National Aeronautics and
Space Administration

Technology, Innovation & Engineering Committee Report
NASA Advisory Council

Presented by:
Dr. Bill Ballhaus, Chair

December 7, 2017

www.nasa.gov/spacetech

TI&E Committee Scope

"The scope of the Committee includes all NASA programs focused on technology research and innovation."

–NASA Advisory Council Technology & Innovation Committee Terms of Reference, signed 6/28/12

TI&E Committee Scope

Technology: a solution that arises from applying the disciplines of engineering science to synthesize a device, process, or subsystem to enable a specific capability.

TI&E Committee Meeting Attendees
December 5, 2017

- Dr. William Ballhaus, Chair
- Mr. Gordon Eichhorst, Aperios Partners LLP (virtual)
- Dr. Kathleen Howell, Purdue University
- Mr. Michael Johns, Southern Research Institute
- Mr. David Neyland
- Dr. Mary Ellen Weber, Stellar Strategies, LLC

TI&E Committee Meeting Presentations December 5, 2017

- Space Technology Mission Directorate Update
  - Mr. Stephen Jurczyk, Associate Administrator, STMD
- Small Spacecraft Technology Program Report Response
  - Mr. Chris Baker, Program Executive, STMD
- Kilopower Project Update
  - Dr. Lanetra Tate, GCD Program Executive, STMD
- Capability Leadership and Engineering Research and Analysis Update
  - Dr. Prasun Desai, Deputy AA for Management, STMD
- Space Technology Investment Plan Update
  - Ms. Vicki Crisp, NASA Deputy Chief Technologist (Acting)
- STMD Strategy Framework Update
  - Mr. Patrick Murphy, Director, Strategic Planning & Integration, STMD
- Space Technology Research Institutes Update and Future Topics
  - Dr. Mia Siochi, NASA Langley Research Center
  - Dr. John Hogan, NASA Ames Research Center

SPACE TECHNOLOGY MISSION DIRECTORATE
SMALL SPACECRAFT TECHNOLOGY

December 5, 2017

TI&E Committee April 2016 Recommendation to STMD AA

Recommendation: STMD conduct an independent study of current small satellite technology developments to determine the appropriate focus for NASA's small spacecraft technology investments.

Reasons:

- NASA is at risk for having STMD's small satellite technology investments duplicated in commoditized capabilities. (consequence of no action)
- Given this, what is the appropriate, discriminating role for STMD vis-à-vis all the other organizations that are developing small satellite technology?

Background on Finding for STMD AA

- STMD commissioned a study by IDA to respond to the NAC TI&E Recommendation to identify “the appropriate, discriminating role for STMD vis-à-vis all the other organizations that are developing small satellite technology.”

- STMD received the recommendations from the IDA study in Spring 2017

Specific Recommendations from the Science and Technology Policy Institute

- **Recommendation 1:** Continue to support precompetitive research & development and risk reduction for platform technologies (propulsion, constellations and autonomy, communications, etc.). Could add additional specialized focus areas (deep space systems, technologies that interface between the bus and specialized payloads, etc.). Add critical industrial commons (database curation, reliability testing, etc.), leveraging existing organizations and successful models.

- **Recommendation 2:** Better communicate the unique role and mission of the SST program.

- **Recommendation 3:** Maintain agency level focus and manage SST from NASA HQ.

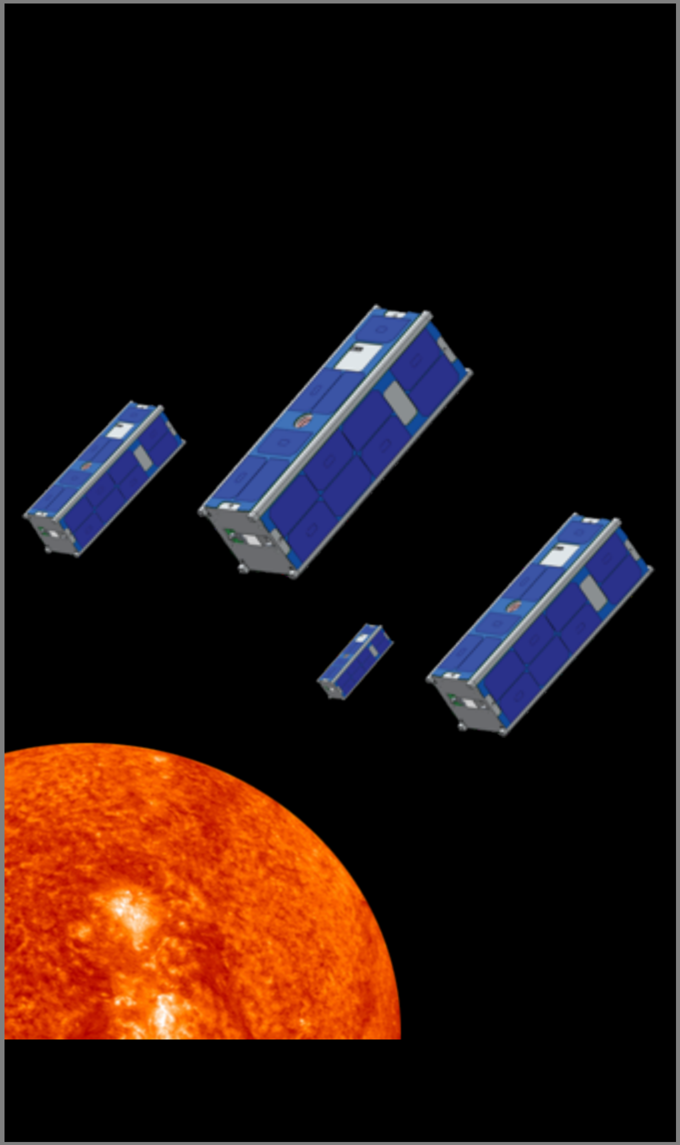
- **Recommendation 4:** Ensure transition partners for SST projects.

- **Additional Recommendations:** Revisit programmatic metrics and continually monitor the portfolio. Explore use of alternative contracting approaches.

TI&E Committee December 2017 Finding for STMD AA

STMD should be commended for following through to implement the recommendations from the IDA Small Satellite study, focusing investments on relevant NASA mission areas and pre-competitive platform technologies. The TI&E Committee is satisfied STMD has met the intent of the July 2016 recommendation.

In executing this plan, there appears to be a bottleneck in acquiring launch opportunities. The Committee is requesting more information to understand the impact and potential means to reduce this delay.



Affordable Distributed Spacecraft Missions.
Large constellations of small spacecraft for multipoint measurement of time variant phenomena (e.g. heliophysics) and smaller more tightly controlled formations for long baseline interferometry and synthetic aperture synthesis.

- **Timing Architectures (without GPS)**
- **Relative and Absolute Position Knowledge (without GPS)**
  Expanding these mission architectures to deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth centric aids.

- **Autonomy and Constellation Management**
  Expanding to deep space increases the need for scalable system autonomy and distributed intelligence across the constellation / formation.

- **Starling "Swarm" Demonstration Missions**
  Series of proposed missions that build on and extend prior SST investments in inter-spacecraft networking and communications, autonomous operations, and formation flight. The series will also target technology gaps for deep space distributed small spacecraft missions including navigation, attitude determination and control outside the range of GPS and Earth's magnetic field.

