RP-21 Steering Committee Meeting

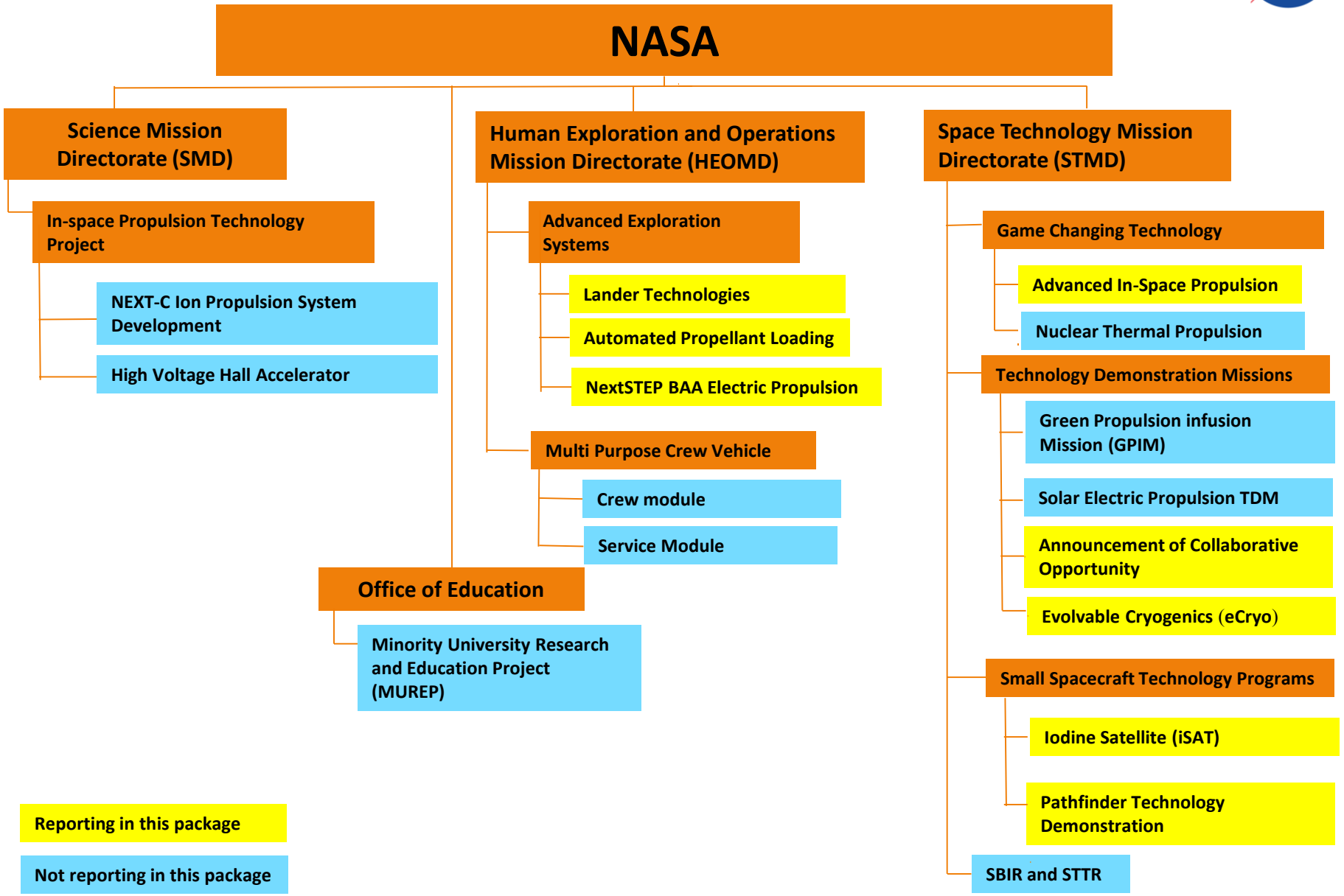
NASA Spacecraft Propulsion Update

March 2, 2016

Mark Klem

NASA Glenn Research Center

NASA Spacecraft Propulsion Sponsorship



HEOMD Advanced Exploration Systems (AES)

Lander Technologies Project

Vision: Develop a Suite of Lander Capabilities that enable Human Exploration beyond Low Earth Orbit.

