National Aeronautics and
Space Administration

Space Technology Mission Directorate
Game Changing Development Program
FY2015 Annual Program Review

Advanced Manufacturing Technology

Presented by:
John Vickers

Date
October 14, 2015

Advanced Manufacturing Technology
FY15 Portfolio and Technology Maturation Story

Project Element Name	Project Element Lead	FY Start	FY End	TRL Start	TRL End	Appendix No.
Manufacturing Initiative (Activity)	John Vickers	FY14	FY16	4	6	
Advanced Near Net Shape Technology	John A. Wagner Marcia Domack	FY14	FY15	3	4	**C-3**
Materials Genome Initiative	Terryl Wallace	FY14	FY16	3	5	**C-7**
Low Cost Upper Stage-Class Propulsion Development	Tony Kim	FY14	FY17	3	6	**C-9**
Additive Construction for Mobile Emplacement	Niki Werkheiser Rob Mueller	FY15	FY17	3	5	**C-12**
Bulk Metallic Glass	Peter Dillon	FY14	FY15	3-4	6	**C-6**
Project Task Name	**Project Task Lead and Participants**	**FY Start**	**FY End**	**TRL Start**	**TRL End**	
National Center for Advanced Manufacturing (NCAM)	John Vickers	FY15				Task Plan
Virtual Materials and Manufacturing for Composites (Task)						
Advanced Integrated Composite Structures (Task)						
LOX/GOX Compatibility Testing for Composite LOX Tank Material (Task)						

AMT Project Overview

Advanced manufacturing is critical to all NASA mission areas. The AMT project elements and tasks develop and mature innovative, advanced manufacturing technologies that will enable more capable and lower-cost spacecraft and launch vehicles. The AMT Project is making use of cutting edge materials and emerging capabilities including: metallic processes, additive manufacturing, composites, and digital manufacturing. The AMT project supports the National Manufacturing Initiative involving collaboration with other government agencies.

Integration with other projects/programs and partnerships

- CIF, SBIR/STTR, STRG, TDM, Centennial Challenges
- HEOMD, ARMD
- Industry, OGA, Academia

Technology Infusion Plan:

- Potential customer infusion (TDM, HEOMD, SMD, OGA, Industry)
- Produce game changing and next generation manufacturing technology and work with various NASA mission directorates and programs(e.g. SLS) to infuse the technology to dramatically improve affordability and capability.
- Collaborate with other Agencies, Industry and Academia.
- Industry Days, NASA roadmap

Key Personnel:

Program Manager: Steve Gaddis

Program Element Manager: Kevin Kempton

Project Manager: John Vickers

Lead Center: MSFC

Supporting Centers: ARC, GSFC, GRC, KSC, LaRC

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Push and Pull

Key Facts:

GCD Theme: Lightweight Materials and Advanced Manufacturing

Execution Status: Thematic Plan

Technology Start Date: N/A

Technology End Date: N/A

Technology TRL Start: 3

Technology TRL End: 6

Technology Current TRL: N/A

- **Technology Lifecycle Phase:** AMT/Project level does not have lifecycle phase, but each technology element does.

Advanced Manufacturing Technology Project Manager Annual Assessment

Technology	Performance			Comments
	T	C	S	
Manufacturing Initiative				Significant engagement with other agencies and the activities of the National Advanced Manufacturing Initiative (e.g. NNMI's).
Advanced Near Net Shape Tech.				Successful sounding rocket flight on October 7th. Resources needed in FY16 to support post-flight analysis due to flight delay. All other milestones on schedule for completion. ANNST is currently unfunded for FY16.
Materials Genome Initiative				Completed all of the FY15 Milestones. Continuation Review scheduled for Oct. 29, 2015 at LaRC.
Low Cost Upper Stage Class Propulsion				Technical – Technical Challenges and complications of EBF3 application of In625 on SLM GRCop-84 for the structural jacket have required additional efforts and schedule than previously anticipated. Schedule – Missed the Original Hot Fire complete date (August 28, 2015, CR submitted). Detailed schedule has been generated that includes a 10 day margin with hot fire testing in the Spring of 2016.
Additive Construction with Mobile Emplacement (ACME)				Completed all FY15 milestones on schedule. Currently one project risk, and it is green.
National Center for Advanced Manufacturing (NCAM)				Schedule – Procurement delays have caused the tasks to be behind schedule.

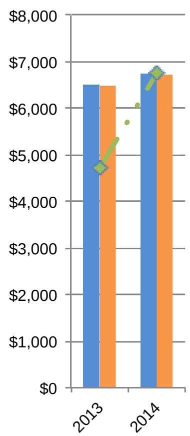
AMT SPI index is 0.77

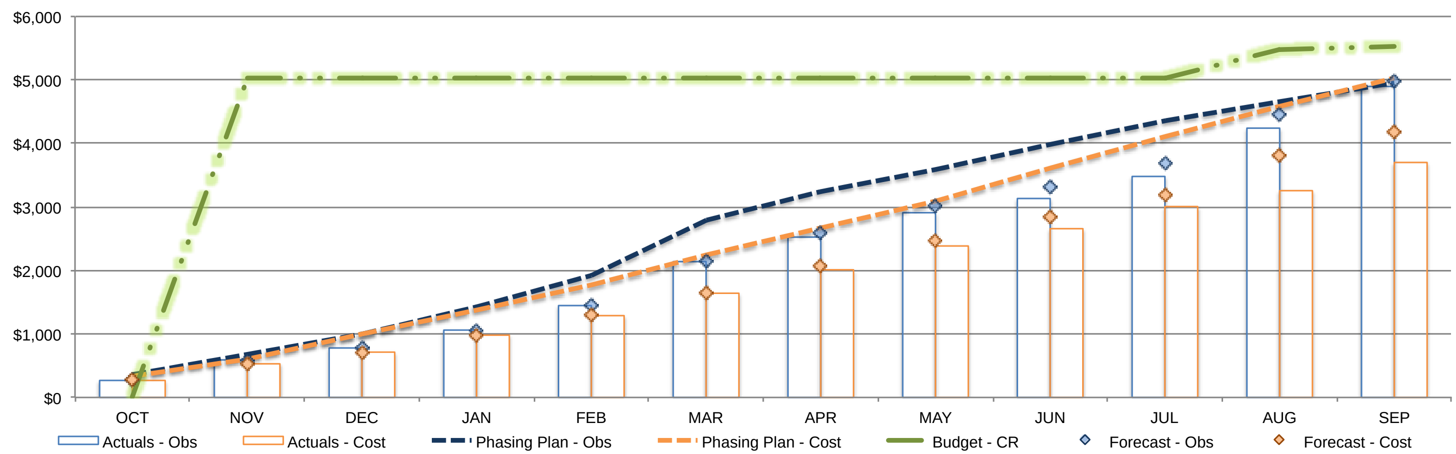
AMT Technical Accomplishments

- Completed design, fabrication, testing, integration and flight of a sounding rocket payload adapter fabricated using the integrally stiffened cylinder (ISC) process. (ANNST)
- New models were developed of the melt pool and thermal effects within a build and build plate. These models will be validated and used to assist SLS in developing processing parameters on a new SLM system. (MGI)
- Designed and additively manufactured two full scale chambers out of GRCop powder. Developed process during 1st chamber build and made improvements for 2nd chamber build based on lessons learned. (LCUSP)
- Constructed martian simulant concrete wall, fabricated sintered basalt pavers, and size-sorted and delivered feedstock. (ACME)

Advanced Manufacturing Technology Resources: Total Obligations and Cost

PY 2015 Financial Status





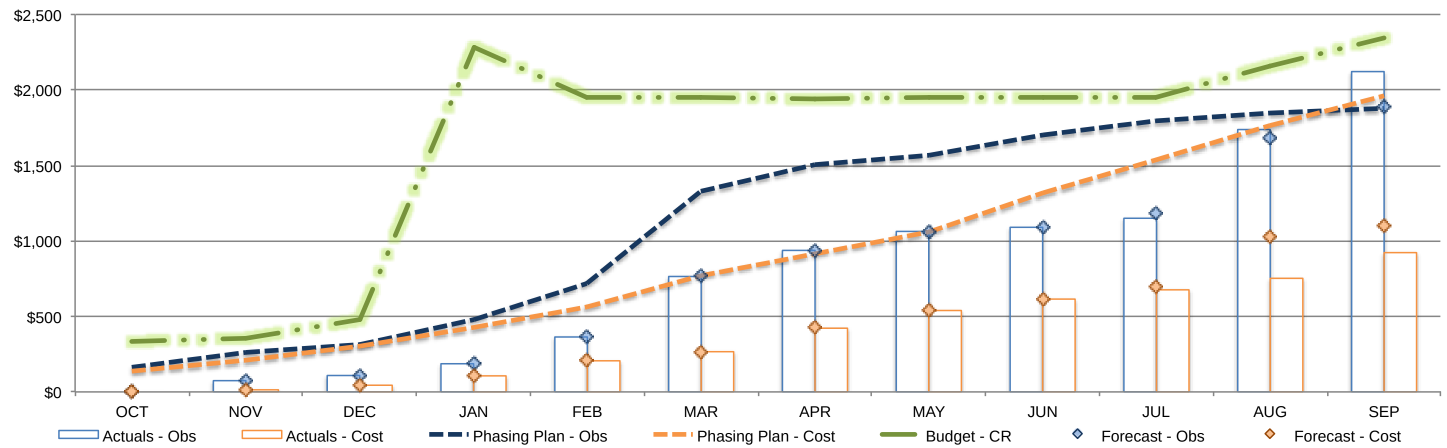
	Cum ($K)	2013	2014	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Carry Out
	Budget	4,728.4	6,749.4	0.0	5,030.5	5,030.5	5,030.5	5,030.5	5,030.5	5,030.5	5,031.7	5,031.7	5,031.7	5,480.8	5,525.0	
Obs	Phasing Plan (RLS)			360.9	666.9	998.3	1,433.7	1,920.8	2,789.6	3,251.0	3,588.5	3,997.3	4,360.3	4,659.9	4,944.5	580.5
Obs	Actuals	6,515.6	6,749.4	269.1	591.2	779.6	1,061.7	1,448.0	2,139.9	2,525.8	2,909.7	3,133.9	3,480.2	4,242.5	4,898.5	626.5
Obs	Forecast			269.0	591.0	779.0	1,061.0	1,448.0	2,140.0	2,595.0	3,004.0	3,314.0	3,687.0	4,470.0	4,971.0	554.0
Cost	Phasing Plan (RLS)			334.5	611.6	990.3	1,374.3	1,764.3	2,237.9	2,664.9	3,080.2	3,612.7	4,103.6	4,580.5	5,030.3	494.7
Cost	Actuals	6,487.8	6,729.7	269.1	530.3	715.1	981.8	1,290.1	1,641.6	2,011.0	2,386.4	2,658.5	3,006.0	3,257.4	3,699.9	1,825.1
Cost	Forecast			269.0	530.0	714.0	980.0	1,289.0	1,641.0	2,080.0	2,480.0	2,838.0	3,201.0	3,822.0	4,179.0	1,346.0

	YTD Status			Explanation required for YTD Variance in excess of 5% from PM Forecast (shaded red)
'15 Obs	Phasing	$	4,945	The obligations are slightly behind plan due to labor under run.
	Forecast*	$	4,971	
	Actuals	$	4,898	
	Variance	$	(73)	
'15 Cost	Phasing	$	5,030	The costs are behind plan for the year due to the delays in the LCUSP Hot Fire Test and the obligations not occurring as soon as initially anticipated. Also behind plan due to labor under run.
	Forecast*	$	4,179	
	Actuals	$	3,700	
	Variance	$	(479)	

* Forecast value is a snapshot of the Forecast from the previous reporting period

Advanced Manufacturing Technology
Resources: Non-Labor Obligations and Cost

PY 2015 Non-Labor Financial Status



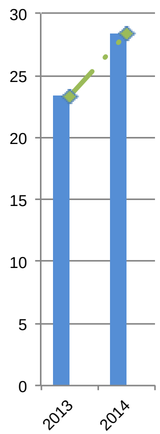
	Cum ($K)			OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Carry Out
	Budget			334.0	358.5	478.0	2,279.4	1,950.7	1,950.7	1,944.7	1,946.7	1,951.4	1,948.5	2,153.8	2,342.1	
Obs	Phasing Plan (RLS)			163.1	262.9	313.9	483.1	721.6	1,326.1	1,503.8	1,567.5	1,698.4	1,791.1	1,845.8	1,873.3	468.8
	Actuals			0.0	74.8	108.7	186.4	364.1	765.2	937.2	1,063.1	1,090.6	1,150.6	1,737.8	2,121.3	220.7
	Forecast			-	75.0	109.0	187.0	365.0	766.0	938.0	1,064.0	1,091.0	1,181.0	1,681.0	1,891.0	451.1
Cost	Phasing Plan (RLS)			136.7	207.6	305.9	423.6	565.1	774.4	917.7	1,059.2	1,313.8	1,534.4	1,766.4	1,959.1	383.0
	Actuals			0.0	13.9	44.3	106.5	206.2	266.8	422.4	539.8	615.3	676.4	752.7	922.8	1,419.3
	Forecast			-	14.0	44.0	106.0	206.0	267.0	423.0	540.0	615.0	695.0	1,033.0	1,099.0	1,243.1

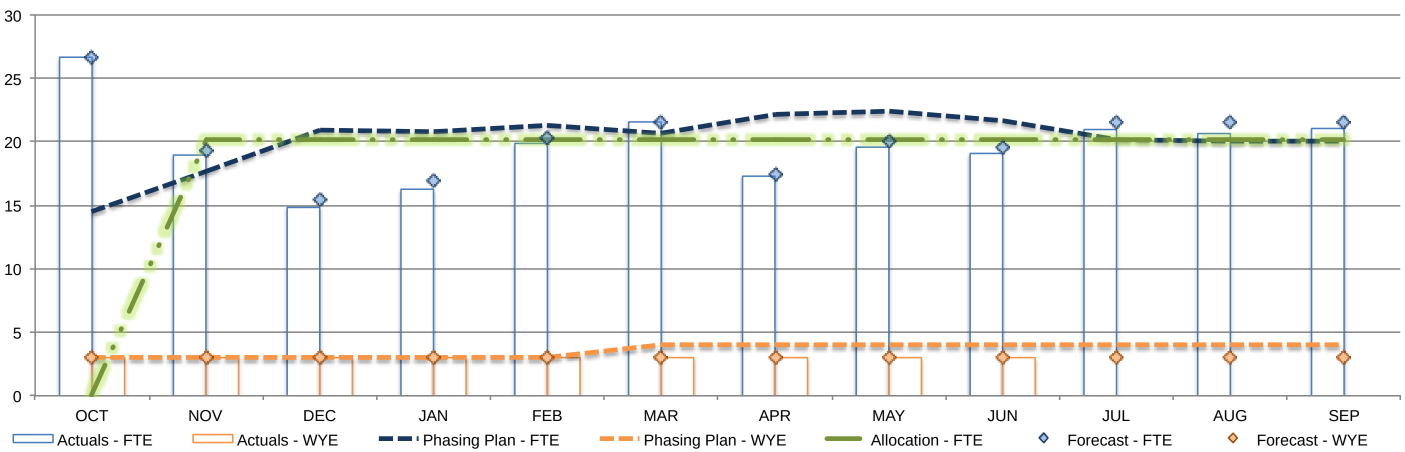
	YTD Status			Explanation required for YTD Variance in excess of 5% from PM Forecast (shaded red)
'15 Obs	Phasing	$	1,873	The obligations are ahead of plan due to NCAM funds obligating prior to the end of the fiscal year and ahead of plan.
	Forecast*	$	1,891	
	Actuals	$	2,121	
	Variance	$	230	
'15 Cost	Phasing	$	1,959	The costs are behind plan for the year due to the delays in the LCUSP Hot Fire Test and the obligations not occurring as soon as initially anticipated.
	Forecast*	$	1,099	
	Actuals	$	923	
	Variance	$	(176)	

* Forecast value is a snapshot of the Forecast from the previous reporting period

