National Aeronautics and
Space Administration

Technology, Innovation & Engineering Committee NASA Advisory Council

Presented by:
Dr. Bill Ballhaus, Chair

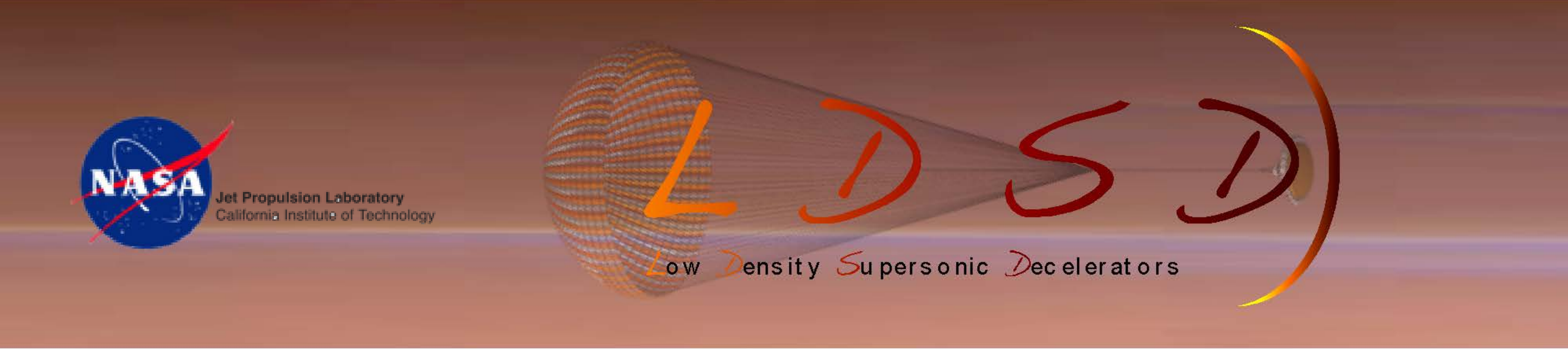
July 31, 2014

T,I,&E Committee Meeting Presentations July 28-29, 2014

- Dr. William Ballhaus, Chair
- Mr. Gordon Eichhorst, Aperios Partners LLC
- Mr. Michael Johns, Southern Research Institute
- Dr. Matt Mountain, Space Telescope Science Institute
- Dr. Dava Newman, Massachusetts Institute of Technology
- Mr. David Neyland, Draper Laboratory
- Mr. Jim Oschmann, Ball Aerospace & Technologies Corp.
- Dr. Mary Ellen Weber, STELLAR Strategies, LLC

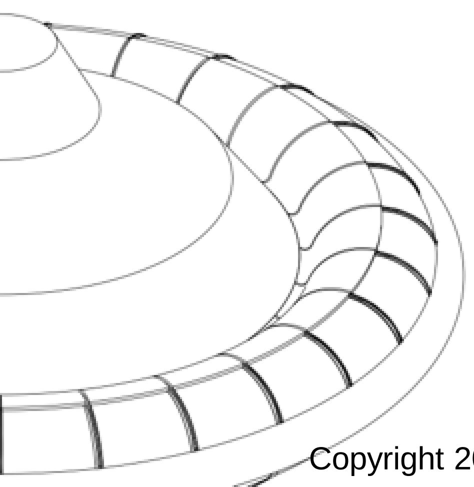
T,I,&E Committee Meeting Presentations
July 28-29, 2014

- Entry, Descent, and Landing Update – LDSD
  - Dr. Ian Clark, Principal Investigator for LDSD, JPL
- Space Technology Mission Directorate Update
  - Dr. Michael Gazarik, Associate Administrator, STMD
- Game Changing Development Program Update
  - Dr. Ryan Stephan, Program Executive, STMD
- Office of the Chief Technologist Overview/Update
  - Dr. David Miller, NASA Chief Technologist, OCT
- Update on Market Studies for Small Spacecraft Technology Program
  - Mr. Andy Petro, NASA Program Executive, Small Spacecraft Technology Program, STMD
- STMD Knowledge Capture Planning
  - Dr. Prasun Desai, Director, Strategic Integration, STMD
- Office of the Chief Engineer Overview and Discussion
  - Ms. Dawn Schaible, NASA's Office of the Chief Engineer
- Joint Meeting with Science Committee



Low Density Supersonic Decelerator

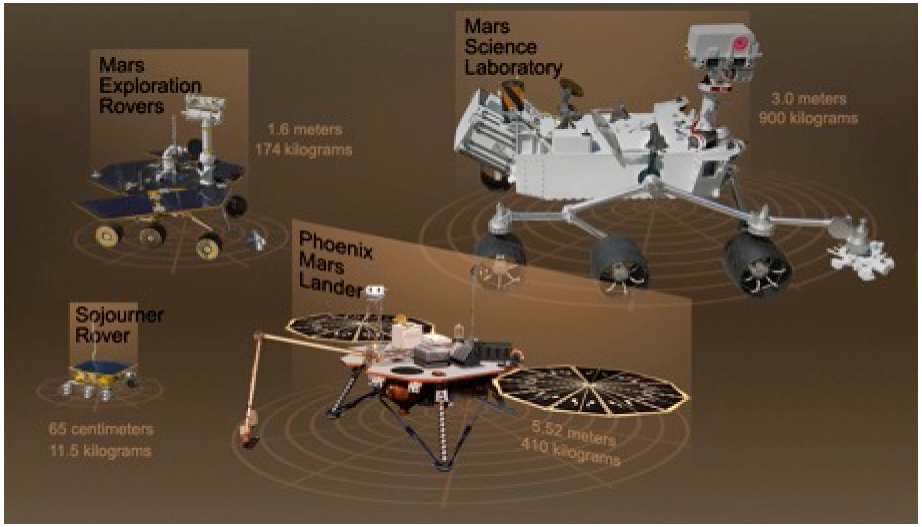
Overview to the NAC Technology, Innovation, and Engineering Committee

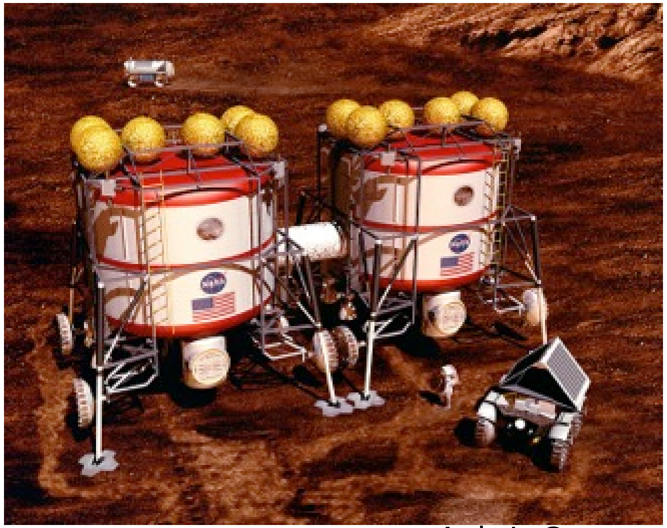


Ian Clark (JPL/Caltech) - Principal Investigator

Square-Cube Law Problem

- As Mars landers grow, ballistic coeff. (β) goes up (square-cube law problem) — currently at 1600 kg landed mass for MSL (Rover + Dry Descent Stage)
- Launch vehicle fairing size not going up, lift / drag not going up





Artist's Concept

- Need to deploy a parachute at Mach ~2, but …
- *As β keeps going up, eventually we hit the ground at Mach > 2*
- Need to begin the scale-up to crewed Mars landers ~50,000 kg (!)
- What can we do before these things hit the ground?