Expand the Capability of Small Spacecraft to Execute Missions at New Destinations

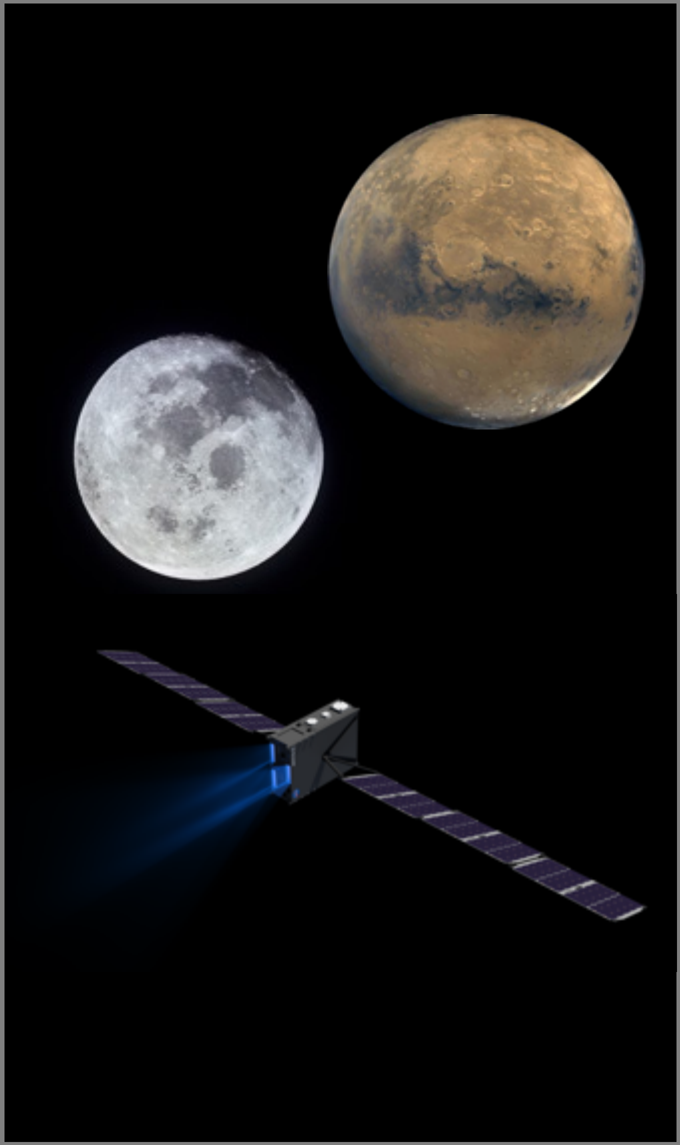
Deep Space Small Spacecraft

Examination of technology gaps for mission concepts proposed to the Planetary Science Deep Space SmallSat Studies program highlighted need for high delta V propulsion and radiation upset tolerant systems for U-class spacecraft. Similar technologies are needed to expand affordable distributed spacecraft missions to deep space (e.g. heliophysics)

- **High $\triangle$V Deep Space Propulsion for Small Spacecraft**
  High impulse per unit of spacecraft and high total impulse, while remaining low power per unit of spacecraft and compatible with secondary payload launch restrictions. Tolerant to the deep space radiation and thermal environment.

- **Affordable Radiation Tolerance for Small Spacecraft Missions**
  Low cost approaches to adding radiation tolerance to commercial off the shelf avionics and other subsystems to increase reliability for deep space missions without sacrificing the ability to leverage innovations in the commercial sector.

- **Deep Space Navigation and Attitude Determination for Small Spacecraft**
  Key technology need is highly accurate position knowledge and precision timing technology for spacecraft that do not depend on GPS or other Earth centric aids.



National Aeronautics and
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Space Technology Mission Directorate