Advanced Manufacturing Technology
Resources: Total Project Workforce FTEs/WYEs

PY 2015 Workforce Status



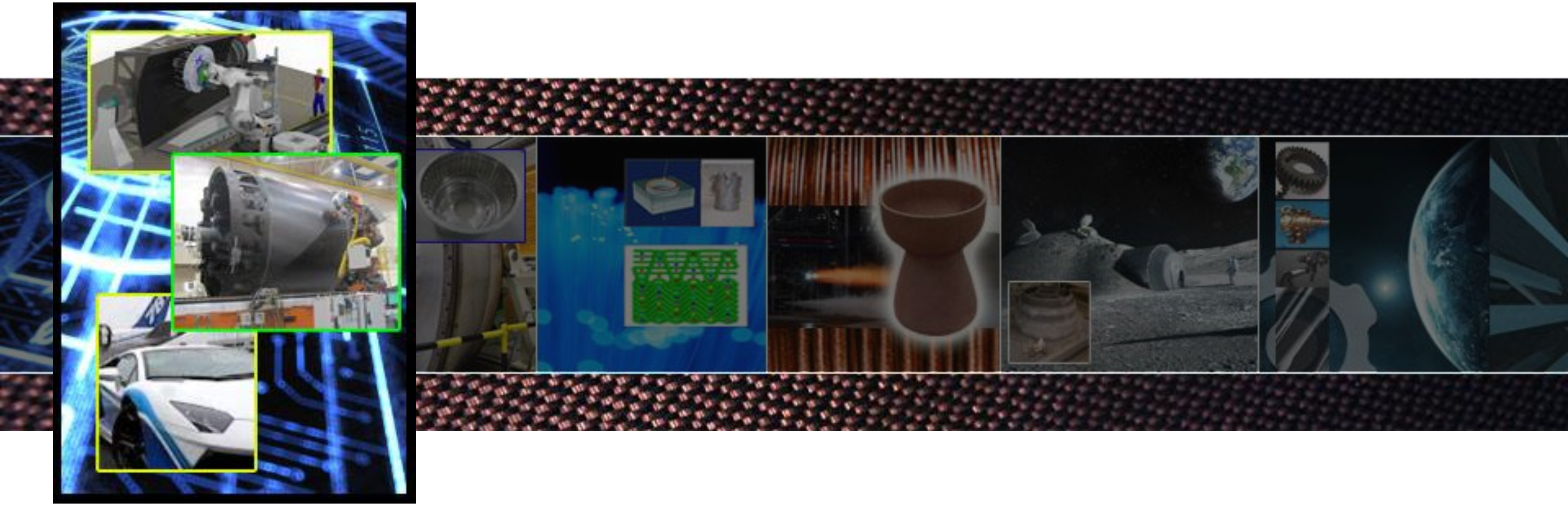


	Incremental	2013	2014	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	2014 Avg
FTE	Allocation	23.4	28.4	0.0	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2
	Phasing Plan (RLS)			14.5	17.7	21.0	20.8	21.4	20.7	22.2	22.4	21.7	20.2	20.1	20.1	20.2
	Actuals	23.4	28.4	26.7	19.0	14.8	16.3	19.9	21.6	17.3	19.6	19.1	21.0	20.7	21.1	19.7
	Forecast			26.7	19.3	15.5	17.0	20.3	21.6	17.5	20.1	19.6	21.6	21.6	21.6	20.2
WYE	Phasing Plan (RLS)			3.0	3.0	3.0	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.6
	Actuals	0.0	0.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	0.0	0.0	0.0	2.3
	Forecast			3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

	YTD Status		Explanation required for YTD Variance in excess of 5% from PM Forecast (shaded red)
'15 FTE	Phasing	20.2	The FTEs are slightly behind plan due to ACME starting off the year slow due to delays with interagency agreement.
	Forecast*	20.2	
	Actuals	19.7	
	Variance	(0.5)	
'15 WYE	Phasing	3.6	The WYEs are behind plan for the year due to the delays in the LCUSP Hot Fire Test.
	Forecast*	3.0	
	Actuals	2.3	
	Variance	(0.8)	

* Forecast value is a snapshot of the Forecast from the previous reporting period

Manufacturing Initiative



AMT
Manufacturing Initiative Overview

The AMT Project supports multiple activities within the Administration's National Manufacturing Initiative. A key component of the Initiative is the Advanced Manufacturing National Program Office (AMNPO), which includes participation from all federal agencies involved in U.S. manufacturing. In support of the AMNPO the AMT Project supports building and Growing the National Network for Manufacturing Innovation through a public-private partnership designed to help the industrial community accelerate manufacturing innovation.

Integration with other projects/programs and partnerships

- STMD, HEOMD, other Centers
- Industry, Academia
- OGA's (e.g., DOD, DOE, DOC, USDA, NASA, NSF)
- Office of Science and Technology Policy, NIST Advanced Manufacturing Program Office
- Generate insight within NASA and cross-agency for technology development priorities and investments.

Technology Infusion Plan:

- PC
- Potential customer infusion (TDM, HEOMD, SMD, OGA, Industry)
- Leverage
- Collaborate with other Agencies, Industry and Academia.
- NASA roadmap

Key Personnel:

Project Manager: John Vickers

Project Element Manager: John Vickers

Lead Center: MSFC

Supporting Centers: ARC, GSFC, GRC, KSC, JPL, LaRC

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Push and Pull

Key Facts:

GCD Theme: Lightweight Materials and Advanced Manufacturing

Execution Status: Thematic Plan

Technology Start Date: N/A

Technology End Date: N/A

Technology TRL Start: 3

Technology TRL End: 6

Technology Current TRL: N/A

- **Technology Lifecycle Phase:** N/A

National Network for Manufacturing Innovation

NASA is an engaged partner with the other agencies in the activities of the National Advanced Manufacturing Program Office and in the manufacturing innovation institutes. We envision increased specific engagement.

- Led by Space Technology Mission Directorate – Multiple Center Participation
- Member of the interagency Advanced Manufacturing National Program Office (AMNPO)
- Member of the NSTC Subcommittee on Advanced Manufacturing
  - Currently participating on the writing teams for the NNMI Program Strategic Plan (SP)
  - Participated in the US-UK workshop on manufacturing innovation and policy
- NASA NNMI Collaboration
  - Executive committee and technical advisory board members
  - Additive Manufacturing Roadmap Advisory Groups
  - NASA researchers can participate in technical projects in areas that align with NASA interests
  - STMD is providing FTE support for ALL solicitations and institutes in the form of technical reviewers during the solicitation process
- Current Institutes - America Makes, Digital Manufacturing and Design Innovation Institute, Lightweight Innovations For Tomorrow, Power America, Institute of Advanced Composites Manufacturing Innovation, Integrated Photonics, Flexible Hybrid Electronics
- Upcoming Institutes - Clean Energy Institute on Smart Manufacturing, Revolutionary Fibers and Textiles
- Consortium for Advanced Manufacturing Foresights - University of Michigan
- Other related initiatives – Materials Genome Initiative, National Nanotechnology Initiative, Biology Engineering (SynBio)

NASA Engagement with Established Institutes

America Makes
National Additive Manufacturing Innovation Institute

National Additive Manufacturing Innovation Institute **- Youngstown, OH**

- **First of the NNMI institutes; established in August 2012**
- **Technology: Additive Manufacturing (aka: 3D Printing)**
- **Prime Awardee: National Center for Defense Manufacturing and Machining (NCDMM)**
- **Primary Federal Funding Agency: DOD - Air Force**
- **Initial $30M federal investment matched by $39M industry, state/local; now at $50M federal, with over 100 participants**

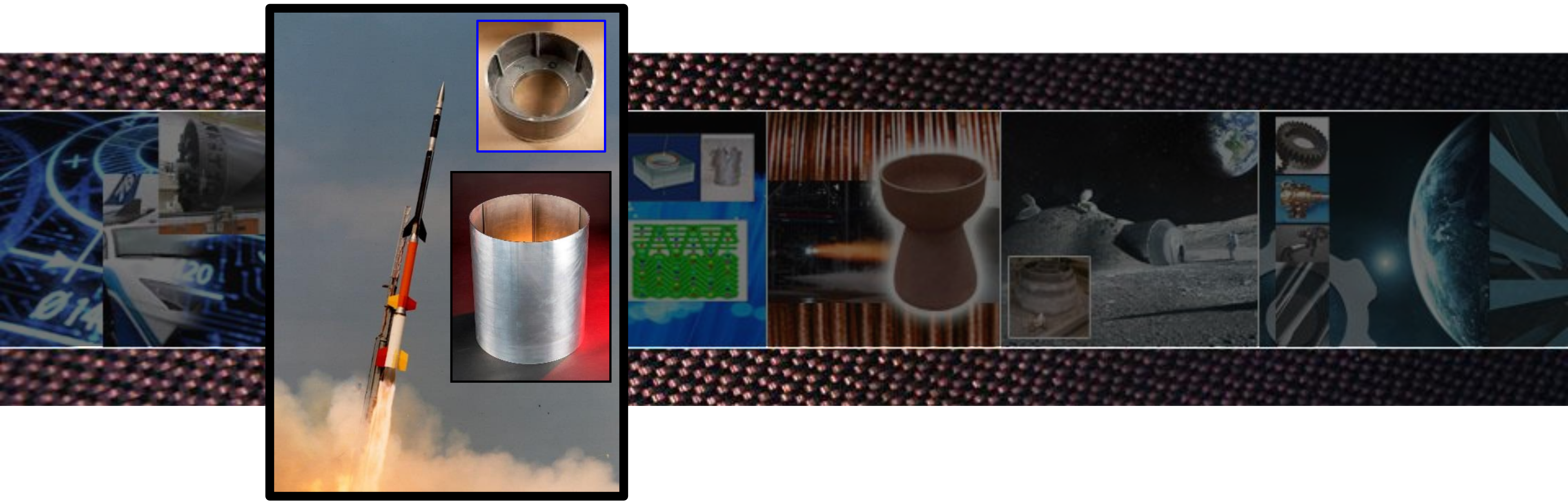
NASA Financial Support

- **May 2015, 3D Printed Habitat Challenge, $2.25 million competition to design and build a 3D printed habitat for deep space exploration, Centennial Challenges program**

NASA Collaboration

- **Executive committee and technical advisory board members (MSFC, LARC, GRC)**
- **Additive Manufacturing Roadmap Advisory Group**
- **NASA researchers can participate in technical projects in areas that align with NASA interests**

Advanced Near Net Shape Technology



ANNST Overview

Overall objective: Develop and mature cryogenic tank manufacturing technology to enable fabrication of single-piece integrally-stiffened launch vehicle structures to replace expensive, heavy, and risky multi-piece welded assemblies. **Status:** Demonstrated feasibility through fabrication of aluminum subscale single-piece cylinders with integrally formed cryogenic tank barrel scale stiffeners using the Integrally Stiffened Cylinder (ISC) process. Successful scale-up of ISC process through fabrication of a single-piece, integrally-stiffened, aluminum sounding rocket (SR) payload adapter. Successful flight demonstration on October 7, 2015.

Integration with other projects/programs and partnerships

- Strong alliance among NASA, ESA, DLR and US and German private industry.
- Firm resource commitment from ESA for FY16 to support scale up to 3-meter (~10 feet) in diameter
- Firm resource commitments from DLR and MT Aerospace for FY16 to increase stiffener height at sounding rocket scale diameter
- Collaboration with ESA via a NASA/ESA MOU on Space Transportation
- Working with International Technologies to establish ISC process capability in U.S.

Technology Infusion Plan

- Technology developed – Integrally Stiffened Cylinder (ISC) process for manufacture of single-piece stiffened structures in a single processing step.
- Potential customers
  - NASA launch vehicle programs (Sounding Rockets, SLS)
  - Commercial launch service providers
  - DoD launch vehicles
- Comments/Anticipated use
  - Fabrication of single-piece stiffened structures using the ISC process represents a paradigm shift from conventional multi-piece welded construction. Potential applications are cryogenic tank barrels, rocket segments, intertank structures.

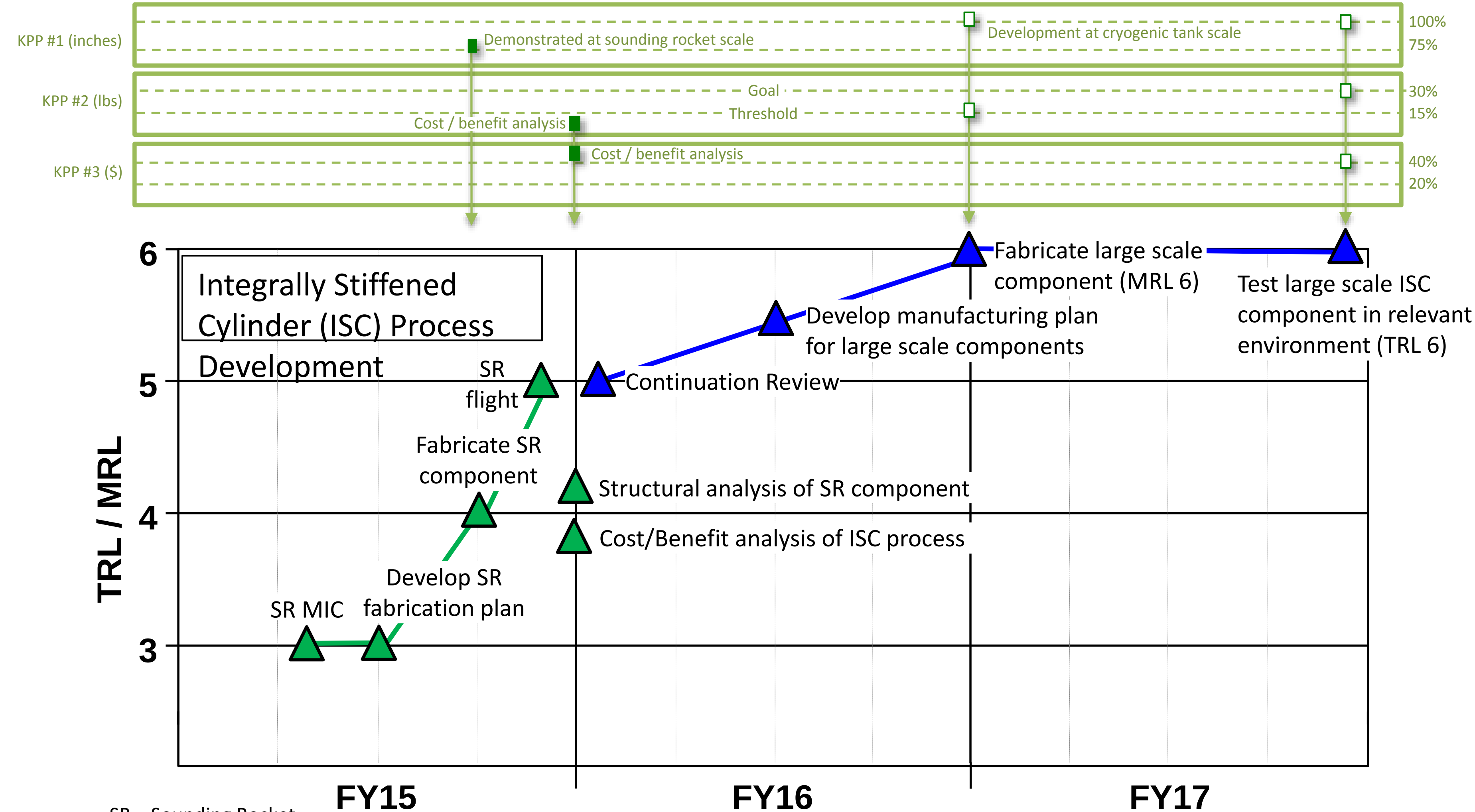
Key Personnel:

Project Manager: John Vickers
Project Element Manager: Marcia Domack/John Wagner
Lead Center: LaRC
Supporting Centers: WFF – Sounding Rocket Payload Team
NASA NPR: 7120.8
Guided or Competed: Guided
Type of Technology: Push

Key Facts:

GCD Theme: Lightweight Materials and Advanced Manufacturing
Execution Status: Year 3 of 3 funded (of 6 planned)
Technology Start Date:
Technology End Date:
Technology TRL Start: 3
Technology TRL End: 6
Technology Current TRL: 3
Technology Lifecycle Phase: Second Formulation Year due to budget cuts

Component and System TRL Quarterly Assessment – ANNST



SR = Sounding Rocket
MIC = Mission Initiation Conference

Funded
Unfunded

Flight Test with SR ISC Component – Q4 FY15
Will advance ISC Process to TRL 5

Goal
Actual Value
Predicted Value

AMT
ANNST Performance

- **Technology Advancements**
  - Demonstrated scale-up of the Integrally Stiffened Cylinder (ISC) process through fabrication of a single-piece integrally-stiffened aluminum sounding rocket payload adapter.
  - Represents a 20 fold increase in scale based on cylinder volume.
  - Demonstrates feasibility of eliminating all longitudinal welds in cryogenic tank barrels.
- **Technology advances mean**
  - ISC process enables 50% cost and 7% weight reductions for cryogenic tank barrel manufacture by eliminating longitudinal welds and minimizing machining.
- **Technology Push**
  - NASA Launch vehicle programs (SLS, Sounding Rockets), Commercial launch providers, Athena, Falcon 9, DoD launch vehicles.
  - Cryogenic tank, dry bay structure, payload fairings and payload adapter applications.