LDSD Decelerators and Test Venues

Jet Propulsion Laboratory
California Institute of Technology

LDSD's technologies will serve as the foundation of supersonic decelerators for the next several decades

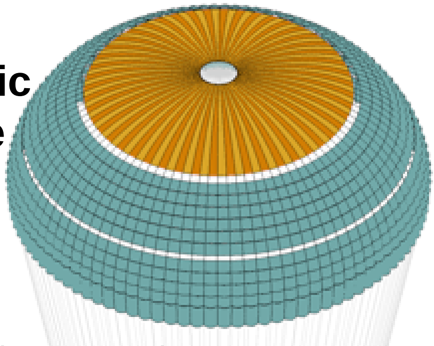
SIAD-R

- 6 m, Mach 3.75 inflatable decelerator
- Negligible aeroelastic deformation
- 50% increase in drag area over MSL

SIAD-E

- 8 m, Mach 3.75 inflatable decelerator
- Ram-air inflated, flexible structure
- 2.25x drag area of MSL

Advanced Supersonic Parachute



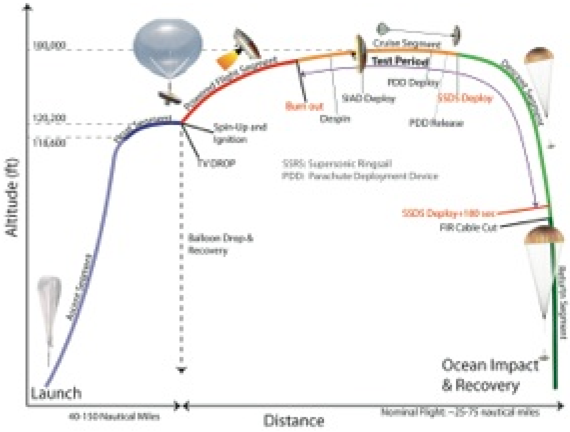
- 30.5 m, Mach 2.5 parachute
- Extensible to reefing and clusters
- 2.5x drag area of MSL parachute

LDSD is developing the infrastructure necessary to enable the qualification and future development of supersonic decelerator technologies

SDV

PDV

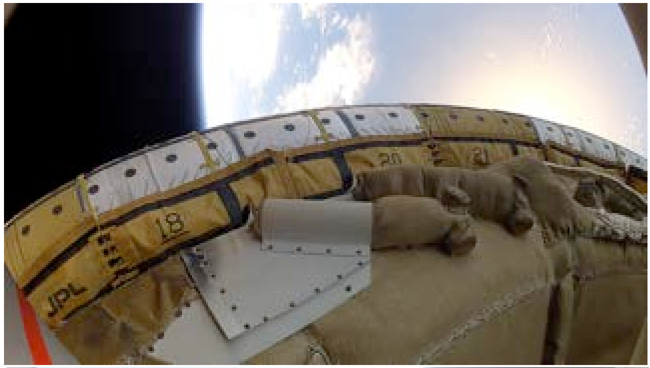
SFDT

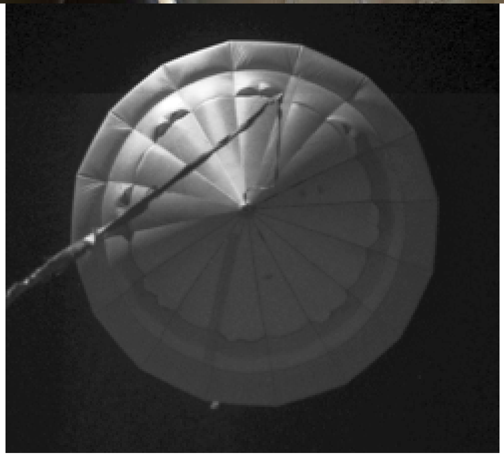


SFDT-1 Technical Success and Firsts

LDSD's SFDT-1 shake-out flight achieved several technical accomplishments and notable firsts:

- Largest blunt body aeroshell ever flown supersonically
- SIAD-R was a phenomenal success
  - Largest Inflatable Aerodynamic Decelerator (IAD) *ever* deployed and tested at supersonic conditions
  - Minimum vehicle disturbances: SIAD inflated to a rigid geometry in <1/3 sec using off-the-shelf automotive gas generators
  - Extremely rigid geometry: Maximum measured aeroelastic deflection of <4 mm during operation, <12 mm during parachute deploy at an internal pressure of <3 psi
  - No observed aerothermal damage or degradation
- Largest ballute (PDD) ever successfully flown at supersonic conditions
- First ever supersonic pilot deployment
- Largest supersonic parachute ever deployed
- Unprecedented quantity and quality of data collected
  - Several order of magnitude increase in the amount of data available on supersonic aerodynamic decelerators
  - Most detailed set of data ever collected on any of the three decelerators flown





Value of SFDT-1 Dataset

- Supersonic parachute inflation is a complex, non-linear dynamical event that demands high quality data to understand the phenomena
- Imagery and dataset collected by SFDT-1 is by far the best *ever* collected on a supersonic parachute inflation
  - >10x camera resolution (inch/pixel vs. ~foot/pixel); 15 and 135 frames per second
  - Resolution and frame rates have enabled additional insights to be made from grainy, 50-year old film of parachute inflations
- Early data analysis suggests that the Disksail configuration has unacceptable supersonic inflation dynamics
  - Transient inflation dynamics appear more important than previously envisioned, at least for this canopy configuration
    - Canopy rebounds, asymmetrical inflations, and local stress concentrations are common characteristics of supersonic inflation
    - Successful inflation requires robust parachute that can transit the intermediate inflating configurations successfully
    - Disksail configuration may not be robust to controlling stresses in the intermediate inflated shapes
- 40 year old paradigms about inflation, onset of parachute loading, and stress environments are being revisited in light of SFDT-1 data
  - Analysis still underway to determine if intermediate inflation stresses should be a concern for currently planned flight programs for NASA (e.g. InSight, Mars 2020)
  - *The LDSD test infrastructure represents a critical NASA resource for understanding parachute dynamics and quantifying the risk for current and future planetary missions*

National Aeronautics and
Space Administration

Space Technology Mission Directorate

NAC Meeting

Dr. Michael Gazarik
Associate Administrator
Space Technology Mission Directorate

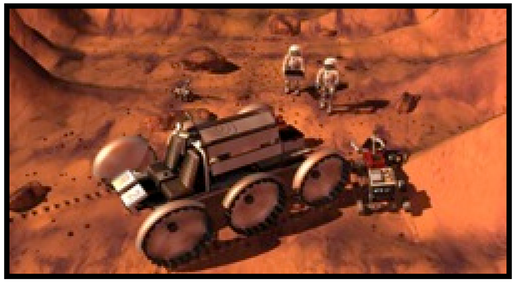
July 28, 2014

STMD Investments to Advance Future Capabilities of Space Launch System (SLS) & Orion

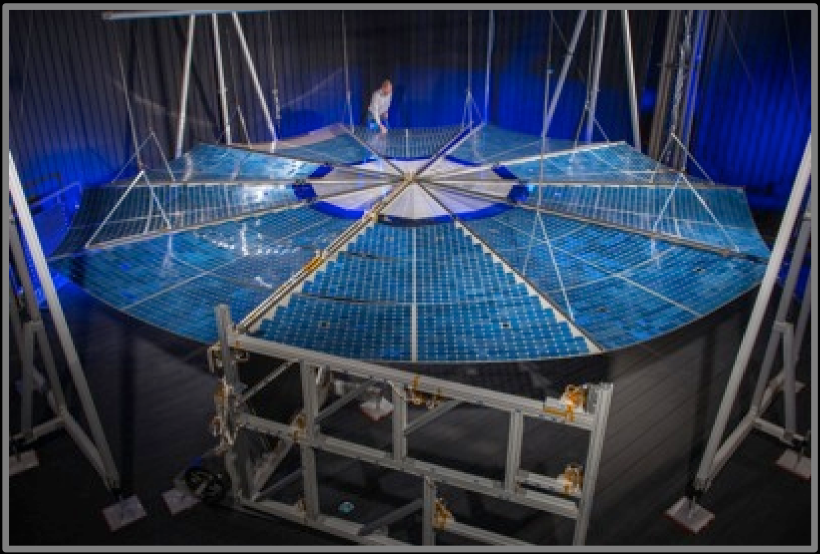
- Composite cryogenic propellant tanks and dry structures for SLS block upgrades
- Cryogenic propellant storage and transfer for upper stage block upgrades
- Additive manufacturing and testing of upper stage injectors, combustion chambers and nozzles
- Phase change material heat exchangers for Orion in lunar orbit
- Woven TPS for Orion heat shield compression pads
- Advanced air revitalization for Orion upgrades

