STMD Technology Strategy
Structures, Materials & Nanotechnology

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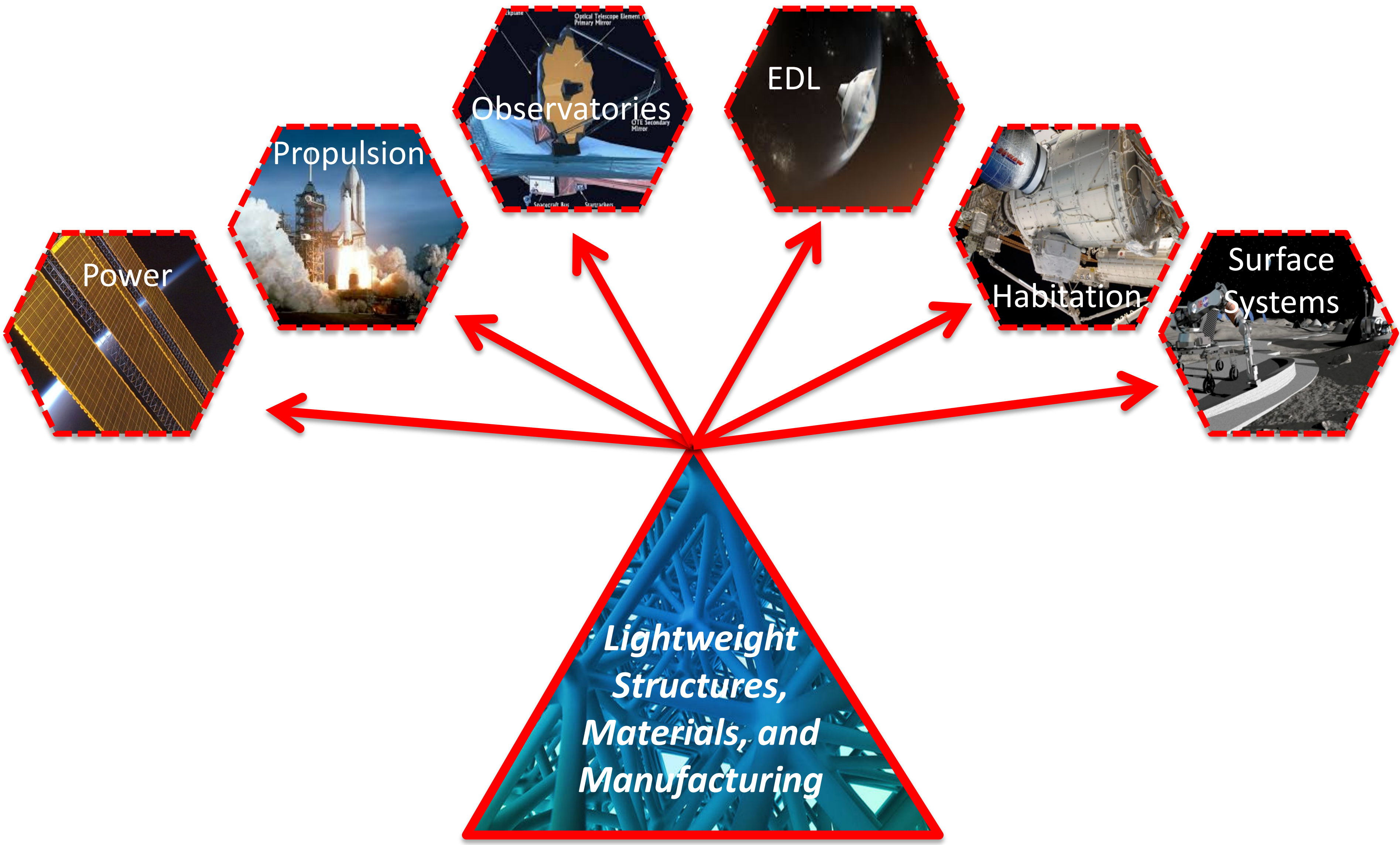
July 25, 2017

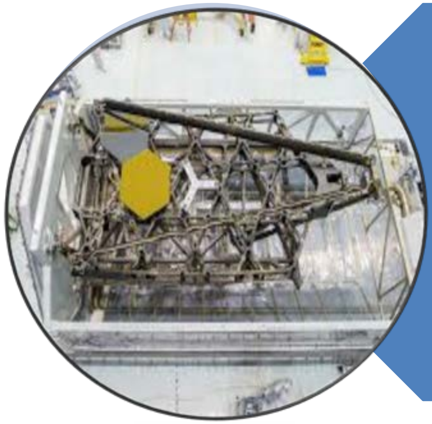
Briefing to NAC TI&E

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



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

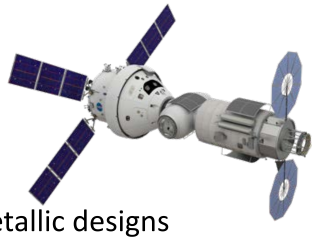
- 50% reduction in overall costs
- 50% reduction in mass compared to State-of-the-Art