Fission-Based Space Power

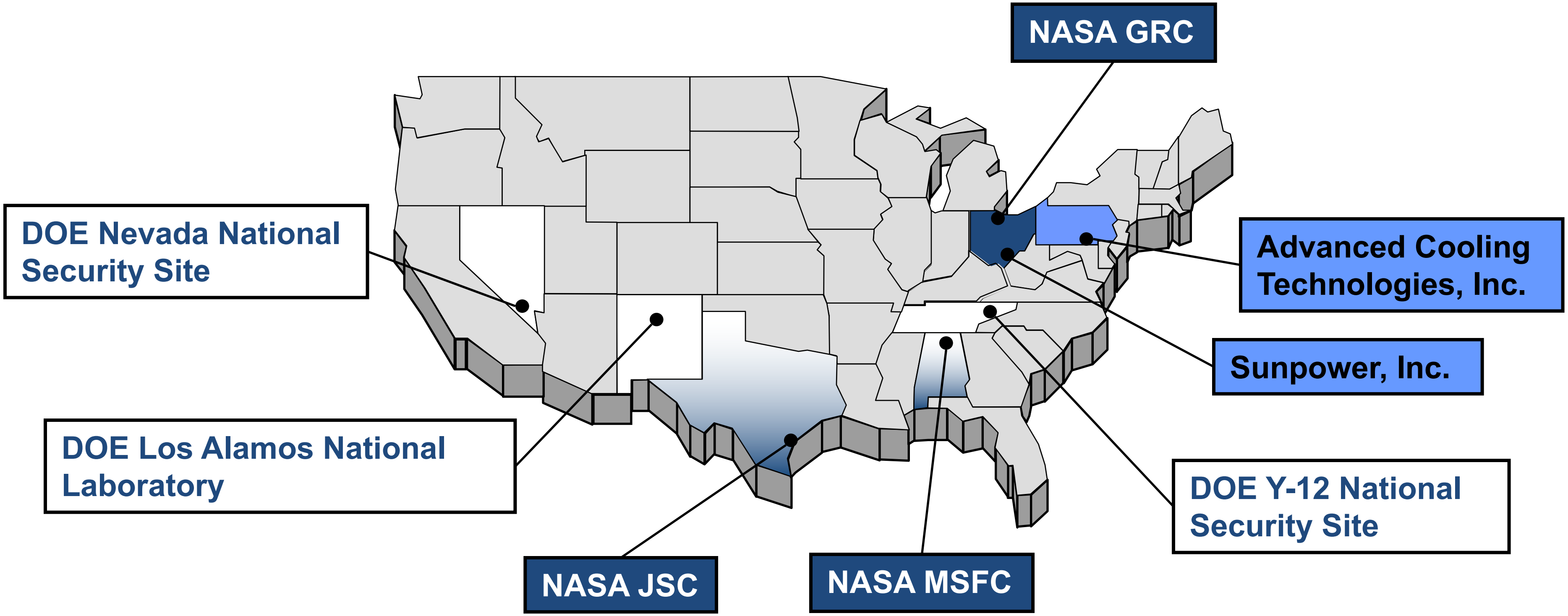
Briefing to the NASA Advisory Committee

Presented by
LaNetra C. Tate, Ph.D.
Program Executive, GCD Program

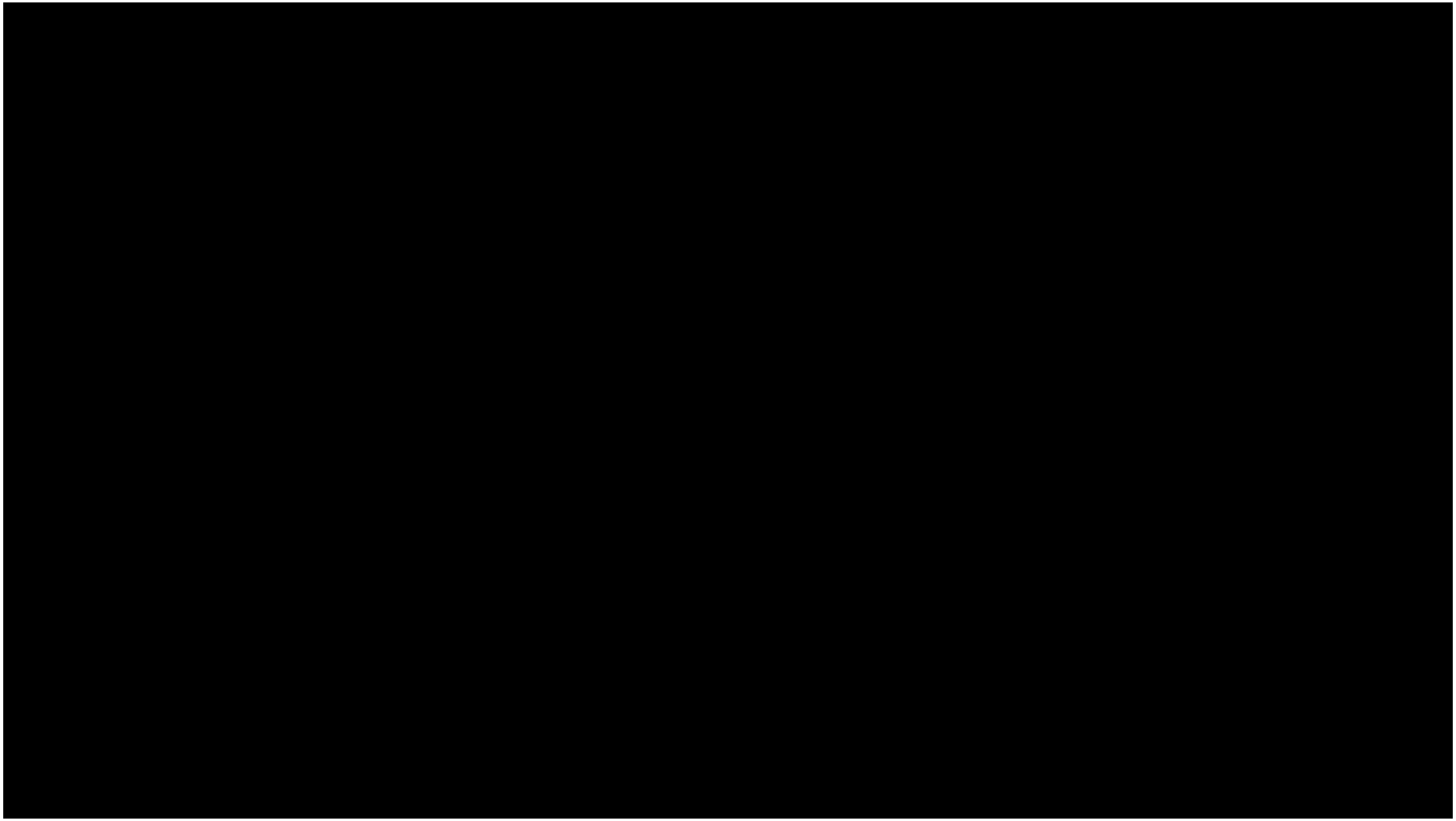
December 5, 2017

www.nasa.gov/spacetech

Kilopower Project Key Members



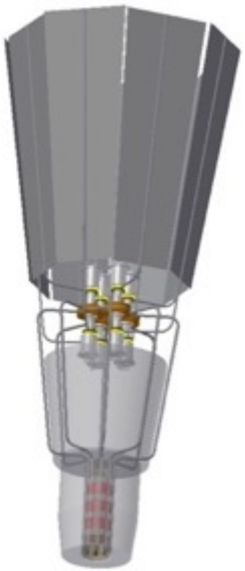
Kilopower Animation



Kilopower project video can be found here: https://youtu.be/DcdfMcjUy_U

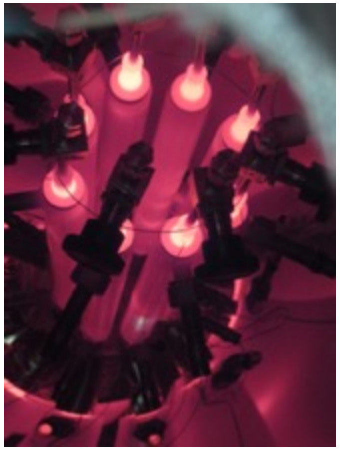
STMD Kilopower Project: Major Development Milestones

DONE!



Notional 1 kW_e Flight System Concept

DONE!

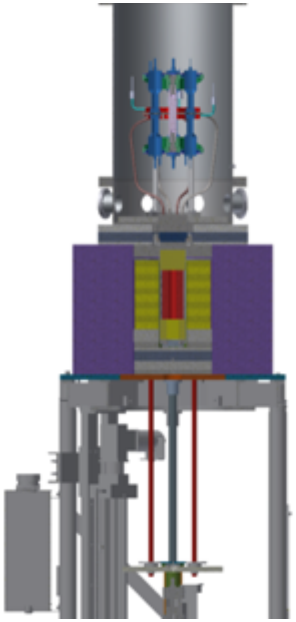


Thermal Prototype & Materials Testing at GRC and Y12

DONE!

Thermal-Vacuum System Test with Depleted Uranium Core at GRC

Underway



Reactor Prototype Test with Highly-Enriched Uranium Core at NNSS

NASA | NNSA National Nuclear Security Administration | Los Alamos NATIONAL LABORATORY EST. 1943 | Y-12 National Security Complex | NNSA Nevada National Security Site

Engineering
Research & Analysis

Dr. Prasun N. Desai
NAC TI&E Committee Meeting
December 5, 2017

What is Engineering Research and Analysis?

- **Definition:** the application or advancement of principles, tools, models, methods, processes, design approaches, etc.
    - Historically supported by Center discretionary funds, Base Research, and Engineering organizations – but such investments have been declining for two decades
- In 2013, *Foundational Engineering Science (FES)* was proposed to address this area, but no FES funding was approved
    - **Basic Research** to explore unknown or poorly understood scientific areas underlying engineering; leads to innovation and discovery
    - **Engineering Methods** address tools, models, standards, knowledge, or techniques for engineering advances; these can significantly reduce major technical or cost barriers
- Capability Leadership Teams have identified numerous areas needing investment to maintain Agency engineering capability
    - Distinct from technology development

Recommendation for the NASA Advisory Council (April 2013)

Recommendation:

The Council recommends that NASA establish a basic research (engineering science) program relevant to its long-term needs and goals.

- The Council suggests that the Chief Technologist collaborate with the Chief Scientist and the Chief Engineer to establish formal guidance and seek funding for basic research in engineering science. The Council further suggests that NASA begin by managing the agency's basic research portfolio as a pilot activity that is funded separately from the Space Technology Program, similar to how OCT coordinates the agency's technology portfolio.

Major Reasons for the Recommendation:

The Council recognizes that the distinction has been established between basic research and technology. NASA's technology programs now have advocacy and, in the form of the Strategic Space Technology Investment Plan (SSTIP), strategic guidance. However, basic research (or engineering science) that may lead to the development of technology and engineering tools are no longer explicitly part of NASA's technology enterprise.

Consequences of No Action on the Recommendation:

Erosion of NASA's research and technology capabilities

Historical Funding of Engineering R&A

- Investments have been made and continue to be made in Engineering R&A, though not always visible and not systematically nor strategically across the Agency
    - STMD funds Entry System Modeling and Advanced Radiation Protection activities in the Game Changing Program with approximately $9M/year
    - ARMD funds Transformational Tools and Technologies Project with approximately $20M/year in areas of CFD, materials and structures modeling, system analysis tools, and combustion modeling
    - HEOMD funds radiation environments and radiation transport modeling in the Advanced Exploration Systems Program with approximately $1.5M/yr
    - SMD, HEOMD programs/missions fund Engineering R&A for specific missions on an "as needed" basis
- No sustained investments across all Engineering R&A technical areas since base funding was eliminated
- No dedicated path present to fund general Engineering R&A unlike that for Technology

Approach Forward

- Each Mission Directorate (MD) will fund and manage Engineering R&A activities using their existing Programs
    - Recommend creation of a "Coordination Board" comprising of representatives from ARMD, HEOMD, SMD, STMD, & OCE
        - Board function is to review prioritized list of Engineering R&A activities identified by CLTs through OCE/EMB and by Mission Directorates
        - Will lead to a more integrated and strategic planning and selection process
    - Through Board deliberations, each MD will select <u>several activities</u> per year (assuming ROM ~$1M each) to fund and manage through their existing Programs that align with their respective mission
        - Note, little more funding in this activity will translate to little less funding of something else
    - Nice balance of two research and two mission focused directorates
- MDs <u>will commit to sustained investment</u> in Engineering R&A activities with understanding that funding for it would increase/decrease with overall MD budget, similar to everything else

TI&E Observations on Engineering R&A

- Engineering R&A 25 years ago was funded out of R&T Base account.
  - These investments were critical to development of CFD, NASTRAN, etc.
  - Due to past R&T budget reductions, R&T Base eliminated.
    - For example, FY05 to FY09 – basic research funding declined $500M, applied research declined $900M. NASA technologists increasingly had to write proposals to compete for research funding.
- Current plans for funding Engineering R&A is good start, but has potential issues.
  - Concern about adequacy of funding level, sustainability of funding, and protection of funds from flight project cost overruns.
- Committee notes challenges over past five years in restarting this activity, but hopeful this approach will work.