STMD Investments to Advance Human Exploration of Mars

- High Powered SEP – cargo and logistics transportation to Mars
- CPST – either chemical or nuclear thermal in-space propulsion for crew transportation
- Composite cryogenic propellant tanks and dry structures – exploration upper stage
- Small Fission Power / Stirling Engine Power – Mars surface power
- HIAD / ADEPT – deployable entry systems for large mass landers
- LDSD – supersonic descent of large landed mass at Mars
- Woven TPS – more efficient and flexible TPS materials for entry
- Advanced close loop Air revitalization and water recovery – reduced consumables
- Mars atmospheric ISRU (oxygen) – life support and ascent vehicle oxidizer
- Humanoid robotics – enhanced exploration and crew workload relief
- Advanced mobility rover – remotely operated exploration
- Optical communications – high bandwidth communications at Mars
- Supersonic Retropropulsion – technology for future large mass Mars landing and reusable launch vehicle
- Synthetic Biology - a synthetic biology-enabled membrane that can be used extensively in life support applications



Test Success:
High-Powered Solar Arrays



MegaFlex Engineering Development Unit (EDU) employs an innovative spar hinge to reduce stowed volume. Alliant Technical Systems (ATK)

ROSA Engineering Development Unit (EDU) employs an innovative stored strain energy deployment to reduce the number of mechanisms and parts. Deployable Space Systems (DSS)

Novel Solar Arrays sized for nominally 20kW/wing BOL

Brought to TRL 5+ by June 2014

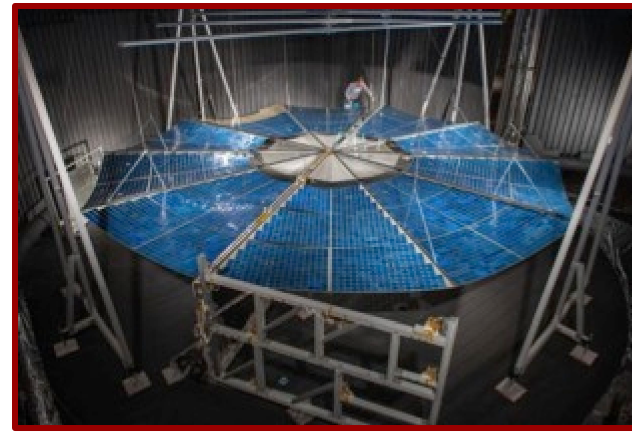
Thermal vacuum deployments + dynamics & strength/stiffness & acoustic/vibration testing + validated models

STMD Solar Electric Propulsion Project
Solar Array Systems Overview

- **OBJECTIVE: Design/build high power (20 kW class) solar array wing that also provided high voltage, high deployed strength and high deployed stiffness & can operate in high radiation and dense induced plasma environments that come with SEP-based human exploration missions**

- **APPROACH: Fund 2 contracts to advance: the fan-fold MegaFlex design (ATK) & the roll-out ROSA design (DSS). Both use flexible blankets to reduce mass (for a given strength & stiffness), stowed volume & recurring cost compared to rigid panel structures.**

- **ACCOMPLISHMENTS:**
  - ✓ **Brought concepts from idea to hardware in 22 months: Passed SRR, MDR, MRR, TRR, and SDR reviews**
  - ✓ **Conducted structural, thermal, and environmental tests on key subsystems & EDU wings**
  - ✓ **PV cell coupon plasma interactions testing**
  - ✓ **Demonstrated TRL 5+ for weightless thermal vacuum deployment & stowed/deployed structural performance**
  - ✓ **Demonstrated credible extensibility to >250kW-class solar array systems (manufacturing, proof of concept testing, analysis)**



ATK MegaFlex Engineering Development Unit (MDU) employs a panel/spar extension hinge subsystem to reduce stowed wing length

DSS ROSA Engineering Development Unit (EDU) employs strain-energy deployed STEM (storable tubular extendable member) booms to reduce mechanical complexity, parts & deployer recurring costs.

GCD’s Flagship Project: Composite Cryotank Technologies & Demonstration (CCTD)

- The Problem:
  - NASA requires an affordable, lightweight vehicle to enable future exploration
- The Solution:
  - Design, fabricate, & test an affordable, low mass composite cryotank
- The Accomplishments:
  - Designed & fabricated a 5.5m diameter composite cryotank
    - Developed using automated manufacturing techniques & out-of-autoclave materials/cure
  - Demonstrated 30% (~3,300 lb) mass savings & 25% cost reduction (~$7M)[1]
- Development Milestones:
  - Tank delivered from Boeing to MSFC on 26 March 2014
  - 45 psi ambient pressure test was performed on 22 May 2014
    - Analytical models updated/correlated
  - Cryogenic pressure test was performed at ~60 psi on 20 July 2014
  - Will perform 80 cryogenic pressure cycles & mechanical loads/pressure test

GPIM Project Summary

- Project Description
  - Public/private partnership involving multiple government organizations and multiple contractors
  - Demonstrate advanced in-space propulsion system based on USAF developed AF-M315E "green" propellant
    - Over $15M of industry/government investment
    - More than a decade of research (handling, performance, etc.)
  - Mature technology to TRL9
  - Baseline mission:
    - Demonstrate ESPA class propulsion subsystem
    - Multiple orbit lowering operations/inclination change

- Project Status
  - Conducted CDR in March 2014
  - Component production and testing underway
  - Manifested Falcon Heavy STP-2 mission, August 2015

Why Green Propellant Matters

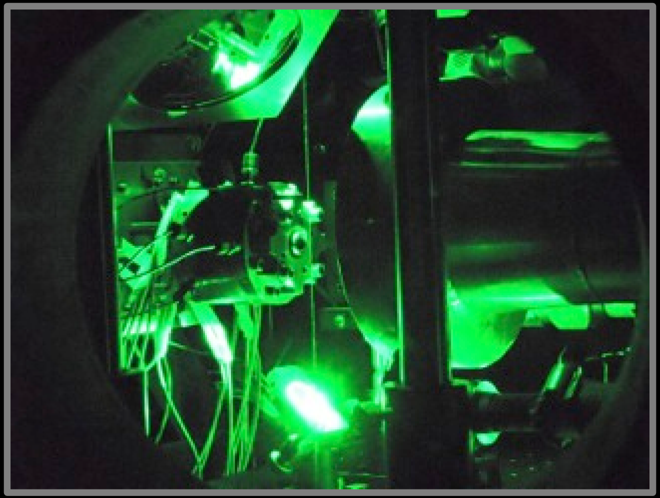
- Propellant Performance
  - ~50% higher density-specific impulse than hydrazine
  - Comparable system performance to bi-propellents
  - Lower temperature capability opens mission trade space
- Science
  - More payload capability or longer mission duration
  - Wide range of spacecraft sizes: large to nano
  - More launch options for benign secondary payloads without hazardous propellants
- Safety
  - Reduced toxicity enables easier handling and processing
  - Human Space Operations
- Economics
  - Reduced launch, range, and operations costs
  - US developed propellant and thrusters enable domestic sources

Aerojet Rocketdyne Technician handles AFM315E propellant

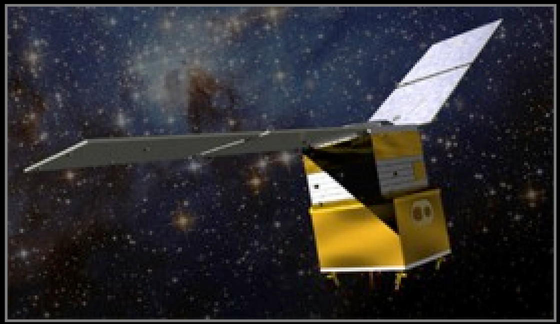
Traditional HAZMAT suit for fueling is not required

