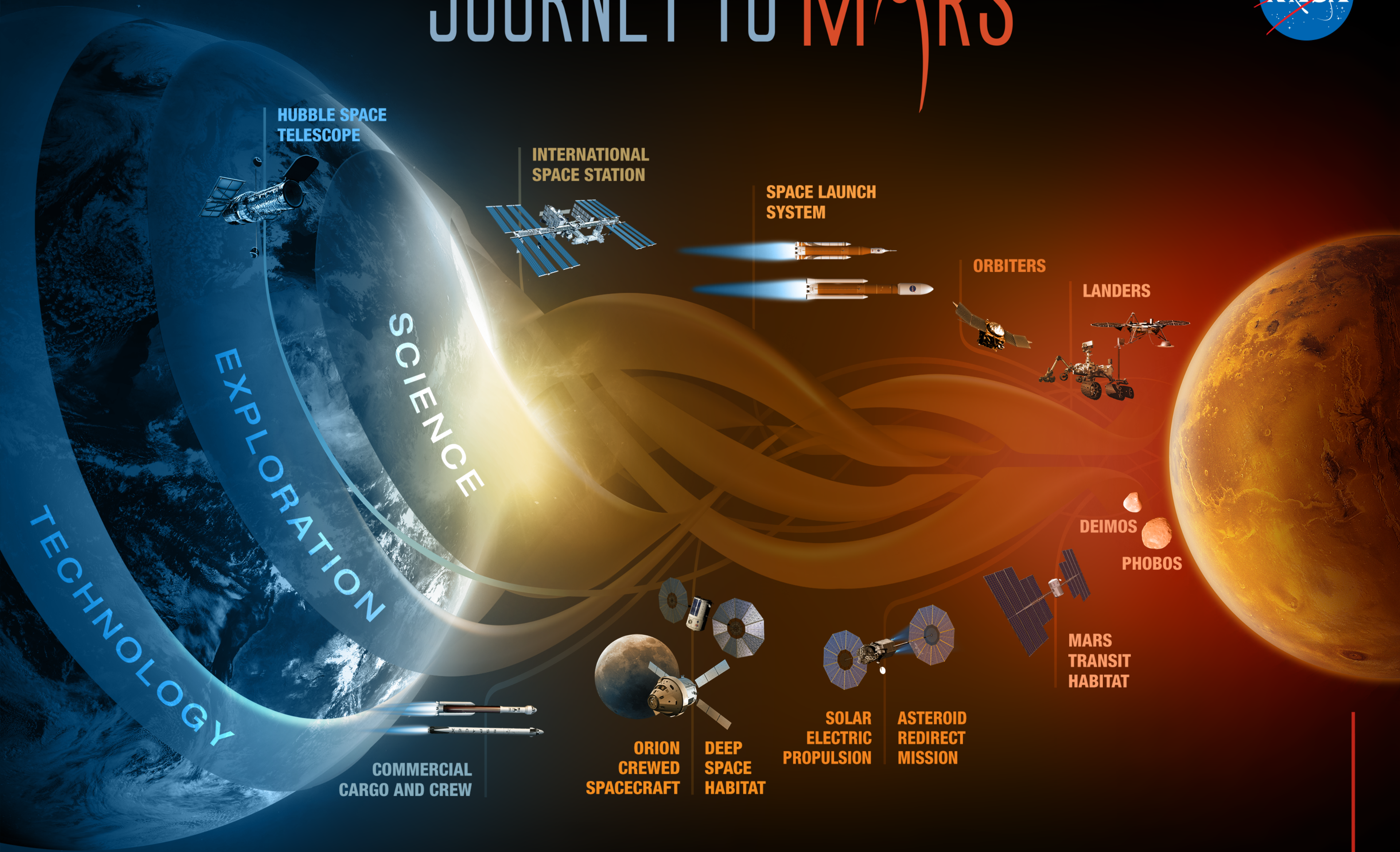
Structures, Materials & Nanotechnology

W. Keith Belvin
NASA Principal Technologist

Advanced Materials for Defense Summit
July 18-19, 2017

JOURNEY TO MARS



HUBBLE SPACE TELESCOPE

INTERNATIONAL SPACE STATION

SPACE LAUNCH SYSTEM

ORBITERS

LANDERS

SCIENCE

EXPLORATION

TECHNOLOGY

DEIMOS

PHOBOS

MARS TRANSIT HABITAT

COMMERCIAL CARGO AND CREW

ORION CREWED SPACECRAFT

DEEP SPACE HABITAT

SOLAR ELECTRIC PROPULSION

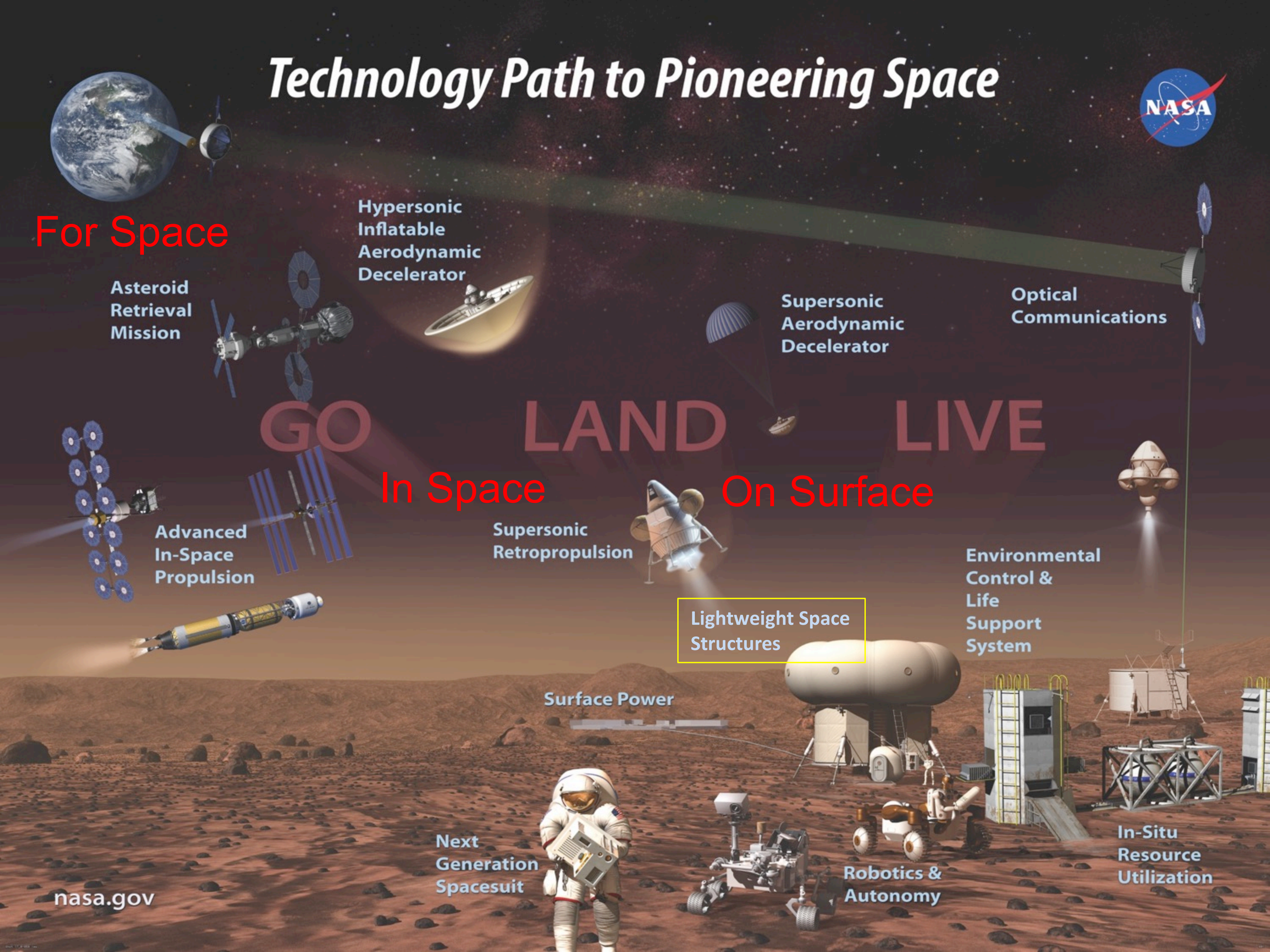
ASTEROID REDIRECT MISSION

MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT

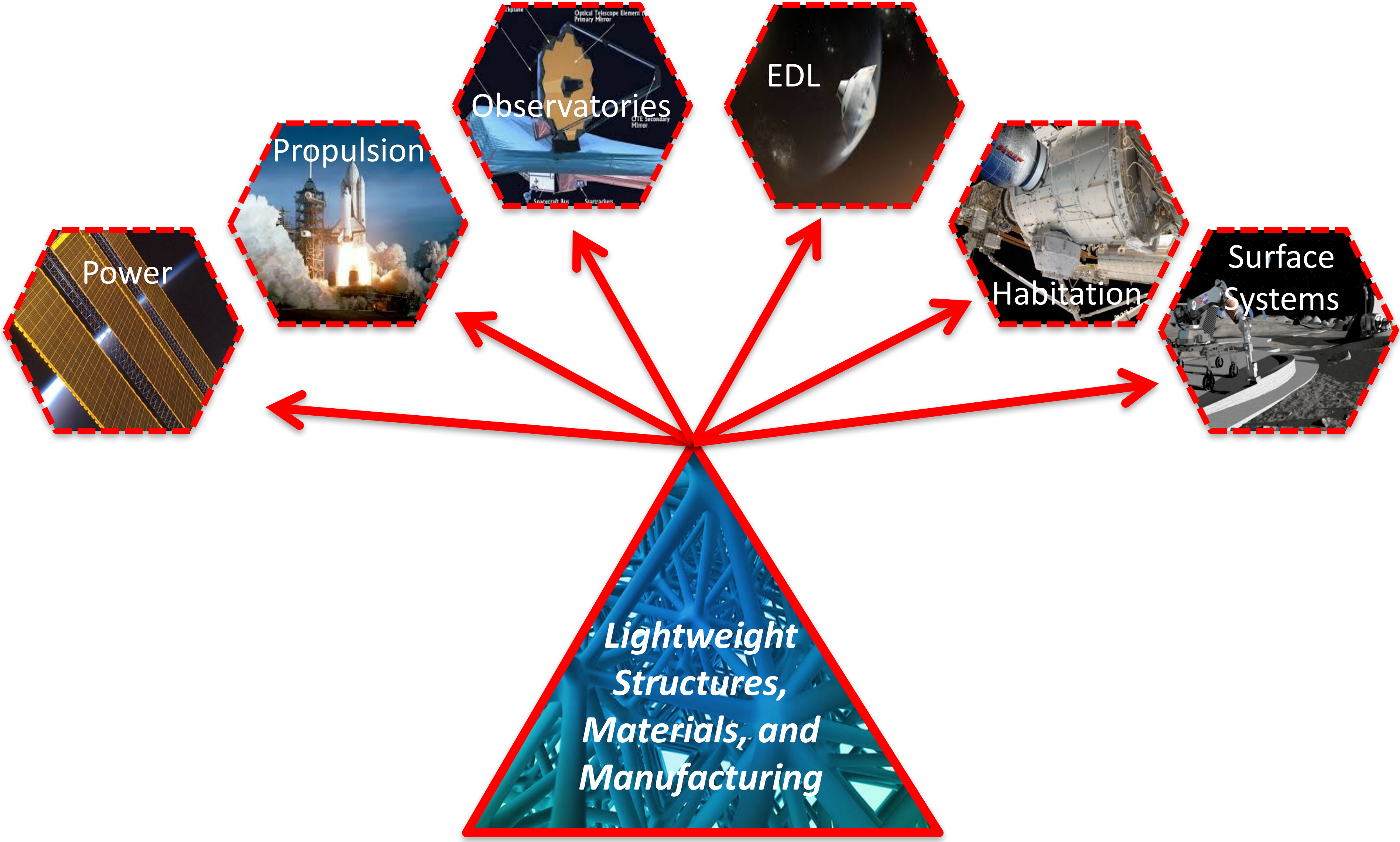
MISSIONS: 1-12 MONTHS
RETURN: DAYS
PROVING GROUND

MISSIONS: 2-3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

Technology Path to Pioneering Space



Lightweight Structures, Materials and Advanced Manufacturing (LSMM) is Crosscutting



Power

Propulsion

Observatories

EDL

Habitation

Surface Systems

Lightweight Structures, Materials, and Manufacturing

Prolific Material Advances

Self-Healing Polymer Films

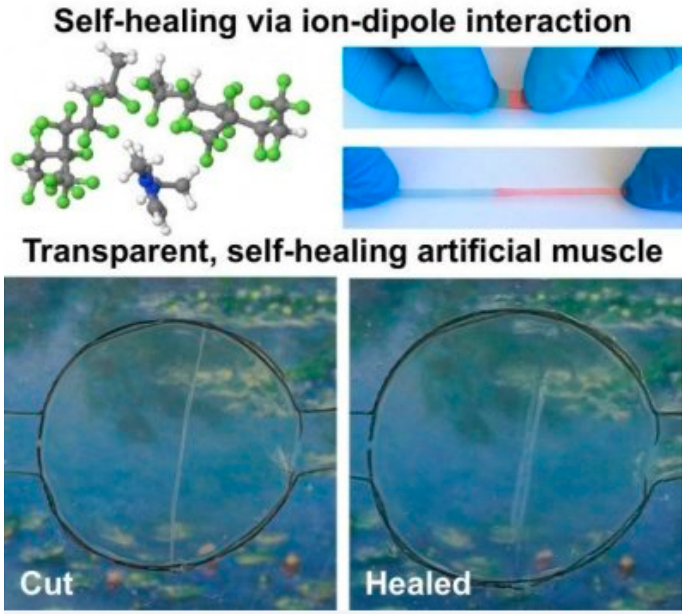
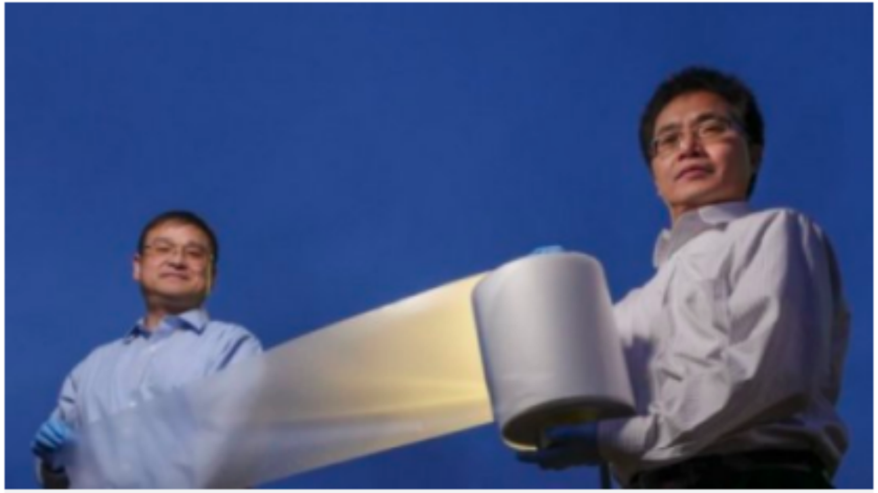


Illustration showing self-healing via ion-dipole interaction.

Credit: University of Colorado, Boulder