National Aeronautics and
Space Administration

STMD's New Strategic Framework Update

Presented by:
Patrick Murphy, Director,
Jay Falker, Deputy Director,
STMD Strategic Planning and Integration

Kevin D. Earle, William M . Cirillo,
David Reeves
Systems Analysis & Concepts Directorate
NASA Langley Research Center

December 5, 2017

www.nasa.gov/spacetech

Revising STMD's Strategic Framework

Approach modeled after Aeronautics Research Mission Directorate's (ARMD's) highly successful strategic framework, incorporating lessons learned and changes where appropriate.

Overall Goal

…is to reframe/repackage our strategy to focus our investment prioritization and communication on impacts, outcomes, and challenges first, and on technologies & systems second.

Customer derived framework.

Shift to customer-oriented, impact-centric focus, with the intent of more transparently communicating impacts to customers & stakeholders.

Increase use of quantifiable measures to increase traceability of decisions, provide clearer guidance, and empower management & technical workforce.

Planned Framework

Mega-Drivers
"Overarching Trend"

Strategic Thrusts
"Vision for Future"

Outcomes
"Overarching, Measurable Goals"

Technical Challenges
"STMD Technical Deliveries"

Mega Drivers

Increasing Access

Major Trends:

- Lowering **costs**
- Increasing launch **availability**
- Decreasing **travel time**
- Diversifying **platforms** (e.g. CubeSats)
- Scalable **transportation** solutions
- New accessible **destinations**

Accelerating Pace of Discovery

Major Trends:

- **Major discoveries** of potentially life-harboring icy moons and exoplanets
- Growing urgency for **Earth-Moon-Sun science** discovery and understanding
- Humanity's desire for ambitious **exploration** of the solar system and ultimately interstellar travel

Democratization of Space

Major Trends:

- Broadening **participation** spectrum, from governments to citizens
- Growth in **private investment** in space
- **Public-private partnerships**
- **International** collaborations

Growing Utilization of Space

Major Trends:

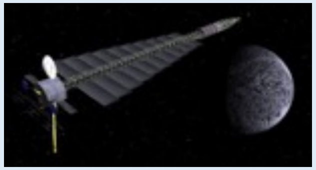
- Space market **diversification** (e.g. servicing, manufacturing, mining, debris removal, tourism)
- Space industry **growth** well surpassing U.S. average GDP growth
- Space-based solutions addressing growing **global challenges**
- Increasing **resiliency** and **safety**

STMD Strategic Thrusts

STMD develops technologies to:

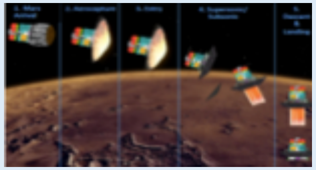
ST1. Expand Utilization of Space

- Enable **servicing, assembly, manufacturing, and resource utilization.**



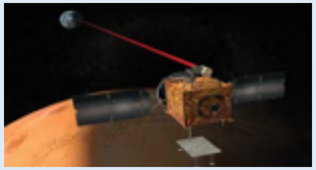
ST2. Enable Efficient and Safe Transportation Into and Through Space

- Provide safe, affordable, and routine **access to space**
- Provide cost-efficient, reliable **propulsion for long duration missions**
- Enable **significantly faster**, more efficient deep space missions



ST3. Increase Access to Planetary Surfaces

- Safely and precisely **deliver humans & payloads to planetary surfaces**
- Increase **access to high-value science sites** across the solar system
- Provide efficient, highly-reliable **sample return** reentry capability



ST4. Enable the Next Generations of Science Discoveries

- Expand access to new environments and measurement **platforms** to enable high-value science
- Enable **substantial increase** in the quantity and quality of science data returned

ST5. Enable Humans to Live and Explore in Space and on Planetary Surfaces

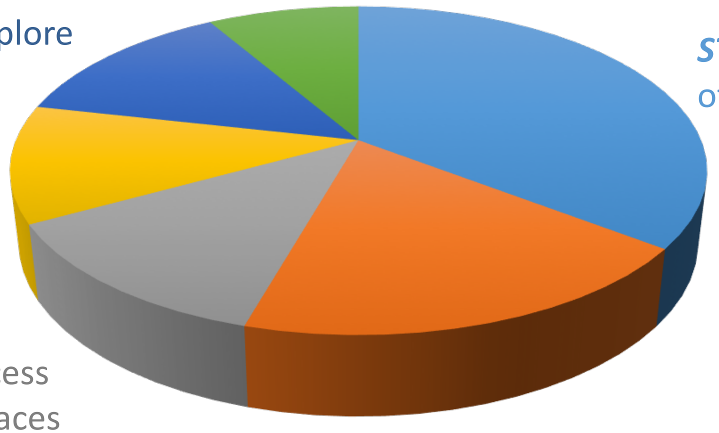
- Provided shielded **in-space habitation** and enable humans to **survive** on other planets
- Provide efficient/scalable **infrastructure** to support exploration at scale
- Increase crew effectiveness and **access to diverse, high-value sites**

ST6. Grow & Utilize the U.S. Industrial and Academic Base

- **Transfer NASA technology** to grow the U.S. industrial & technology base
- Expand **public-private partnerships** for mutually-beneficial technology developments.
- **Drive U.S. innovation** & expand opportunities to achieve the NASA dream

Current STMD Investments

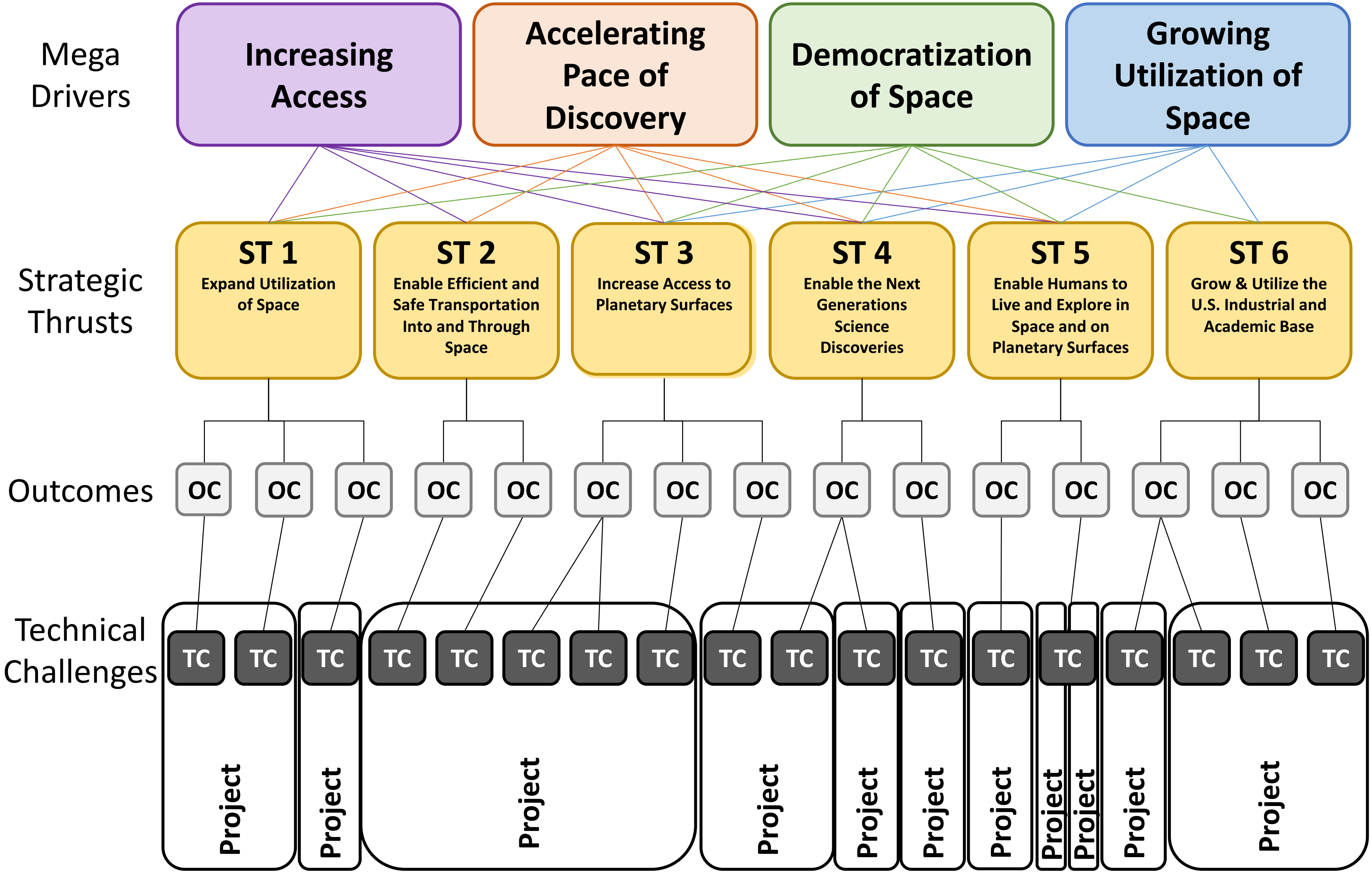
FY17 Operating Plan ($686M)