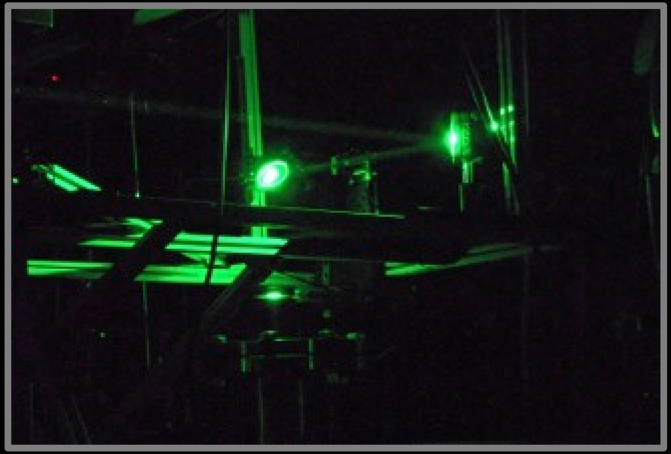
Flight proven green propellant system enhances U.S. industrial competitiveness

Test Success:
Green Propellant Infusion Mission



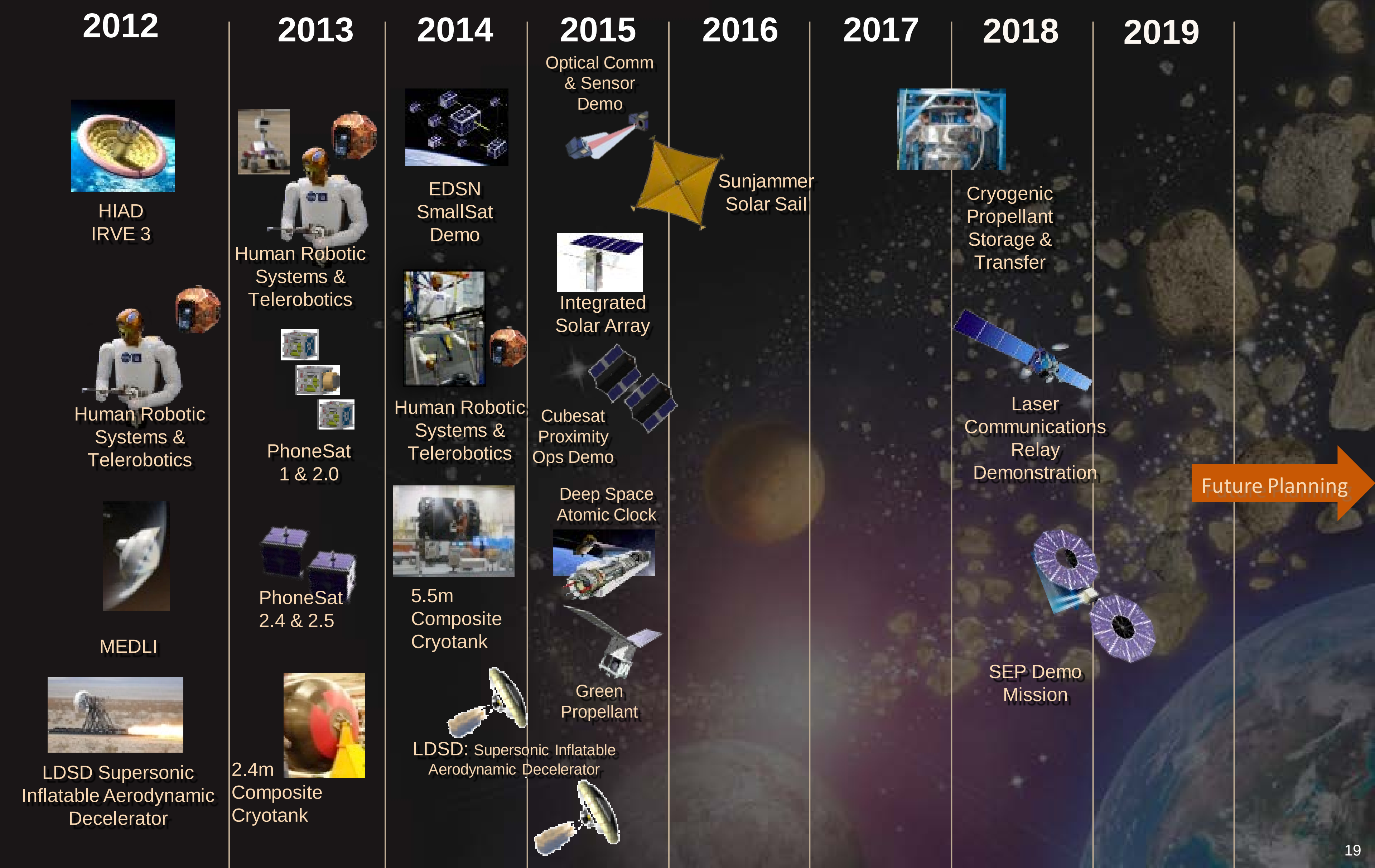
1N thruster plume chemistry using laser diagnostics





- ❖ The 1N Engineering Model thruster (flight thruster design) testing has completed with over 11,000 pulses. This testing demonstrates that the 1N thruster has the performance and capability to conduct the GPIM mission.
- ❖ The 22N Engineering Model thruster (flight thruster design) is progressing through manufacturing with the injector system and is on track for hot fire testing this year.

CY Major Events & Milestones



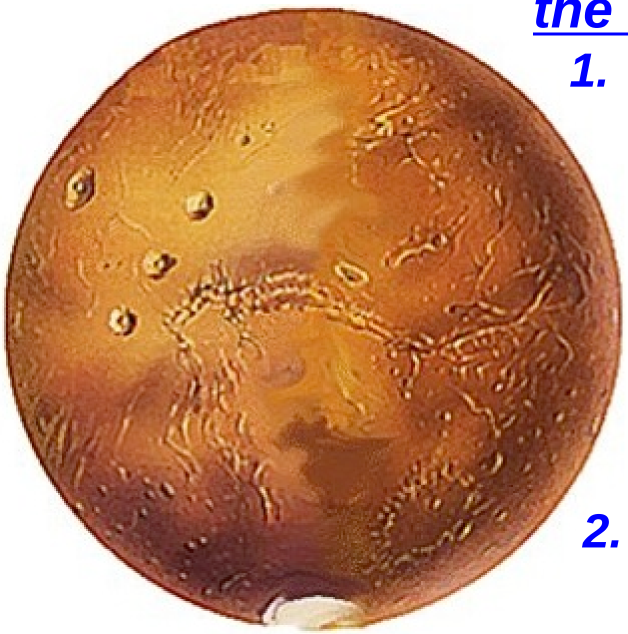
National Aeronautics and
Space Administration

Space Technology Mission Directorate

Game Changing Development Program Update

Ryan Stephan
Program Executive, STMD/GCD
29 July 2014

Select GCD Projects By Programmatic Alignment (Mars 2020)



STMD Will Develop Two Payloads for Infusion into the Mars 2020 Mission:

1. ***In Situ Resource Utilization (ISRU) Demonstration***
   - ***Competitively selected technology demonstration to convert Mars' atmosphere into valuable oxygen (fuel & life support)***
   - ***Benefits both robotic & human exploration:***
     - ***Reduced Earth-launch mass & mission cryogenic storage burden***
     - ***Reduced burden on EDL systems***
2. ***Mars Entry, Descent, and Landing (EDL) Instrument (MEDLI-2)***
   - ***Developing sophisticated instrumentation suite to acquire critical EDL data benefiting future exploration missions***
   - ***Instrument both heat shield AND backshell***
   - ***Benefits Include:***
     - ***Valuable flight data to validate analytical models (Reduced TPS design margins)***
     - ***Data necessary to reconstruct planetary entry***

Select GCD Projects By Programmatic Alignment (ISS)[1]

STMD Leverages, and Partners With, the Valuable On-Orbit National Asset:

1. ***SPHERES SLOSH Experiment***
   - ***KSC, FIT, & MIT partnered to develop demonstration hardware for ISS***
   - ***Hardware delivered to ISS in January 2014***
   - ***Three experimental sessions completed subsequent to hardware delivery***
   - ***Performed microgravity experiments to obtain slosh data for model correlation/validation***
2. ***Phase Change Material (PCM) Heat Exchanger***
   - ***Develop & demonstrate 2 PCM heat exchangers***
   - ***Will retire risks associated with microgravity operation of large-scale PCM heat exchanger for infusion into Orion TCS***
3. ***Station Explorer for X-Ray Timing & Navigation Technology (SEXTANT)***
   - ***Partnering with NICER project (SMD) to demonstrate advanced, autonomous navigation technology using Pulsars as beacons***

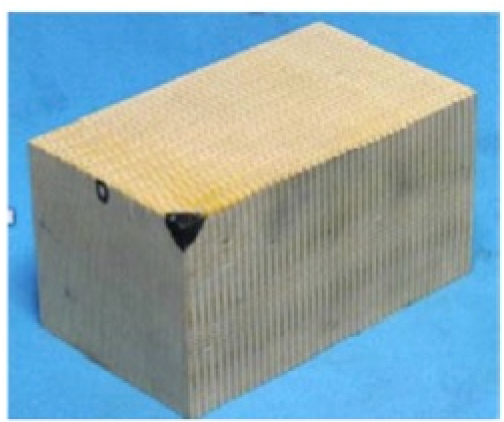
[1]List does NOT include all planned ISS demos

Select GCD Projects By Programmatic Alignment (Orion & SLS)

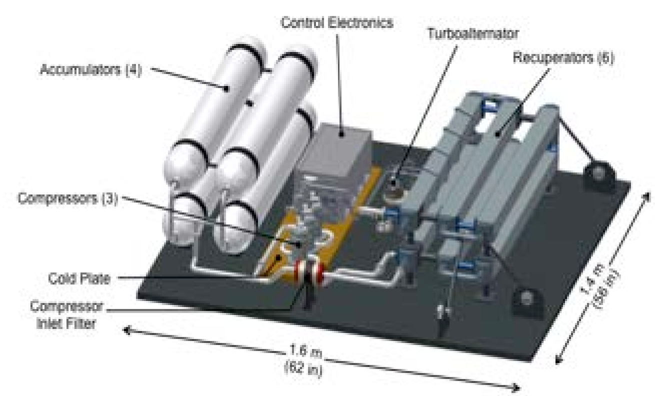
STMD is Developing Critical Technologies to Enable Orion & SLS Exploration:

1. ***3D Multifunctional Ablative TPS (3D MAT)***
   - ***Maturing woven TPS for infusion into Orion***
   - ***Compression pad is required to meet severe structural and thermal loading***
2. ***Composite Cryotank***
   - ***Fabricated & currently testing 5.5m diameter composite cryotank***
3. ***20 Watt, 20 Kelvin Cryocooler***
   - ***Develop high capacity cryocooler to enable zero boil-off of liquid hydrogen***

5.5m diameter composite cryotank



3D MAT TPS Billet



Turbo-Brayton Flight Cryocooler Concept

Select GCD Projects By Programmatic Alignment (SMD/Discovery)

STMD is Maturing Revolutionary Technologies for Discovery 2014[1]:

- ***Technologies were highlighted during April Technology Workshop***
- ***Technologies included in July's draft AO***
- ***MOU signed to mature two technologies to TRL 6 by the end of FY 2017***

1. ***Heat Shield for Extreme Entry Environment Technology (HEEET)***
   - ***Low mass (40%), high performance TPS material for planetary entry missions***
   - ***SMD will provide \$10M incentive***
2. ***Deep Space Optical Communication***
   - ***Communication technology providing order of magnitude higher data rates for deep space exploration***
   - ***STMD will GFE flight hardware***
   - ***SMD will provide \$30M incentive***

[1]List does not include additional technologies being matured by TDM (ASA, GPIM, & DSAC)

David W. Miller
NASA Chief Technologist

NAC TI&E Meeting, July 28-29, 2014

TECHNOLOGY DRIVES EXPLORATION

#321TechOff

Agency Investment for Low TRL Research

- **Need a program for fundamental knowledge discovery**
- **New capability includes both products and processes**
- **Potential processes:**
  - Design and test under uncertainty
  - Integrated, multi-physics modeling
  - Solving the inverse problem
  - Model-based systems engineering
  - Massively computer-aided design environment
- **Key benefits:**
  - Identifies potential detrimental couplings earlier in design process
  - Permits solutions that leverage favorable couplings
  - High fidelity, integrated models used directly in the design process
  - “What-ifs” posed by stakeholders could be answered in real time
  - Design decisions could be revisited, raw data re-analyzed
  - Enhance productivity & quality, reduce risk, improve communications, more in-depth independent assessment
  - Could dramatically reduce time and cost of custom design
  - Test campaigns more efficient, uncertainty quantified, data archived
  - Reduced conservatism leads to more capability or lower cost

T&I Committee Finding and Recommendation for STMD AA

Recommendation:

- The T&I Committee recommends that STMD characterize the small spacecraft mission market pull.
  - Civil, military, intelligence, commercial, academia
  - What is the technology's potential utility and societal benefits?
- Identify what is NASA's particular role in developing capabilities for this market. How can NASA "move the needle"?

Major Reasons for the Recommendation:

- There may be real potential in developing capability to improve space mission effectiveness by using small satellites.
- The market pull associated with small satellites has not been well characterized for the NAC T&I Committee.

Consequences of No Action on the Recommendation:

Erosion of NASA's science and technical capabilities

Space Technology Mission Directorate

Small Spacecraft Technology

MARKETS & MOTIVATIONS

Andrew Petro

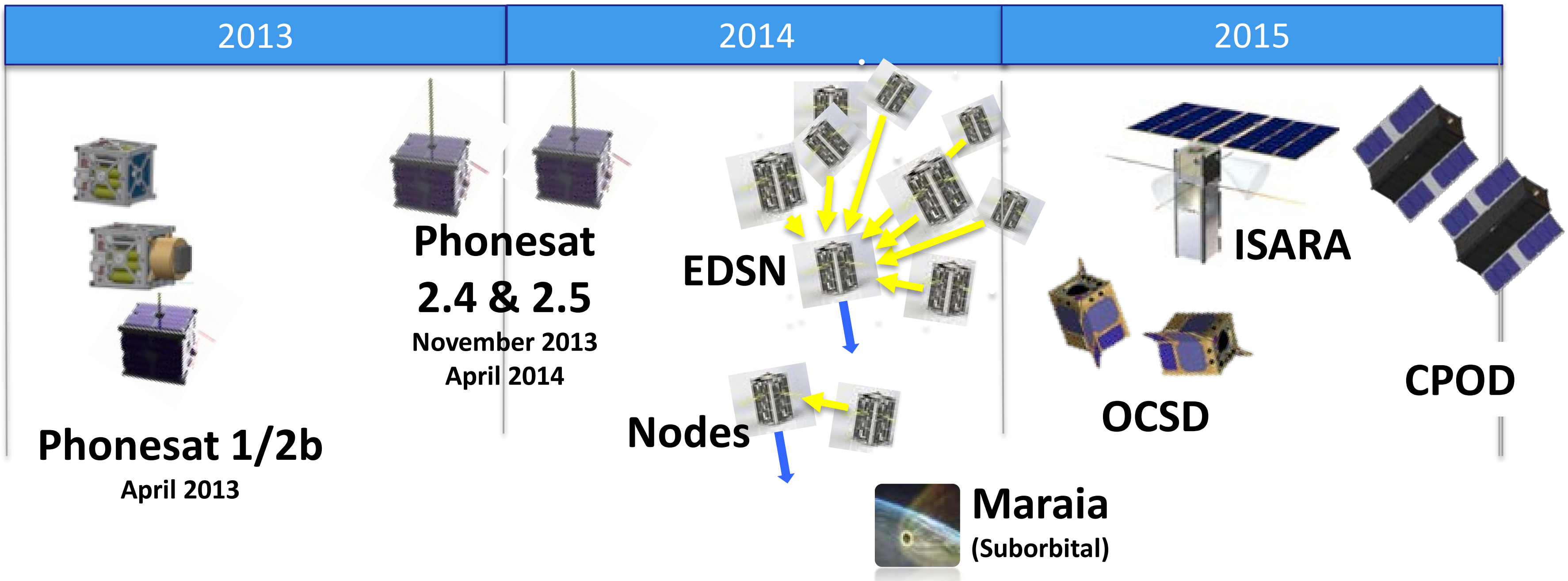
Briefing to the NASA Advisory Committee
July 28, 2014