Impact Goals

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

Key Agency Structures and Materials Technology/Capability Needs:
PT Perspective

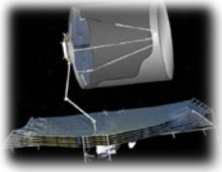
1) *Human-Rated Composite Structures for Launch, Transit, Deep-Space Vehicles and Habitation*



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

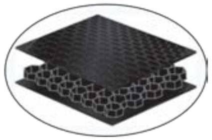
2) *In-Space Manufacturing and Assembly of Large-scale Precision And Non-Precision Structures*

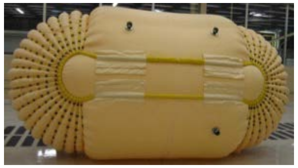


Capability Challenge
- ≥ 50 m modular solar arrays, < 1kg/m^2
- ≥ 10-12 m diameter aperture with 10s of picometers stability
- Factor of 2 life extension for exploration vehicles
- Hardware in the loop simulation for assembly agent V&V.

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)

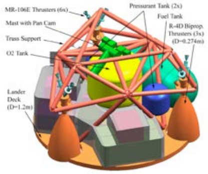
Driving Need

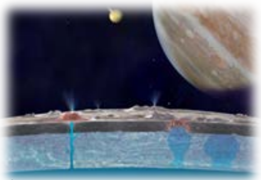
Europa – 2020's

Habitats needed for the Phobos/Mars Orbit Mission - 2033

Active structural control for large-aperture telescopes - 2035

4) *Materials and Structures for Extreme Environments*





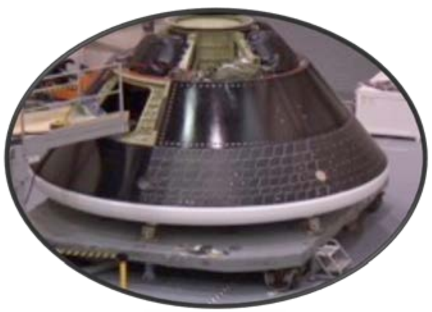
Capability Challenge
- High Temp Carbon-Carbon Rocket Nozzles (50% less mass and 50% more thermal margin over SOA metallic nozzles)
- Cold Temp Mechanisms operating at ~50K
- Seals and Coatings for dust environments
- Radiation Shielding material systems.

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

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

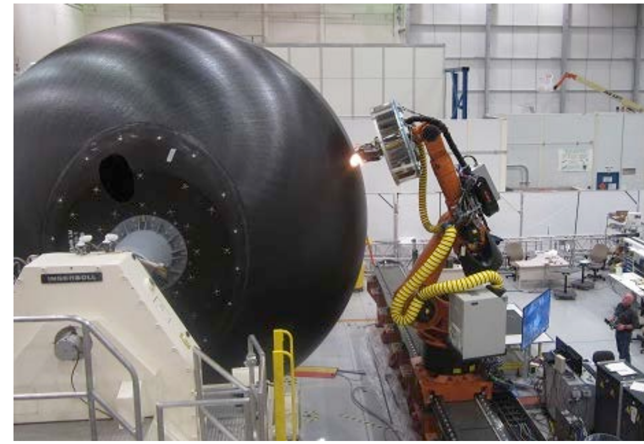
- **Benefits of composites:-** Lightweight - Durable - Low cost
- **Challenges:** Immature capabilities limit use and rate of innovation
- <u>Dry structures:</u> Fairing, inter-tank, inter-stage, adapters;
- <u>Cryo structures:</u> Liquid oxygen, liquid hydrogen;
- <u>Pressurized structures:</u> Habitable,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

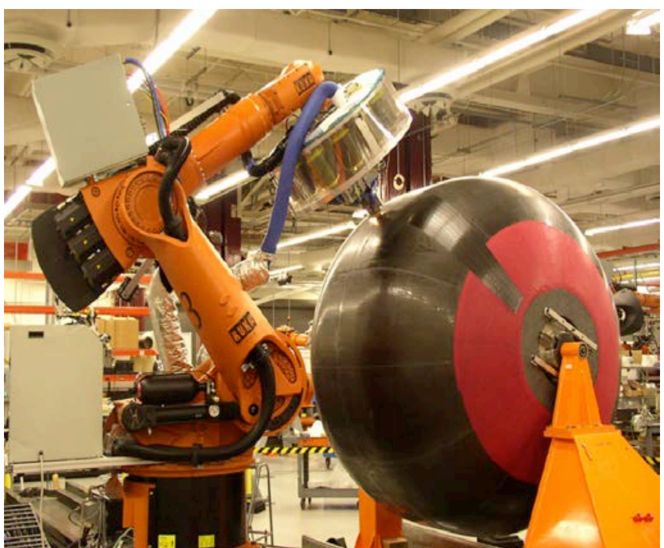
The technology focus areas for this capability include:

- 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 (CCT) & 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

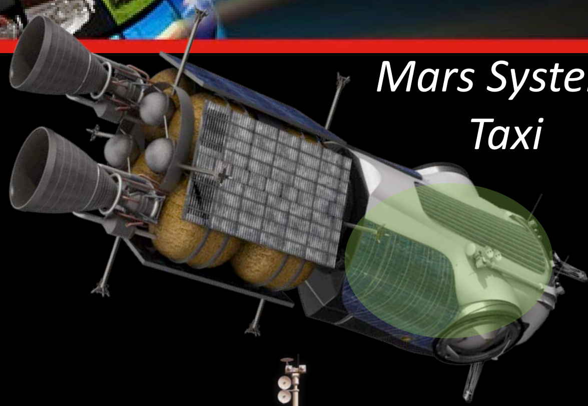




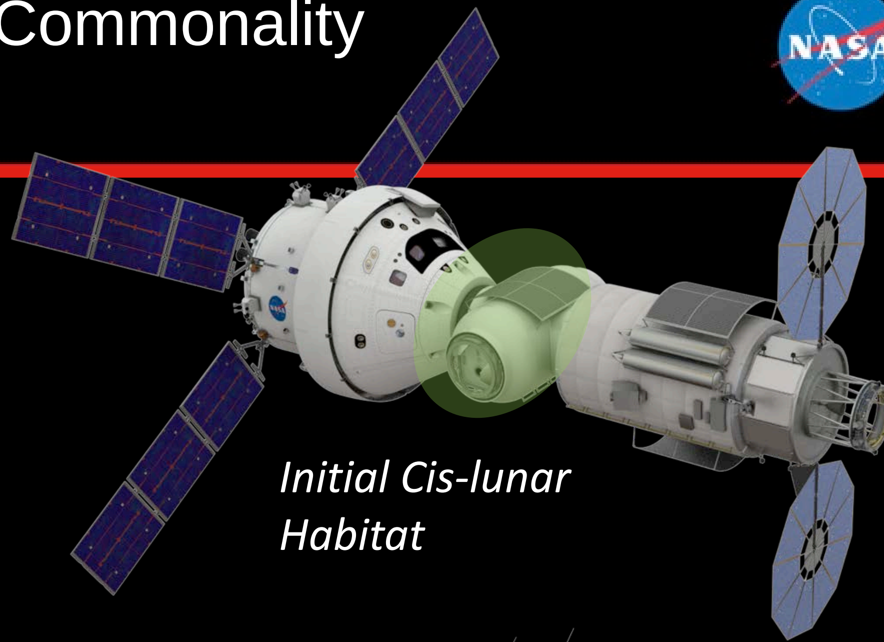
CCT Technology Infusion

- 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 (CCT)
- XS-1 will use advanced, lightweight composite cryogenic propellant tanks and a new version of the Space Shuttle and SLS RS-25 main engine
- 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



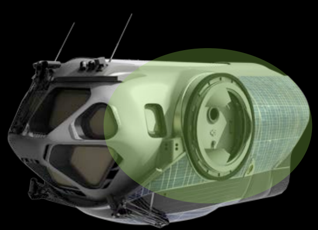
Mars System Taxi

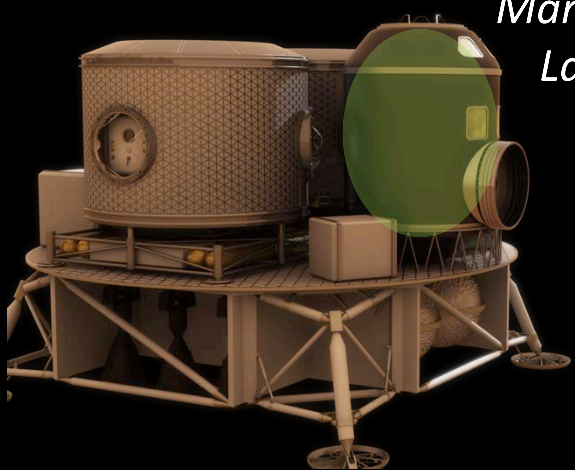


Initial Cis-lunar Habitat

Mars Surface Rover

Phobos Exploration Vehicle (PEV)

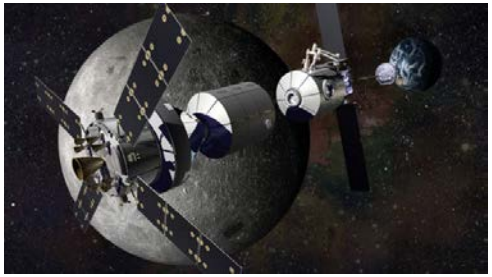


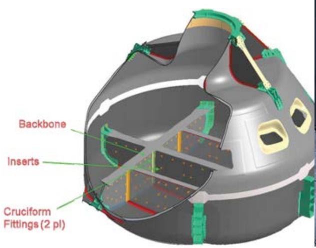


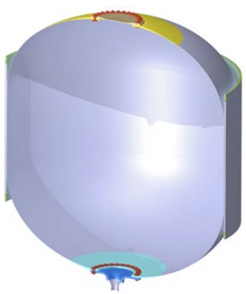
Mars Crew Lander

Mars Ascent Vehicle (MAV)

Composite Habitat?