Objectives:

Lander Tech is three separate but synergistic efforts:

- **Lunar CATALYST (Lunar Cargo Transportation and Landing by Soft Touchdown)**
  - Support U.S. industry led robotic lunar lander development via three public-private partnerships.
  - Infuse or transfer landing technologies into these public – private partnerships
- **Identify risk reduction tasks for a HEOMD Mars lander as guided by the Evolvable Mars Campaign/HAT**
  - Infuse Autonomous Landing and Hazard Avoidance Technologies into planned HEOMD and SMD missions (Mars 2020)
  - Support general lander capability/ risk reduction in areas of In-Situ Resource Utilization (ISRU) compatible propulsion system
- **Lander Element Lead for Resource Prospector Mission**
  - Provide lunar lander support to RP for any partner identified
  - Assess Partner's Lander performance
  - Provide integrated Loads / Environments / CAD analysis for integrated spacecraft
  - Provide Trajectory Design for integrated spacecraft

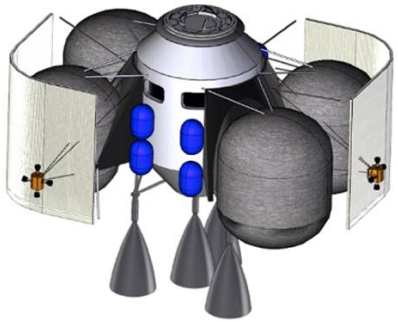
Also incorporates ISRU Liquefaction efforts

= Supports propulsion related focus

Team:

MSFC (lead), GRC, JSC
Industry (Lunar CATALYST) Partners:
Masten, Astrobotic, Moon Express

MSFC Additively Manufactured 4 Klbf LOX/LCH4 Engine

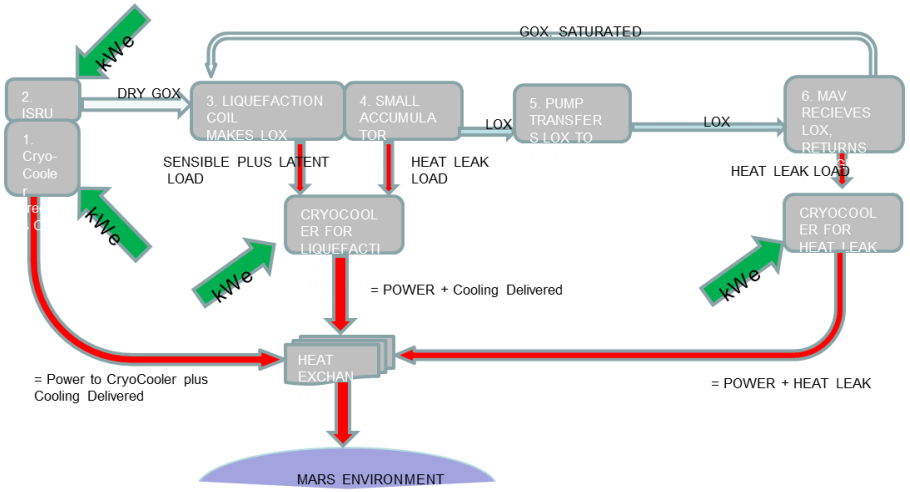


Mars Ascent Vehicle (MAV) 2-stage, pump-fed engine concept (Incorporates ISRU generated LOX)

Lander Technologies Project

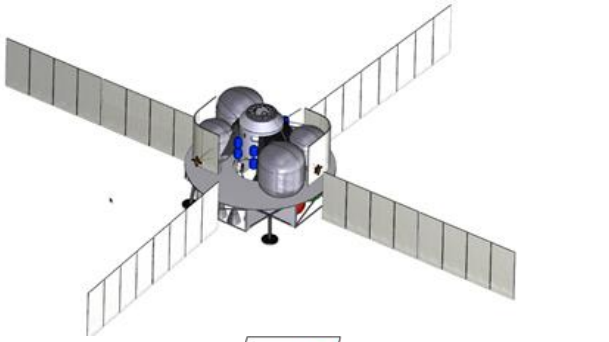
Vision: Develop a Suite of Lander Capabilities that enable Human Exploration beyond Low Earth Orbit.