Key Performance Parameters			
Performance Parameter	State of the Art	Threshold Value	Project Goal
KPP1 – Cryogenic Tank Barrel Longitudinal Welds	ET LH2 tank – 7200 in.	1800 inches	0 inches
KPP2 – Cryogenic Tank Weight	ET – 54K lbs	15% less	30% less
KPP3 – Cryogenic Tank Cost	ET - $60M	20% less	40% less

ANNST Technical Accomplishments and Technical Challenges

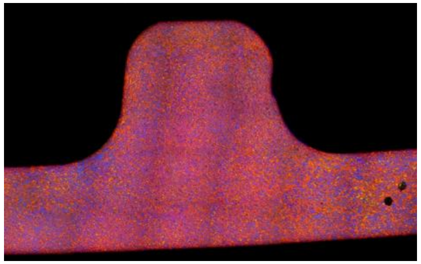
- **FY15 Technical Accomplishment**
  - Completed design, fabrication, testing and integration of a sounding rocket payload adapter fabricated using the integrally stiffened cylinder (ISC) process.
- **Technology firsts**
  - New Technology Report, “Integrally Stiffened Cylinder (ISC) Processing Technology”, LAR-18593-1, December 15, 2014; Patent pending.
  - New Technology Report, “In-situ Selective Reinforcement of Near Net Shape Formed Structures”, LAR-18600-1, December 18, 2014; Patent pending.
- **Technical challenges**
  - A cylinder of this size and complexity had never been formed before using the ISC process.
    - Designed tooling to maximize probability of success during forming.
  - As-formed cylinders were slightly out-of-round.
    - Modified machining plan to maximize wall thickness of sounding rocket flight cylinder and match machined mating hardware.
    - Payload adapter successfully fabricated, flight qualified, integrated into sounding rocket payload assembly.

AMT
ANNST – Proposed Plans for FY2016

- **Proposed plans for FY16**
  - Technical Objectives
    - Scale-up to 3 meter (10 feet) diameter utilizing existing industrial infrastructure.
    - Fabricate SR scale cylinder with cryogenic tank scale stiffeners.
    - Complete analysis of data from sounding rocket flight and preliminary ground testing.
  - ANNST is currently unfunded for FY16
    - Resources needed in FY16 to support post-flight and ground test data analysis.
    - See backup for over guide request.

Payload Adapter Made Using the Integrally Stiffened Cylinder (ISC) Process

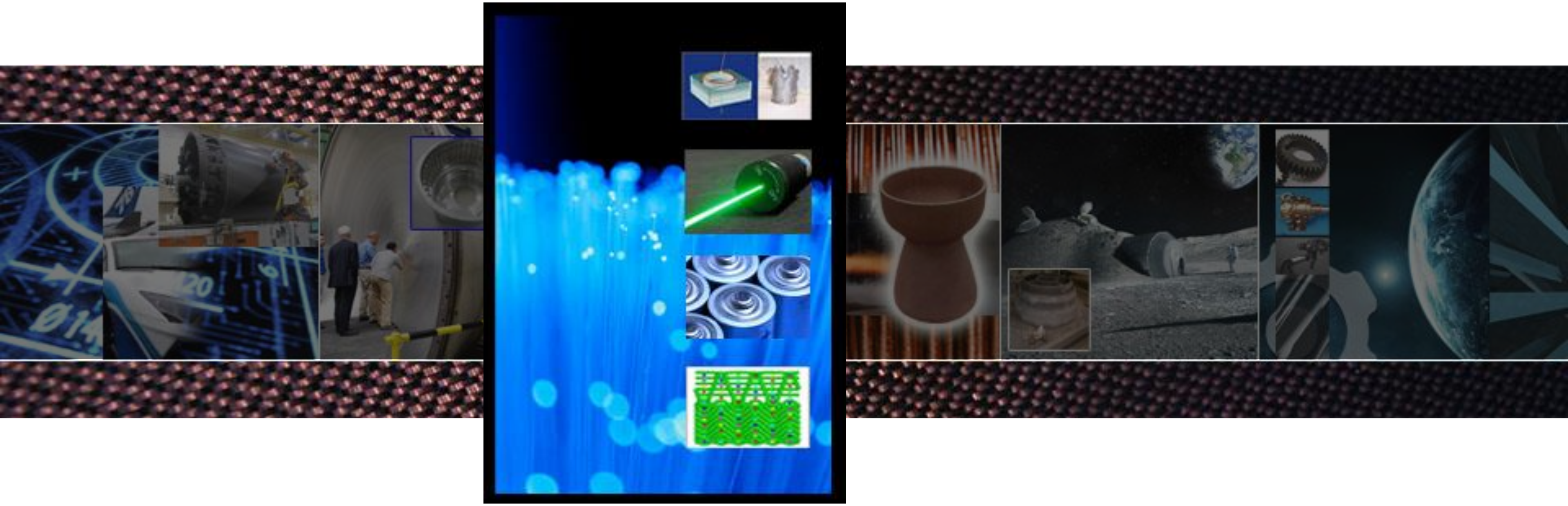
Analysis and Testing Qualify Cylinder for Flight



Sounding Rocket Payload Assembly with NNS Cylinder

Sounding Rocket Flight
October 7, 2015

Materials Genome Initiative



MGI Overview

Overall objective: Develop computational tools to assist in the manufacture, design and certification of new materials and processes. These tools will reduce the time and costs to infuse new materials while also improving reliability. This program is currently focusing on additive manufacturing as this technology has high payoff for NASA and requires computational design tools.

Integration with other projects/programs and partnerships

- NASA Launch vehicle programs (SLS).
- Commercial launch providers.
- DoD launch vehicles.
- ARMD advanced manufacturing efforts.
- Commercial airframe manufacturers

Technology Infusion Plan:

Tech infusion:

- PC – SLS.
- PC - DoD, Establishing collaborations with DoD via the National MGI effort. Work in NASA MGI element is complimentary with efforts in DoD
- PC – Alcoa, Establishing a SAA to evaluate design tools for use in manufacture of light alloy components.
- Comments/Anticipated use - Process and materials design tools will be developed and supplied to the SLS program to assist in the manufacture and qualification of components via additive manufacturing.

Key Personnel:

Program Element Manager: Steve Smith/ Terryl Wallace

Project Manager: John Vickers

Lead Center: LaRC

Supporting Centers: ARC, GRC, MSFC

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Push

Key Facts:

GCD Theme: Lightweight Materials and Advanced Manufacturing

Execution Status: Year 2 of 3

Technology State Date: Oct. 2013

Technology End Date: Sept. 2016

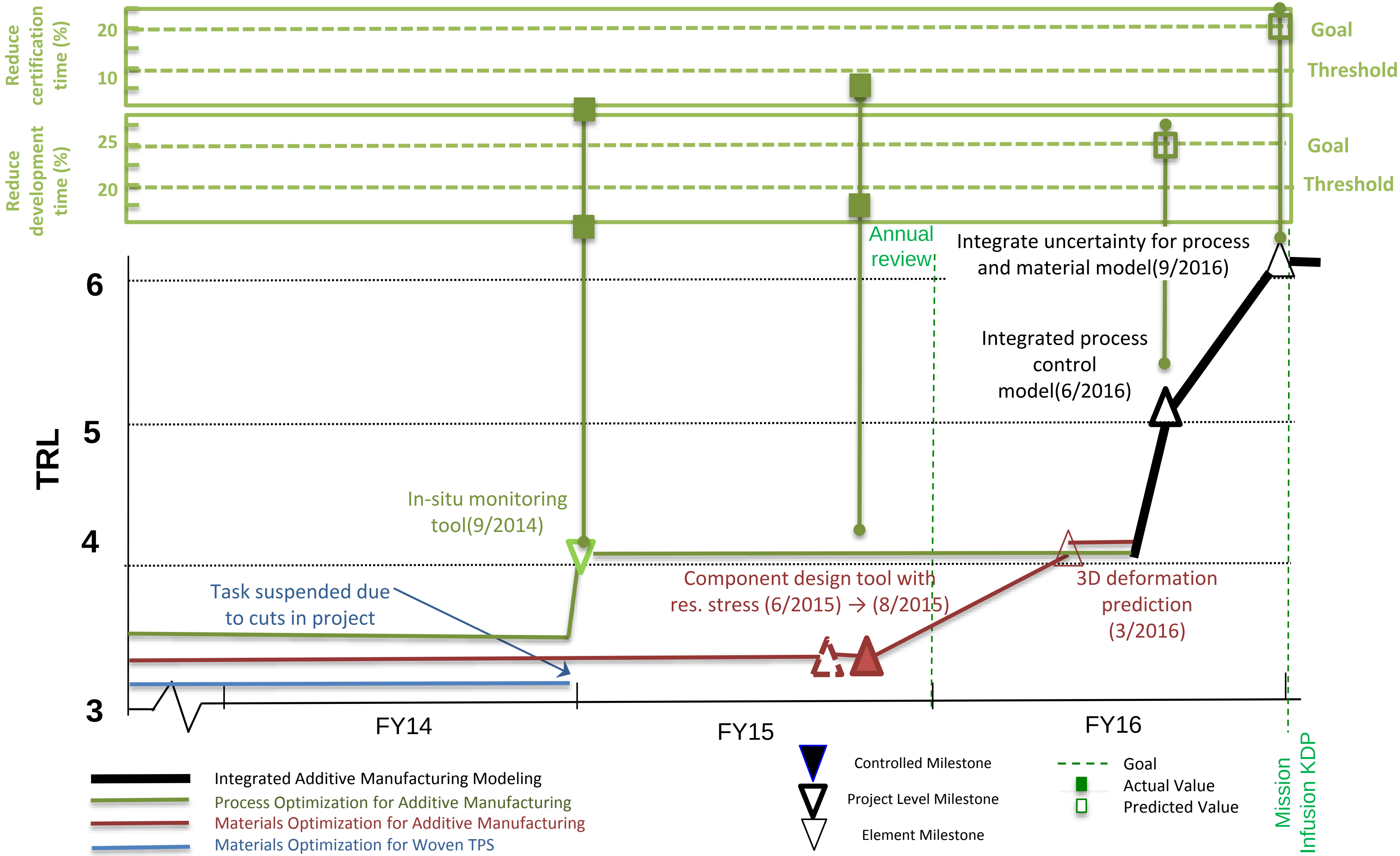
Technology TRL Start: 3

Technology TRL End: 6

Technology Current TRL: 3

Technology Lifecycle Phase: Implementation

Component and System TRL Quarterly Assessment – MGI



AMT
MGI Performance

- **Technology Advancements**
  - Demonstrated a thermal model for selective laser manufacturing to model melt pool and thermal history that is also capable of quantifying part distortion and residual stress for manufacturing of components for SLS program.
  - Provided a detailed data schema highlighting the critical data parameters for collection for SLM processing and a proposed method to utilize this data for process improvements.
- **Technology advances mean**
  - Design models will result in reduced development cycle time and certification costs.
    - Currently applying work to affect development time for new SLM system at MSFC.
- **Technology Push**
  - NASA Launch vehicle programs, Commercial launch providers, DoD launch vehicles.
  - ARMD advanced manufacturing efforts, Commercial airframe manufacturers.

Key Performance Parameters

Performance Parameter	State of the Art	Threshold Value	Project Goal
KPP1 – Reduce development time for additively manufactured component	SOA is the current development cycle for the pogo Z- baffle, which is still to be certified, by the SLS program.	Reduce the baseline development cycle time by 20% through the utilization of process control and computationally guided design.	Reduce the baseline development cycle time by 25%.
KPP2 – Reduce time and cost for component certification	SOA is the time and cost to certify the pogo Z-baffle, which is still to be certified, by the SLS program.	Reduce cost for component certification of at least 10% through application of computational tools to reduce testing and characterization burden for certification.	Reduce certification costs by 20%.

MGI Technical Accomplishments and Technical Challenges

FY15 Technical Accomplishment

- **New models were developed of the melt pool and thermal effects within a build and build plate.**
  - These models will be validated and used to continue assisting SLS in developing improved processing parameters on a new SLM system.
  - A TIM was conducted at MSFC. Greater collaboration between the MGI team and the SLS manufacturing team was created. The SLS manufacturing team has allowed the MGI team direct access to one of the SLM systems and the in-situ monitoring cameras on this system.

Technical challenges

- Close coordination between work at centers and needs of SLS Project is required and has presented a challenge.
- Lack of existing material properties and process parameters from SLS Project.

Materials Genome Initiative
Technical Accomplishment: Thermal Modeling of Additive Manufacturing

Milestone: Deliver component design tool. *Completed August 2015*

Deliverable: Demonstrate a residual stress prediction model for an identified component to be manufactured by the SLS program.

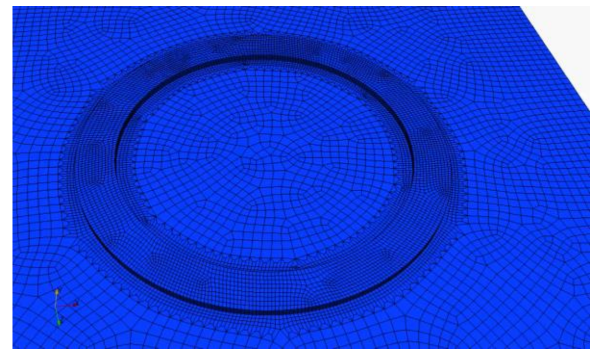
Problem: The performance of additive manufactured parts relies on the thermal history throughout an entire component. This requires understanding of the thermal history of entire components for material from the molten state to room temperature.

Objective: Develop thermal models to predict material solidification and cooling as a part is manufactured. These models will be used to predict part distortion and residual stress and to guide the manufacturing process to reduce the time and cost to integrate additively manufactured components in service.

Approach: 3D FEM models incorporating transient heat diffusion with phase change (thermal model) and Eigen strains (distortion and residual stress models) were developed and compared to experimental observations.

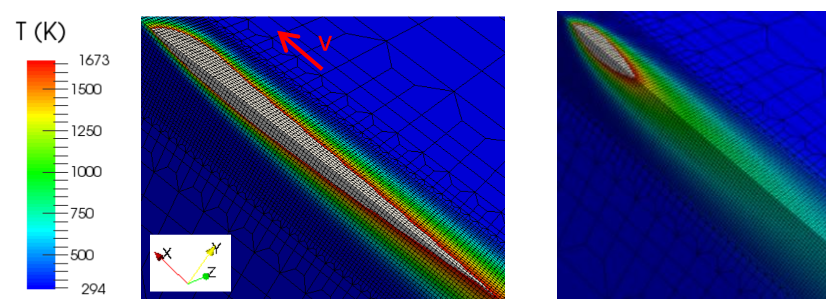
Impact: Thermal models applied to evaluate melt pools for use on old and new ("production") systems. The parameters necessary on new system to develop similar processes is very different. These modified parameters have been supplied to MSFC.