Major FY17 Investments:

ST1: Satellite Servicing RESTORE-L, In-Space Robotic Manuf & Ass'y, Laser Comm Relay Demo, Small Spacecraft Tech
ST2: Solar Electric Propulsion, Nuclear Thermal Propulsion, e-Cryo, Green Propellant Infusion Mission
ST3: Hypersonic Inflatable Aerodynamic Decelerator, Propulsive Descent Technology, MEDLI 2, Entry Systems Modeling
ST4: Deep Space Optical Comm, High Performance Spacecraft Computing, Coronagraph, Deep Space Atomic Clock
ST5: Human Robotic Systems, Astrobee, Kilopower, Extreme Environment Solar Power, Next Generation Life Support
ST6: Technology Transfer Program, Centennial Challenges, Regional Economic Development

Technical Challenge Implementation



National Aeronautics and
Space Administration

Space Technology Research Institutes 2016

Computationally Accelerated Materials Development for Ultra High Strength Lightweight Structures

Mia Siochi

NASA Advisory Committee Meeting
December 5, 2017

Computationally Accelerated Materials Development for Ultra High Strength Lightweight Structures

Topic Focus
Ultra high strength lightweight structural material enabled by Materials Genome Initiative (MGI) computational guidance

Distinctive Features of Topic
- MGI approach that spans entire materials development cycle
- Requires demonstration article with challenging property targets at the end of performance period
- Panel properties specified are at least double that of state of the art carbon fiber composite properties
- Properties defined with systems guidance on overall payoff in mass reduction for aerospace systems

Computational Guidance Spans Materials Development Cycle
- Application-guided structural materials design – predictive modeling of material properties including load transfer mechanisms that will influence material and structure design
- Computationally guided design, synthesis, and processing to enable macroscale fabrication of ultra high strength composite
- Accelerated testing and evaluation of material properties to inform iterative advancement of materials design, synthesis, and processing

NASA Contribution to Emerging Materials Technology Development
- Provide the mission pull to define relevant material properties that make insertion into NASA missions plausible
- Leverage DoD investments in electrically conductive materials to enable the advancement of high strength materials with broad commercial implications for aerospace
- Theoretical understanding of ultra high strength CNT structures that complements internally funded advancements in prototyping and structural design of advanced high strength composite structures

NASA Space Technology Research Institute

US COMP

University of Utah

Michigan Tech University

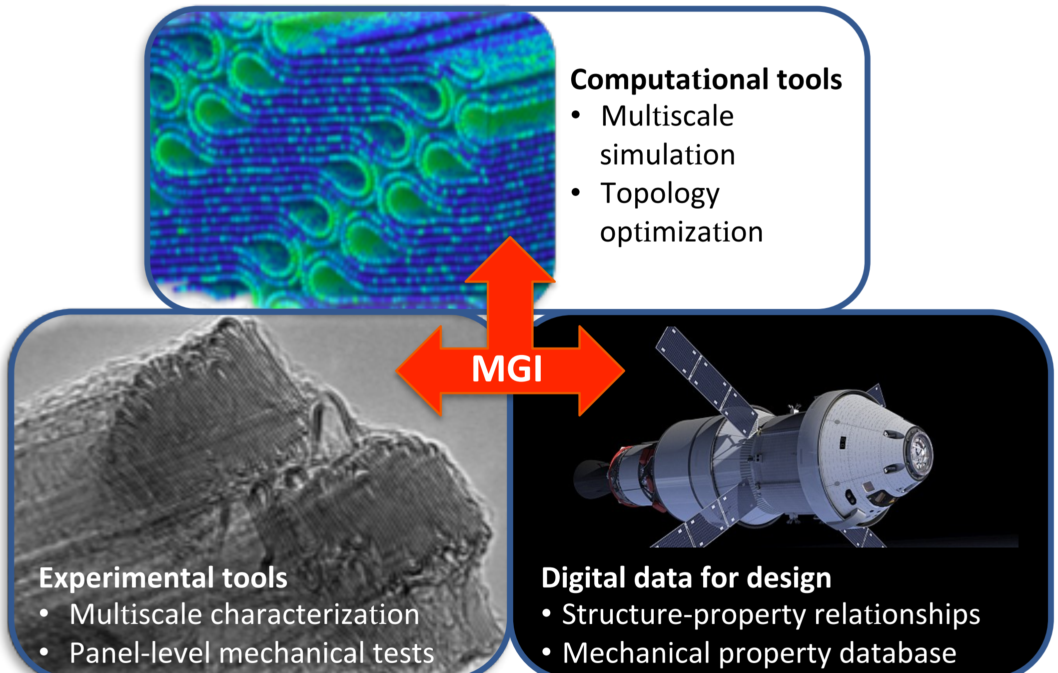
Florida State University

Massachusetts Institute of Technology

Pennsylvania State University

Virginia Commonwealth University

University of Minnesota



Georgia Tech

University of Colorado

nanocomp TECHNOLOGIES, INC.

SOLVAY

Florida A&M University

Johns Hopkins University

https://www.nasa.gov/press-release/nasa-selects-proposals-for-first-ever-space-technology-research-institutes

US-COMP Organizational Structure

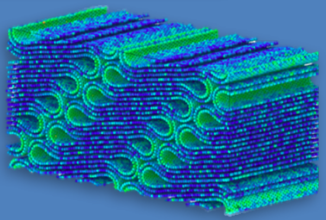
Technical Advisory Board (TAB)

Leadership Team

Simulation & Design Team (SDT)

Team lead: Greg Odegard
Michigan Technological University

- Force field development
- Atomistic/molecular modeling
- Meso-scale modeling
- Continuum modeling



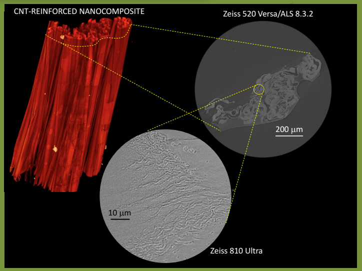
Testing feedback & model validation

Material structure

Testing & Characterization Team (TCT)

Team lead: Mike Czabaj
University of Utah

- Materials characterization
- Mechanical testing
- Thermal and electrical testing



Optimized material design

Synthesis feedback

Validation

Characterization

Prototypes

Structure data

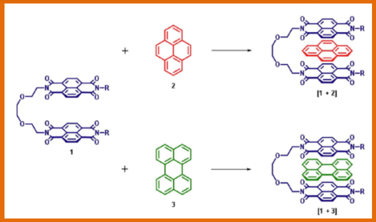
Quality feedback

Test panels

Material Synthesis Team (MST)

Team lead: John Hart
Massachusetts Institute of Technology

- Ultra-dense CNT structures
- CNT/polymer interfaces



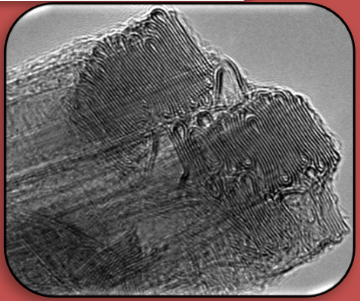
Manufacture feedback

Material prototypes

Material Manufacturing Team (MMT)