<u>Composite Habitat: ?</u>

- 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*).

<u>Composite Crew Module</u>

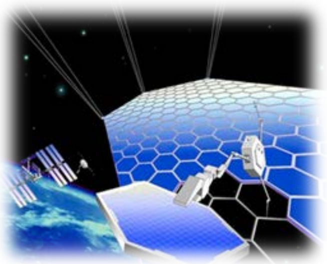
- CCM showed modest mass savings over metals for this application. Many complex load cases, cut outs, and constraints limit composite benefits.

<u>Composite Cryo Tank</u>

- 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.

ISA and ISM- Critical Technologies

ISA & ISM



In-Space Manufacturing /
In-Space Assembly

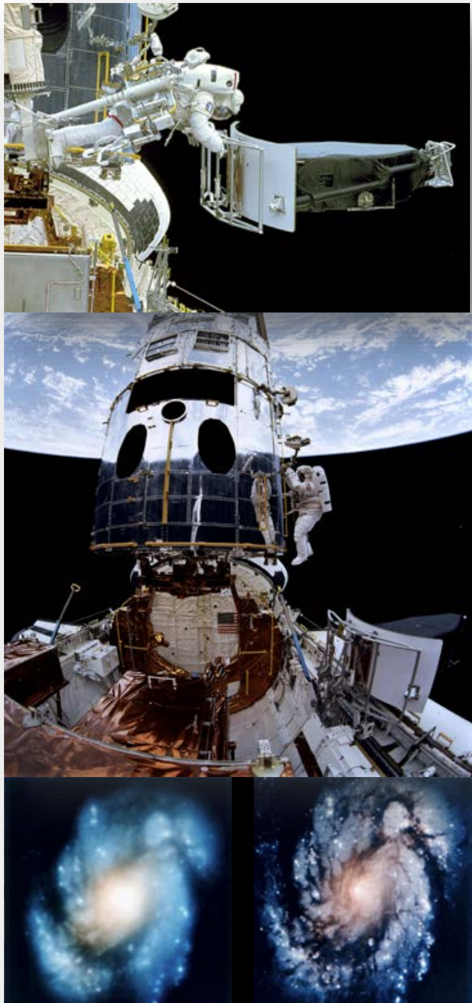
- Compelling need: provides for new capabilities for space vehicle design/build, upgrade and maintenance to reduce cost and improve resilience
    - **Persistent Assets - servicing and repair extend lifetime**
    - **iSA enables large space assets – mitigates launch volume constraints**
    - **Disassembly and reuse for multi-mission vehicles**
    - **iSM reduces spares and enables earth independence**

This focus area is aimed at developing the technologies needed to deploy, assemble, aggregate, and/or manufacture large and/or complex in-space and surface systems without astronaut extravehicular activity (EVA). The benefit of this capability is that can alter the current spacecraft-manufacturing paradigm by enabling in-space creation of large spacecraft systems. The elimination of the need for the integrated system to survive launch loads and environments will simplify the integration and pre-launch testing. The capability can allow repurposing, upgrading, or reconfiguring assets in space.

The technology focus areas for this capability include:

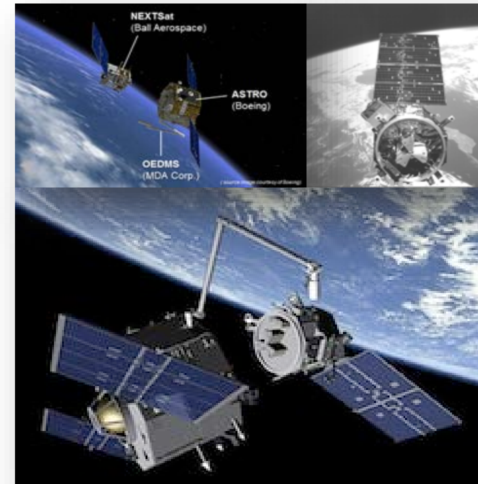
- Materials and processes for in-space manufacturing
- Modular and “plug-and-play” open architectures
- Reversible joining
- Autonomous assembly
- Surface construction with ISRU
- Manufacturing certification
- High fidelity simulation for agent training and certification

Background: History of Space Assembly Operations



STS-61 Hubble (1993 NASA)
(1993, 1997, 1999, 2002, 2009)

ISS (1998-2011 International)



Orbital Express (2007 DARPA)

