Space Technology Mission Directorate
Game Changing Development Program
Nuclear Thermal Propulsion Project – Cryogenic Fluid Management Studies for NTP
Jonathan Stephens, Arthur Werkheiser, Eric Carlberg, Jason Hartwig and David Plachta, NASA, August, 2018
OBJECTIVE(S):

- Develop the NTP CFM Concept of Operations
  - Vehicle Description ✓
  - Mission Analysis & Design Reference Missions ✓
  - Ground Processing and Launch Operations ✓
  - Aggregation ✓
  - Flight Operations ✓
  - Off-Nominal Operations
    - Pre-launch
    - Flight
  - System Verification Test at SSC

- Identify CFM Requirements to close the mission
  - Enabling
  - Potentially enhancing
  - Define Key Performance Parameters
NTP Crew Vehicle Aggregation in NRHO

1 Sol

10 Sol

- Launch elements separately to LDHEO
- 180 day low ΔV transfer to NRHO using RCS
- Aggregate, rendezvous and dock stages in NRHO
- Checkout and ready vehicle

NRHO

LDHEO

Launch to LDHEO

Launch to LDHEO

Launch to LDHEO

Launch to LDHEO

Deep Space Hab

Inline Stage #1

Inline Stage #2

Inline Stage #3

Core Stage

Stage Docking

Stage Docking

Stage Docking

Stage Docking

Complete Vehicle

Orion Crew Hab Checkout and Logistics

Orion Checkout Crew Return

SLS Block 2 Launch Vehicles

Date

NTP Vehicle Conceptual Design

NASA/GCD – CFM Concept of Operations
NTP Crew Vehicle
Earth to Mars Transit

1 Sol
180 day low ΔV transfer to LDHEO
Rendezvous with Mars Crew
Perform TMI burn with NTP for 159 day transit
Perform MOI burn with NTP into 10 sol orbit at Mars
RCS maneuvers in 10 sol
NTP burn from 10 sol to 1 sol
RCS maneuvers in 1 sol

10 Sol
NRHO
LDHEO

Mars Orbit Insertion (MOI)

Maneuvers to final orbit

6 day arrival to Parking orbit

159 day transit

Trans Mars Injection (TMI)

SLS Block 2 Launch Vehicles

NTP Vehicle Conceptual Design
NASA/GCD – CFM Concept of Operations
NTP Crew Vehicle
Mars to Earth Transit

Assumes 622 day stay for 2033 Mars Mission

- 622 day stay in Mars orbit
- RCS plane change / apotwist
- Perform TEI burn with NTP for 159 day transit
- Perform EOI burn with NTP into LDHEO
- Rendezvous with Orion for Crew return to Earth

Trans Earth Injection (TEI)

Earth Orbit Insertion (EOI)

NRHO
LDHEO

159 day transit
180 day transfer to NRHO

Mars Crew Return
Orion Return (with crew)

SLS Block 2 Launch Vehicles

NTP Vehicle Conceptual Design

NASA/GCD – CFM Concept of Operations
Aggregation Timeline

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Launch</th>
<th>Assembly</th>
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<th>LDHEO</th>
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- SLS Launch cadence allows a launch every ~180 days
- Inline Tank 1 spends 3.0 years in orbit before Trans Mars Injection
- Each element is fully capable of maneuvering: RCS, Guidance
- Each element will dock with the “stack” as soon as possible
- NRHO & LDHEO have similar thermal environments and are the “warmest” orbits of all mission phases.
  - Thermally, both orbits are a factor of 3 to 4 lower than LEO
- This Mission Design is Notional
### Hydrogen Consumption - Notional

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<th>INLINE 3</th>
<th>INLINE 2</th>
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<td>CORE</td>
<td>INLINE 3</td>
<td>INLINE 2</td>
<td>INLINE 1</td>
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</table>

- Based on baselined Hydrogen use – Cascade flow
- This is likely NOT the best way to managed the Hydrogen
  - Core tank bottom gets Gamma Ray & Neutron heating
- **This analysis assumes** Passive CFM is optimized, Active Cooling (Cryocoolers) are utilized and Low Leakage, Long Duration Cryocouplers and Valves are utilized to achieve “near zero” losses.
- Each of the 3 engines require 28 pounds/sec of Hydrogen
### Manned Mars Mission Timeline

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Trans Mars</th>
<th>Mars Orbit</th>
<th>Mars Loiter</th>
<th>Depart Prep</th>
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<th>Earth Orbit</th>
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<td>963</td>
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<table>
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<th>Nuclear Thrust</th>
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<th>Burn 2</th>
<th>Burn 3</th>
<th>Burn 4</th>
<th>Totals</th>
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<td>Start up (minutes)</td>
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<td>minutes</td>
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<td>Cooling Time (Hours)</td>
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<td>30</td>
<td>hours</td>
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This indicates Tank is Empty or not required