The findings, which were published today in the *journal Advanced Material*, represent the first time scientists have created an ionic conductor, meaning materials that ions can flow through, that is transparent, mechanically stretchable, and self-healing.

Newly engineered material can cool structures with zero energy consumption



CU boulder researchers demonstrating their newly engineered material.

Credit: Image courtesy of University of Colorado at Boulder

The new material, which is described today in the journal *Science*, could provide an eco-friendly means of supplementary cooling for thermoelectric power plants, which currently require large amounts of water and electricity to maintain the operating temperatures of their machinery.

Prolific Material Advances

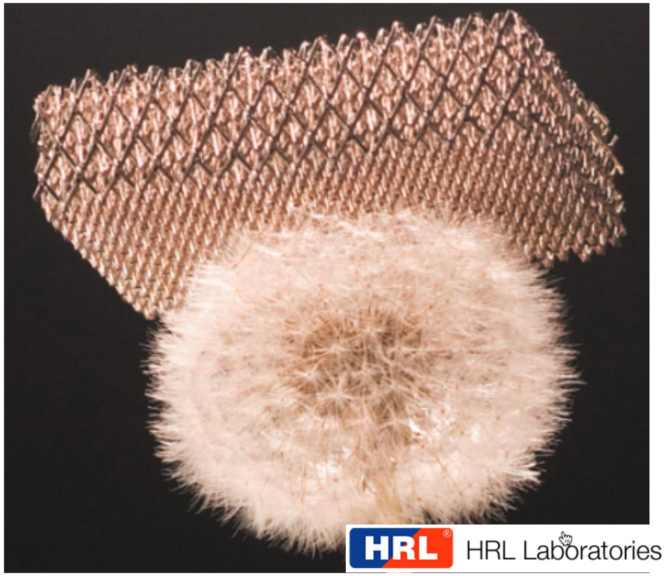
Spray paint with 0.2% reflectance

Credits: Surrey Nanosystems

Vantablack S-VIS

Manufactured from CNTs and other organic materials dispersed in carrier solution. As the solution evaporates, it leaves behind a structured coating that is then subjected to further processing steps. This process functionalises and binds the coating structure together whilst forming optical cavities which trap light.