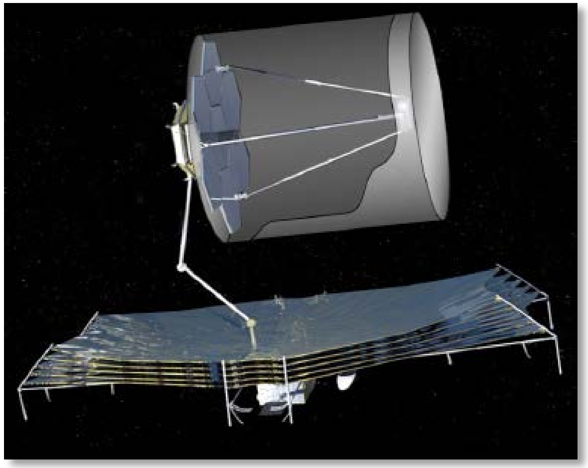
- Orbital Replacement Units
- Fuel Transfer

EASE/ACCESS STS-61B (1985 NASA)

ISA & ISM: Science and Exploration

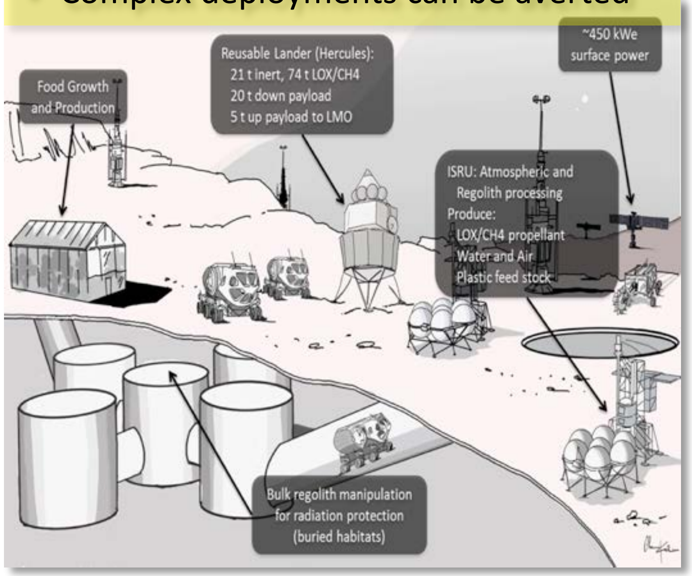
In-Space Assembly and Manufacturing Provides for Affordability and Resilience

- Assembly provides aggregation of systems from multiple launches
- Servicing and repair extend lifetime
- Disassembly and reuse of radically changes the supply architecture
- Complex deployments can be averted



High Definition Space Telescope (HDST)

- 12-20 meter Primary Mirror
- High Dimensional Stability (10s of picometers)
- Deploy/Assemble
  - Thermal Sunshield
  - Primary Mirror
  - Secondary Mirror and Subsystems



Surface ISRU – Manufacturing and Assembly

- Design with low strength materials (polymers/ceramics)
- Additive manufacturing of finite sized modules
- Assembly of processed parts into systems
- Reversible joining technology

Cis-Lunar Gateway?

- Module Based Design for Docking/Berthing
- Modular Subsystems for repair/assembly
- Long reach arms for berthing/disassembly

Engineering Design and Technology For Resilience

Previous 10-15 years
Fixed, focused, governed

- **Highly specialized platforms**
- **Fixed capabilities**
- **Costly**
- **Focused mission portfolio**
- **Long development time**

Point Solutions for Asymmetric Warfare

Moving from Custom Build to Composability and Integration

Now…..The Future
Modular, adaptable, autonomous

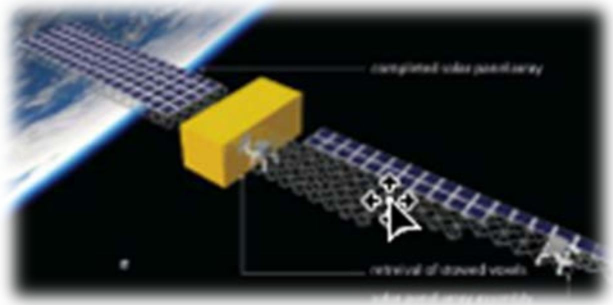
- **Flexible platforms**
- **Adaptable to capabilities**
- **Affordable**
- **Resilient to new threats**
- **Short development time**

Composable, Agile Solutions for Multiple Missions and Threats

Jeffery P. Holland, PhD, PE (SES)
Engineered Resilient Systems (ERS) Community of Interest (COI) Lead
Director, US Army Engineer Research and Development Center (ERDC)
Director, Research and Development, US Army Corps of Engineers

In-Space Assembly (ISA)

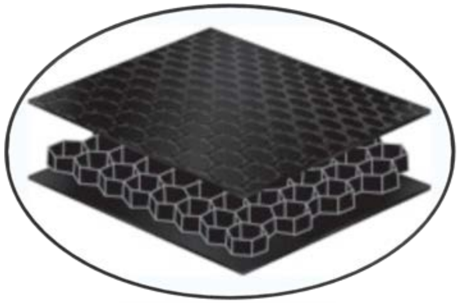
Develop and enable the autonomous assembly technologies and modular interfaces required to reduce payload packaging volumes and open up new space systems design/build/launch/operations. This includes development of the on-orbit and surface assembly capabilities, as well as the required simulation based certification, characterization & verification.