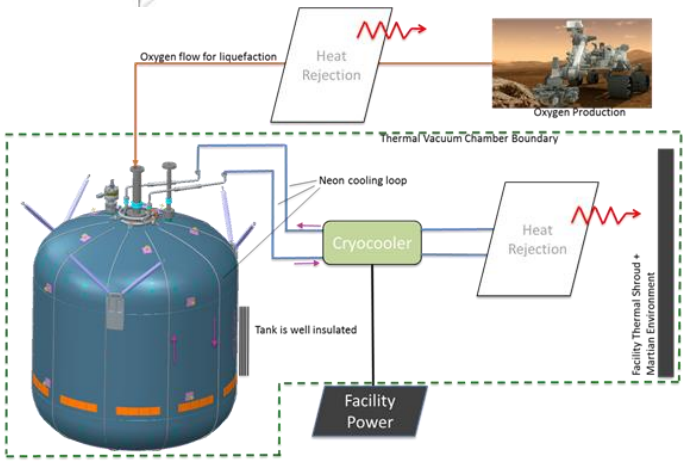
Lander Technology, Liquefaction of ISRU Propellants (GRC – Lead; MSFC/JSC - Team)



Key accomplishments:

- Completed initial sizing of liquefaction system for Martian system
- Performed trade study on location of liquefaction
- Planned task to begin investigating and demonstrating liquefaction





Objectives:

- Develop a basic liquefaction sub-system modeling approach/models that can be integrated with the In-Situ Resource Utilization sub-system models for system to give architecture level decision guidance.
- Conduct a trade study for comparing liquefaction methodologies within a Mars Ascent Vehicle tank.
- Conduct a trade study for understanding the importance of variables (such as day/night cycle) that could be used to improve/optimize the system performance (over steady state operation).
- Prepare a test plan that enables the verification of the analytical models developed.

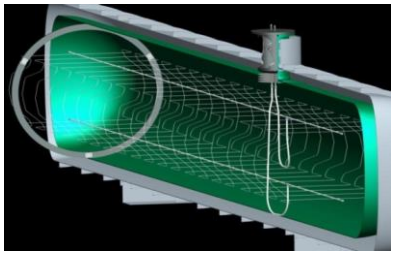
Advanced Exploration Systems

Automated Propellant Loading (APL) - Integrated Ground Operations

- Demonstrate LH2 zero loss storage, loading and transfer operations via testing on a large scale in a relevant launch vehicle servicing environment. (KSC, GRC)

Key Accomplishments:

- LH2 testing and analysis of data with the Integrated Refrigeration And Storage (IRAS) tank at KSC
- Ground Operation Demonstration Unit (GODU) tests completed in CY15:
  - » IRAS Tank Initial Chill-Down with Refrigerator
  - » No-Vent Fill LH2 Loading Test
  - » Boil-Off Heat Leak Measurement Test
  - » Zero Boil-Off Test
  - » Liquefaction Test all at the 30% LH2 Fill Level.