Thermal model of SLM build (powder bed not shown)



Thermal model of melt pool for adjusted scan speeds on old (M1) and new (X-line) SLM systems

X-line: v=2500 mm/sec M1: v=600 mm/sec



White shows melted region ($T>T_{melt}$)

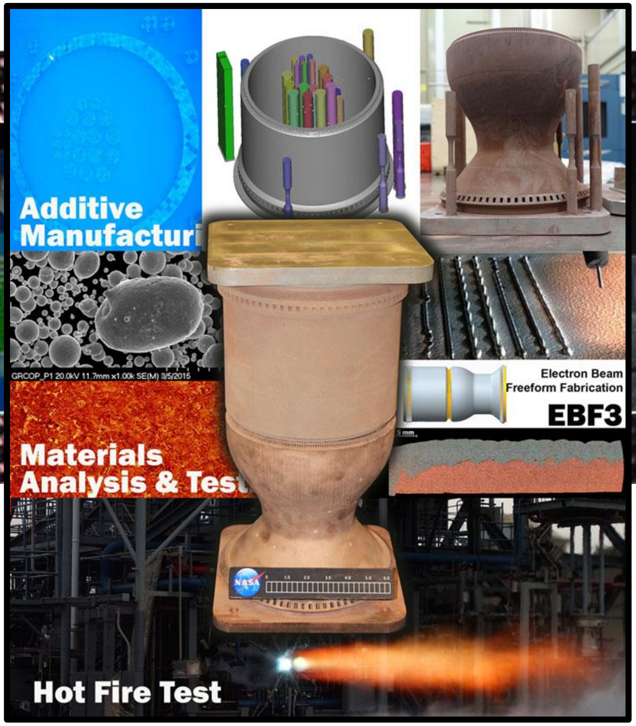
MGI
Plans for FY2016

- Continuation Review scheduled for Oct. 29 at LaRC.

- The element will work closely with the SLS program to define needs from the SLS program where these computational tools can assist in the greatest means possible. Have established partnership with SLS program. (POC: Kristin Morgan)

- Stacey Bagg awarded follow-on proposal to do volumetric residual stress measurements at Oak Ridge National Laboratories (ORNL). Scheduled for Nov. 18-22.

Low Cost Upper Stage-Class Propulsion



AMT
Low Cost Upper Stage-Class Propulsion Overview

The LCUSP will demonstrate the ability to produce a low cost upper stage-class propulsion system using additive manufacturing technologies. LCUSP will do this by (1) developing a copper alloy additive manufacturing design process, (2) building a 25K-class regenerative chamber and nozzle, (3) testing components individually, and (3) demonstrating as a system in a hot fire resistance test.

Integration with other projects/programs and partnerships

- Liquid Propulsion System (LPS) Test Bed being developed at MSFC with additive manufactured components such as injectors, LOx and H2 Turbopumps wants to utilize the LCUSP Combustion Chamber or utilize the capability established under this project to fabricate a chamber.
- Industry partners are investigating possible partnerships with LCUSP for possible opportunities for fabrication of SLM combustion chambers.

Technology Infusion Plan:

PC, Propulsion, HEOMD, Potential use in manufacturing process of flight engines 2017. Military & Industry (SpaceX, Aerojet-Rocketdyne, Orbital-ATK, ULA, Blue Origin, ASRC Federal, numerous copper machine shops, suppliers, and electronics manufactories.

Infusion Status as of September 2015: Fabricated GRCop-84 Combustion Chamber Liners & applied Inconel625 on SLM GRCop-84 samples. Testing and Inspections are on-going with good results thus far.

Key Personnel:

Project Manager: John Vickers

Project Element Manager: Tony Kim

Lead Center: MSFC

Supporting Centers: LaRC & GRC

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Push

Key Facts:

GCD Theme: LMAM, Lightweight Materials and Advanced Manufacturing

Execution Status: Year 2 of 3

Technology State Date: April 2014

Technology End Date: June 2017

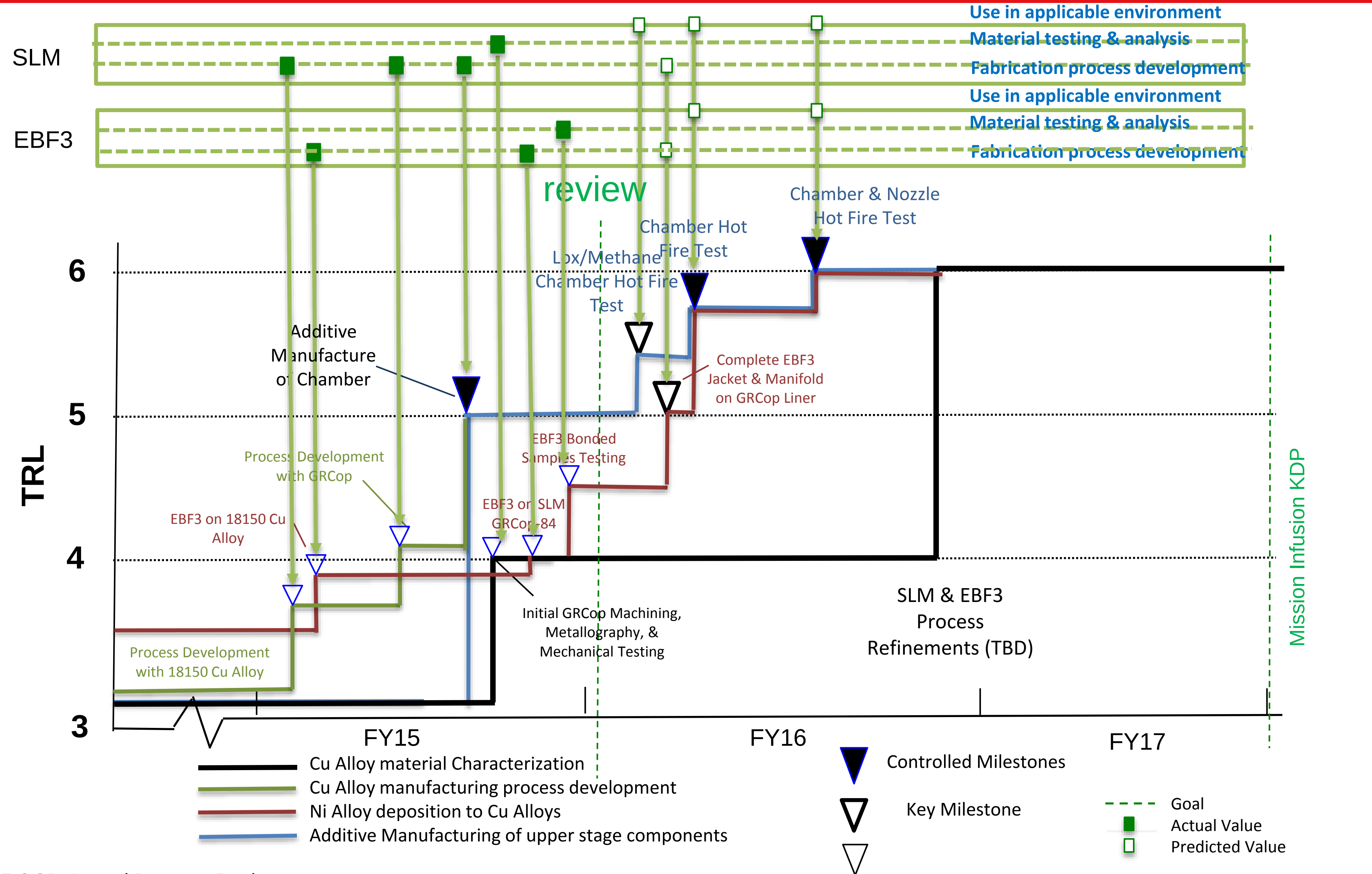
Technology TRL Start: 3

Technology TRL End: 6

Technology Current TRL: 4

Technology Lifecycle Phase: Implementation (Phase C/D)

LCUSP Component and System TRL Quarterly Assessment



LCUSP Performance

- **Technology Advancements**
  - Selective Laser Melting (SLM) fabrication with GRCop-84 powder for rocket components. (combustion chamber liner)
  - Electron Beam Free Form Fabrication (EBF3) application of In625 on SLM GRCop-84. (structural jacket for combustion chamber)
- **Technology advances mean**
  - Additive Manufacturing techniques to reduce cost and shorten schedule as well as produce intricate rocket propulsion components that may have been expensive or impossible to build with conventional techniques.
- **Technology Push**

Key Performance Parameters			
Performance Parameter	State of the Art	Threshold Value	Project Goal
Process control of using Copper via SLM	SLM demonstrated with Inconel 718, Inconel 625, and Al 357, and CoCr by MSFC, but not with copper	Demonstrate parameter set that allows fabrication of monolithic structures to be used for mechanical properties and surface finish testing	Develop an optimized parameter set to maximize build speed, control surface finish, and maximize mechanical properties of SLM copper
Copper alloy material characterization using SLM	Not established for copper	SLM'd GRCop-84 thermal conductivity at 90% of baseline extruded GRCop and remaining material properties at or greater than those of OFHC Copper	90% of baseline extruded GRCop material properties
Deposition of nickel alloy to SLM Copper	Demonstrated for pure nickel to pure copper, but not for nickel alloys to copper alloys	Deposition of nickel alloy to copper alloy that remains intact at the bod through a thermal cycle and with minimum defects	Deposition of nickel alloy onto copper alloy with a ductile transition zone and mechanical properties equivalent to cast annealed condition
Manufacture of AM upper stage engine components	SLM upper stage engine components demonstrated with Inconel 718, Inconel 625 by MSFC, but not with Copper (GRCop) chambers	Demonstrate build of subscale components or subassemblies with properties and geometry sufficient to be utilized in initial subscale testing	Demonstrate build of full-scale monolithic GRCop component parts with materials properties and geometric tolerance meeting key design features that allow successful tests with flight like conditions

LCUSP Technical Accomplishments and Technical Challenges

- Fabrication of 2 sets of SLM GRCop-84 Combustion Chamber Liners with coolant channels.
- A new re-coater system with an array of blades was invented, developed and implemented to mitigate residual stress deformation (>30 micron divots) avoiding propagation of perturbations on SLM. A patent may be pursued for this solution.
- Build Plate bonding challenge would cause failed part, but was overcome by using a steel build plate with a “primed” by printing 1mm Inconel 718 layer.
- Obtaining GRCop-84 Power from vendor that delayed the project schedule significantly but mitigated with SLM practice with more common copper powder surrogates.
- High reflectivity of copper powder for SLM limiting the amount of energy reaching the powder affecting melt pool and thereby affecting densification and angled laser application to avoid possible damage to optics and laser.
- Oxidation of GRCop-84 during Hot Iso-static Press (HIP).
- EBF3 Machine “electron beam current run away” error condition was addressed by professional maintenance service to the EBF3 control system.

LCUSP Plans for FY2016

- **Plans for FY16**
  - SLM GRCop-84 Regen Methane Chamber Hot Fire. (Nov. 2015)
  - Application of EBF3 Inconel 625 Jacket on SLM GRCop-84 Liners.
    - On 1st set of liners (pathfinder)
    - On 2nd set of liners for the Hot Fire Test Article
  - Fabricate SLM Nickel Regen Nozzle.
  - Hot Fire test of LCUSP Combustion Chamber (March 2016) & integrated Combustion Chamber/Nozzle. (April/May 2016)
  - Material Property Characterization. (Testing & Analysis)

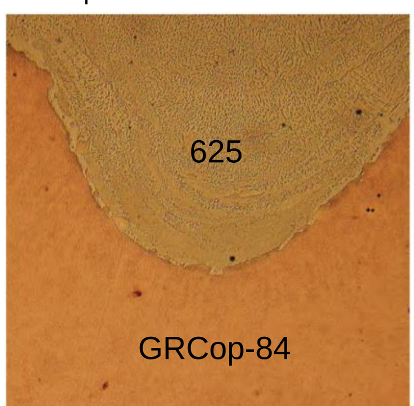
LCUSP Year End Review

MSFC

- Second set of full forward and aft segments are complete.
- Allows the original set to be used in riskier process trials (HIP and EBF3) which provides the relevant geometry to maximize learning opportunities from the trials.
- 2nd Set uses lessons learned and has improved surface finish.
- Witness samples and materials properties specimens run with part to characterize the build quality further and progress on our materials property tasks.
- **Inconel 718 Nozzle** Conceptual Design is complete and detailed design is progressing.
- Weld prep and final machining drawings for the chamber are released.

GRC

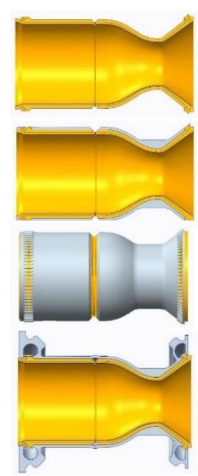
- Presented preliminary results of SLM GRCop-84 characterization at **JANNAF meeting** in Nashville.
- Performed initial tensile testing in Inco 625. Mixed results indicate the need to HIP assembly following jacket build.
- Auger spectroscopy on white **precipitate phase observed** in GRCop-84 post HIP indicates that it is elemental Chromium. This finding is not a cause for concern.
- Initial microscopy on Inco 625 / GRCop-84 interface completed, and we have been working with LaRC to refine processing parameters.
- Worked through **oxidation issues** associated with our HIP vendor and have HIP'd two sets of GRCop-84 liners.



LaRC

Electron Beam Freeform Fabrication (EBF3)

- EBF3 parameters for application of In625 jacket have been developed and repeatable on 3.5" diameter Cu pipes, weld ring trial, and GRCop-84 SLM channel section.
- Trials building 1.5" diameter In625 manifold revealed challenges such as compressive residual stresses that affect the application. Continued application varying deposition parameters are showing promise.



Step 1: Weld nozzle to chamber

Step 2: Deposit structural jacket

Step 3: Deposit support vanes

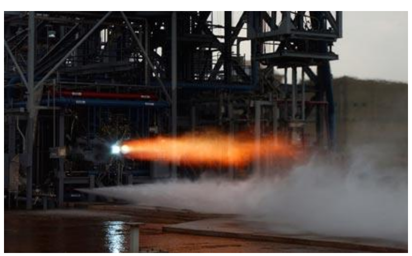
Step 4: Deposit manifolds

Test @ MSFC

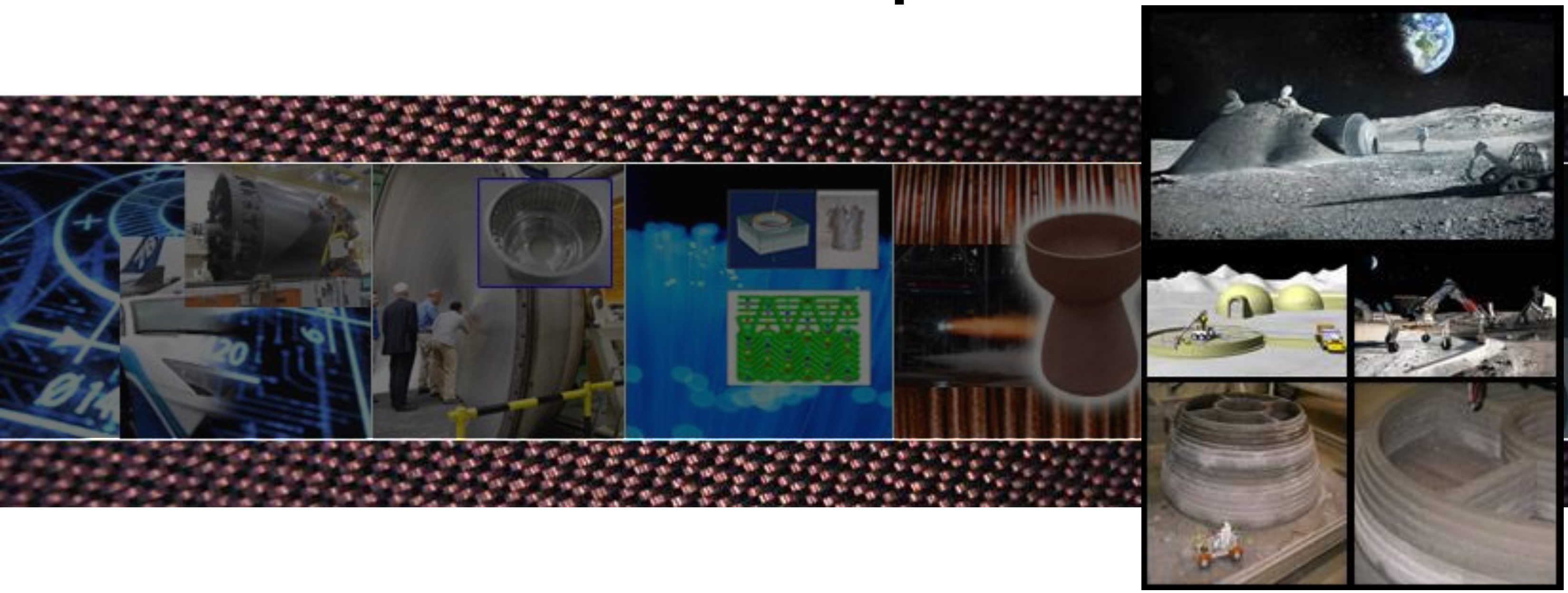
A LOx/Methane regenerative combustion chamber made with GRCop-84 is planned for fabrication in Sept and the Hot Fire Test is scheduled for Sept/Oct 2015.