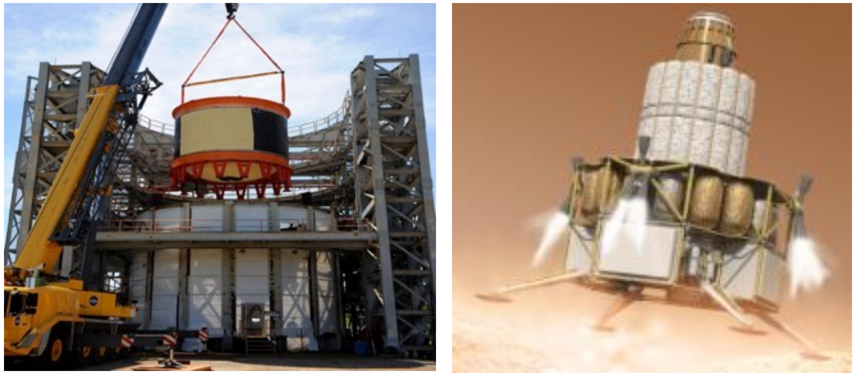
Microlattice material, 99.99% air



Credits: HRL Laboratories

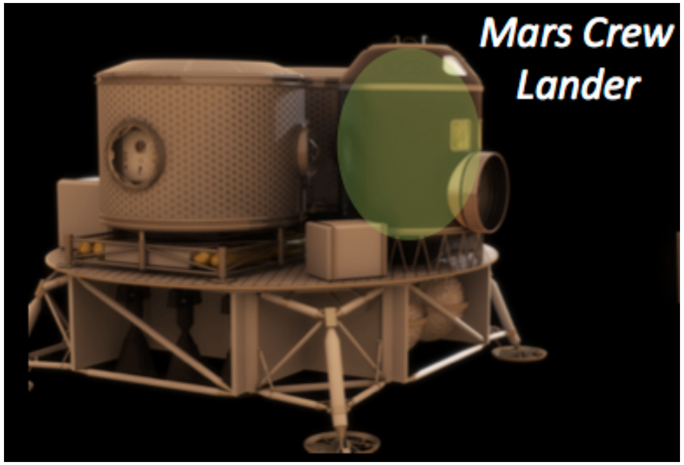
Polymer microlattice template is customized as desired using HRL’s photopolymer waveguide process. That polymer template is then electroplated with layers of nickel-phosphorus according to desired density requirements. After plating, the polymer is chemically removed. The remaining hollow tubular microlattice wall thickness of approximately 80 nanometers. The microlattice weighs only about one tenth as much as carbon fiber.

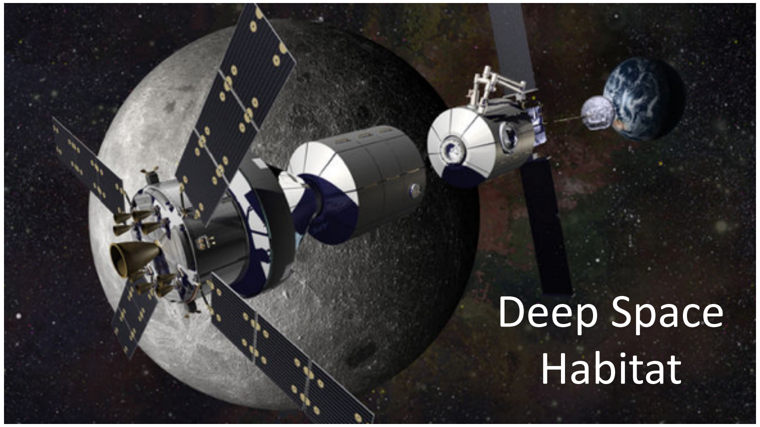
Human-Rated Composite Structures



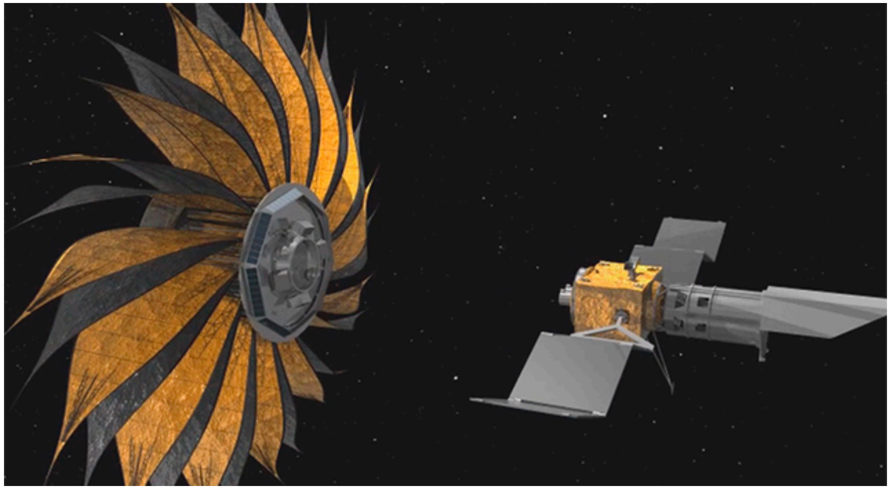
Composites for Exploration

NASA Launch and Commercial Space

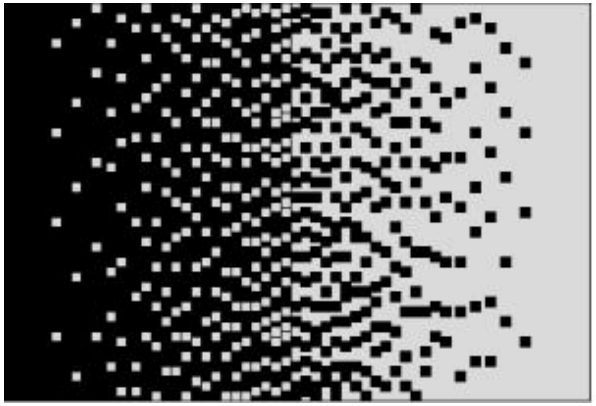




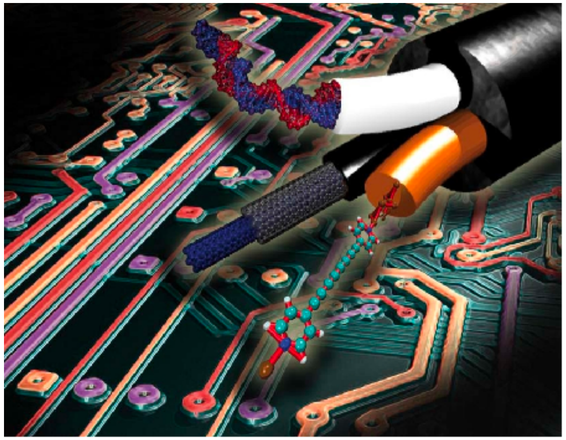
NASA Material Systems



Deployable Structures (Starshade)



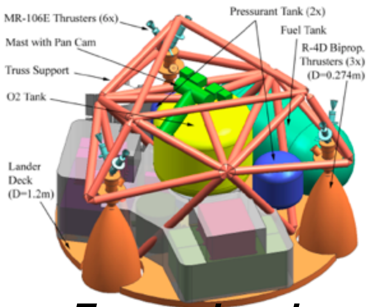
Functionally Graded Materials and Manufacturing



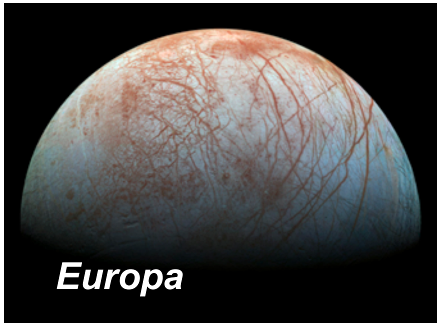
Integrated Function

SoftGood Systems

NASA Extreme Environments



Europa Lander
Launch ~2023



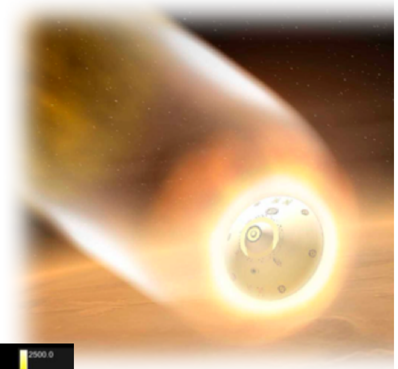
~50K min - 125K Max

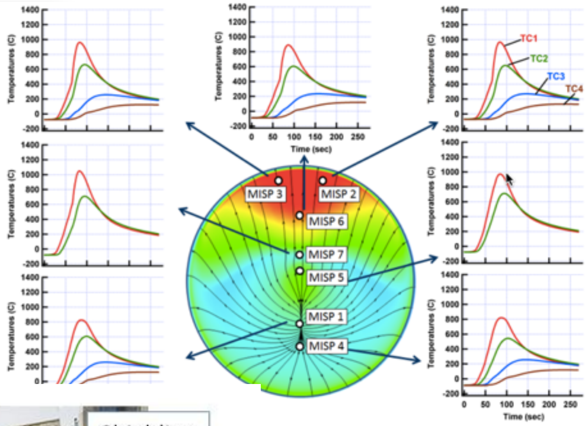
Venus

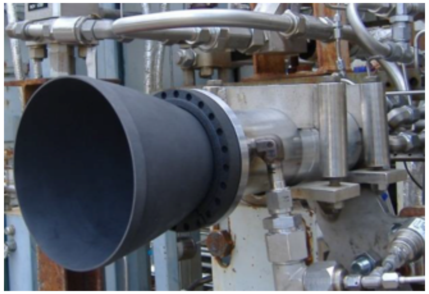
737K Mean, 0.015% Sulfur Dioxide

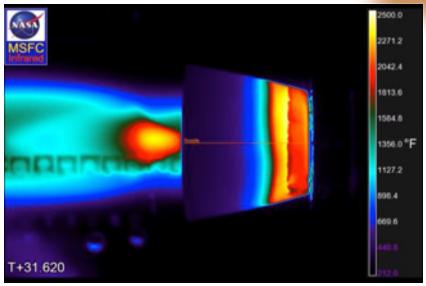
NTP W/Re sample loaded into heating coil ~4000^{0}F