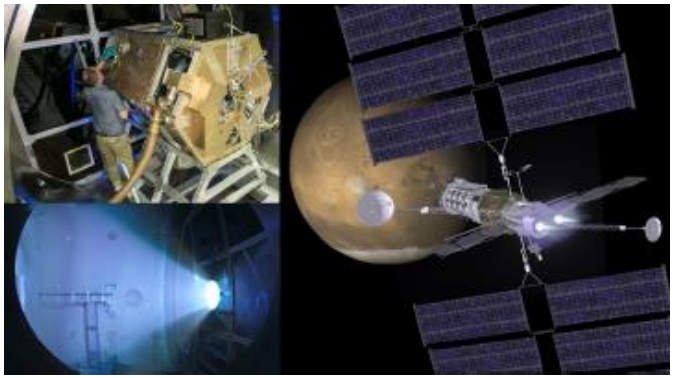


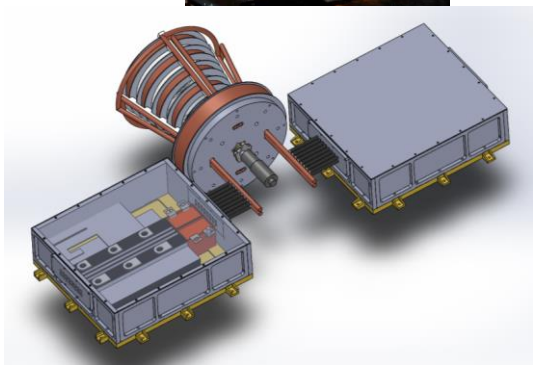
LH2 Densification Heat Exchanger

NextSTEP BAA Electric Propulsion

Developing high power EP technology systems in the 50 to 300 kW range to support NASA mission objectives for Human Exploration

- Next Strategic Technology Exploration Partnership (NextSTEP) Broad Area Announcement (BAA) selected 3 propulsion systems for development
  - Ad Astra: VASIMR (Variable Specific Impulse Magnetoplasma Rocket)
  - MSNW: ELF-250 (Electrodeless Lorentz Force)
  - Aerojet-Rocketdyne: Nested Hall Thruster
- 1-yr. base development contracts with two 1 yr. options
  - Primary goal is to demonstrate 100-hour of continuous, steady-state operation of propulsion system at 100-kW.
    - System includes thruster, power processing unit, feed system, and other key subsystems.
    - Key performance goals include Isp range of 2,000 to 5,000 s, total system efficiency > 60%, operational life > 10,000 hrs, total system specific mass < 5kg/kw, and scalable to MW levels
- Contract status - Implementing Three Contracts
  - Ad Astra – Contract ATP on Aug 7, 2015. Kickoff meeting was held on Aug 26, 2015.
  - MSNW – Contract ATP on Sept 18, 2015. Kickoff meeting was held on Nov 10, 2015.
  - Aerojet-Rocketdyne – Contract ATP on Jan 15, 2016. Kickoff meeting was held on Feb 11, 2016.



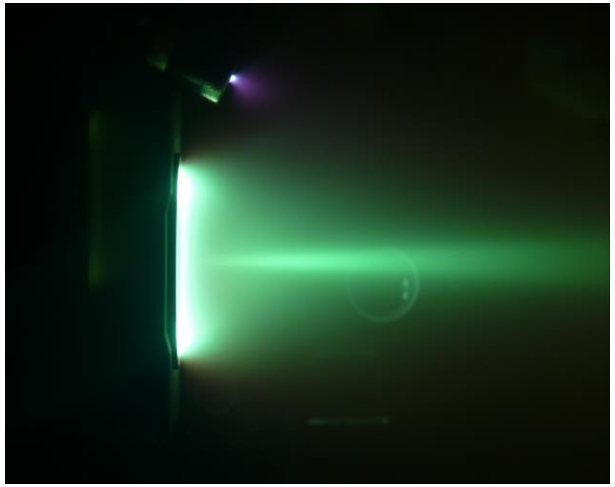


STMD Game Changing Development (GCD) Program

GCD Advanced In-Space Propulsion (AISP)

Iodine 600 W Hall Thruster

- Busek delivered thruster to GRC from SBIR Phase II
  - Completed 30 hours of testing at 600W.
  - Cathode operated on Xenon.
- Power Processing Unit (PPU) moving towards CDR in March 2016. Delivery in Summer 2016
- Cathode emitter materials evaluation continuing
- Integrated system test planned for Sept-Dec



High Temperature Boost Power Processing Unit

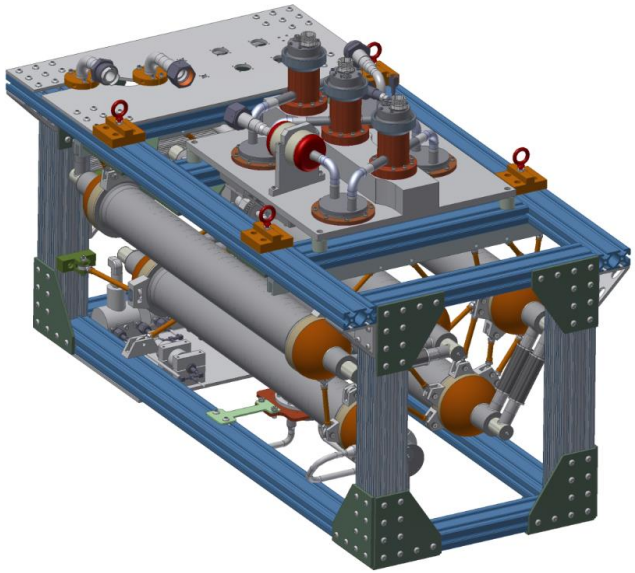
- High temperature operation with lowered switching loss at high frequency to reduce mass and volume with comparable or better efficiency
- Prototype 2.5kW discharge module tested at 100C with 300Vin and 800Vout. Demonstrated >97% efficiency
- Project continuation approved in Sept for additional 2 years - *but recent budget cuts will delay or cancel activity*.