Chamber Hot Fire Test Start Expected to start Jan 2016. Approximately 2 month test of SLM copper chamber with nickel based structural jacket followed immediately with integrated nozzle.

Once LCUSP hot fire is accomplished, further integrated testing of the chamber and nozzle assembly maybe possible on the Liquid Propulsion System (LPS) Test Bed perhaps late FY16 w/ Lox & H2 Turbopump.



Additive Construction with Mobile Emplacement



ACME Overview

- Additive Construction with Mobile Emplacement (ACME) is 2D and 3D printing on a large (structure) scale using in-situ resources for construction materials.
- ACME is a joint effort between NASA/GCD and the U.S. Army Corps of Engineers (USACE).
- Applications are in the construction of infrastructure on terrestrial and planetary surfaces.

Integration with other projects/programs and partnerships

- Partnership between MSFC, KSC, the USACE, Contour Crafting Corporation (CCC), and the Pacific International Space Center for Exploration Systems (PISCES).
- A portion of the work completed through a collaboration with the JSC Hypervelocity Impact group.
- ACME personnel involved in the 3D Printed Habitat Centennial Challenge rules committee and serving as judges and subject matter experts (SME) for the various activities.
- 3D printing materials research involves members of industry (BASF, Premier Magnesia) and academia (Auburn University, Mississippi State)
- In-Situ Resource Utilization (ISRU) project integration & uses

Technology Infusion Plan:

- Potential Customer: Plan for technology use by USACE in domestic and international venues. HEOMD, Industry also potential customers.
- Phased approach for maturation of hardware: ACME units will serve as prototypes for the USACE devices which will be used in forward bases for B-Huts.
- ACME project advances in-situ resource utilization (ISRU) , contour crafting, and zero launch mass construction materials development.
- Designed for use on planetary surfaces, can be deployed prior to human landing. Technology developed has terrestrial applications, and has large implications for the art of the possible in construction

Key Personnel:

Project Manager: John Vickers

Project Element Managers: Niki Werkheiser and Rob Mueller

Lead Center: Co-led by MSFC and KSC

Supporting Centers: None

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Push for planetary ISRU, pull for terrestrial applications

Key Facts:

GCD Theme: LMAM

Execution Status: Year 1 of 3

Technology Start Date: 1/31/15

Technology End Date: 9/30/17

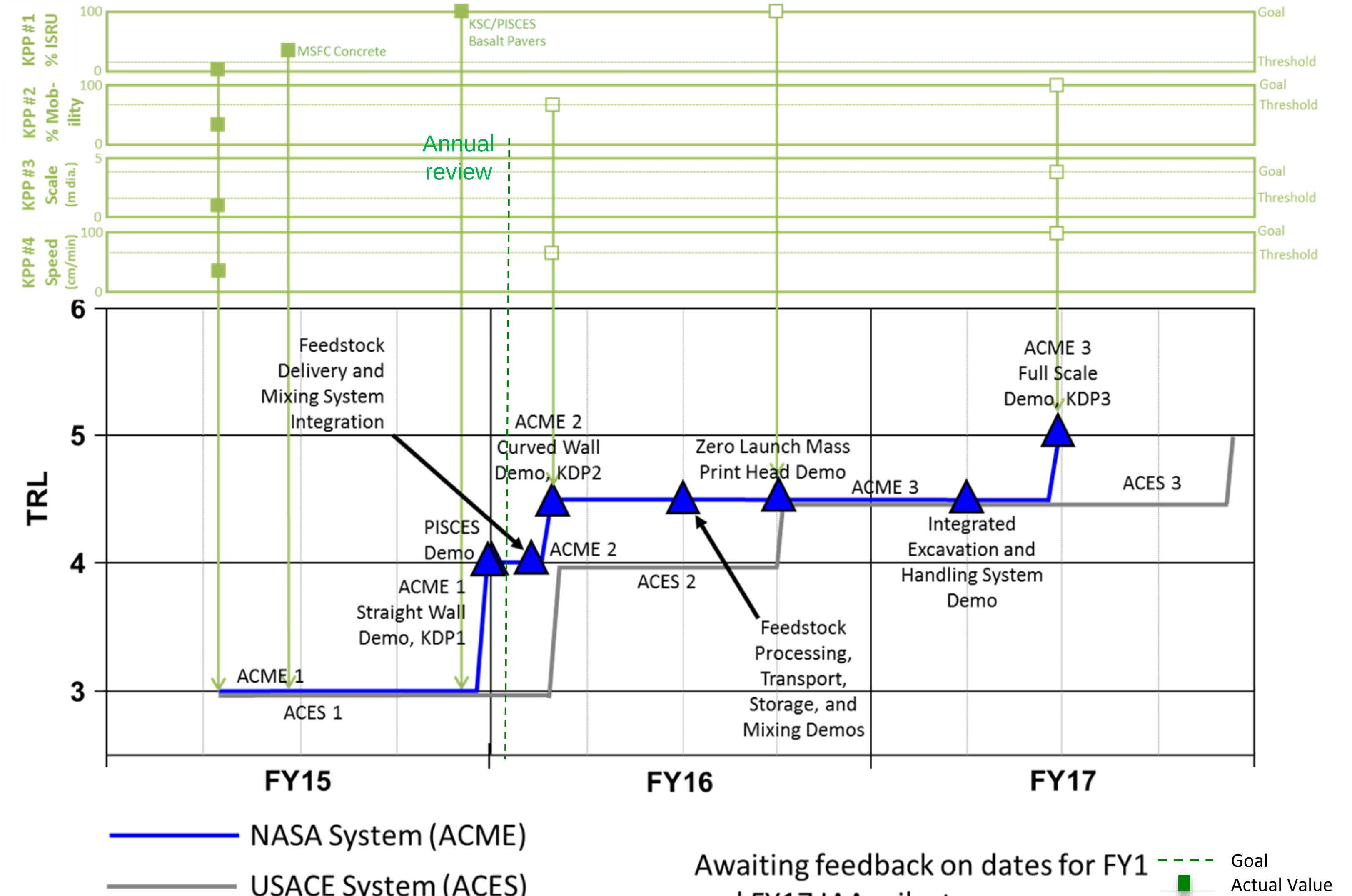
Technology TRL Start: 3

Technology TRL End: 5

Technology Current TRL: 4

Technology Lifecycle Phase: Formulation (Phase A)

ACME
Component and System TRL/KPP Assessment



Awaiting feedback on dates for FY16 and FY17 IAA milestones.

AMT
ACME Performance

- **Technology Advancement**
  - Construction Material – an extrudable martian simulant concrete mixture.
  - Basalt Pavers – successful design for crack-free sintered basalt pavers.
  - Feedstock Size-sorting/Delivery – successful delivery of size-sorted material.
- **Technology advance means**
  - Proof-of-concept for contour crafting technologies / additive construction applications in in-situ resource utilization.
  - Accommodating the cooling properties of basalt by paver design; advancing design based on construction material properties.
  - Proof-of-concept for size-sorting and delivery of in-situ materials for printing.
- **Technology push and pull**

Key Performance Parameters

Performance Parameter	State of the Art	Threshold Value	Project Goal
KPP-1 Construction Material	Contour crafting with water-based concrete	Use in-situ regolith materials for manufacturing feedstock using imported binders	Use in-situ regolith materials for manufacturing feedstock using no imported feedstock materials
KPP-2 Emplacement	Gantry mechanisms that are fixed in locations	Non-gantry robots in fixed locations	Mobile-ready print system
KPP-3 Construction Scale	Small concrete dome: ~1m high	In-situ regolith structure pad and curved wall; 1m diameter dome	In-situ regolith structure pad and curved wall; 4m diameter dome
KPP-4 Print Head Construction Speed (1cm thick layers material)	30cm/minute	60cm/minute	100cm/minute

ACME Technical Accomplishments and Technical Challenges

ACME Technical Accomplishments:

- Contour crafted martian simulant concrete wall segment constructed.
- Hypervelocity impact testing of martian simulant concrete.
- Demonstration of an delivery/size sorting prototype system.
- Demonstration of remote site preparation in a planetary analog location.

Technical Challenges:

- Not all concrete mixtures can be extruded, and using basaltic aggregate is non-standard. Mixtures were experimentally modified to find an extrudable (3D printable) simulant-bearing concrete.
- Designing paver molds to accommodate the thermal properties of simulant (which tends to shrink when cooled), as well as identifying the proper sintering temperature profile.
- Tele-operated robotic emplacement of inter-locking pavers; various concepts have been traded to select the best design for constructing the Vertical Takeoff/Vertical Landing pad.

ACME Plans for FY2016

Plans for FY16

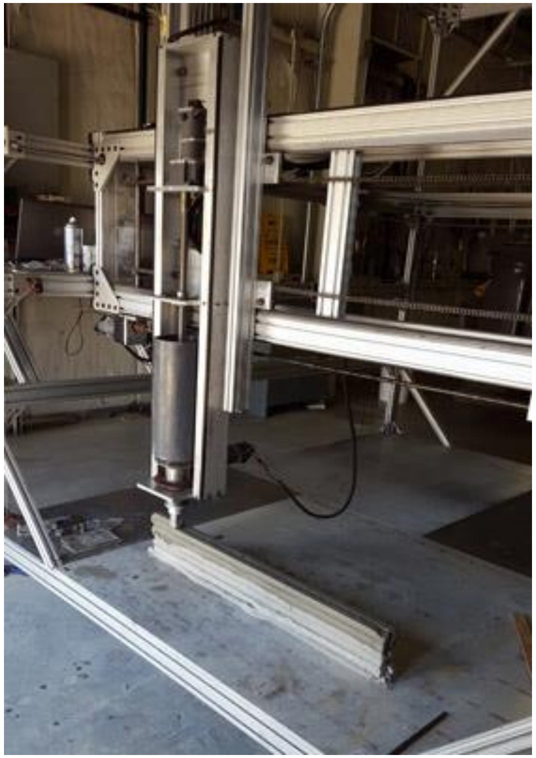
- Sub-scale curved wall additive construction at lab location using regolith simulant materials (11/23/15)
- Construction of Vertical Takeoff-Vertical Landing (VTVL) pad at PISCES location (12/31/15)
- Feedstock processing/transport hardware demonstration (3/31/16)
- Binder storage and mixing hardware demonstration (4/30/16)
- Pallet design & fabrication (4/30/16)
- Zero launch mass construction material print head demonstration (6/30/16)
- Testing of VTVL pad (7/31/16)

Threats

- None currently identified.

ACME Year End Review
Martian Concrete Straight Wall Segment

- **Construction of a straight wall segment using martian simulant concrete. (completed 9/25/15)**



National Center for Advanced Manufacturing (NCAM)

AMT
National Center for Advanced Manufacturing (NCAM) Overview

NCAM seeks to create partnerships to solve technology-based problems – ranging from activities with one or more companies to solutions to national grand challenge problems. Specifically, to create a public/private partnership in which the resources of NCAM and MAF (and beyond) are integrated with the broader capabilities of industry and research organizations to solve problems that are important to align with NASA missions and the U.S. manufacturing base. Public/private partnership – Cooperative Agreement between NASA, the State of Louisiana, Louisiana State University. Located at the Michoud Assembly Facility, New Orleans, LA. Led by Louisiana Center for Manufacturing Sciences.

Integration with other projects/programs and partnerships

- STMD, HEOMD, other Centers
- Industry, Academia
- OGA's (e.g., DOD, DOE, DOC, USDA, NASA, NSF)
- Public/private partnership – Cooperative Agreement between NASA, the State of Louisiana, Louisiana State University. Located at the Michoud Assembly Facility, New Orleans, LA. Led by Louisiana Center for Manufacturing Sciences.

Technology Infusion Plan:

- PC
- Potential customer infusion (TDM, HEOMD, SMD, OGA, Industry)
- Leverage
- Research and Innovation Ecosystem - Foster an integrated framework of technology partners – Government, Industry, Academia
- Focus areas: composites, metals joining, digital manufacturing, robotics and automation

Key Personnel:

Program Element Manager:

Project Manager: John Vickers

Lead Center: MSFC

Supporting Centers: N/A

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Push and Pull

Key Facts:

GCD Theme: Lightweight Materials and Advanced Manufacturing

Execution Status: Thematic Plan

Technology Start Date: N/A

Technology End Date: N/A

Technology TRL Start: 3

Technology TRL End: 6

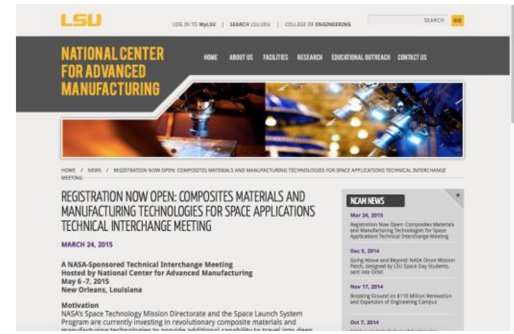
Technology Current TRL: N/A

- **Technology Lifecycle Phase: N/A**

National Center for Advanced Manufacturing Accomplishments

White House Fact Sheet October 27, 2014: President Obama Announces New Actions to Further Strengthen U.S. Manufacturing

"NASA is expanding its efforts to engage industry and academia on advanced manufacturing topics central to the nation's space mission through its National Center of Advanced Manufacturing…"



The NASA National Center for Advanced Manufacturing (NCAM)

- Public/private partnership – NASA, the State of Louisiana, Louisiana State University. Located at the Michoud Assembly Facility, New Orleans, LA. Led by Louisiana Center for Manufacturing Sciences.
- April 1, STMD EPMC: National Center for Advanced Manufacturing (NCAM)
- May 6-7 - Technical Interchange Meeting in composites materials and manufacturing technologies for space applications in New Orleans.
- May 8 - LCMS was selected by NIST for Advanced Manufacturing Technology (AMTech) award valued at $500,000.
- June 16 - NASA, Louisiana Economic Development (LED) and university leaders celebrated the renewal of their partnership in the National Center for Advanced Manufacturing during a signing ceremony in New Orleans.
- August 3 – LSU/NCAM awarded $20 Million NSF grant to form Louisiana Advanced Manufacturing Consortium
- NCAM FSW class - See the video at youtube https://www.youtube.com/watch?v=0YkvdE1Ae8o

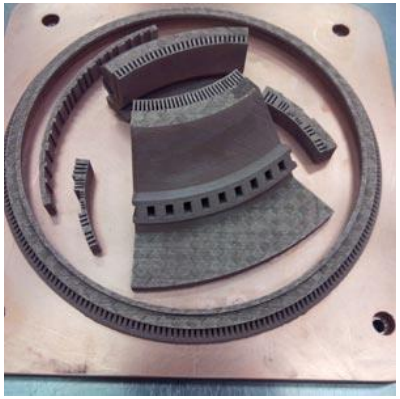
Project Summary Performance

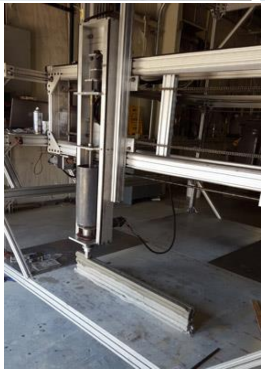
Project	Summary Performance				Rationale
	Technical	Cost	Schedule	Programmatic	
Quarter 1					Schedule yellow due to constraints caused by delays in receiving the GRCop AM powder for LCUSP. Technical yellow is due to concern with AM manufacture of the copper chamber with GRC materials for the LCUSP. Programmatic yellow is due to concern that the ANNST project can meet their objectives with the reduced funds.
Quarter 2					Schedule yellow due to ACME IAA agreement delays and MGI slip of milestone to insure proper measurement of material properties can be provided. Programmatic yellow is due to low cost and schedule reserve on ANNST and ACME.
Quarter 3					Technical yellow due to LCUSP technical challenges of material process development for EBF3 In625. Also ACME difficulties with extruding martian simulant concrete. Schedule yellow due to ACME, LCUSP,MGI and BMG all having schedule issues and concerns affecting milestones.
Quarter 4					Schedule is yellow due to delays in the LCUSP Chamber Hot Fire Test.