MEDLI

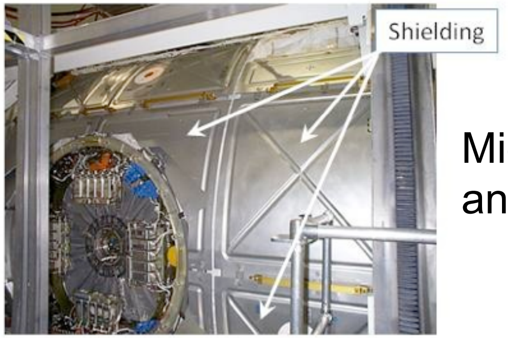








C-C NE Attached to Engine ~2400^{0}F
Multiple Commercial Engine Candidates

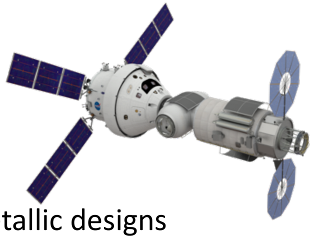


Micrometeoroid and Orbital Debris

Key Agency Structures and Materials Technology/Capability Needs:

PT Perspective

1) Human-Rated Composite Structures for Launch, Transit, and Deep-Space Vehicles and Habitation



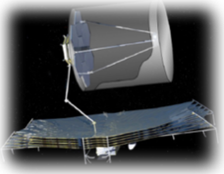
Capability Challenge

- 5-m class habitable structures
- 10m-class launch vehicle structures
- >30% mass reduction potential over metallic designs

Driving need

- Early exploration missions: Proving ground – Earth independent
- Launch vehicle structures - SLS Universal Stage Adapter for EM2 and Upper Stage Lox tank for EM3/EM4 early 2020's
- Cislunar habitats mid-2020's, Mars Hab/MAV 2030's

2) *In-Space Manufacturing and Assembly of Large-scale Precision And Non-Precision Structures*



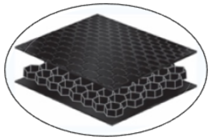
Capability Challenge

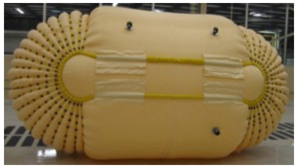
- ≥ 50 m modular solar arrays, < 1kg/m^2
- ≥ 10-12 m diameter aperture with 10s of picometers stability
- Factor of 2 life extension for exploration vehicles
- Hardware in the loop simulation for assembly agent V&V.

Driving need

- Large solar arrays needed for SEP vehicles in 2028 per the EMC
- Large aperture telescopes – 2030-2040 (LUVOIR)
- iSA and iSM technology to TRL 6 prior to mission formulation

3) *Lightweight, Multifunctional Materials, Manufacturing & Structures for Deep-Space Exploration Systems*





Capability Challenge

- Mass reduction of >30% compared to unintegrated systems.
- Example: integrating radiation protection and thermal control
- Deployable and Softgood structural systems with < 1/6 volume
- Advanced materials > stiffness (150 GPa/[g/cm3]), strength (3 GPa/[g/cm3]) and fracture toughness (0.3 N/mm)

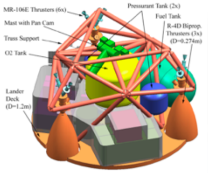
Driving Need

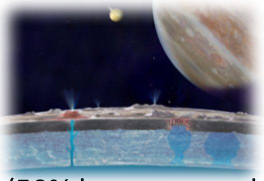
Europa – 2020's

Habitats needed for the Phobos/Mars Orbit Mission - 2033

Active structural control for large-aperture telescopes - 2035

4) *Materials and Structures for Extreme Environments*





Capability Challenge

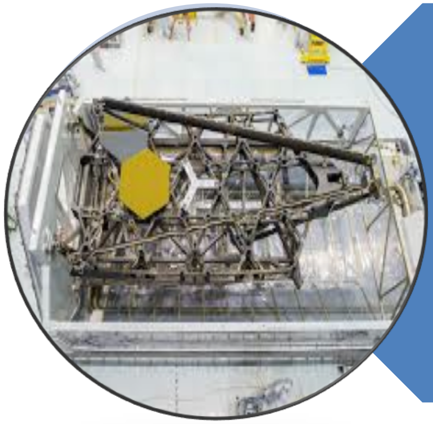
- High Temp Carbon-Carbon Rocket Nozzles (50% less mass and 50% more thermal margin over SOA metallic nozzles)
- Cold Temp Mechanisms operating at ~50K
- Seals and Coatings for dust environments
- Radiation Shielding material systems.

Driving need

- Initial exploration missions - Proving ground – Earth independent
- SLS Upper Stage nozzle extension for EM3/EM4 early 2020's
- Mars Descent Vehicles mid 2020's - 2030's
- Europa missions beginning in mid 2020's

LSMM- Addressing Critical Challenges

Using the technology strategy, each capability area addresses the agency priorities and big challenges only solvable by a comprehensive approach.



Technical Goals

- 50% reduction in overall costs
- 50% reduction in mass compared to State-of-the-Art

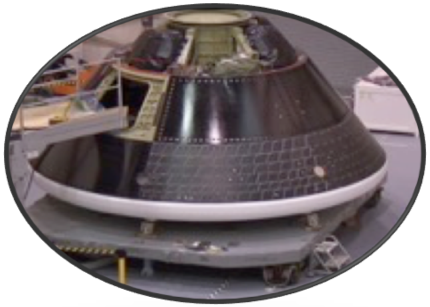
Impact Goals

- Accelerate the adoption of LSMM space technologies
- Increased payload to Mars

Human-Rated Composite Structures Critical Technologies

Compelling need: “Half the weight at half the cost”

Human Rated Composites



This focus area is aimed at driving technological advancements to provide provide additional functionality, reduce the mass, and reduce cost for human rated composite structures. Touches all NASA Mission Directorates: Human Exploration and Operations, Aeronautics Research, Science, Space Technology - Spans multiple NASA Centers and discipline/capabilities (materials/manufacturing/structures); Industry and academia, Aeronautics Advanced Composites Program, DOD, DARPA, DOE

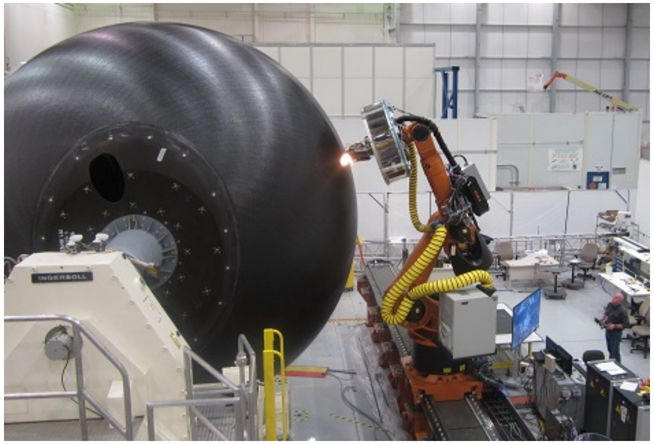
- **Benefits of composites:-** Lightweight - Durable - Low cost
- **Challenges:** Immature capabilities limit use and rate of innovation
- Dry structures: Fairing, inter-tank, inter-stage, adapters;
- Cryo structures: Liquid oxygen, liquid hydrogen;
- Pressurized structures: Habitable, solid rocket boosters, propellant systems

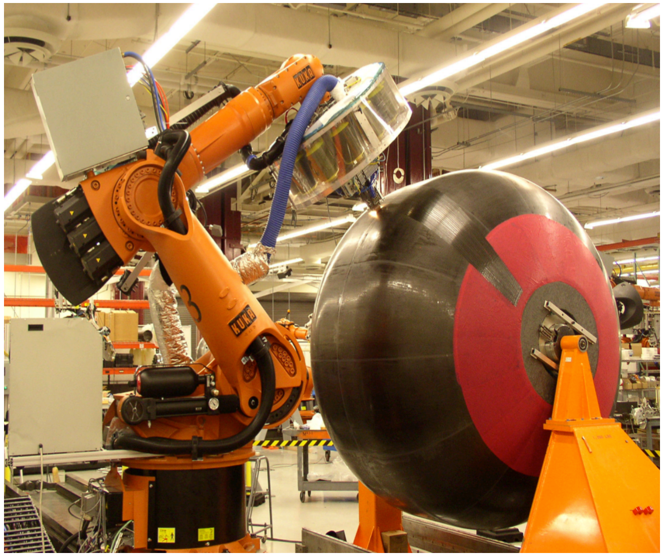
The technology focus areas for this capability include:

- Tailored Design and Certification Criteria
- Storage tanks (space power)
- Lox compatibility
- Cryo-fluid and thermal management
- Cryogenic Bonding
- Thin-ply materials
- Accelerated allowable/building block
- Damage tolerance
- Analytical tools
- NDE
- Out-of-autoclave
- Joints (polar, y-joints, dissimilar materials)
- Ultra light weight core/CNT’s
- Tailorable properties - new design possibilities
- Advanced computational technologies - Certification by analysis
- Fast-precision-cost effective manufacturing
- Mechanical, thermal and physical properties/behavior (e.g. testing)
- NDE capabilities
- Modeling and simulation of materials/processes/manufacturing
- In-situ damage detection