Small Satellites Market Pull

- NASA State of the Art Report
- SMD-STMD study of how small spacecraft can address Decadal Survey mission needs – starting in Aug-Sept 2014
- Informal assessments of market pull
  - Annual Government Cubesat Forum – (NASA, USAF, NRO, NRL, DARPA, ORS, etc.)
  - Smallsat and Cubesat conferences
- Identified civil and commercial markets:
  - Earth remote sensing
  - Space weather and heliophysics
  - Communications
  - NEA exploration (i.e., ARM secondary payloads)
  - In-space subscale testing of technology
  - Education and public outreach
- Launch demand market studies (rideshare, ISS deploy, small launchers)

Small Spacecraft Technology Program

Projects: 2013-2015



Smallsat Technology Partnerships
13 projects with NASA-University collaboration

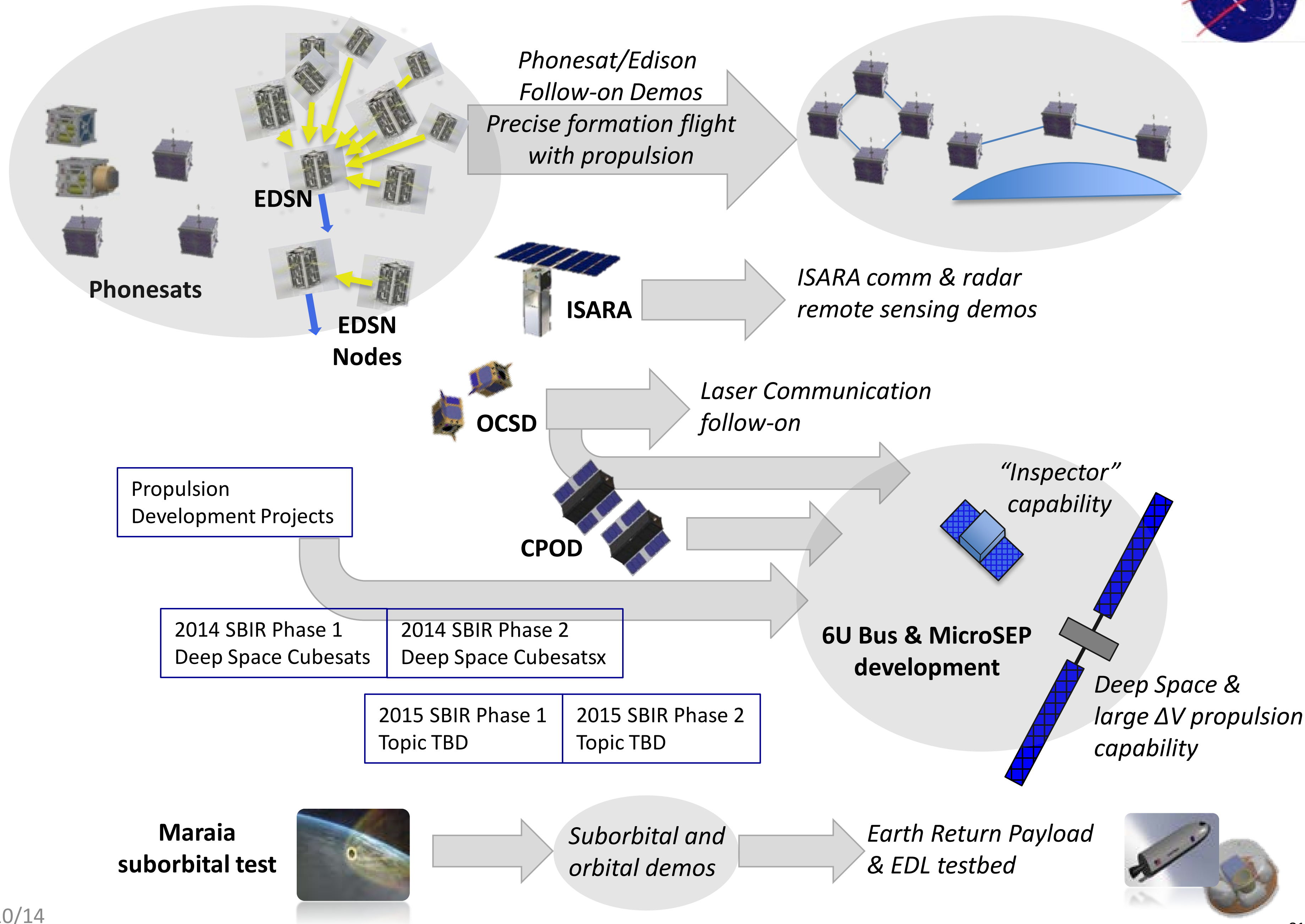
5 Propulsion Technology Projects

SBIR - Deep Space Cubesats

EDSN: Edison Demonstration of Smallsat Networks
ISARA: Integrated Solar Array and Reflectarray Antenna
OCSD: Optical Communications and Sensor Demonstration
CPOD: Cubesat Proximity Operations Demonstration

www.nasa.gov/smallsats

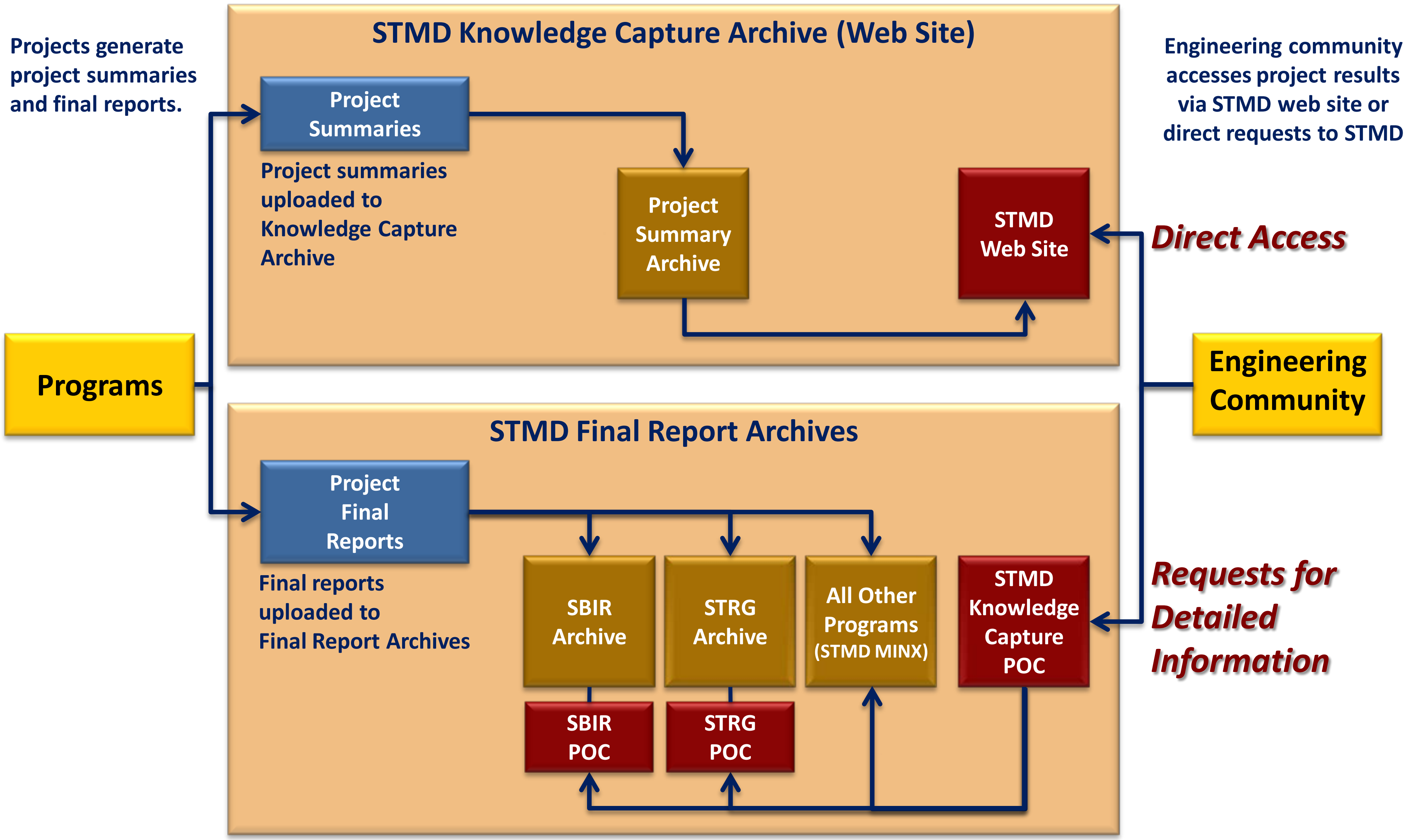
Small Spacecraft Technology "Pathways"