In-Space Robotics, Manufacturing and Assembly (IRMA)

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
  - o Wallops Sounding Rocket

High TRL – Technology Demonstration Missions

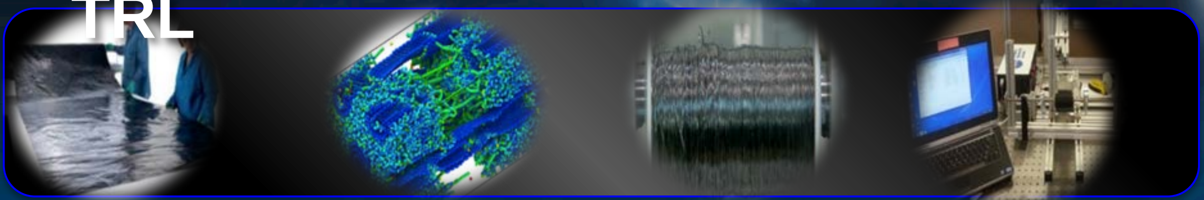
Hybrid CF/CNT Demo Unit

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

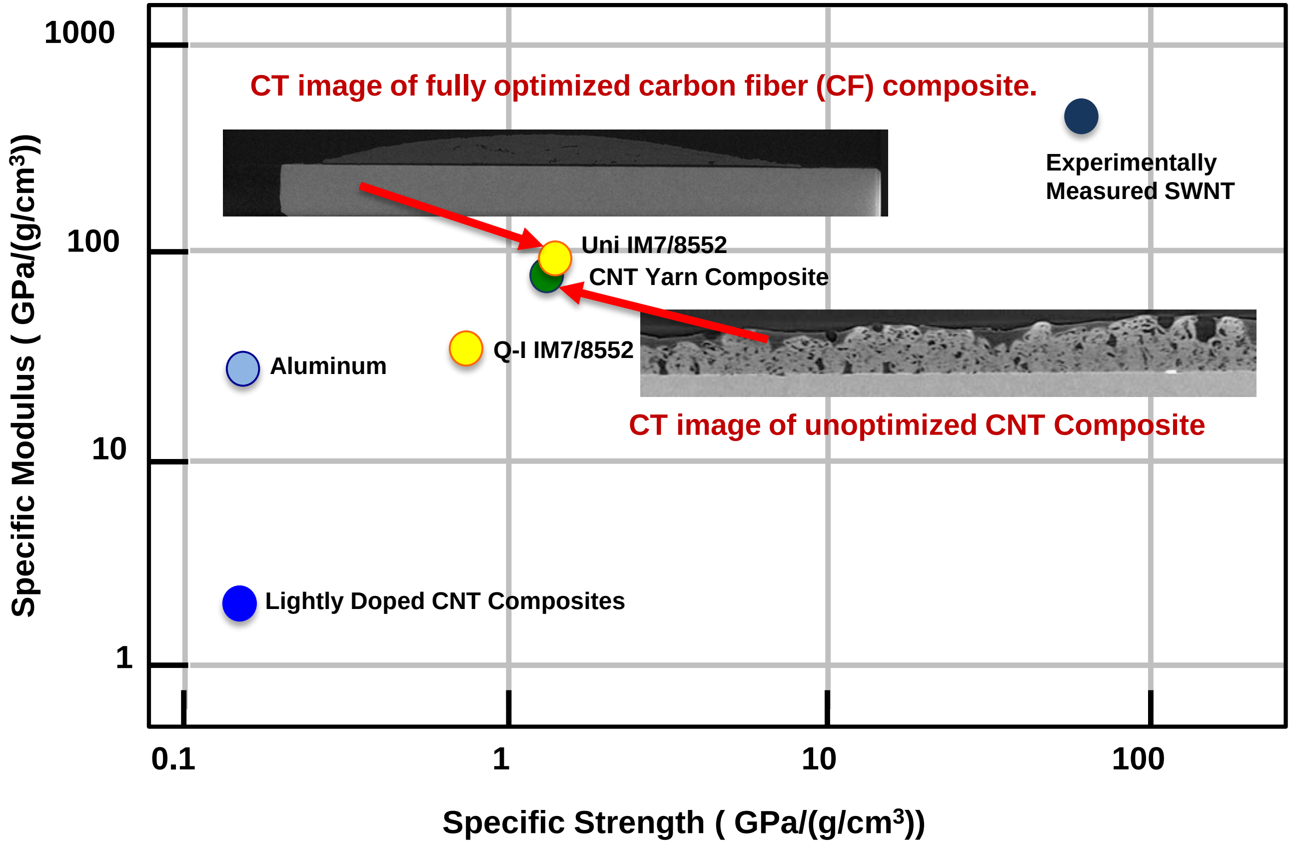


Early Stage

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

TECHNOLOGY PIPELINE

Where are we with structural CNT?