- Mission Elapsed Time includes aggregation
- Inline Tank 3 spends 4 years in orbit with Hydrogen in it
- Quiescent CFM (100 X Days), Nuclear Engine Hot-Fire (Minutes), Reactor Cool Down (Hours)
- This analysis assumes Passive CFM is optimized, Active Cooling (Cryocoolers) are utilized and Low Leakage, Long Duration Cryocouplers and Valves are utilized to achieve “near zero” losses.
NTP Specific CFM Elements Across Multiple Propulsion Pieces

- Specific to Hydrogen Based NTP
  - “G” denotes ground testing required to TRL 6
  - “F” denotes flight demo required to TRL 6
- Enhancing
- Enabling

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<tr>
<th>Technologies</th>
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<td>Automated Cryo-Couplers</td>
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<td>Cryogenic Thermal Coating</td>
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<td>High Capacity, High Efficiency Cryocoolers 90K</td>
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<td>High Vacuum Multilayer Insulation</td>
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<td>Liquefaction Operations (MAV &amp; ISRU)</td>
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<td>Liquid Acquisition Devices</td>
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<td>Low Conductivity Structures</td>
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<td>MPS Line Chilldown</td>
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<td>Para to Ortho Cooling</td>
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<td>Thermodynamic Vent System</td>
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<td>Tube-On-Shield BAC</td>
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<td>Tube-On-Tank BAC</td>
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<th>Lunar Aggregation (no production)</th>
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Colored boxes need to fly to get to TRL 6
Potential for Architecture Enhancement
Currently Listed in Architecture Baseline

W. Johnson & J. Stephens “Cryogenic Fluid Management Roadmapping Exercise”
Updated July 26th, 2018
## CFM Technology Needs (2/2)

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<th>Technology</th>
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Potential for Architecture Enhancement
Currently Listed in Architecture Baseline

**W. Johnson & J. Stephens “Cryogenic Fluid Management Roadmapping Exercise”**
**Updated July 26th, 2018**
NTP CFM Tech Maturation Plan

FULL SCALE INTEGRATED SYSTEM DEMONSTRATION

1.0 Initial CFM System Requirements and Conceptual Design
2.0 Develop CFM System Concept of Operations
3.0 Identify initial set of enabling CFM technologies

MISSION ANALYSIS AND ARCHITECTURE DESIGN ASSESSMENT

4.1.1 Requirements Identified - System Sizing and Preliminary Design
4.1.2 Component Development Design, Build and Test
4.1.3 Subsystem Integration and Acceptance Test
4.1.4 Subsystem Demo Testing
4.1.5 Test Results Assessment comparison to requirements

COMPONENT / SUBSYSTEM DEMONSTRATIONS

4.2.1 Requirements - Size, Mass, Heat, Power and Leakage Rates
4.2.2 Valve Development Component and Fixture Testing
4.2.3 Valve Design, Manufacture and Testing
4.2.4 Test Results Assessment comparison to requirements

4.3.1 Requirements - Cryo-Coupler Development and Fixture Testing
4.3.2 Cryo-Coupler Design, Manufacture and Testing
4.3.3 Test Results Assessment comparison to requirements

Potential Enhancing Technologies that could be Risk Mitigation to enable architecture closure

- Line Chilldown
- Axial Jet / Spray Bar Pump Based Mixing
- Advanced External Insulation
- Unskirted Mass Gauging
- Thermodynamic Vent System
- Structural Heat Load Induction (Fragment / Detachable)
- Propellant Management / Liquid Acquisition Devices
- Propellant Transfer
- Broad Area Cooling
- Pressurization Systems - Helium/Autogenous
Lunar Distance High Earth Orbit – (LDHEO)

- Stack orbits the Earth at a distance about equal to Moon
- 10 day orbit
- Very little time spent near Earth
- Lunar apogee is 400,000 km as is this orbit
Near Rectilinear Halo Orbit – (NRHO)

- Aggregation in NRHO
- Elliptical Orbit (very little time near the moon)
- Orbital Period: 6 to 14 days
- 70,000 km x 2,000 km
• Active CFM heat collection via Broad Area Cooling (BAC) tubing networks on LH2 tanks
• 0.75” SOFI on LH2 tanks
• MLI, 40 layers ($\varepsilon^* = 0.0005$ to $0.0022$) on LH2 tanks
• MLI, 3 layers ($\varepsilon^* = 0.005$) on LH2 tanks support structure
• Tank support structure strut/skirt combination
  - Struts: S-Glass shank with Titanium inserts
  - Skirts: Al-2219
• Avionics/Power heat collection via pumped cooling loops
• Heat rejection via double-sided composite heat pipe radiators
## Environmental Heating of Cryogenic Tanks - Aggregation -