Busek BHT-600
Images courtesy of Busek Co Inc

Game Changing Technology

20 Kelvin - 20 Watt Cryocooler

- Development of a Reverse Turbo-Brayton Cryocooler operating at 20 Kelvin with 20 Watts of refrigeration lift.
  - Applicable to liquid hydrogen storage for launch vehicles and propellant depots with zero boil-off.
  - Creare – SBIR Phase III
  - Completed warm and cold module designs, control electronics (rack mounted) design; mechanical system packaging design
  - Performed an assessment (analysis-based) of final design's ability to meet Cryocooler KPP's
  - Passed the Final Design Review in June, 2015
  - GRC acceptance – Spring, 2017



Space Technology Mission Directorate (STMD)

STMD Announcement of Collaborative Opportunity (ACO) Awards - Propulsion

- Objective: Utilizing Public-Private Partnerships to Accelerate Space Technology System Capabilities,
- Industry Non-reimbursable Space Act Agreement with HQ funding NASA activities
- ACO awards are two year efforts

Busek

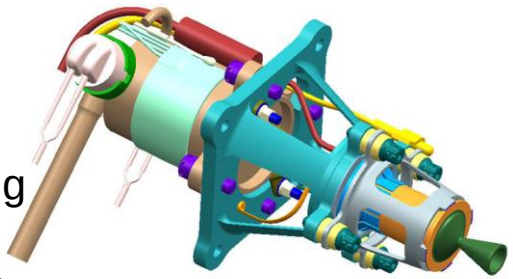
- Partnership with NASA GRC and MSFC for maturation of Busek's 5N Green Monopropellant Thruster
- Busek is advancing to larger spacecraft systems using a unique catalyst bed geometry scaled from successful smaller thrusters
- Work is continuing from Phase I and Phase II SBIR's
- Test two engineering model (EM) thrusters with AF-M315E to confirm Busek's measured performance, gain significant additional run times including a life test, and plume characterization

Busek Monopropellant Thruster
Image: Busek Co website

STMD Announcement of Collaborative Opportunity (ACO) Awards - Propulsion

Aerojet Rocketdyne

- Partnership with NASA GRC and GSFC
- 2 year effort for flight qualification for customer applications of the AF-M315E propellant GR-1 (1 N) thruster
- GSFC will lead the test plan development and oversight for all testing
- GRC will conduct the initial heavyweight testing to optimize the injector design and optimize the catalyst bed; GRC will also conduct the qualification testing of the improved GR-1 thruster

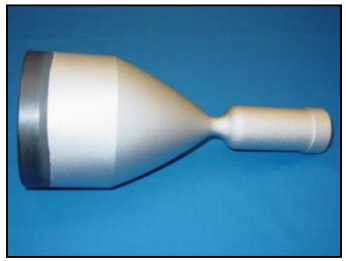


Aerojet Rocketdyne GR-1 Thruster

Source. "GPIM AF-M315E Propulsion System", Spares, R.A, et. al. 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference &Exhibit AIAA 2013-3849 15-17 July 2013, San Jose, California

Orbital ATK (OA)

- Partnership with NASA MSFC
- OA is working on large thruster designs using American manufactured LMP-103S and thrusters
- OA and ECAPS (Swedish supplier of LMP-103S propulsion systems) are partnered in the effort to bring LMP-103S into the domestic inventory of US propulsion systems
- Hot-Fire testing of 440 N (100 lbf) LMP-103S thruster
- OA working with Plasma Processes Inc. on the development of thruster
- Plasma Processes is continuing a Phase I and Phase II SBIR program as part of the development