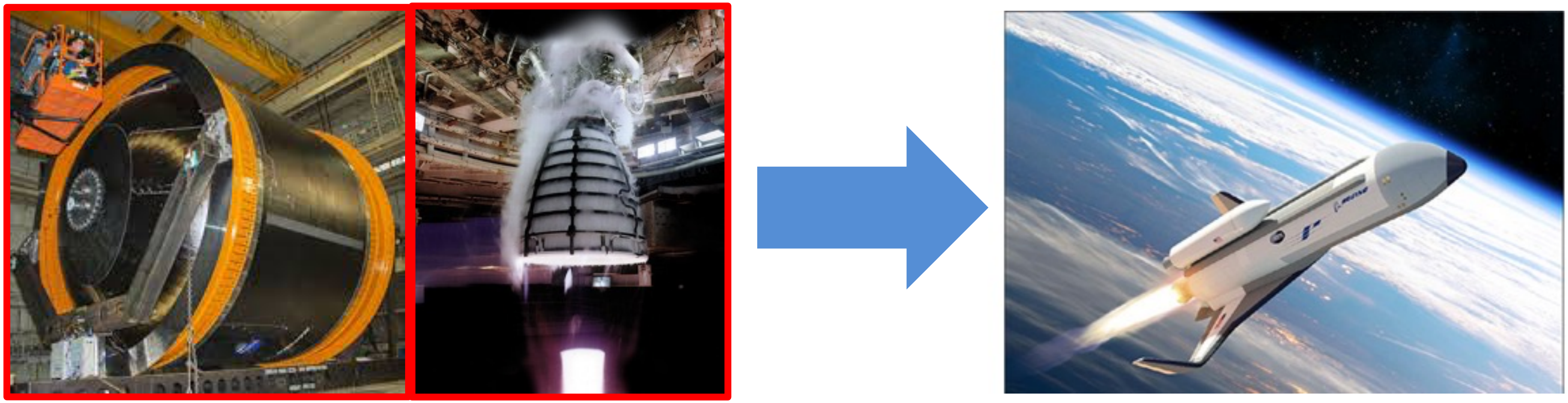
Composite Cryotank Technologies & Demonstration Project

- **Main objective: Design, build, and test large prototype composite cryogenic propellant tanks as technology demonstrators for future launch vehicles**
- **Main accomplishments: 2.4 meter and 5.5 meter diameter composite cryotanks built by Boeing and tested at MSFC**
- **Main outcome: Completed in 2014, project met or exceeded technical objectives and tipped the balance for infusion**





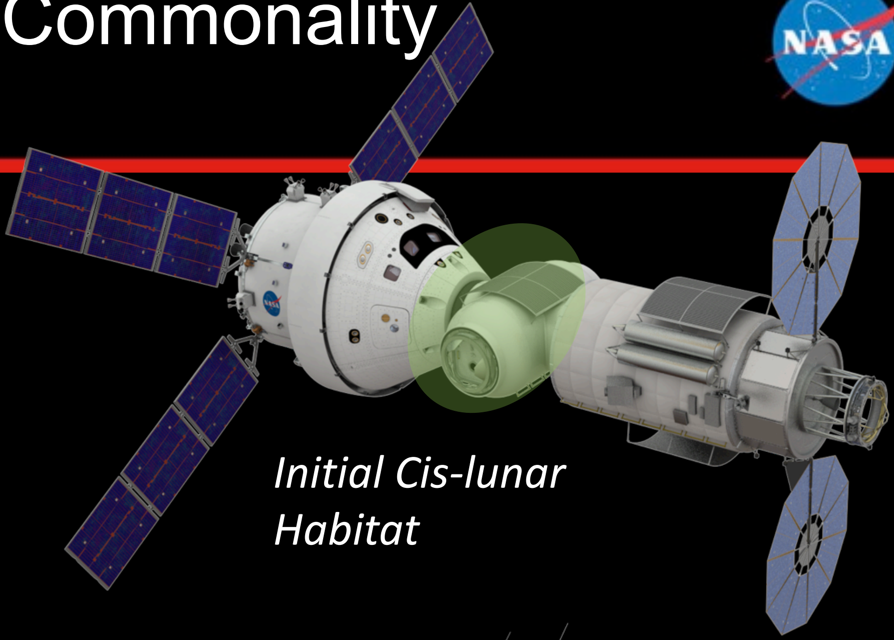
Technology Infusion



- ***DARPA has selected Boeing for the Agency's Experimental XS-1 Spaceplane***
- ***The XS-1 program is integrating numerous state-of-the-art technologies, some previously developed by NASA***
- ***XS-1 will use advanced, lightweight composite cryogenic propellant tanks and a new version of the Space Shuttle and SLS RS-25 main engine***
- ***STMD previously completed a development project to test one of the largest composite cryogenic fuel tanks ever manufactured***
- ***The RS-25 engine is the most efficient engine of its type in the world and NASA has identified significant cost and time saving advanced manufacturing technologies such as 3D printing***

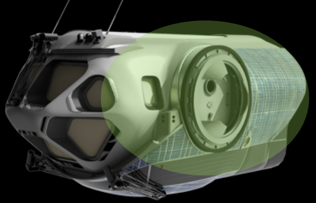
EMC Small Habitat Commonality

Mars System Taxi

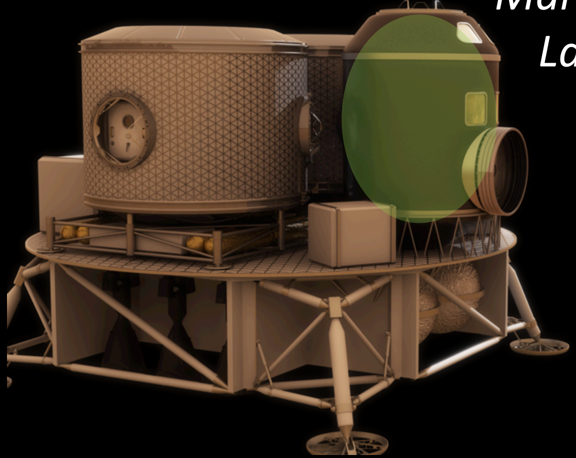


Initial Cis-lunar Habitat

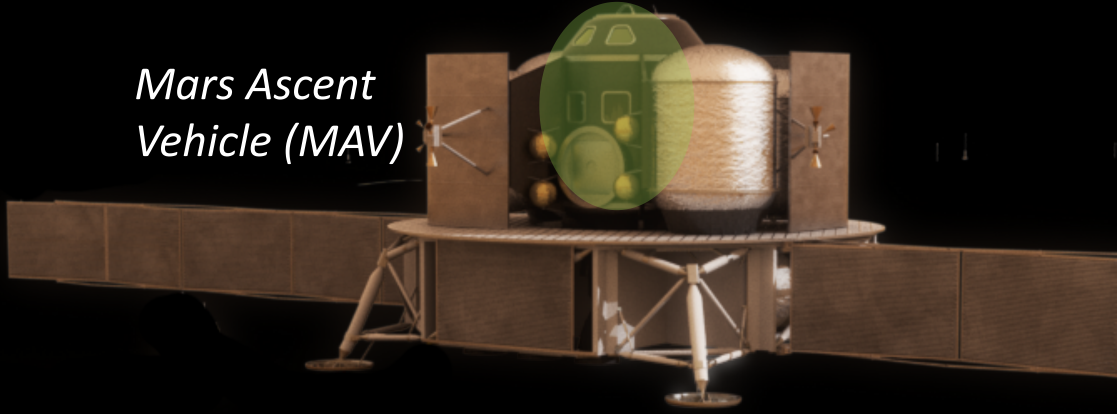
Mars Surface Rover



Phobos Exploration Vehicle (PEV)



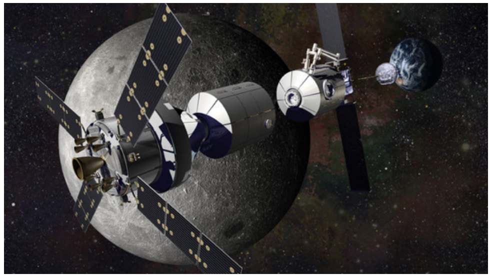
Mars Crew Lander

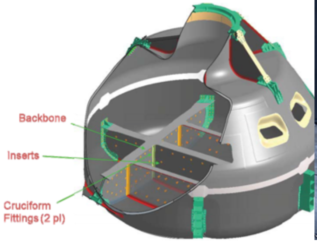


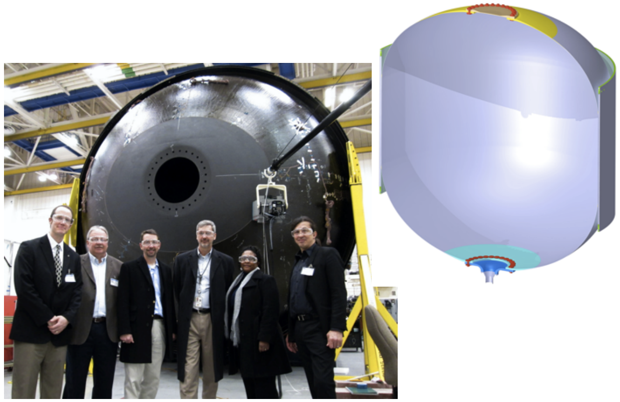
Mars Ascent Vehicle (MAV)

Chris Moore – EMC presentation to the NAC Research Subcommittee, March 7, 2016

Composite Habitat?







Composite Habitat: ?