Significant Technical Challenges

- LCUSP
  - Technical challenges of material process development for EBF3 In625 on GRCop.
- MGI
  - Close coordination between work at centers and needs of SLS Project is required and has presented a challenge.
  - Lack of existing material properties and process parameters from SLS Project.

Year End Review



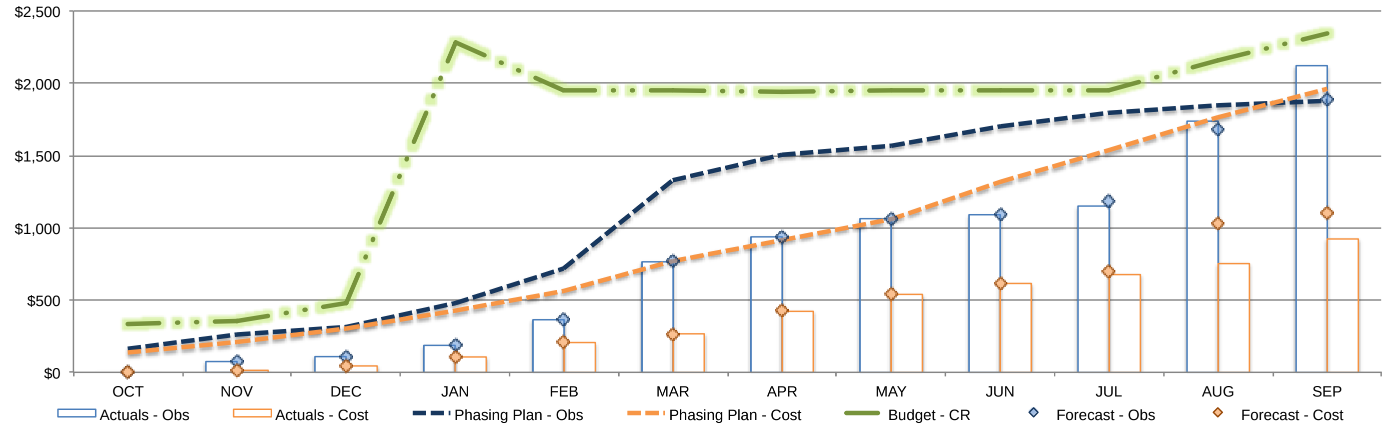


Back Up Charts

<These charts feed Quarterly Reporting. All charts are required. >

Resources: Non-Labor Obligations and Cost

PY 2015 Non-Labor Financial Status



	Cum ($K)			OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Carry Out
	Budget			334.0	358.5	478.0	2,279.4	1,950.7	1,950.7	1,944.7	1,946.7	1,951.4	1,948.5	2,153.8	2,342.1	
Obs	Phasing Plan (RLS)			163.1	262.9	313.9	483.1	721.6	1,326.1	1,503.8	1,567.5	1,698.4	1,791.1	1,845.8	1,873.3	468.8
	Actuals			0.0	74.8	108.7	186.4	364.1	765.2	937.2	1,063.1	1,090.6	1,150.6	1,737.8	2,121.3	220.7
	Forecast			-	75.0	109.0	187.0	365.0	766.0	938.0	1,064.0	1,091.0	1,181.0	1,681.0	1,891.0	451.1
Cost	Phasing Plan (RLS)			136.7	207.6	305.9	423.6	565.1	774.4	917.7	1,059.2	1,313.8	1,534.4	1,766.4	1,959.1	383.0
	Actuals			0.0	13.9	44.3	106.5	206.2	266.8	422.4	539.8	615.3	676.4	752.7	922.8	1,419.3
	Forecast			-	14.0	44.0	106.0	206.0	267.0	423.0	540.0	615.0	695.0	1,033.0	1,099.0	1,243.1

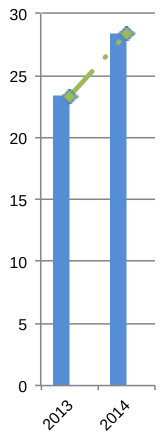
	YTD Status			Explanation required for YTD Variance in excess of 5% from PM Forecast (shaded red)
'15 Obs	Phasing	$	1,873	The obligations are ahead of plan due to NCAM funds obligating prior to the end of the fiscal year and ahead of plan.
	Forecast*	$	1,891	
	Actuals	$	2,121	
	Variance	$	230	
'15 Cost	Phasing	$	1,959	The costs are behind plan for the year due to the delays in the LCUSP Hot Fire Test and the obligations not occurring as soon as initially anticipated.
	Forecast*	$	1,099	
	Actuals	$	923	
	Variance	$	(176)	

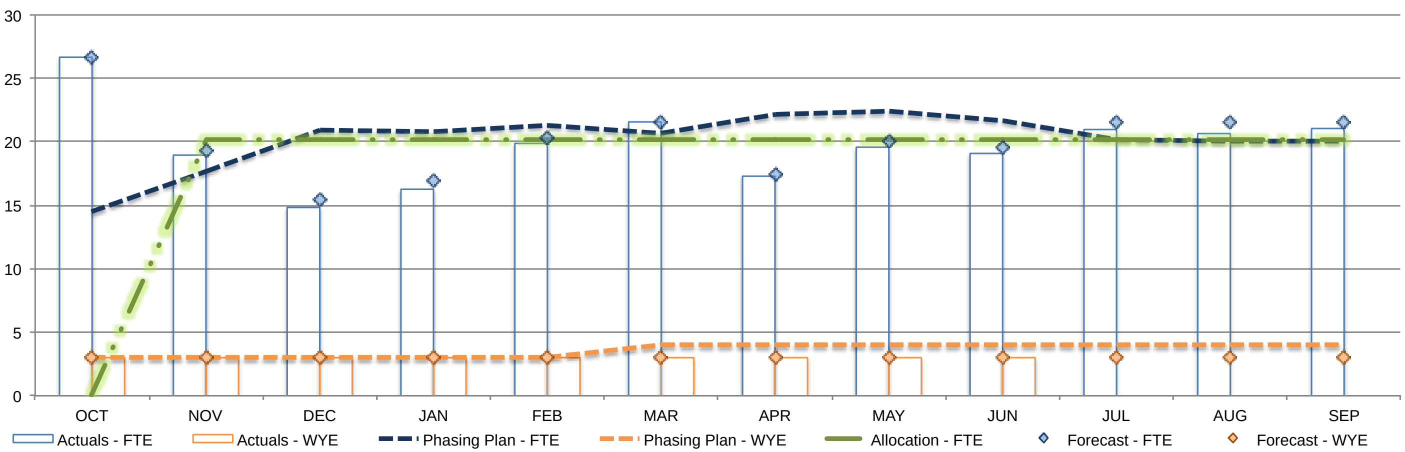
* Forecast value is a snapshot of the Forecast from the previous reporting period

AMT is 47% Costed and 91% Obligated for FY2015

Resources: Total Project Workforce FTEs/WYEs

PY 2015 Workforce Status





	Incremental	2013	2014	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	2014 Avg
FTE	Allocation	23.4	28.4	0.0	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2
	Phasing Plan (RLS)			14.5	17.7	21.0	20.8	21.4	20.7	22.2	22.4	21.7	20.2	20.1	20.1	20.2
	Actuals	23.4	28.4	26.7	19.0	14.8	16.3	19.9	21.6	17.3	19.6	19.1	21.0	20.7	21.1	19.7
	Forecast			26.7	19.3	15.5	17.0	20.3	21.6	17.5	20.1	19.6	21.6	21.6	21.6	20.2
WYE	Phasing Plan (RLS)			3.0	3.0	3.0	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.6
	Actuals	0.0	0.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	0.0	0.0	0.0	2.3
	Forecast			3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

	YTD Status		Explanation required for YTD Variance in excess of 5% from PM Forecast (shaded red)
'15 FTE	Phasing	20.2	The FTEs are slightly behind plan due to ACME starting off the year slow due to delays with interagency agreement.
	Forecast*	20.2	
	Actuals	19.7	
	Variance	(0.5)	
'15 WYE	Phasing	3.6	The WYEs are behind plan for the year due to the delays in the LCUSP Hot Fire Test.
	Forecast*	3.0	
	Actuals	2.3	
	Variance	(0.8)	

* Forecast value is a snapshot of the Forecast from the previous reporting period

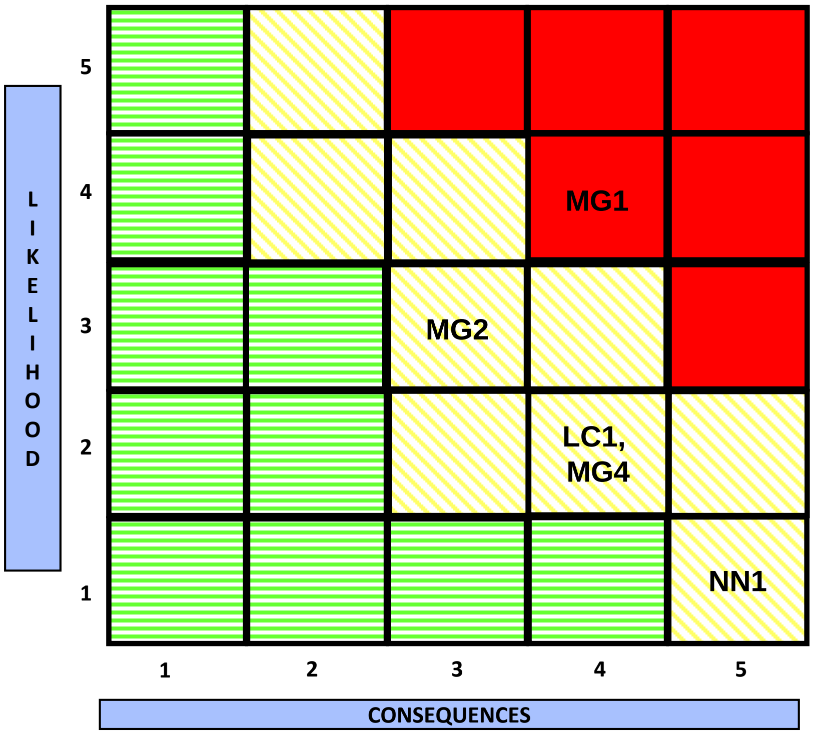
AMT
ANNST Over Guide Requests for FY16

- **Over-Guideline Requests**
  - **Leverage FTE support from STMD and SLS**
    - FTE requests below reflect additional FTE needed for each task
  - **Post-sounding rocket flight and ground test data analysis**
    - 0.2 FTE and $30K procurement
    - Required due to sounding rocket flight being delayed to October 7.
    - Decision needed by October 30, 2015
  - **Support for maximizing stiffener height**
    - 0.2 FTE and $20K procurement
    - Partnership with forming vendor to modify existing sounding rocket mandrel and produce scaled-up cylinders with taller stiffeners.
    - Decision needed by December 31, 2015
  - **Support for scale-up of ISC process to 3 meters and develop technology infusion plan**
    - 0.5 FTE and $650K procurement
    - Have a confirmed opportunity to advance the ISC process to launch vehicle scale and have firm commitments from ESA and DLR for continued partnership. Matching NASA funding required for continued partnership.
    - Decision needed by December 31, 2015

AMT
ACME Over Guide Requests for FY17

- **Over-Guideline Requests**
  - **Partner with JPL and Caterpillar for a mobility system for the nozzle.**
    - **Like a robot arm with awesome stability/accuracy software.**
    - **Mounted on a CAT system.**
  - **Team developing proposal and expect to submit around December 2015.**

ADVANCED MANUFACTURING TECHNOLOGY
Risk Summary



ID	Trend	Approach/ Affinity	Risk Title
LC1	↓	M/T	EBF3 weld technology
NN1	→	M/T	First flight of near net shape (NNS) sounding rocket (SR) part
MG1	→	M/T	In-situ monitoring system setup and verification
MG2	→	M/T	Heat input model from physics-based model
MG4	→	M/T	Material properties

Criticality
- High
- Med
- Low

L x C Trend
- ⇩ Decreasing (Improving)
- ⇧ Increasing (Worsening)
- ⇨ Unchanged
- ☐ New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: T-Technical C-Cost Sc-Schedule
- Sa-Safety

Updated 10/7/15

Advanced Near Net Shape Technology
Risk Summary

Updated 9/15/15

Current Risk Status

Likelihood					
5					
4					
3					
2					
1		~~3**~~		~~2**~~	1*
	1	2	3	4	5
	Consequence				

*Consequence to sounding rocket flight
**Consequence to ISC process development

Risks
1. First flight of near net shape (NNS) sounding rocket (SR) part
2. Low fabrication schedule margin
3. NNS SR Part Specifications

Risk ID	Trend	Affinity	Approach
1	⇩	T	M
2	⇩	Sc	M
3	⇩	T	M

Criticality
- High
- Med
- Low

L x C Trend
- ⇩ Decreasing (Improving)
- ⇧ Increasing (Worsening)
- ⇨ Unchanged
- ☐ New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: T-Technical C-Cost Sc-Schedule Sa-Safety

AMT/ ANNST

First Flight of Near Net Shape Sounding Rocket Part

Updated 9/15/15

Risk ID #
1

Trend

MED

Criticality

Current L/C
1x5

Affinity Group
Technical

Planned Closure
10/6/15

Open Date
05/05/2015

Risk Statement : **Approach: Mitigate**

Given that the near net shape (NNS) part being fabricated for the sounding rocket (SR) using the Integrally Stiffened Cylinder (ISC) manufacturing process has not flown under the SR program, there is increased risk of the skin structurally failing in flight.

Context

Status

Completed structural analysis using flight loads specific to the location of the ISC part on the sounding rocket and results indicate a very high margin of safety.

Bend test of an identical part manufactured using the ISC process confirmed strain levels below 10% of material yield at maximum anticipated flight loads, confirming a large margin of safety.

Bend testing of the complete payload stack, with flight cylinder integrated, confirmed deflections within anticipated tolerances at maximum anticipated flight loads.

Risk is at minimum achievable through mitigation approaches.