### Environmental heating rates (Watts)

<table>
<thead>
<tr>
<th>tank</th>
<th>orbit</th>
<th>composite struts</th>
<th>aluminum skirt</th>
<th>titanium skirt</th>
<th>with the MLI on skirts removed</th>
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<tbody>
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<td>composite struts</td>
<td>aluminum skirt</td>
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<td>62.2</td>
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<td>844.1</td>
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<td>201.4</td>
<td>758.1</td>
<td>199.8</td>
<td>697.8</td>
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</tbody>
</table>

| In-Line Tank | NRO | 43.9 | 59.1 | 51.7 | 187.4 | 813.1 | 163.1 |
|              | LDHEO | 41.5 | 53.8 | 48.8 | 177.3 | 769.8 | 153.4 |
|              | LEO beta=0 | 125.7 | 162.0 | 135.5 | 712.6 | 2,840.7 | 685.9 |
|              | LEO beta=70 | 127.5 | 172.3 | 141.9 | 735.7 | 2,916.7 | 711.3 |

**NOTE:** 44% margin added to these results

Model generated by Steven Suterlin  
NASA/MSFC/ED04

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- Multiple 20 K, 20 W cryocoolers (Two Fault Tolerant)
  - Core Tank: 6 cryocoolers (maximum of 4 operating)
  - In-line Tank: 5 cryocoolers (maximum of 3 operating)

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Eric T. Stewart  
NASA/MSFC/ER43  
256-544-7099  
Eric.T.Stewart@nasa.gov
Nuclear Heating (Liability)

- Image is measured NERVA data
- When Reactor is “Hot”, it generates Gamma ray & Fast Neutron Heating
- Hydrogen absorbs both very well.
- Shielding is difficult or expensive (heavy)
- Core tank is most effected
Nuclear Heating

- Calculated using optimization model that factors in desired crew dose rates in habitat
- Shield sizes and materials optimized using a genetic algorithm
- Conservative estimate is ~3 mT (1 mT per engine), results in ~10 kW heating per engine

NOTES: Low sample size in optimization case (coarse calculation). Actual masses will be further reduced from those shown here.
Nuclear Heating

- Conservative estimate is ~3 mT (1mT per engine), results in ~10 kW heating per engine
  - While this is significant heating, it is not enough heating to self pressurize the tank.
  - The amount of energy required to pressurize the tank is on the order of 400kW and will be achieved by autogenous pressurization during engine hot-fire.
  - Analysis of a 2-Phase boost pump currently in work. There appears to be no technical challenges with a boost pump and main pump working together.

- The bigger problem for CFM maybe the latent heat in the tank and the balance of LH2 in the core tank.

- The reactors (engines) run for just a few minutes at a time (5 to 12 minutes), but require pulse cooling for hours afterwards; up to 36 hours for the longer runs.

- The amount of LH2 that is required for cooling will vary inversely to time; 3 to 7% of the LH2 mass consumed during each burn.
Effects on Hydrogen Inventory

**Liabilities**

- **Environment**
  - Sun, Moon and Earth are all heat sources
  - Aggregation in NRHO requires liquid hydrogen to be stored for three years. However, NRHO and LDHEO are thermally “benign” relative to LEO.
  - Transport environment is cold.

- **Vehicle Structure**
  - Skirts: Structure that interfaces with the tank
  - Struts: Can be used with skirts and designed for extremely low thermal conductivity
  - MLI on propellant tank (~40 layers)
  - MLI on vehicle structure
  - Tank penetrations
    - An be a significant source of heat
    - Must be insulated

- **Crycoolers**
  - Tank pressure control without loss of propellant

- **Operational Strategy**
  - The flexibility to manage how/when hydrogen flows from tank-to-tank is an asset.
  - Cascade method is currently baselined, but is probably not optimal.