  - Short Duration
  - Long Duration
  - Ascent Vehicles
- The mass savings of composites over metals for habitats is unknown. Need clean sheet design for this application using advanced composites design (*thin ply*), materials (*CNT*), and manufacturing technology (*tow steering*).

Composite Crew Module

- CCM showed modest mass savings over metals for this application. Many complex load cases, cut outs, and constraints limit composite benefits.

Composite Cryo Tank

- CCT showed ~ 25-30% mass savings over metals for this application. Large amount of acreage structure with few cut-outs and primarily in-line loads.

Emerging Composite Materials Enablers?

Recent advances in new materials, processing, and computations:

- Thin Ply Composites
- CNT based composites
- Low-defect fibers – high strength
- Computations – multiscale modeling, mesoscale dynamics
- Integration of experimental and computational data to accelerate materials design and process control – big data analytics
- Engineered Cellular/Lattice Structures
- Fiber reinforced 3-D printing
- …

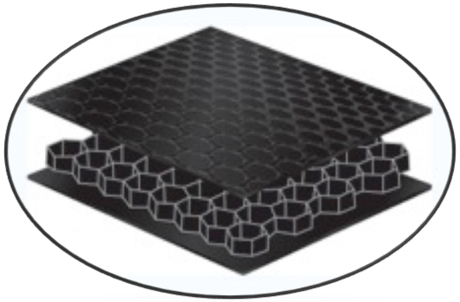
Future Composites Thrusts

NASA held several Technical Interchange Meetings with industry to capture and create a strategy for composites development needs.

- **Consensus on key thrusts for future investment:**
  - Lightweighting
  - Damage tolerance / nondestructive evaluation
  - Modeling and simulation
  - Joint performance and weight
  - Out-of-autoclave materials
  - Certification / Inspection

Multifunctional LSMM -Critical Technologies

Multi-functional Materials



Lightweight, Multifunctional Materials, Manufacturing & Structures for Deep-Space Exploration Systems

Compelling need: addresses the “gear ratio” element of a crewed Mars exploration architecture

This focus area is aimed at driving technological advancements to provide provide additional functionality, reduce the mass, and reduce cost in an integrated structural system. The area includes introduction of new materials, innovative designs, and novel manufacturing methods.

The technology focus areas for this capability include:

- Structures (wet/dry)
- Storage tanks (space power)
- Scalable modular
- Adopting new materials
- Design complexity/structural integration
- Multi-material structural integration
- Functionally graded
- Inflatables/soft goods
- Ultra light weight core/CNT’s
- Hybrid (metallic to PMC) joints
- Multifunctionality (load, thermal-cryo/high temp, permeability, MMOD, radiation)
- Fast-precision-cost effective manufacturing
- In-Space Manufacturing: Enabling technology areas for this capability include:
- Mechanical, thermal and physical properties/behavior (e.g. testing)
- Joining dissimilar materials
- NDE capabilities
- Modeling and simulation of materials/processes/manufacturing
- In-situ damage detection

Space Technology Pipeline of Innovation: CNT Materials Example

New Technology Partners

- SBIR Phase I, II & III
- Flight Opportunities
  - Wallops Sounding Rocket

High TRL – Technology Demonstration Missions

Hybrid CF/CNT Demo Unit

Mid TRL - Game Changing Development

Commercial Scale CNT Yarn Mfg

Demo Article Process Prototype

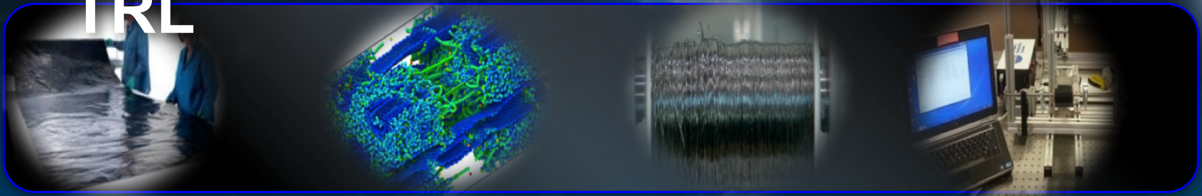
CNT COPV Mfg

CNT COPV Burst Test Articles

CNT COPV Flight Tests

Hybrid CF/CNT Composite

Low TRL



CNT Sheet

Computational Nanomaterials

High Strength CNT Yarn

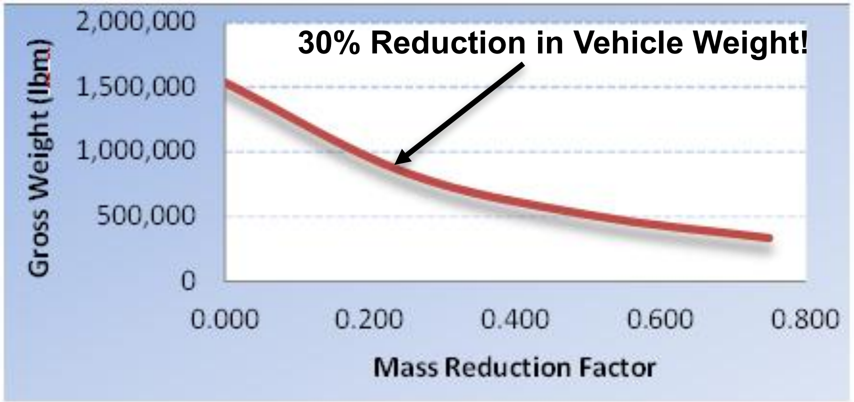
CNT Processing Development

Early Stage

- Space Tech Research Grants (ESI)
- Center Innovation Fund
- Center IRAD

TECHNOLOGY PIPELINE

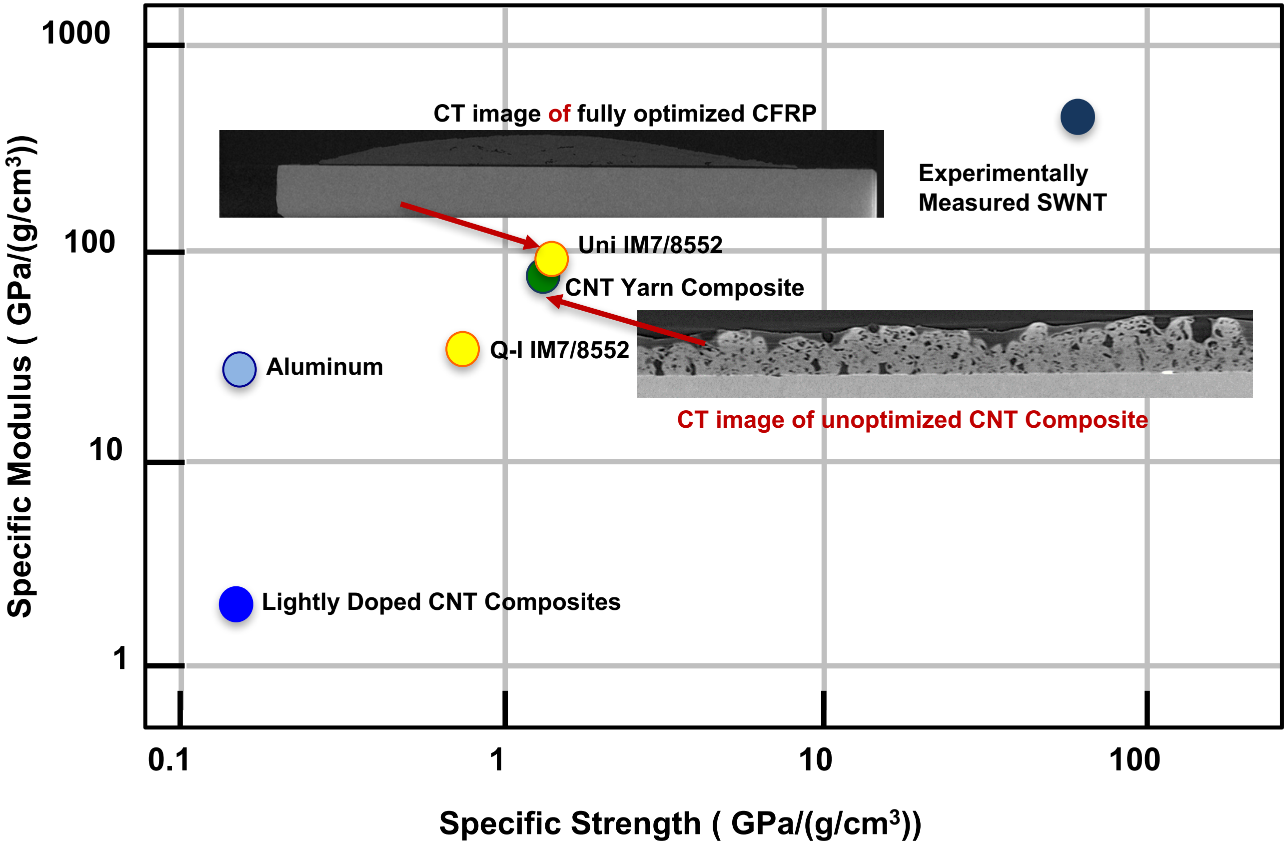
CNT Reinforced Composites Flight Demonstrated as a Primary Structural Component



30% Reduction in Vehicle Weight!

Flight Test Successfully Completed May 2017

Where are we with structural CNT?