440 N LMP-103S thruster during manufacturing at Plasma Processes Inc.

Evolvable Cryogenics (eCryo) Project

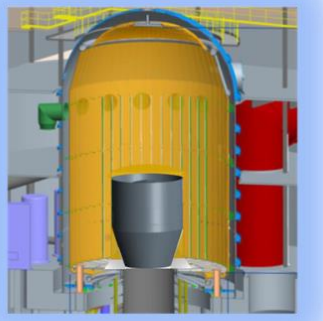
Develop, integrate, and validate cryogenic fluid management technologies (CFM) at a scale relevant to and meeting the mission needs for NASA missions and SLS/Stages

Objectives:

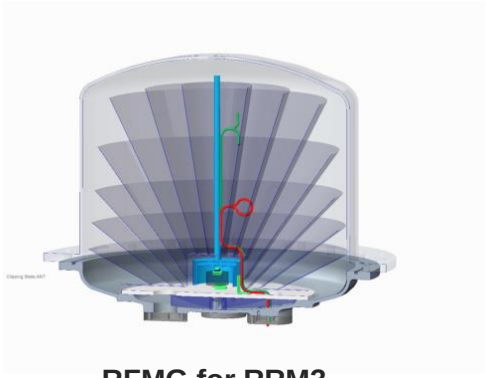
- Technology development for extended missions focused on the needs of the SLS upper stage.
- Evolutionary development of new technology demonstrating near term gains which are shared with industry.
- Increase capabilities of analysis tools to perform predictive simulations for missions with in-space cryogenic systems.

Technology Demonstrations:

- Use existing Agency assets and infrastructure to mature cryogenic propellant technologies
  - Testing ranges from components to entire systems
  - Scale of testing will be limited only by facility capabilities.
- Subsystem tests and system tests need not use flight-like components



SHIIVER Test Article



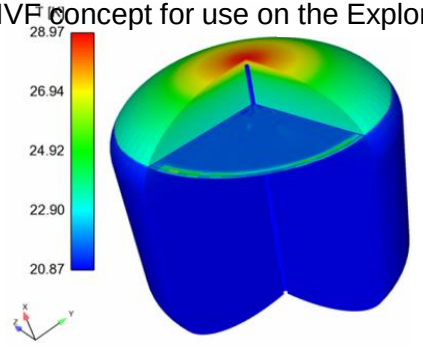
RFMG for RRM3 Mission

Team:

GRC (lead), MSFC
Industry Partners: TBD
International Partners: CNES providing comparative analysis of CFM.

Products:

- **Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER):** Large liquid hydrogen tank/cryogenic stage test bed used to investigate heat reduction techniques including; vapor cooling, multilayer insulation, structures and penetrations.
- **Development & Validation of Analysis Tools (DVAT):** Advancement of numerical tools to cover cryogenic fluids in both settled/unsettled conditions.
- **Radio Frequency Mass Gauge for the Robotic Refueling Mission 3 (RFMG for RRM3):** Test and demonstrate RFMG technology on the GSFC RRM3 at the International Space Station (liquid methane).
- **Improved Fundamental Understanding of Super Insulation (IFUSI):** Reduce the gap between the research of Multilayer Insulation (MLI) systems and the practical applications of MLI systems
- **Integrated Vehicle Fluids (IVF):** Evaluate the extensibility of the IVF concept for use on the Exploration Upper Stage (EUS).



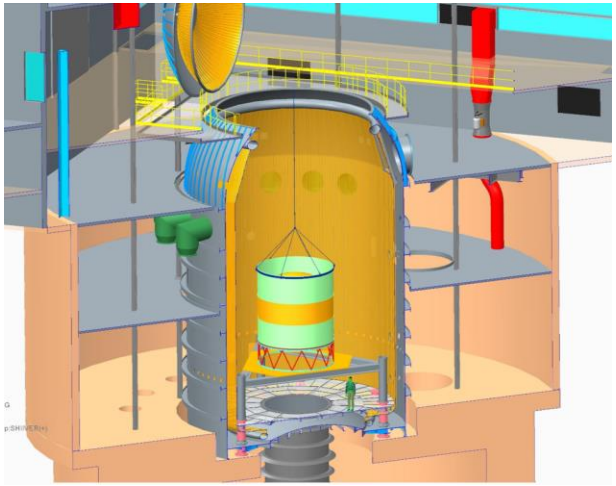
DVAT: CFM Analysis

SLS/Stages

Evolvable Cryogenics (e-Cryo) Project

Structural Heat Intercept, Insulation, and Vibration Test Evaluation Rig (SHIIVER):

