  - Refurbish, refuel, & reuse landers
  - Propellants can come straight from Lunar water or from processing plant
- **Outpost Expansion, Lunar Settlement, & Tourism**
  - Lunar regolith, concrete, bricks, and metals can be used for radiation shielding and infrastructure and habitat construction
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

- 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
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.

Infrastructure Elements:
- Lunar Gateway
- Space Station
- Crew Transfer Vehicle
- Solar Electric Propulsion
- Chemical Transfer Module
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)

Scaling Studies – MLI and Active Thermal Control

(MLI) Penetration Heat Leak Study

Sight Glass during Line Chilldown

LAD Outflow Test

RF Mass Gauging

Composite Strut Study
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

Flight representative Turbo-Brayton Cryocooler used in technology maturation
• 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
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-Brayton Cryocoolers may be better for large scale
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.

Notes:
1. Boundary Temperatures approximately 78 K & 293 K.
2. Residual gas nitrogen.
3. Legend data (25, 40, 55) means: 25 mm thickness, 40 layers, and 55 kg/m2 bulk density ($\rho$, $\eta$, $\phi$).
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
1. Clyde Parrish “In-Situ Space Resource Utilization” presentation at STAIF 2005
4. Donald Rapp *Use of Extraterrestrial Resources for Human Space Missions to Moon or Mars* Springer Praxis 2013.
8. Pat Troutman et. al “Orbital Aggregation and Space infrastructure System” international Astronautical Congress IAC-02-IAA.13.2.6, 2002