Team lead: Richard Liang
Florida State University

- Manufacturing scale-up
- Materials characterization



Bio-Manufacturing for Deep Space Exploration

NASA's Space Technology Research Institute:

The Center for the Utilization of Biological Engineering for Space (CUBES)

John A. Hogan Ph.D. (CUBES COR)
Bioengineering Branch
NASA Ames Research Center
Moffett Field, CA

Bio-Manufacturing for Deep Space Exploration – STRI Goals

1. *In situ* Microbial Media Production

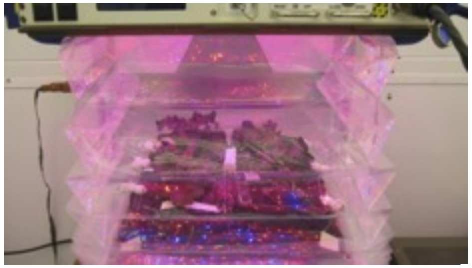
- Conversion of carbon dioxide, water, and other needed resources to microbial substrates ("*In situ* media" production) - supports rapid heterotrophic growth
- Supporting physico-chemical and biological methods that process local resources

2. *In situ* Production of Mission Products

- Developing microorganisms with targeted metabolisms to produce target products using *In situ* media
- Novel systems for growth and harvesting of target products
- Demonstration of manufacture of products for mission applications

3. *In situ* Food Production

- Increase yield, volume efficiency, and photosynthetic efficiency
- Enhance overall nutritional attributes
- Enhance secondary product recovery from inedible biomass

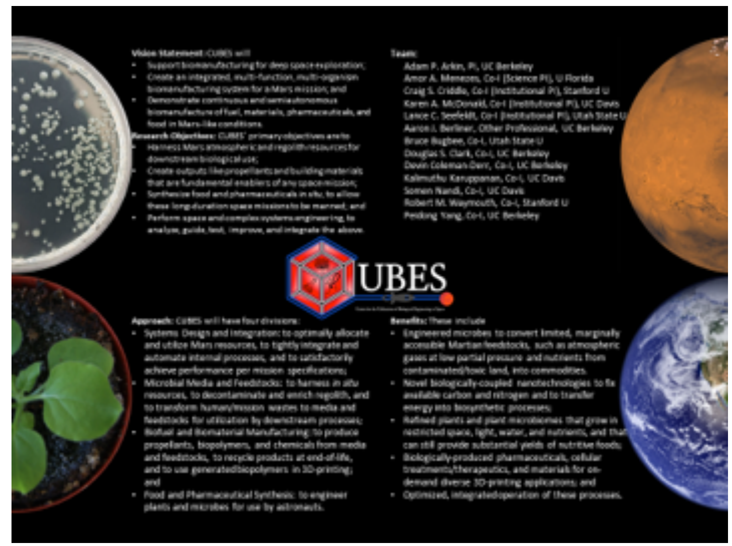


CUBES

The Center for the Utilization of Biological Engineering for Space

Lead Institution:
University of California Berkeley

Collaborating Institutions:
Stanford University
University of California – Davis
Utah State University
University of Florida
Physical Sciences Inc.



5 years - up to $3M/year budget

NASA/CUBES Kick-off Meeting held 10/19-20/2017

December 2017
Space Technology Highlights

Important STMD Milestones in FY 2017-18:

- CoBALT flights with Masten to advance autonomous landing and hazard avoidance technology
- SEXTANT/NICER launched in May and completed check-out/began reporting science data
- Solar Electric Propulsion PDR in August 2017
- Restore-L (Satellite Servicing demo) PDR in November 2017
- Small Spacecraft demos launched in November 2017 (OCSD/ISARA); CPOD still ready for launch
- DSAC/GPIM flight demonstrations awaiting launch on STP-2 (NET June 2018)
- Kilopower 1kW demo in March 2018

Green text indicates completed milestone.

SC Finding: Esteemed NASA Civil Servant Workforce

The Science Committee (SC) wishes to acknowledge the community's great esteem for its civil servant colleagues. NASA civil servants have worked tirelessly in many roles – as project scientists, mission planners, analysts, archivists, project managers, engineers, and more – to enable the breakthrough science of NASA's missions. The TI&E Committee would like to also emphasize the value of NASA civil service technologists and researchers that invent, acquire, and adapt advanced technologies and capabilities (e.g., engineering methods) to the needs of NASA's science and exploration projects.

The commitment, professionalism, and dedication of NASA's civil servants have earned the respect and gratitude of the science and engineering community. The community considers its civil servant colleagues – along with the missions they support – a national treasure.

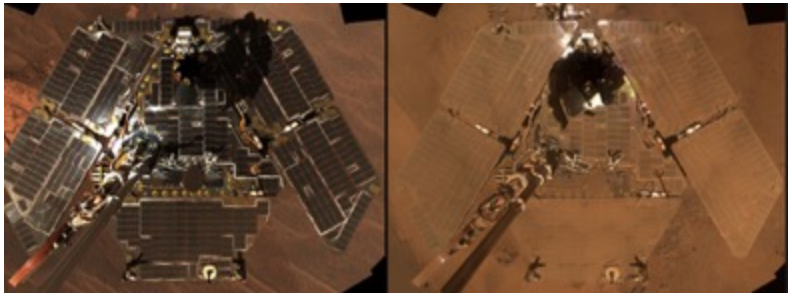
BACK-UP

Surface Power

- **No off-the-shelf options exist to power long-term human surface missions**
  - Power systems used on previous robotic missions (e.g. MER, Phoenix, MSL) do not provide sufficient power: all less than 200 W

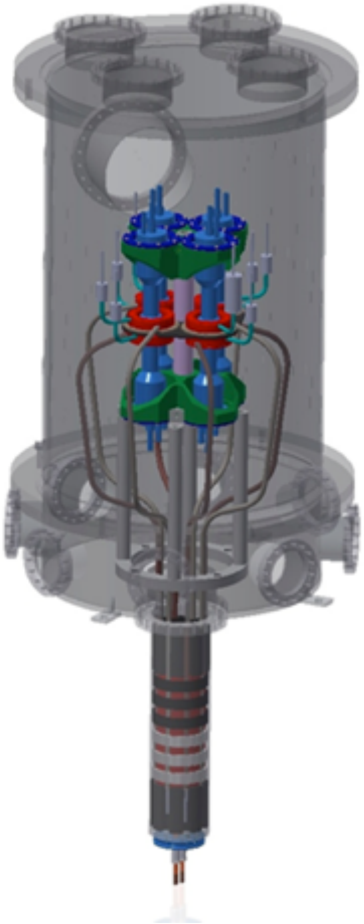
- **Projected human exploration power needs…**
  - Up to 40 kW day/night continuous power
  - Power for ISRU propellant production (pre-crew arrival)
  - Power for landers, habitats, life support, rover recharging (during crew operations)
  - Technology options: Nuclear Fission or Solar PV with Energy Storage
  - Need compact stowage, robotic deployment, survivable for multiple crew campaigns (>10 yrs), long distance power transmission (1-2 km), and contingency options for extended dust storms

- **Mars environment represents significant challenge to systems:**
  - CO_2 atmosphere, 3/8th gravity, 1/3rd solar flux of Earth orbit, >12 hour night, 170 to 270K temperature cycles
  - Large seasonal and geographical sunlight variations, long-duration dust storms, high winds