- The two composites shown have nearly equal specific strength and modulus despite the far from optimal structure of the CNT composite
- Optimizing the materials and processing of the CNT composite will yield specific mechanical properties multiple times larger than carbon fiber composites

Institute for Ultra-Strong Composites by Computational Design (US-COMP)

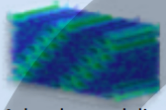
Lead: Michigan Technological University

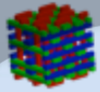
Simulation & Design Team (SDT)

Team lead:

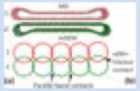
Internal tasks
- Refine molecular, mesoscale, and continuum modeling methods
- Develop and validate new force fields

Collaborative tasks
- Optimize material design
- Understand multiscale failure events
- Characterize interface formation and behavior


Molecular modeling


Topology optimization


Continuum modeling


Mesoscale modeling

Testing feedback & model validation

Failure analysis

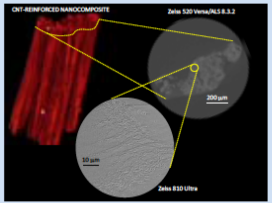
Testing & Characterization Team (TCT)

Team lead:

FLORIDA A&M UNIVERSITY

Internal tasks
- Develop methods for Nano-, meso-, and bulk-scale testing and characterization

Collaborative tasks
- Conduct standardized testing of manufactured test panels
- Characterize material failure



3D X-ray CT

Optimized material design

Synthesis feedback

US COMP

Quality feedback

Test panels

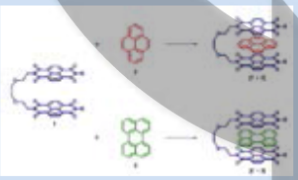
Material Synthesis Team (MST)

Team lead:

SOLVAY

Internal tasks
- Establish precise patterning synthesis
- Optimize hierarchical nano/micro structures

Collaborative tasks
- Explore and test material designs from SDT
- Fabricate material prototypes


Interacting bisimide and pyrene

Manufacture feedback

Material prototypes

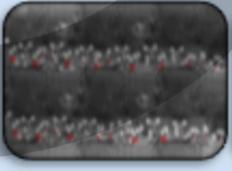
Material Manufacturing Team (MMT)

Team lead:

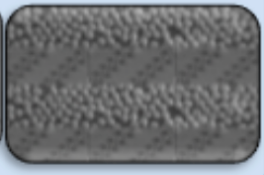
nanocomp TECHNOLOGIES, INC. SOLVAY

Internal tasks
- Scale-up manufacturing

Collaborative tasks
- Fabricate test panels

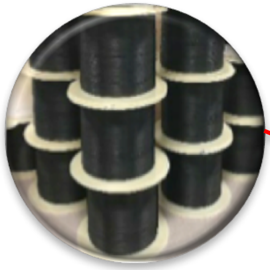

Crystalline CNT polymer composite

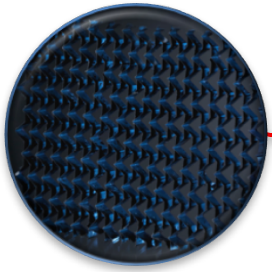

Crystalline CNT structure

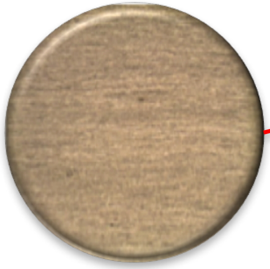

Hybrid composite

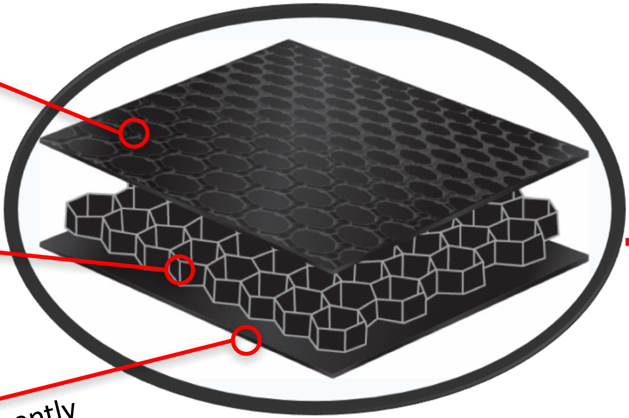
MGI Approach - Computation driven long-range-order CNT assemblage design and scale up manufacturing based on novel concepts of graphitic crystal CNT assemblage for developing ultra-high strength materials

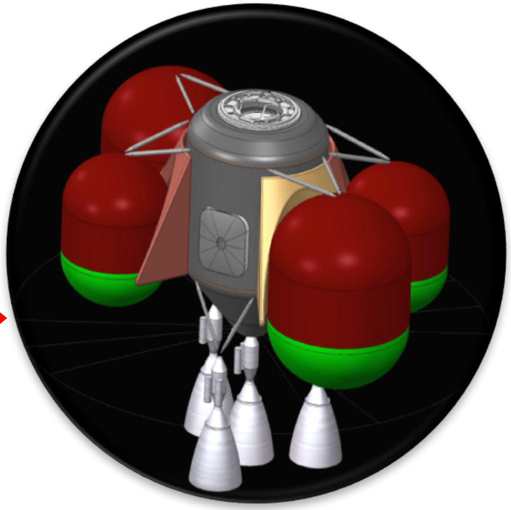
Concept: Super Lightweight Damage Tolerant Pressure Vessels







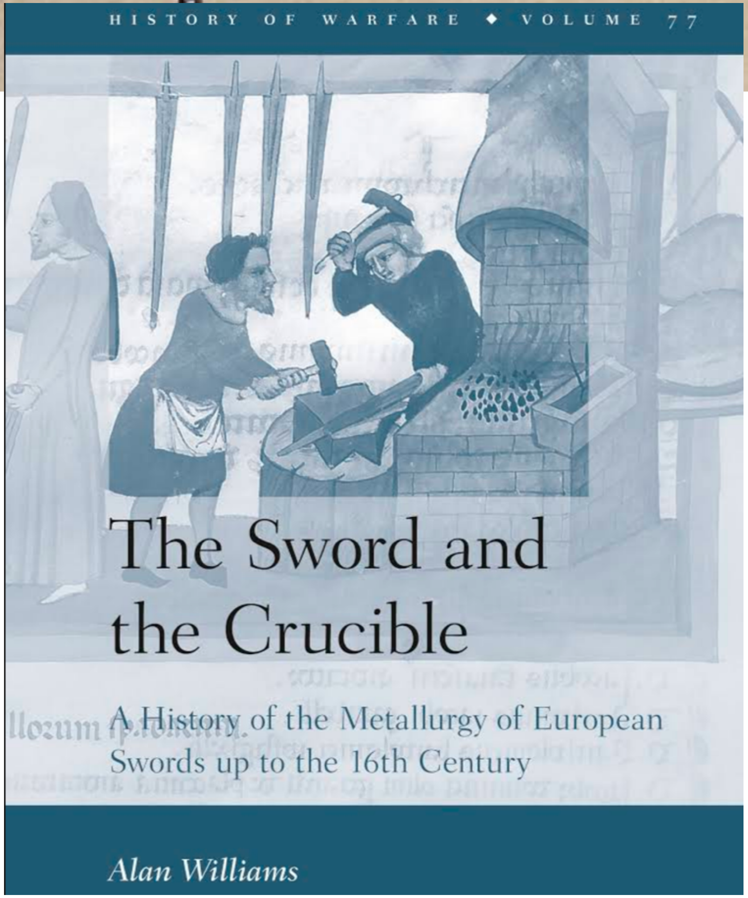




Description of Idea:

- Structural element
  - Ultralightweight high strength CNT core
  - Super Lightweight facesheets
    - Ultra thin-ply bottom facesheet for hermeticity
    - High strength CNT top facesheet
- Develop design parameters using mechanical properties from sandwich coupons
- Scale up of optimum sandwich structure towards superlightweight, damage tolerant composite pressure vessel

Steel Swords *circa ~900-1100 AD*

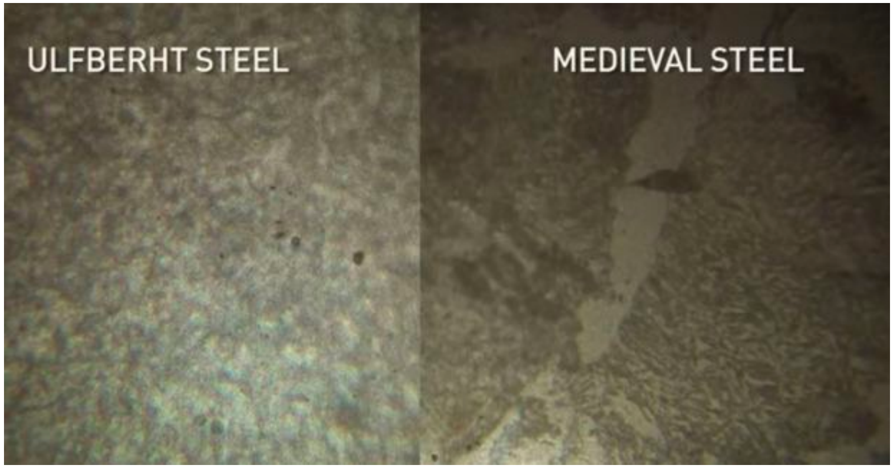


HISTORY OF WARFARE ◆ VOLUME 77

The Sword and the Crucible

A History of the Metallurgy of European Swords up to the 16th Century

Alan Williams



The homogeneous crystal structure of cast steel improved its strength and hardness.