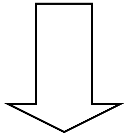
Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
A structural analysis of the sounding rocket part will be conducted based on estimated flight loads and anticipated material properties.		4/17/15		4/30/15	1x5
An identical part manufactured using the ISC process will be subjected to bend testing prior to payload integration to characterize strength.				9/9/15	1x5
The flight part will be subjected to integration and testing, including bend testing, in the payload flight configuration.				9/15/15	1x5
A conventionally manufactured part will be available for payload integration if the test results on the NNS part are not satisfactory.				8/17/15	1x1

AMT/ ANNST

Low Fabrication Schedule Margin

Updated 9/15/15

Risk ID #
2



Trend

LOW

Criticality

Current L/C
1x4

Affinity Group
Schedule

Planned Closure
06/14/2015

Open Date
05/05/2015

Risk Statement : **Approach: Mitigate**

Given that fabrication of this sounding rocket part involves developing new processing parameters for longer cylinder lengths, the ISC process development may prove more difficult than expected, thereby causing schedule impact on delivery of the sounding rocket part. On-time delivery is also subject to material availability and international shipping regulations.

Context

Status

Aluminum 6061 material delivered to vendor on 4/27/2015.

Fabricated parts delivered to Wallops Flight Facility on June 12. Risk can be closed.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
Perform an expanded search for suitable aluminum alloy 6061 product forms, both domestic and international.		3/1/15		3/30/15	2x4
Research international shipping regulations to expedite material delivery to forming vendor and final part to Wallops Flight Facility.		3/1/15			2x4
Investigate reducing the forming temperature and preheat time to reduce the total time for part fabrication.		5/7/15		5/22/15	1x4
A conventionally manufactured part will be available for payload integration if the NNS is not delivered on schedule.				6/14/15	1x1
CLOSED				7/22/15	

Updated 9/15/15

Risk ID #
3

Trend

LOW

Criticality

Current L/C
1x2

Affinity Group
Technical

Planned Closure
08/14/2015

Open Date
05/05/2015

Risk Statement : **Approach: Mitigate**

Given that the NNS SR part is the first of this size and geometry to be fabricated using the ISC process there is increased risk that the part cannot be successfully fabricated. Risk is primarily associated with forming a part of larger diameter and length than any prior parts. There is also recognized risk that the part may distort during post-fabrication heat treatment beyond what can be corrected during final machining and that the part will not have mechanical properties at least equivalent to the conventionally manufactured part.

Context

Status

Fabricated cylinders distorted slightly during heat treatment but this can be accommodated during machining of the sounding rocket part.

Mechanical property tests of subscale 6061 cylinders indicated values comparable to handbook properties for other 6061 wrought products.

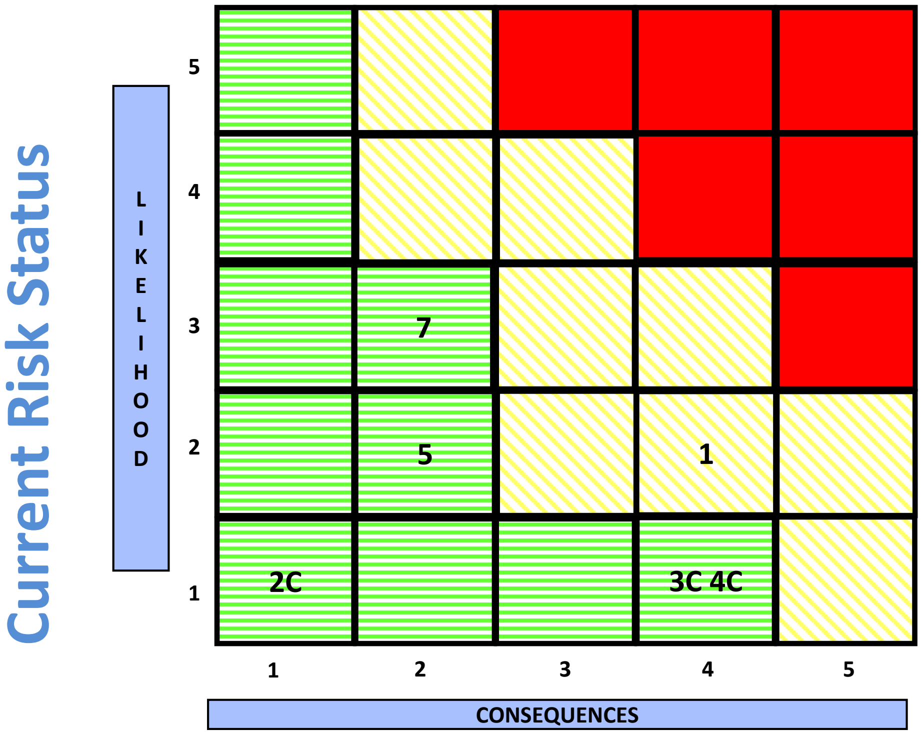
Mechanical property tests on a sounding rocket scale cylinder indicate excellent property uniformity with location and orientation and that values are comparable to handbook properties for 6061 wrought products.

Risk can be closed.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
Design SR part to capitalize on prior experience with aluminum 6061 and geometry (wall thickness; stiffener spacing and size) to increase probability of success.		2/1/15		3/20/15	2x4
Fabricate the ISC part with sufficient wall thickness to correct for post-fabrication distortion.		3/7/15		3/22/15	2x4
Perform preliminary mechanical property tests on subscale 6061 stiffened cylinders fabricated using the ISC process.		4/28/15		5/29/15	1x4
A conventionally manufactured part will be available for payload integration if the NNS is not delivered on schedule.				6/14/15	1x1
Perform mechanical property tests on a sounding rocket scale 6061 stiffened cylinder fabricated using the ISC process.		6/22/15		8/14/15	1x2
CLOSED, pending Project Office concurrence.					

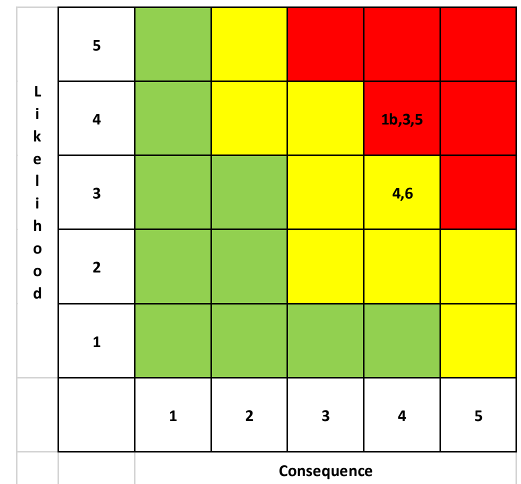
Risk Summary

Updated 9/10/15

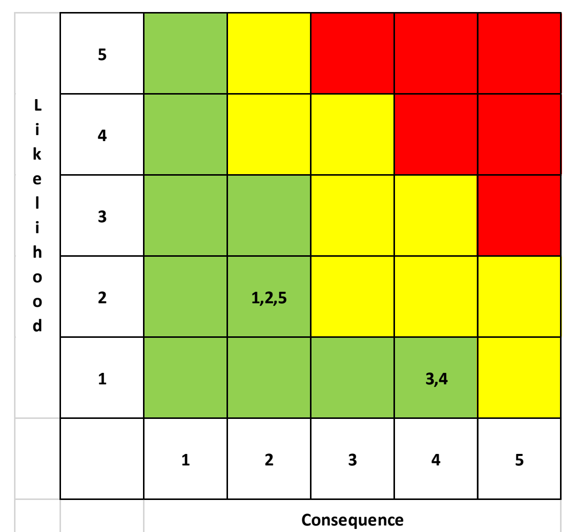


1 -	EBF3 weld technology of Inconel 625 on GRCop-84
2 -	Chamber parts joint and potential leakage (CLOSED)
3 -	GRCop process development difficulty (CLOSED)
4 -	GRCop blockage of coolant passages (CLOSED)
5 -	Coolant passages not adequately cooling chamber
6 -	GRCop powder single vendor (CLOSED)
7 -	EBF3 System maintenance issues could arise

Initial Risk Positions



Risk Positions after Planned Mitigations



AMT/ LCUSP

EBF3 Weld Technology of Inconel 625 on GRCop-84

Risk ID #
1

Trend

MEDIUM

Criticality

Current L/C
2x4

Affinity Group
Technical

Planned Closure
12/25/2015

Open Date
12/17/2014

Risk Statement: **Approach: Mitigate**

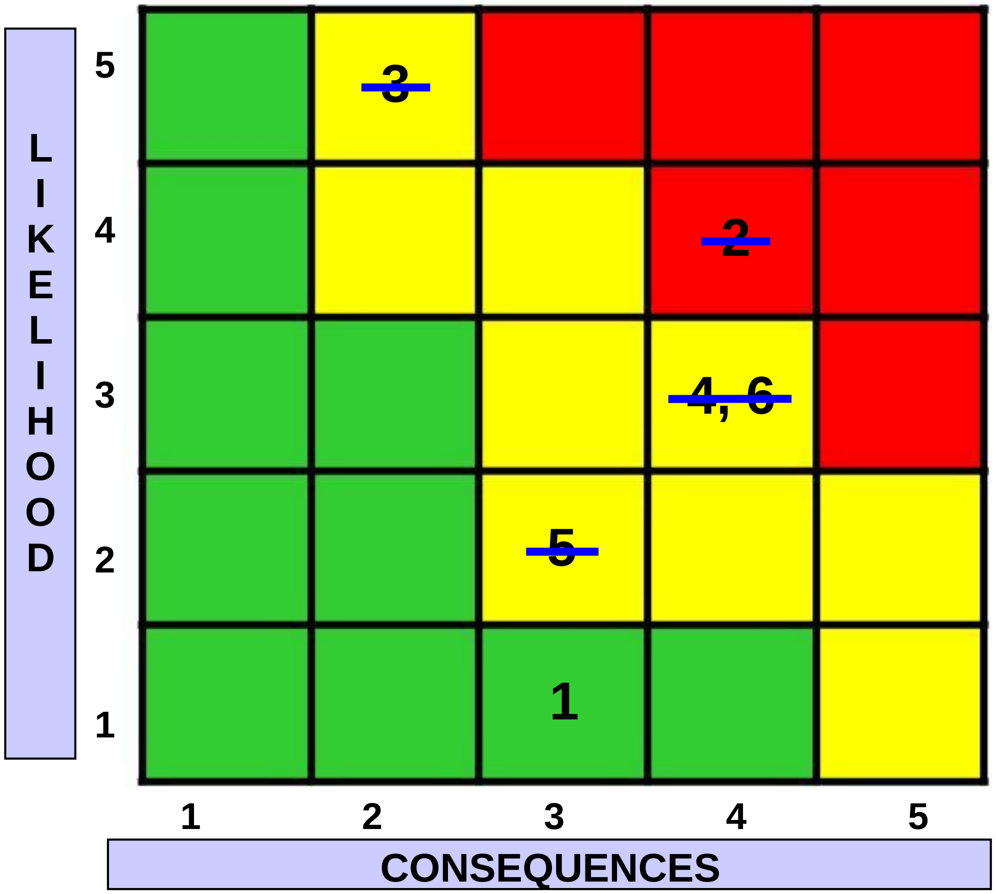
Given that this project involves developing new processing parameters in an effort to deposit a Ni-alloy onto the GRCop liner, there are risks associated with deposition of this jacket and with the modeling of the transition region thereby with the possibility that the combined jacket/liner part does not meet the structural or geometric requirements. The result can impact schedule and technical and additional steps will be need to be taken to allow this application.

Context: EBF3 application of Inconel on other material process has been used before, but the EBF3 application of Inconel on GRCop-84 has never been done previously.

Status: In July & August 2015, extensive application trials were accomplished on 3.5" Cu Tubes and on a 3" tall SLM GRCop-84 chamber section with coolant channels. Currently, the trial samples are at GRC for sectioning, inspection, and analysis. Experiments on available materials have advanced the EBF3 application of the Inconel 625 and the EBF3 operators are focused on the task.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C1.
1. EBF3 deposition parameters are being developed that do not exhibit hot cracking by modifying the total thermal input (limiting the temperature of the Cu will lower the expansion due to CTE) when depositing In625 on to a pure Cu flat plate.				12/2014	3/4
2. Experiments are planned on a C18150 Chamber Simulator to assess the effect of higher strength and hoop stresses in a cylindrical geometry		7/2015		skipped	2/4
3. Prior to EBF3 deposition of the In625 structural jacket on the actual test article, experiments are planned on GRCop subcomponent sections built with internal passages to measure the impact of EBF3 deposition		7/2015		9/2015	2/3
4. Metallurgical analyses are planned to examine the microstructures and precipitate morphologies at the interface between the GRCop and In625		On going as samples are made		12/2015	2/2

AMT
ACME Risk Assessment



Risk ID	Risk Definition	Approach	Est. Closure Date
1	Procurement risk associated with ACME nozzles	Mitigate	~~7/31/15~~ 9/30/15
~~2~~	~~Insufficient procurement dollars for raw materials / hardware procurements~~	~~Closed~~	~~9/30/15~~ ~~7/20/15~~
~~3~~	~~Unnamed personnel needs~~	~~Closed~~	~~9/30/15~~ ~~7/20/15~~
4	~~Insufficient time allowed for major procurements~~	~~Closed~~	~~9/30/15~~ ~~7/20/15~~
~~5~~	~~Presence of GCD Procurement Dollars Results in Reduced USACE Funding in FY16 and FY17~~	~~Closed~~	~~9/30/15~~ ~~2/8/15~~
~~6~~	~~Concrete composition research and development for straight wall~~	~~Accept~~	~~9/30/15~~

	Total			0-30 days			30 - 60 Days			60 - 90 Days			> 90 Days		
R, Y, G	0	0	1	0	0	1	0	2	0	0	2	0	1	5	0
Open	1			1			2			2			6		
Closed	5														

iew

5 X 5 is per System Engineering Handbook NASA/SP-2007-6105

1

Trend

Low

Criticality

Current L/C
1 x 3

Affinity Group
Cost, Schedule

Planned Closure
~~07/31/2015~~
09/30/15

Open Date
01/08/2015

Risk Statement : Given that Contour Crafting Incorporated is a relatively new company run by a single person (who owns the patents on the technology), there is a possibility they do not have the personnel or ownership of the licenses to deliver the nozzle on schedule resulting in delays in the assembly and testing of ACME 2.

Approach: Mitigate

Context: In order to make equipment available to the USACE and continue to mature additive construction technology on schedule, a nozzle must be procured early in FY15.

Status: 09/22/15 Agreement signed. Contract expected the week of 9/28/15. Trend is now down, changed likelihood from 3 to 1.

09/14/15, Dr. Khoshnevis informed us the licensing agreement will be signed at 10AM on 9/22/15.

07/20/15 added "or ownership of the licenses" and "nozzle" to risk statement.