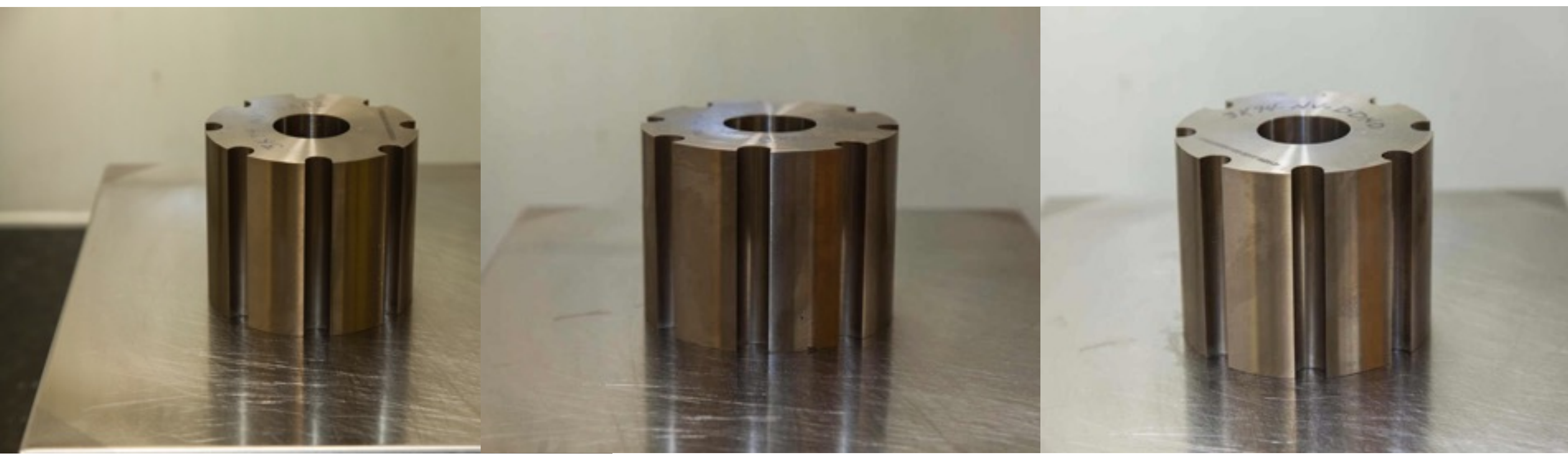
STMD Small Fission Power ("Kilopower") Technology Development Project

- **Innovation:**
  - A compact, low cost, fission reactor for exploration and science, scalable from 1 kW to 10 kW electric
  - Novel integration of available U-235 fuel form, passive sodium heat pipes, and flight-ready Stirling convertors
  - Provides about 10x more power than the Multi-Mission Radioisotope Thermoelectric Generator
- **Impact:**
  - Can be scaled up to provide modular option for human exploration missions to the Mars/Lunar surface
- **Goals:**
  - Full-scale nuclear system-level test of prototype U-235 reactor core coupled to flight-like Stirling convertors at relevant operating conditions
  - Design concepts that show scalability to 10 kWe for Mars surface power
- **Leveraging:**
  - Leverages existing DOE/NNSA nuclear materials, manufacturing capabilities, test facilities, nuclear safety expertise, and $5M DOE/NNSA co-funding



Kilopower
FY17 Technical Accomplishments

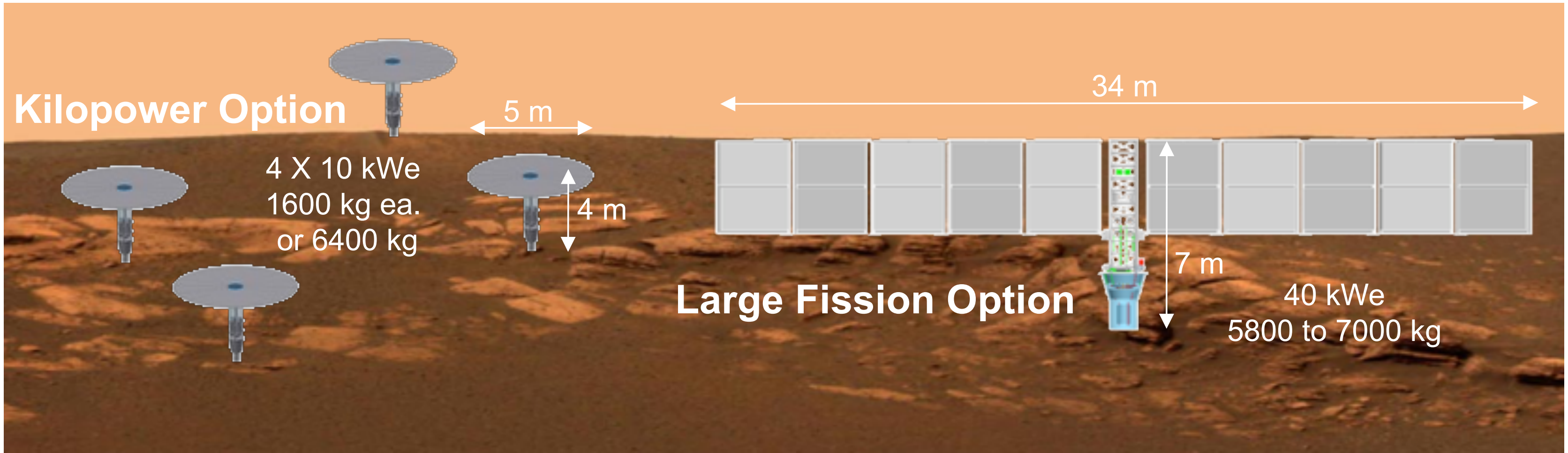
- **Highly enriched uranium core sections delivered to Nevada**
  - Three sections required to make 1 experiment core
  - Y-12 National Security Complex accelerated completion of all 3 cores
  - Cores meet dimensional and chemical/radiological requirements



Machined Highly Enriched Uranium Core Section Delivered by Y-12

Small Fission Power:
Scalability for Surface Power

- The Kilopower reactor design can be scaled up to 10 kWe and used in multiples to provide the 40 kWe needed for human exploration on planetary surfaces
  - The same fuel supplier, fuel form, and fuel fabrication process would be used; the same neutron reflector and control rod configurations would be used; the same test facility and test personnel would be used
  - Scaled up versions of the same heat transfer and power conversion designs would be used
- Utilizing multiple smaller reactors to perform the mission could yield several advantages:
  - The smaller unit size and mass facilitates packaging in landers and simplifies the deployment process
  - Individual units can be deployed as needed as the base station is built up; they can be shut down and relocated to address evolving mission needs
  - Multiple units provide greater redundancy and fault tolerance



STMD Kilopower Project: 1 kWe Demonstration

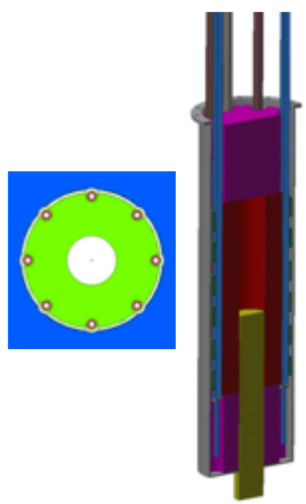
- **KRUSTY – Kilowatt Reactor Using Stirling Technology, a 1 kWe reactor prototype test**
  - **Materials testing** to fill gaps in UMo fuel data (e.g., temperature dependent creep) and evaluate interactions/diffusion at the heat pipe interface
  - Design, build, and test a **reactor thermal prototype** using an electrically heated stainless steel core mockup and a full array of experimental sodium heat pipes to demonstrate thermal performance
  - Conduct a **non-nuclear system test** using an electrically heated depleted uranium core with prototypic sodium heat pipes coupled to a flight-like Stirling power module
  - Complete a **nuclear system demonstration** with a prototype highly enriched uranium core and a flight-like neutron reflector to achieve sustained nuclear criticality at representative space operating conditions