- **Time Duration**
  - Tanks are in NRHO for extended periods of time
  - Significant time between hot-fires to recondition propellant

**Assets**

- **Environment**
- **Vehicle Structure**
- **Crycoolers**
- **Operational Strategy**
- **Time Duration**

**Nuclear Heating**

- Requires shielding to mitigate
- Possible fluid dynamic issues internal to propellant tank
Summary – CFM for NTP

- CFM for NTP is a challenge
  - Long duration mission (years!!!)
  - Nuclear Heating
  - Technology development for some elements are needed.
  - Active cooling is needed to enable mission
    - Requires both Mass and Power

- Aggregation currently in NRHO
  - Fairly benign environment thermally relative to LEO
  - Heat loads associated with the baseline structure are manageable
    - Six Cryocoolers on Core Tank
    - Five Cryocoolers on each Inline Tank

- Heat loads during ground operations and during ascent are currently being evaluated
- Operational strategies provide many “knobs” to turn to maximize the LH2 life, but are very nascent at this time.
  - Example: Cascade Flow vs Run Tank method
- **Two-Stage Cooling Trade – Glenn Research Center**
  - Evaluates the potential Mass and Power savings with two-stage cooling vs one-stage

- With two-stage cooling, 90K cryocoolers are used for heat intercept to minimize the requirements on the 20K cryocoolers
- 90K cryocoolers have lower Specific Mass and Specific Power than 20K cryocoolers
- Results from a recent study indicate two-stage cooling trades favorably for NTP
Two Stage Cooling for LH$_2$

- Tank heat load plotted vs. 20 K cooler lift for 2 Stage and 1 Stage concepts
  - Size of 20 K cooler is substantially reduced for 2 Stage concept

- Recent NTP study found significant advantages to 2-stage cooling

<table>
<thead>
<tr>
<th></th>
<th>Temp., K</th>
<th>Lift, W</th>
<th>Active System Mass, kg</th>
<th>Input Power, W</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>20K Class</strong></td>
<td>24.2</td>
<td>16.5</td>
<td>275</td>
<td>1150</td>
</tr>
<tr>
<td><strong>90K Class</strong></td>
<td>55</td>
<td>94</td>
<td>192</td>
<td>880</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>467</td>
<td>2030</td>
</tr>
<tr>
<td><strong>Single 20K Class Stage Cooling</strong></td>
<td>24.2</td>
<td>114</td>
<td>1500</td>
<td>7000</td>
</tr>
</tbody>
</table>
An update to ZBO modeling is complete for NTP, LH$_2$ storage

- Thermal control system mass is compared for passive, 1 Stage and 2 Stage concepts
- For these large tanks, active cooling saves mass after ~ one month in LEO
- Two stage cooling saves mass and power, while greatly reducing 20K cryocooler requirement

### CAT Improvement

<table>
<thead>
<tr>
<th>CAT Improvement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>20K-20W Cryocooler Developments (24.2 K LH$_2$ storage temp)</td>
<td>50 W/W Specific Power, 3.7 kg/W Specific Mass</td>
</tr>
<tr>
<td>90K-150 W Cryocooler Development</td>
<td>9W/W Specific Power, 0.36 kg/W Specific Mass</td>
</tr>
<tr>
<td>Cooling Strap Contact Resistance</td>
<td>10 K/W</td>
</tr>
<tr>
<td>Broad Area Cooling Pressure Drop</td>
<td>Tube gas velocity and pressure drop found</td>
</tr>
<tr>
<td>Tank Insulation Seam Heat</td>
<td>Open butt seam assumed with 3mm gap.</td>
</tr>
<tr>
<td>Tank Insulation Pin Heat</td>
<td>1 pin every 30 cm, Nylon</td>
</tr>
<tr>
<td>Penetration to tank MLI seam</td>
<td>Q estimated from parametric relationship assuming MLI butt with Cryolite</td>
</tr>
<tr>
<td>Insulation on structure and penetrations</td>
<td>20 layers of MLI assumed, Modified Lockheed Eqn. with scale factor 6 used</td>
</tr>
</tbody>
</table>
Trade Studies

• Potential use of Cryogenic Thermal Coatings for NTP – Kennedy Space Center
  - Developed a new concept where a combination of “solar white” and MLI could yield an improved flexible insulative radiation shield.

• Benefits of loading densified hydrogen for NTP – Kennedy Space Center
  - Large thermal capacitance of densified hydrogen allows the hydrogen to be held for a longer time before Active Cooling is needed.
Forward Work

• Evaluate Structural options for thermal optimization (Design → Structural Analysis → Thermal Analysis)
  - Struts vs Skirts
  - Aluminum vs Titanium vs Composite
  - Include tank penetrations (Fill/Drain, Pressurization, Vent)

• Conduct a Thermal “Soak Back” Analysis
  - Heat conducted through the structure and penetrations during engine hot-fire and reactor cool down.

• CFD Analysis to evaluate the behavior of the Core Stage propellant during engine hot-fire.

• CFD Analysis to evaluate the feasibility of using Tube-On-Tank Broad Area Cooling integrated with cryocoolers for pressure control in micro-g – Glenn Research Center