2014 Work Plan for the NAC

*“**Knowledge Capture**: Offer suggestions on how to establish and the most useful approach for a Knowledge Capture program. Past NASA technology incarnations left no real knowledge behind for use in the future. NASA’s Space Technology Mission Directorate and Human Exploration and Operations Mission Directorate want to be the places where others check first for what has been done, how to do, and what was learned. These organizations want to be on the cutting-edge and a resource for others.”*

STMD Knowledge Capture Implementation



Previous Recommendation for the NASA Advisory Council

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

Office of the Chief Engineer Update

Dawn M. Schaible

July 29, 2014

Chief Engineer, Chief Scientist, Chief Technologist Vision for FES

- Foundational Engineering Sciences (FES)
  - Utilize the existing programmatic portfolio within the Space Technology Mission Directorate (STMD) to manage these new investments
  - Evaluate and prioritize the input from the Engineering, Technology and Science Communities
  - Partner with Industry, Academia and other Government Agencies
  - Select a portfolio of pilot projects and begin to invest in Foundational Engineering Sciences for our future

T,I,&E and Science Committees Recommendation for the NAC

Recommendation:

The Council recommends that the STMD AA & SMD AA engage with each other and their communities to determine how policies and procedures could be modified to allow the infusion of new mission-enabling and mission-enhancing technologies developed by Principal Investigators, STMD or others in small to medium class missions.

Major Reasons for the Recommendation:

- In highly competitive program solicitations, such as Discovery and Explorer, there is a disincentive to propose new technology because of the perceived risk.
- As a result, NASA may be missing an opportunity to leverage scientifically beneficial technology through small and medium science missions. In the long-term, this could erode NASA's scientific and technical capabilities.
- If the Agency wants to encourage and infuse appropriate new technologies in its small and medium class missions, it must develop a policy that provides a pathway to the inclusion of these technologies in the solicitation release.

Consequences of No Action on the Recommendation:

Erosion of NASA's science and technical capabilities

Back-Up

NRC Capability Assessments

NRC RECOMMENED CAPABILITY	TECHNICAL CHALLENGES	CAPABILITY GAP	STMD Investments
Mars EDL	High - technologies needed for a Mars EDL system capable of handling very large payloads have yet to be identified.	High - payload capacity of the necessary EDL systems are currently far beyond the capability of existing EDL systems	Multi-speed regime, opportunistic approach: • Hypersonic & Supersonic inflatable Aerodynamic Decelerators • Propulsive Decelerators • Conformal & Woven Thermal Protection Systems • improved system models • MEDLI and Mars 2020 instrumentation
Radiation Protection	High - a suitable approach for providing adequate radiation safety has yet to be identified	High - the ability to provide the level of radiation safety required for a human mission to the Mars surface is so far beyond the state of the art	• Largely focused in HEOMD • STMD focus on developing prototype of integrated system to mitigate solar event risks through modeling and forecasting. Shift to GCR shielding analytical models
Fission Power (100KW)	Medium - extensive experience with reactor technologies, although some new technologies would be needed to provide reliable, long-term operation in space and on the surface of Mars.	Medium – despite past accomplishment in nuclear power technology in general and space nuclear power in particular, it has been almost 50 years since a U.S. space nuclear power program succeeded in conducting a flight test of a fission power reactor	• NTEC guidance to focus on 1-10 kW fission power system using Stirling conversion technology for in-space and planetary surface power generation • Finish 40kW non-nuclear system demonstration.
In-Space Cryogenic Propulsion	Medium – even though high-performance in-space cryogenic propulsion systems are already operational, new technologies are needed in-space fuel handling and long-term storage.	Medium - improvements needed to extend the in-space storage and operational lifetime of existing systems	• Cryogenic propellant management technologies including passive insulation, mass gauging and active cooling

NRC Capability Assessments

NRC RECOMMENED CAPABILITY	TECHNICAL CHALLENGES	CAPABILITY GAP	STMD Investments
Nuclear Electric Propulsion	Medium - challenges associated with the fission power system	High - higher power levels required for the fission power and electric propulsion engines relative to the state of the art.	• Trade studies indicate that nuclear thermal propulsion is preferable approach at least in the near term
Nuclear Thermal Propulsion	Medium - the NERVA program developed most of the technologies that would be needed by an operational NTP system	Medium - the NERVA program tested a full-scale system, but the state of the art has degraded somewhat during the ensuing 40 years	Largely focus of HEOMD • ground testing technologies for nuclear thermal propulsion systems • system component technologies STMD focus on cryogenic propellant storage
Solar Electric Propulsion	Low - SEP systems are well developed with a long history of operation in space	High - the power level of state-of-the-art systems is so far below the power level needed for a crewed spacecraft transiting to and from Mars	Demonstrate a extendable 50kW system • High power solar arrays • High power, high thrust electric propulsion thrusters • Power processing & power management • Xenon storage tanks
SLS Heavy Lift Launch Vehicle	Low - no technological breakthroughs are required to complete SLS development	Low - designed to avoid the need either for new technologies or for substantial improvements to existing technologies	• Large-scale, low-cost lightweight composite structure demonstration • Cryogenic Propellant Management technologies • Cryogenic Composite Propellant Tanks

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Planetary Ascent Propulsion	Medium - past experience with lunar ascent engines and existing in-space propulsion systems provide a solid foundation for developing the technologies needed for Mars	Medium - improvements are needed to advance available technologies enough to provide the power needed ascent from Mars	• Early-stage work in hot gas TVC For planetary ascent vehicle, and single-Stage-to-Orbit Mars ascent vehicle engine
ECLSS	Medium - ECLSS technologies and systems are already operational	High – substantial improvements are needed to extend the lifetime and increase the reliability of existing technologies and systems	• Focused approach in partnership with HEOMD to develop closed loop air revitalization and water recovery • Delivery of water technologies to HEOMD, now shifting to focus on closing the air loop
Habitats	Medium - NASA has extensive experience in designing and building habitats in LEO, culminating with the ISS	Medium – substantial improvements are needed to extend the lifetime and increase the reliability of existing technologies and systems and to assure that habitat systems work as expected in the partial gravity of the Moon and/or Mars	Inflatable habitats main focus in in HEOMD. STMD focus is in component level and conceptual work • ultralight flexible shielding film for extreme heat and radiation • expandable/foldable structures for habitats • self-deploying, composite habitats • inflatable airlock designs • Integrated advanced habitat design
EVA Suits	Low - substantial research and experience with EVA suits in space and, to a lesser extent, on the surface of the Moon	Medium – advances are needed to accommodate the long duration of a human mission to the Mars surface during transit and on the surface	• Delivering rapid cycle amine system and variable oxygen regulator system to HEOMD. • Delivering high-performance EVA glove • Continued work on high energy density batteries