- The two composites (CNT and CF) 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 CF composites

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

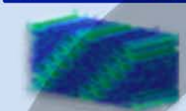
Lead: Michigan Technological University

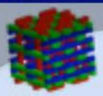
Simulation & Design Team (SDT)

Team lead:

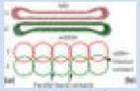
Internal tasks
- **Refine molecular, mesoscale, and continuum modeling methods**
- **Develop and validate new force fields**

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

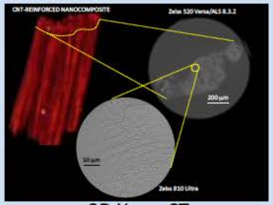
Testing & Characterization Team (TCT)

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

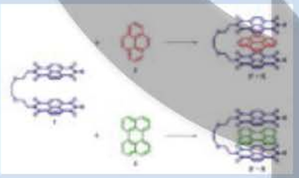
Material Synthesis Team (MST)

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:

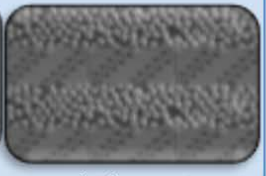
nanocomp TECHNOLOGIES, INC. SOLVAY

Internal tasks
- **Scale-up manufacturing**

Collaborative tasks
- **Fabricate test panels**

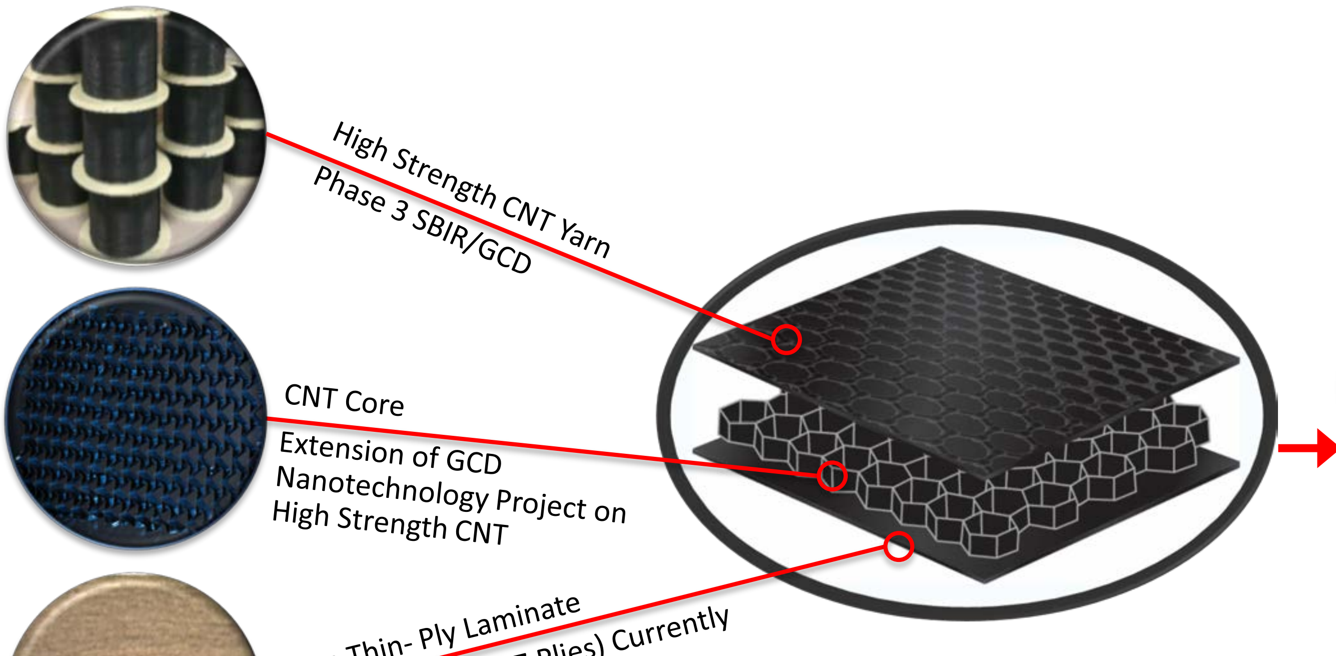

Crystalline CNT polymer composite

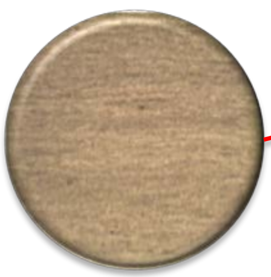

Crystalline CNT structure

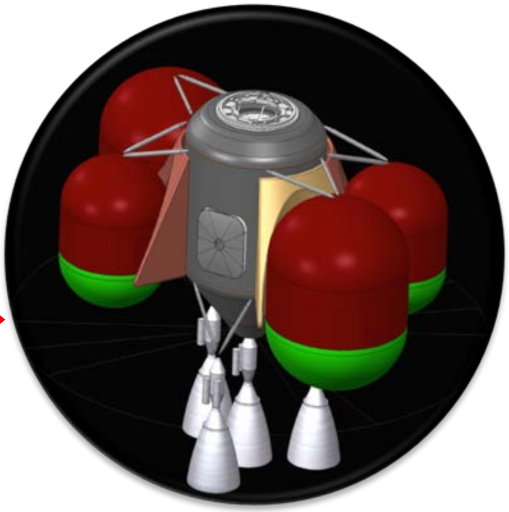

Hybrid composite

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



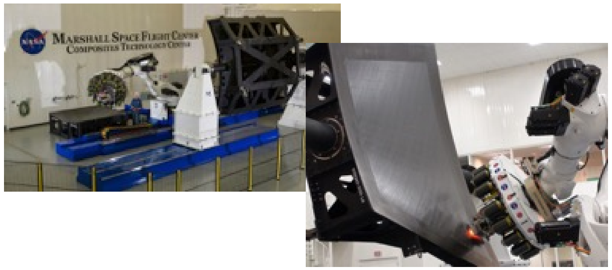




Description of Idea:

- 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

Advanced Manufacturing Technology



Composites Technology for Exploration (CTE)