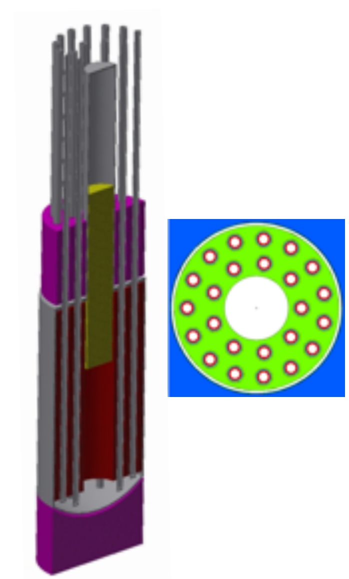
4.3 kW_t / 1 kW_e

28.4 kg U-235

8 perimeter heat pipes

11 x 24 cm reactor core





43.3 kW_t / 10 kW_e

43.7 kg U-235

24 embedded heat pipes

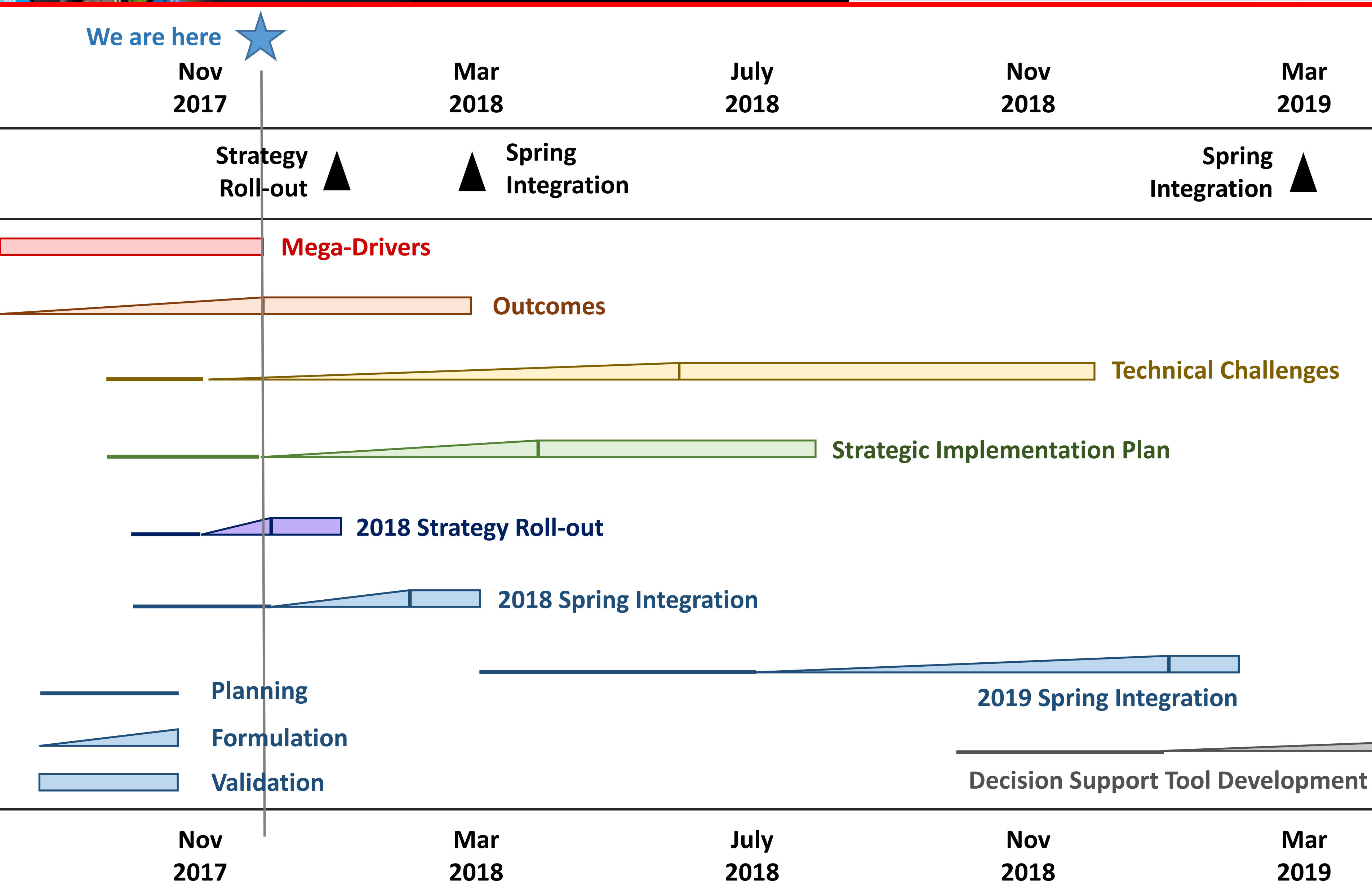
15 x 28 cm reactor core

The design is scalable from 1 kWe → to 10 kWe

Partial List of Engineering R&A Prioritized Investments

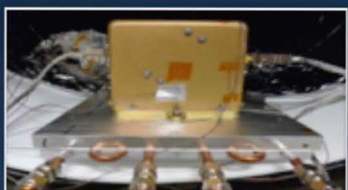
- *Development of Durability and Damage Tolerance analysis and test method tools for applications such as thin Composite Overwrapped Pressure Vessel liners or additive manufactured hardware*
- *Computational fluid dynamics algorithms tailored to emerging computer hardware technology*
- *Probabilistic analysis to quantify structural reliability (long term effort to move away from Factor of Safety)*
- Multidisciplinary/multiphysics analyses to enable simultaneous design and analysis at intersection of disciplines (e.g., Structures, Thermal, Load & Dynamics, GN&C, Acoustics, Mechanical Systems, Materials and Manufacturing) which exploits growth of computational capabilities and fabrication freedom being enabled by advanced manufacturing methods
- Computational NDE Methodologies
- Entry systems modeling
- NASA version of SPENVIS, ESA's Space Environments Information System
- Space Environments and Effect tools
- Materials database for spacecraft charging
- Space weather models and tools
- Flight Mechanics tools
- Sustainment of existing tools (ex: MAPTIS, NASGRO, Materials Outgassing/TPS databases)

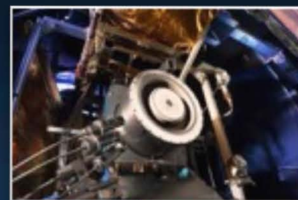
Path Forward



FY 2018-19 Program Highlights

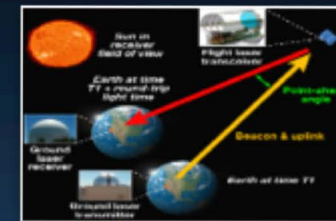
RRM3
January 2018
RRM3 Launch, carrying the eCryo Radio Frequency Mass Gauge for demo



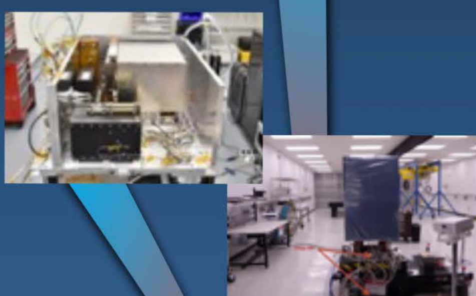


SEP
May 2019
Propulsion Subsystem Completion

LCRD
June 2019 Launch



DSOC
June 2019
Critical Design Review



DSAC & GPIM
December 2017
Initial Launch Capability aboard STP-2

Pathfinder Demonstrators
2018 and 2019

eCryo
May 2019
SHIVER testing

Space Technology Research Institutes
Additional Institutes will be awarded

2017 | **2018** | **2019**

Ongoing

Flight Opportunities
provides access to suborbital test environment

Centennial Challenges
New challenges initiated; Cube Quest Cubesats ready for flight on EM-1

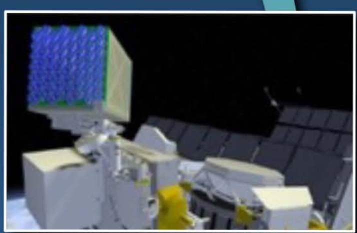
FY 2018-19 Highlights

Kilopower
January 2018
KRUSTY test

Nuclear Thermal Propulsion
September 2018
Depleted Uranium Fuel Element Test and NTP System Concept Review

Mars Entry, Descent and Landing Instrumentation 2 (MEDLI2)
March 2019
Hardware delivery

High Performance Spaceflight Computing
April 2019
Critical design (middleware) complete



SEXTANT
November 2017
Experiment complete

Astrobee
September 2018
Operations demo

Next Generation Life Support: Spacecraft Oxygen Recovery
September 2018
Deliver Phase II prototype

Composite Technology for Exploration
July 2019
Complete combined longitudina
& circumferential joint manufacturing & testing

2017 | **2018** | **2019**