- Concept Review held in August 2015
- Concept of Operations document baselined
- Tank SOW Prepared and RFP issued
- MLI SOW Prepared
- Facility assembly integration and test plans development initiated
- Stake holder review for the Integration Plan and Instrumentation - April 2016.
- Tank received – Quarter 1, 2017
- Build-Up in Plum Brook B2 Facility FY2017
- Testing in FY18



Small-scale Laboratory Investigation of Cooling Enhancements (SLICE)

- Study small-scale vapor-cooling designs to understand:
  - How heat is removed from the skirt wall
  - Cooling channel attachment methods
  - Attachment effectiveness/optimization of heat transfer mechanisms
  - Thermal resistance of conductive materials
- Results will be applied to the SHIIVER vapor-cooled skirt design
- SMiRF testing to begin May 2016, complete December 2016

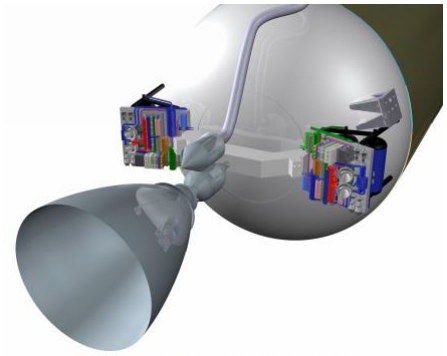
Evolvable Cryogenics (e-Cryo) Project

Improved Fundamental Understanding of Super-Insulation (IFUSI)

- Completed assembly, checkout, and commissioning of calorimeter capable of maintaining boundary temperatures of 20 K and 90 K.
- Completed low temperature (90 K emission) transmissivity testing.
- Demonstrated calorimeter operability with warm boundary temperature of up to 300 K.
- Awarded contracts for two MLI repeatability testing

Integrated Vehicle Fluids (IVF)

- The eCryo IVF for SLS task will conduct studies, testing, and analyses of the IVF system in order to provide answers to a subset of the Four Questions (4Q) set forth by the SLS Spacecraft/Payload Integration and Evolution (SPIE) Advanced Development Group to address the feasibility of the IVF system for the SLS Exploration Upper Stage (EUS)



Centaur Converted to IVF

(eCryo): Flight Test of the Radio Frequency Mass Gauge

Objective:

- Test and demonstrate the Radio Frequency Mass Gauge (RFMG) technology on the GSFC Robotic Refueling Mission 3 (RRM3)

Approach:

- RRM3 mission, utilizing ISS platform, will demonstrate several new technologies including the RFMG
- RFMG will gauge the liquid quantity in the RRM3 cryogenic source dewar (50 L volume, liquid methane) throughout the mission
- RFMG performance goal: better than ± 2% full-scale uncertainty
- Alternate RRM3 mass gauge data includes sensor array and flow meter. No settled gauging during mission.

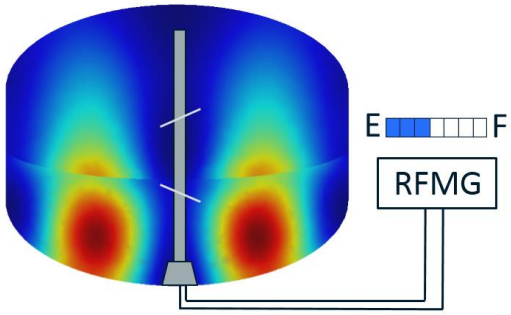
Benefits:

- Validation of the RFMG technology in a relevant environment
- RFMG helps fulfill a RRM3 primary mission requirement to monitor fluid quantity
- Collaboration between STMD/eCryo and the GSFC Satellite Servicing Capabilities Office
- Helps fulfill STMD goal of infusing new technologies