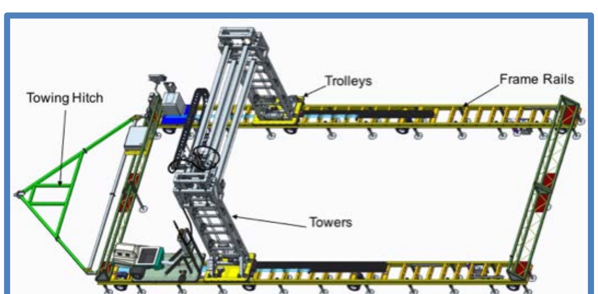
- Demonstrate weight-saving, performance-enhancing bonded joint technology for large-scale composite hardware.

Low Cost Upper Stage-Class Propulsion (LCUSP)

- Demonstrate AM of Combustion Chamber - integrated hot fire test (chamber & nozzle)

Additively Manufactured Oxidizer Turbopump (OTP)

- Demonstrate AM of rotating, vaned and pressure vessel components in relevant oxygen turbopump environments.



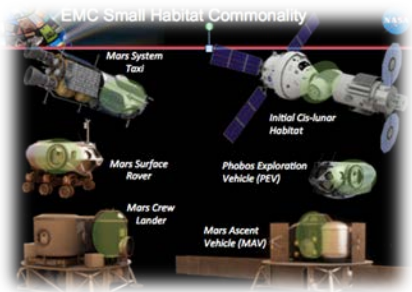
Additive Construction w/ Mobile Emplacement (ACME)

- 3-D printer aimed at autonomous construction of planetary surface structures using in-situ materials for both binder and aggregate components. (w/ US Army Corp of Eng.)

Summary

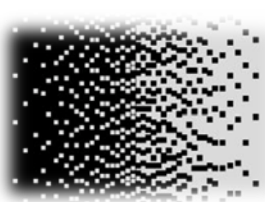
Structures/Materials/Nanotechnology

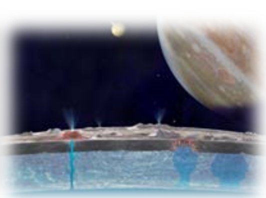
Human Composites



iSA & iSM

Advanced Structural Materials





Performance

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

Resilience

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

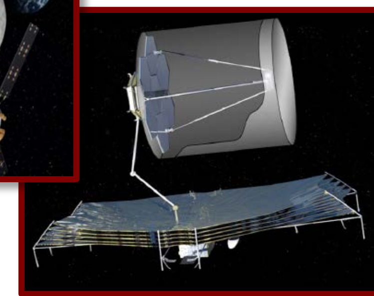
Affordability

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

Urgency

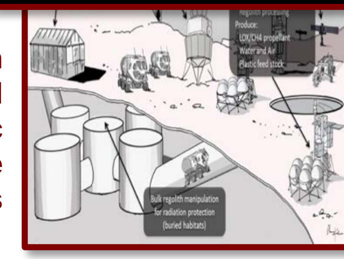
- *Mars Architecture & Habitats*
- *Planetary and Astrophysics*
- *iSA & iSM rev tech*

Planetary Science / Exoplanet Observatories



Human Cis-Lunar (EMC)

Human And Robotic Surface Systems



OGA and Commercial Space

Notional Pathfinder Demo