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Crew Health	Medium - final solutions to many physiological and psychosocial threats to crew health have yet to be identified	Medium - solutions to some issues are rather well defined, but others still require substantial research	Focus of HEOMD, STMD focus is in largely low-TRL work: • rapid electrochemical detection and identification of microbiological and chemical contaminants for manned spaceflight • microfluidic extraction of DNA for Identification of unknown organisms in microgravity • multi-modal neuro-diagnostic tool for exploration missions • microfluidic label-free sensing for rapid multiplexed pathogen detection in space
ISRU Mars Atmosphere	Low - technologies to achieve the ISRU capabilities described above have been demonstrated on Earth	High - there is a large gap between the capabilities of the small-scale experiments completed to date and the development of a full-scale operational system capable of reliable operation during long-term exposure to the partial gravity, dust, atmosphere, and radiation environment found on the surface of Mars	• Partnered with HEOMD and SMD for robust system for oxygen production from Lunar and Martian Resources including a Technology demonstration of ISRU system on Mars 2020

Integrated Multi-Physics Modeling

- **Current Practice**
  - Separate CAD and analysis tools used for each discipline
  - Interactions assessed, trades developed between domain experts
- **Proposed Process**
  - Couple CAD and analysis tools for disciplines that exhibit potential coupling (e.g., temporal, spatial), considering hybrid scales
    - Ensuring comparable accuracy over comparable parametric ranges
    - Validate coupling behaviors
  - Evaluate performance and conduct trades using appropriate metrics and optimization tools
- **Potential Benefit**
  - Identifies potential detrimental couplings earlier in design process
  - Permits solutions that leverage favorable couplings
  - Allows broad and rapid trade-space exploration

Solving the Inverse Problem

- **Current Practice**
  - Design parameters are inputs, performance metrics are outputs
  - Designs are optimized based upon experience at sub-system level
  - Designs are analyzed using high fidelity simulations
- **Proposed Process**
  - Performance metrics are inputs, design parameters are outputs
  - Use high fidelity, integrated models that capture system behavior
  - Embed these models (or surrogates) in an optimization problem
    - E.g., reduced order models, describing functions
- **Potential Benefit**
  - High fidelity, integrated models used directly in the design process
  - Can contour the iso-performance design space

Model-Based Systems Engineering

- **Current Practice**
  - Requirements, designs, analyses, data captured in documents
    - Not amenable to data extraction, independent analysis & assessment
  - They are not “living” documents that can easily adapt over a project or be leveraged by follow-on projects
- **Proposed Process**
  - Formalized application of modeling to support system development (e.g., requirements, data analysis, V&V) throughout the lifecycle
  - Capture these products in interactive modeling framework
    - Discoverable design revision history, lessons learned, trade-able requirements, extractable raw data with available analysis code
- **Potential Benefit**
  - “What-ifs” posed by stakeholders could be answered in real time
  - Design decisions could be revisited, raw data re-analyzed
  - Enhance productivity & quality, reduce risk, improve communications, more in-depth independent assessment

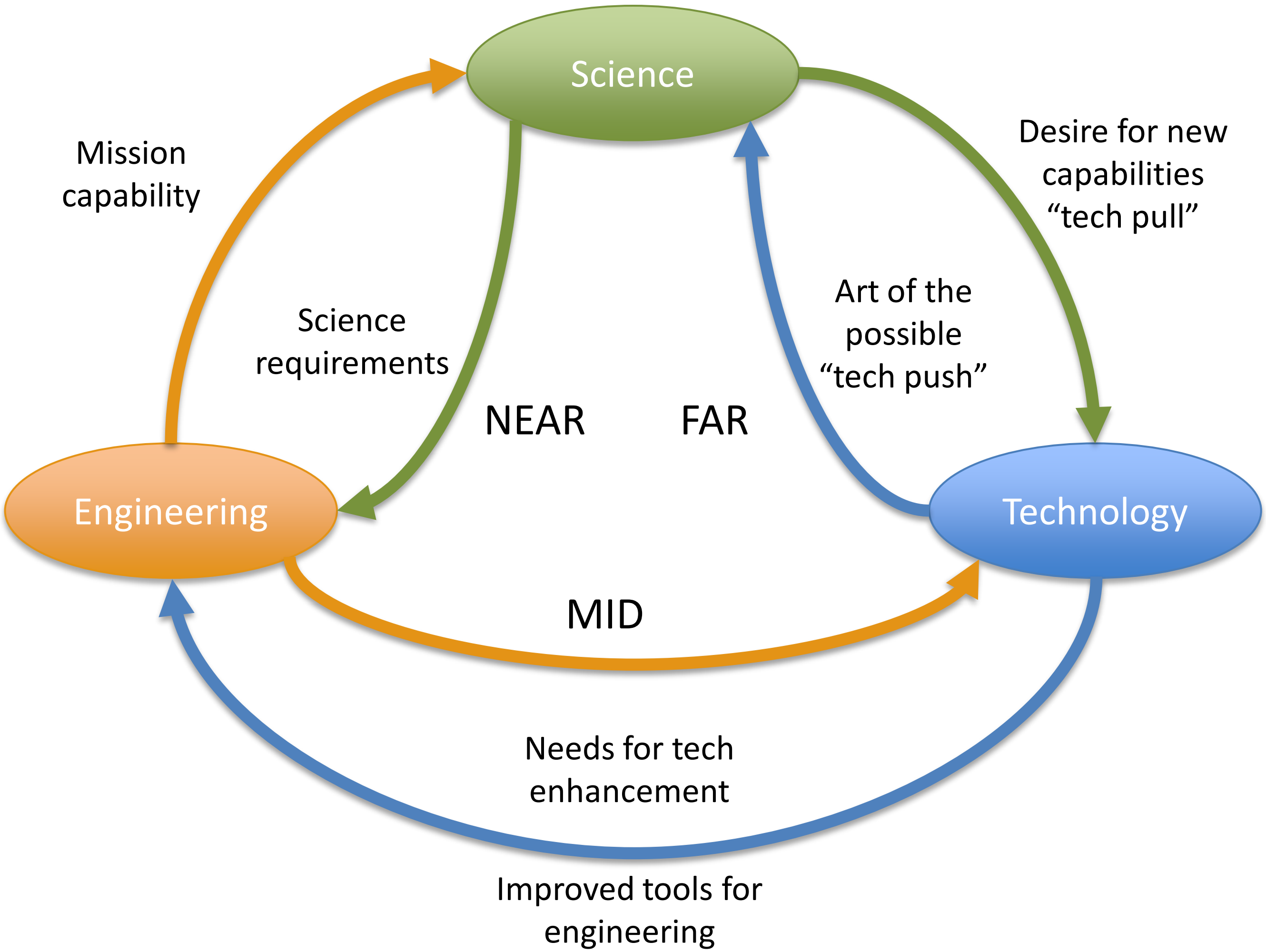
Integrated Design Environment

- **Current Practice**
  - Disciplinary design teams working separately and exchanging results infrequently by “throwing their results over the transom”
  - Early arrival at point design that requires subsequent “band aids”
  - Integrated multi-disciplinary conceptual design (e.g., Team-X)
- **Proposed Process**
  - Turn the preliminary design process (and beyond?) into a real-time conversation between domain experts
    - Assume computation power is infinite and cost is insignificant
  - Exploit MBSE, Integrated multi-physics and multi-scale models, Inverse solution and iso-performance techniques
  - Complement DARPA Adaptive Vehicle Make (AVM) program
- **Potential Benefit**
  - Could dramatically reduce time and cost of custom design
  - Carry multiple, substantially different designs to mitigate risk

Design and Test under Uncertainty

- **Current Practice**
  - Models, H/W & S/W developed, UFs are levied, and subjected to often worst case, conservative environments
  - Models tuned, workmanship assessed, requirements validated
- **Proposed Process**
  - Models inform test design which improves model predictive accuracy
  - For example,
    - Models, uncertainties, performance metrics developed and likelihood of meeting requirements assessed
    - Sensitivities of metrics from model & uncertainty parameters inform both model-based redesign and test campaign designs, respectively
    - Tests designed to reduce parametric and identify non-parametric uncertainties
  - Algorithms w/limited application, tool development-validation needed
- **Potential Benefit**
  - Test campaigns more efficient, uncertainty quantified, data archived
  - Reduced conservatism leads to more capability or lower cost

Dialogue between Science, Engineering & Technology



All three dialogues must exist led by experts in the disciplinary areas involved. The goal is to facilitate these dialogues.