Schedule:

- Anticipated launch in late 2017
- Up to 2 year mission duration

RRM3 payload concept (courtesy GSFC)

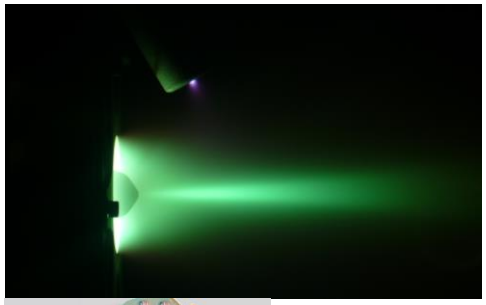


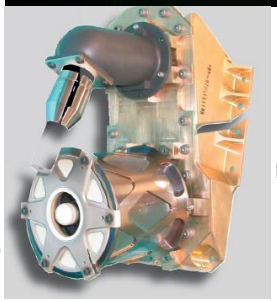
STMD Small Spacecraft Technology Program (SSTP)

STMD Small Spacecraft Technology Program

Iodine Satellite (iSAT)

- NASA MSFC is leading the flight system and spacecraft development. 12U CubeSat. Demonstrate plane and altitude changes during a 90 day mission
- NASA GRC is propulsion system lead (leveraging GCD AISP investments for modular PPU)
- Spacecraft and mission design:
  - 200W Busek iodine Hall thruster tested for 80-hrs at NASA GRC. Cathode operated on xenon
  - Planning for Spring propulsion system CDR.
  - Focus of work is on cathode and feed system development.
  - PPU nearing design completion.

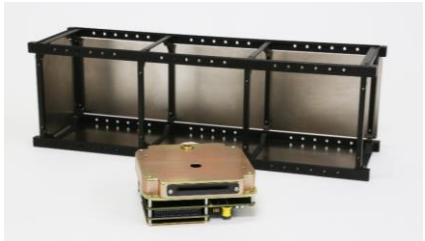




Busek BHT-200
Images courtesy of Busek Co Inc

Pathfinder Technology Demonstration (PTD)

- NASA ARC is leading the flight system and spacecraft development
- NASA GRC is propulsion system lead
- 6U CubeSat spacecraft bus to be operated by NASA for new propulsion or other technology sub-systems demonstrations.
- PTD supporting SBIR Commercialization Readiness Project with Busek for development of 100 uN thrusters for a flight opportunity. Contract kick off February 2016.



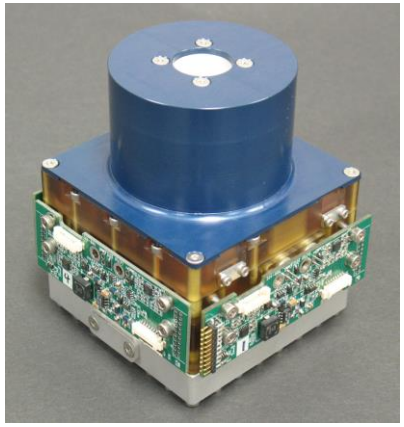
Busek HARPS
Images courtesy of Busek Co Inc

STMD Small Spacecraft Technology Program

Propulsion Tipping Point Awards
Utilizing Public-Private Partnerships to Advance Tipping Point Technologies advancing promising “tipping point” technologies with commercialization potential that aligns with NASA goals and objectives

Tethers Unlimited

- Hydros: High-Thrust, High-Isp Propulsion with Non-Toxic, Non-Explosive, Non-Pressurized, ISRU-Compatible Propellant: Water
- Uses electrolysis cell to split water propellant into gaseous hydrogen and oxygen
- 12 month development and test of a flight unit



Hydros
Source: Tethers Unlimited website

Aerojet Rocketdyne

- High Thrust, High Delta-V Green Propulsion for CubeSats
- MPS-130 Modular Propulsion System, which utilizes AF-M315E hydroxyl-ammonium-nitrate (HAN) based ionic liquid blend for propellant.
- MPS-130 leverages technology efforts developed through the NASA Green Propellant Infusion Mission (GPIM)
- 18 month development and test of a 1U flight unit

Aerojet MPS-130
Source: Aerojet Rocketdyne website