Crucible Steel - very fine microstructure with few inclusions.

Rapid Advances in All Material Types (1 of 2)

- **Synthesis/Processing**
  - 2D and 3D nanomaterials (graphene, CNT, …)
  - Aided by computational approaches
    - Materials Genome Initiative
    - Big Data Analytics

- **Manufacturing**
  - Additive Manufacturing (3D and 4D)
  - Near Net Shape - AM and injection molding (metals)
  - Electronic Textiles – Conformal printed electronics
  - Digital Materials – voxel level assembly, gradient materials
  - Synthetic Biology
    - Grow in-situ materials and structures
    - Self Replication - sequences of DNA can be designed to recognize and bond with each other -possible to build structures from them

Rapid Advances in All Material Types (2 of 2)

- **Multifunctionality**
  - *Sensing*
  - *Actuation*
    - Thermoelectrics, Piezoelectrics
    - Magnetostrictive, Electrostrictive
    - Shape Memory
    - Extreme Environments, e.g. Graphene Aerogel Insulators

Controls
(autonomy, AI – learning)

- **Nano Engineering**
  - CNT, BNNT, Graphene – 3-10 X SOA Strength
  - Bio inspired plastics – Molecular Super Glue
  - Designer – Atoms to Applications
  - Metamaterials
  - Cellular Materials – Foams, Micro-Lattice
  - Gene Decoding – Spider Silk

Summary:
Key Materials/Manufacturing Trends

>10X Higher Strength and Lighter Weight

- Nano Engineered, Low Defect, MGI

Additive Manufacturing Anywhere, Any Scale

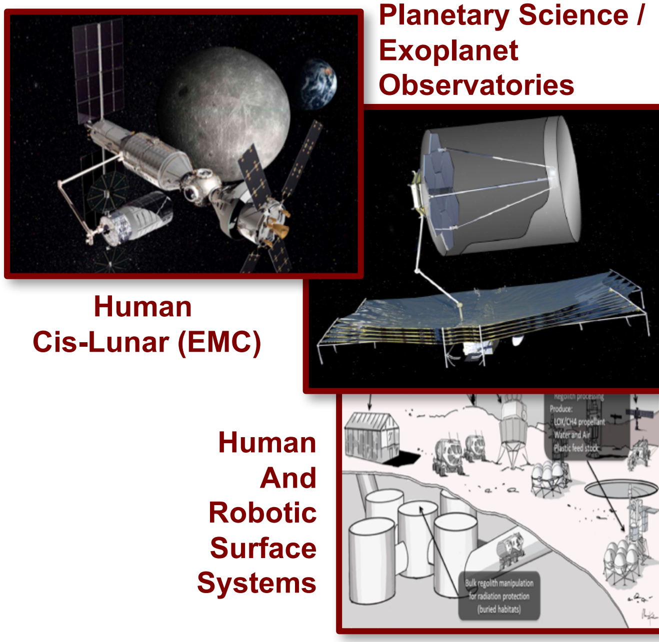
- 3D and 4D (Morphing)

Self Assembly

- Digital Materials, Collectives (micro-robotics)

Multifunctional, stimuli responsive

- sensing and actuation



Planetary Science / Exoplanet Observatories

Human Cis-Lunar (EMC)

Human And Robotic Surface Systems

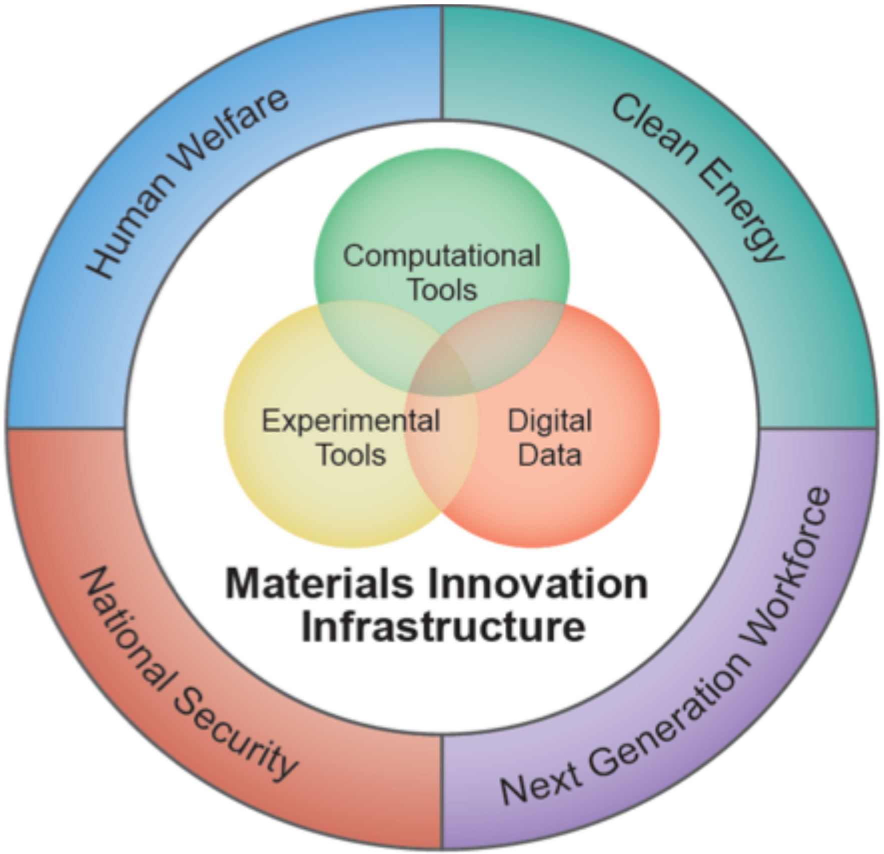
Performance
- *30-50% lower mass*
- *Reduced packaging volume*

Resilience
- *Durability/Reparability*
- *Modular/Re-configurability*
- *Upgradable/Life Extension*

Affordability
- *30-50% lower production cost*
- *Lower life-cycle cost*

BACKUP:
THE MATERIALS GENOME INITIATIVE

to decrease the cost and time-to-market by 50%



Develop a Materials Innovation Infrastructure

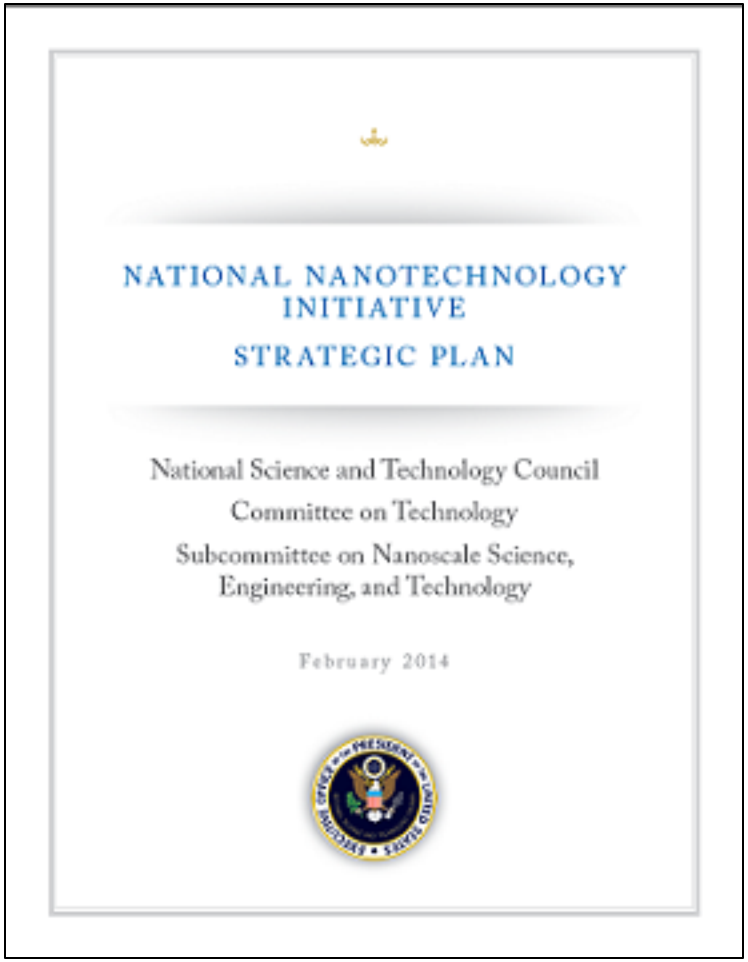
Achieve National goals in energy, security, and human welfare with advanced materials

Equip the next generation materials workforce

Materials Genome Initiative for Global Competitiveness

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

Backup:
National Nanotechnology Initiative



NATIONAL NANOTECHNOLOGY INITIATIVE

STRATEGIC PLAN

National Science and Technology Council

Committee on Technology

Subcommittee on Nanoscale Science, Engineering, and Technology

February 2014

The vision of the National Nanotechnology Initiative (NNI) is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society.

The NNI expedites the discovery, development, and deployment of nanoscale science, engineering, and technology to serve the public good through a program of coordinated research and development aligned with the missions of the participating agencies.

- Advance a world-class nanotechnology research and development program;
- Foster the transfer of new technologies into products for commercial and public benefit;
- Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology; and
- Support responsible development of nanotechnology.