Additional statuses available in notes section of this slide.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1 Line up procurement through an existing NASA contract	Potentially 12% of quote	1/8/15	N/A	~~7/31/15~~ 9/30/15	1/1
2 Procurement can be delayed, but the time allocated to learn from the first NASA/ACME nozzle prior to procurement of the first ACES nozzle will be affected.	none	10/8/15	N/A	1/1/16	1/1

Key and Controlled Milestones

	FY15 Key and Controlled Milestones	Baseline Completion Date	Actual Completion Date	Estimated Completion Date	Variance Explanation
	FY15 Q1 (Oct 1 through Dec 31)				
MGI	Prediction of Deposit Shape (layer height and width) 3D thermal history, residual stress, and Distortion	12/30/14	12/30/14		
LCUS	Begin Mechanical Testing	12/31/14	12/31/14		
	FY15 Q2 (Jan 1 through March 31)				
ANNST	Mandrel Design TIM	1/15/15	1/28/15		
LCUS	Nozzle Design Complete	2/27/15	2/27/15		
LCUS	Begin GRCop Powder Procurement #2	1/30/15	4/30/15		Scheduled for 6 weeks, however Procurement was actually 6 months
	FY15 Q3 (Apr 1 through June 30)				
ANNST	Develop plan for fabrication of sounding rocket component	6/30/15	3/30/15		Develop fabrication, testing, and analysis plans for Sounding Rocket applications for an ISC barrel - Completed early in order to reduce schedule risk
MGI	**Deliver Component Design Tool to Demonstrate Improved Component Reliability for Reduced Mass**	**6/30/15**	**8/31/15**		**Requested 2 month delay due to difficulty with measurement equipment**
LCUS	Application of AM Structural Jacket & Manifolds Complete	5/29/15		10/15/15	The test completion date slipped due to delays in manufacturing complete chamber
LCUS	Begin Hot Fire Test - Chamber	6/30/15		1/6/16	The test completion date slipped due to delays in manufacturing complete chamber
LCUS	**Manufacture of Selective Laser Melting (SLM) Copper Chamber Complete**	**4/30/15**	**4/30/15**		
ACME	Sub-scale Straight Wall Additive Construction Demo at Lab Location	4/30/15	9/25/15		Milestone slipped due to difficulties extruding Martian simulant-based concretes

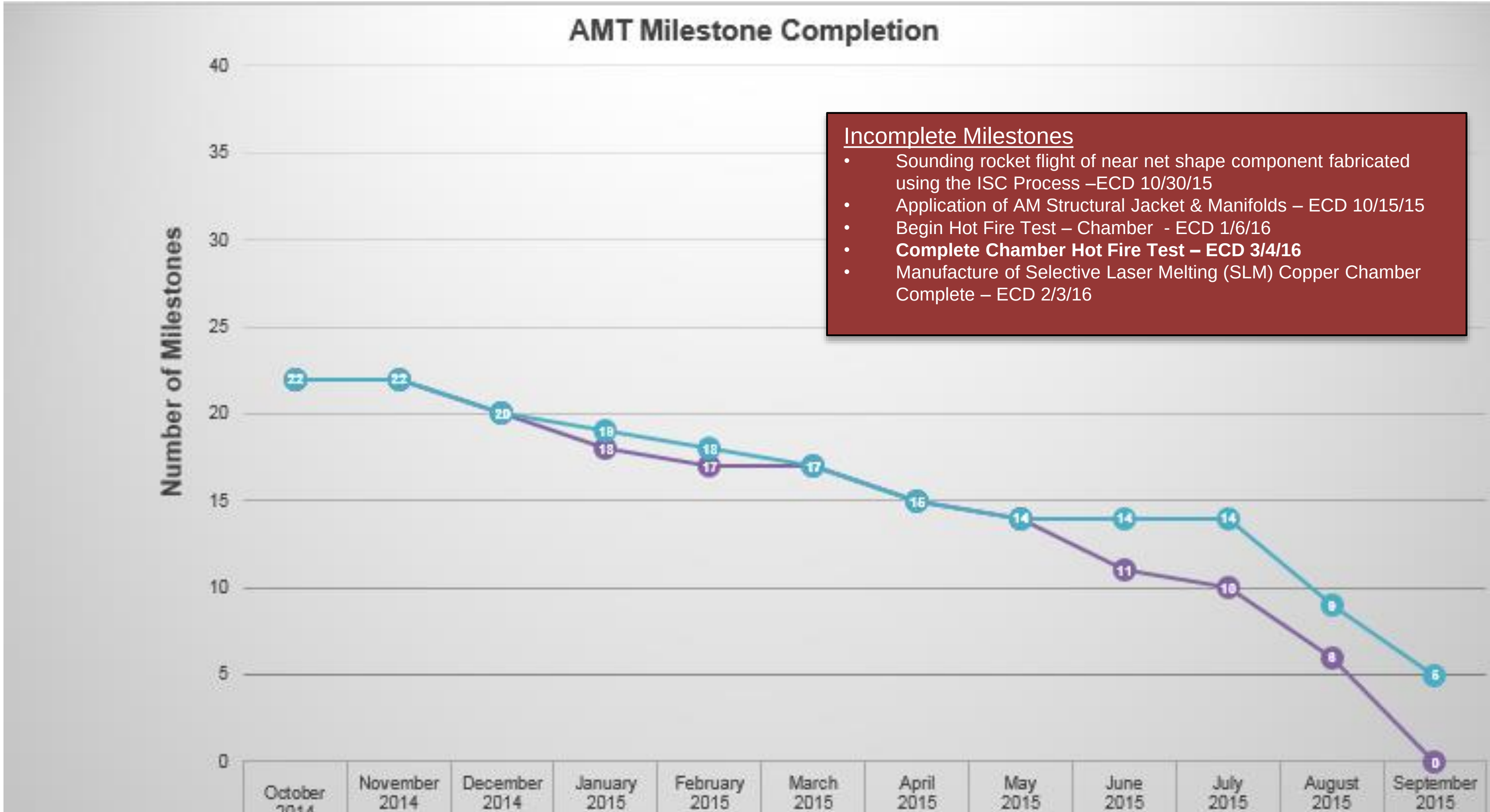
NOTE: Bold font represents Control Milestone

Key and Controlled Milestones

	FY15 Key and Controlled Milestones	Baseline Completion Date	Actual Completion Date	Estimated Completion Date	Variance Explanation
	FY15 Q4 (Jul 1 through Sep 30)				
ANNST	**Design and Fabricate Sounding Rocket Scale Mandrel**	**9/30/15**	**5/31/15**		
ANNST	Structural Analysis of Sounding Rocket Component	9/18/15	8/24/15		Structural analysis shows safety factors above 5 for sounding rocket component at anticipated flight loads; indicates a very high margin of safety.
ANNST	Sounding rocket flight of near net shape component fabricated using the ISC Process.	9/30/15		10/30/15	Sounding rocket flight re-scheduled due to payload integration delays unrelated to the ANNST NNS component.
MGI	Develop Data Schema for Process Parameters of SLM Development Part.	9/30/15	9/30/15		
LCUS	Mechanical Testing Complete - IN625/GRCop Bonded Samples	7/31/15	8/12/15		Mico-Structural Analysis Complete, Mechanical Test Coupons planned to be built and tested in 2nd Quarter of 2016 for IN625/GRCop Bonded Samples. Slip resulted from lack of GRCop availability and EBF3 equipment problems.
LCUS	**Complete Chamber Hot Fire Test**	**8/28/15**		**3/4/16**	**The test completion date slipped due to delays in manufacturing complete chamber.**
LCUS	Chamber Delivery to Test	8/31/15		2/3/16	The test completion date slipped due to delays in manufacturing complete chamber.
ACME	Regolith/Binder combination layered structure subjected to Hyper-Velocity Micro-meteorite/Ballistic Impact Testing – demonstration	8/31/15	8/31/15		
ACME	Field Demonstration of Rover-mounted Implement in Situ Field Demonstration (PISCES)	9/30/15	9/30/15		
ACME	Demonstration of Sub-scale Excavation/Size-sorting Regolith Stimulant Delivery System	8/31/15	9/28/15		Delay in arrival of the MIPR caused a slip in the milestone.
ANNST	Cost benefit Analysis	9/30/15	8/7/15		CBA shows 50% cost reduction and 7% mass reduction enabled by the ISC process

NOTE: Bold font represents Control Milestone

Milestone Completion and Burndown



	October 2014	November 2014	December 2014	January 2015	February 2015	March 2015	April 2015	May 2015	June 2015	July 2015	August 2015	September 2015
Milestones Remaining (Baselined Completion)	22	22	20	18	17	17	15	14	11	10	6	0
Milestones Remaining (Actual Completion)	22	22	20	19	18	17	15	14	14	14	9	5

<u>Incomplete Milestones</u>

- Sounding rocket flight of near net shape component fabricated using the ISC Process –ECD 10/30/15
- Application of AM Structural Jacket & Manifolds – ECD 10/15/15
- Begin Hot Fire Test – Chamber - ECD 1/6/16
- **Complete Chamber Hot Fire Test – ECD 3/4/16**
- Manufacture of Selective Laser Melting (SLM) Copper Chamber Complete – ECD 2/3/16

Purple – Milestones Baselined / month
Blue – Milestones Completed / month

Technology Transfer or Infusion

- **Technology**
- **New Technology Request**
- **Invention Disclosure**
- **Patents Pending**
- **Patents**
- **Licensing Agreements**
- **Space Act Agreements**
- **Comments**

Use Excel file sent with the template and located on NX

	Technology	New Technology Request	Invention Disclosure	Patents Pending	Patents	Licensing Agreements	Space Act Agreements	Comments
	<Title of Technology>	<Number>	<Number>	<Number>	<Number>	<Number>	<Number>	<Provide Short description where applicable>
ANNST				LAR-18593-1, December 15, 2014; Patent pending				New Technology Report, "Integrally Stiffened Cylinder (ISC) Processing Technology",
ANNST				LAR-18600-1, December 18, 2014; Patent pending				New Technology Report, "In-situ Selective Reinforcement of Near Net Shape Formed Structures",

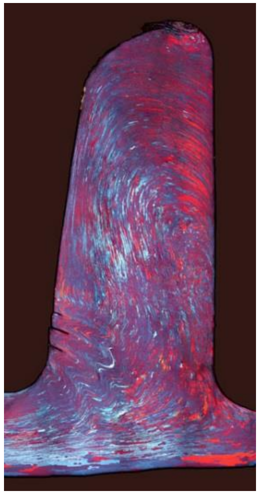
EPO: Activities, Conferences, and Students

- **Conferences, Technical Publications, Students, and EPO Activities**

Use Excel file sent with the template and located on NX

EPO: Activities

Date	EPO Activity (Quarter 4)	Representative
9/3/2015	Optical micrograph from analysis of Integrally Stiffened Cylinder selected for publication in the 2016 Buehler calendar. (image below)	ANNST
8/24-28/2015	Keck Institute Workshop on 3D Additive Construction for Space using In-Situ Resources	Rob Mueller, Corky Clinton, Jennifer Edmunson, Mike Fiske, Van Townsend
9/18/2015	Media tour for the release of “The Martian” at MSFC	Jennifer Edmunson
ongoing	3D Printed Habitat Centennial Challenges Rules Committee	Jennifer Edmunson, Rob Mueller



EPO: Conferences

Project Name	Type	Conference, Journal, Symposium, NASA Technology Report	Publication Title	Author(s)
AMT: LCUSP, ANNST, ACME	Exhibits	AIAA SciTech Conference	Exhibited materials as part of the STMD booth	
AMT: ANNST	Conference attendance, presentation	Mission Initiation Conference		
AMT: MGI	Technical Publication	CIMJSEA (Center for Integrative Materials Joining Science for Energy Applications) annual meeting in Columbus, OH	"Computational Process Modeling for Additive Manufacturing"	Stacey Bagg/MSFC in collaboration with Dr. Wei Zhang/The Ohio State University
AMT: MGI	paper	Neutron Characterization of Additively Manufactured Components Workshop at Oak Ridge National Lab.		Craig Brice
AMT: ACME	Conference attendance	Stacking Layers II Symposium (Tallahassee, FL)		Rob Mueller
AMT: MGI	Conference attendance	Minerals, Metals and Materials Society (Orlando, FL)		Chantal Sudbrack (GRC) and Jake Hochhalter (LaRC)
AMT	Conference attendance	Composites Materials and Manufacturing Technologies for Space Applications TIM in New Orleans		John Vickers, John Fikes
AMT: MGI	Technical Publication	3rd World Congress on Integrated Computational Materials Engineering (ICME 2015), Colorado Springs, CO.	Multiscale Modeling of Thermal Protection Materials I: Atomistic Modeling of Constituent Properties	John Lawson (ARC); Joshua Monk (ARC); Charles Bauschlicher (ARC); Steven Arnold (GRC); Pappu Murthy (GRC); Brett Bednarcyk (GRC)
AMT: MGI	Technical Publication	3rd World Congress on Integrated Computational Materials Engineering (ICME 2015), Colorado Springs, CO.	Multiscale Modeling of Thermal Protection Materials II: Micromechanical Modeling of Composite Performance	Steven Arnold (GRC); Pappu Murthy (GRC); Brett Bednarcyk (GRC); John Lawson (ARC); Charles Bauschlicher (ARC); Joshua Monk (ARC)
AMT: LCUSP	Technical Publication	JANNAF: Joint Army Navy NASA Air Force (Nashville, TN)	Evaluation of GRCop-84 Produced using Selective Laser Melting	Bob Carter/GRC
AMT: MGI	Invited talk	Advanced Qualification of AM Materials Workshop, sponsored by LLNL		C.Sudbrack/GRC
AMT: ACME	Technical Publication	AIAA SPACE 2015	On The Development of Additive Construction Technologies for Application to Development of Lunar/Martian Surface Structures Using In-Situ Materials	Mike Fiske
AMT: ACME		Composites and Advanced Materials Expo, Dallas TX	Development of Additive Construction Technologies for Application to Development of Lunar/Martian Surface Structures Using In-Situ Materials	Erick Ordonez
AMT: LCUSP	Technical Publication	2015 International Astronautical Congress, Jerusalem, Israel	Material Characterization of Additively Manufactured Components for Rocket Propulsion	Bob Carter/GRC
AMT: MGI	Conference attendance	Materials Science & Technology (MS&T) 2015, Columbus, OH	Poster	Chantal Sudbrack/GRC

EPO: Students

	Student Name	Institution	Level
			<High School, Undergraduate, Graduate, PhD, Post Doc, Professor, Research Associate, Research Scientist>
ANNST	Cecilia Stoner	Princeton University	Junior
ANNST	Wyatt Witzen	North Carolina State University at Raleigh	Senior
ANNST	Peyton Young	University of Virginia	Senior
ANNST	Austin Hehir	Virginia Polytechnic Institute and State University	Freshman
ANNST	Brian Katona	Kent State University	Masters
ACME	Samantha Frederick	Mississippi State	Graduate

Economic Development

- **Vendor Name**
- **Contract Number**
- **What is being completed**
- **Where is the work being completed**
- **Type of Business**
- **Program Year Cost**

Use Excel file sent with the template and located on NX

Publically Releasable Technology Charts

<These charts multiple GCD data requests and <u>all</u> <u>charts</u> are required. Please review questions on the next chart to ensure proper data control>

<Only update these charts if there have been changes since the STI review was completed>

Data Release

Please answer the questions below:

	Status
Was the data been reviewed by the NASA Center and approved for release? ▪ Science and Technical Information Review	
Are the pictures of the people included NASA Civil Servants? If not, has permission been granted for use?	
Are images included in the briefing? If so are these NASA images? If not, please provide reference for inclusion and to ensure that licensing agreements are in place. (See Chart 23)	ANNST – all pictures are NASA owned
Is a Space Act Agreement mentioned or included? If so, please ensure that this is approved for release.	

If pictures are not confirmed, all will be removed from the following charts to ensure release.

Advanced Manufacturing Technology (AMT)

STATUS QUO

- Widespread recognition of the problem
- Long and costly RDT&E and production
- Lack of integrated design and manufacturing
- Expensive and incremental manufacturing technology advancements

NEW INSIGHTS

- New innovative materials continually being developed and improved.
- Computer-based modeling improvements due to computational advancements.
- Improvements in the areas of sensing, automation, software, networking, physical sciences, etc.

PROBLEM / NEED BEING ADDRESSED

Innovative, low-cost manufacturing processes and products including: metallic processes, additive manufacturing, composites, and digital manufacturing

PROJECT DESCRIPTION/APPROACH

Develop advanced manufacturing technologies that enable the development of more capable and lower-cost space missions and launch vehicles.

- Identify strategic/critical technologies and manufacturing capabilities
- Mature "Game Changing" high impact technologies to address and close technology gaps
- Utilize and integrate computational and model-based technologies
- Implement projects across NASA centers with partnerships with other government agencies, industry and academia

QUANTITATIVE IMPACT

- Demonstrate 5X-10X reduction in cost and schedule.
- Address National needs manufacturing is the most important cause of economic growth – 70% of private sector R&D, over 90% of patents issued, and 60% of U.S. engineering and science jobs.

PROJECT GOAL

- Produce game changing or next generation manufacturing innovation and technology
- Create technologies that dramatically improve affordability, capability or reduce schedule
- Address the technology gaps in manufacturing capabilities in areas such as: composites, metals, additive manufacturing, inspection, model-based tools, environmental solutions
- Utilization of computational and model-based technologies that integrate the disciplines (i.e. materials, design, and manufacturing)

Advanced Near Net Shape Technology Integrally Stiffened Cylinder Process Development

STATUS QUO

- SOA is multi-piece welded construction of components machined from thick Al plate
- 90% material to waste
- High cost; labor intensive
- Welds are sites for defects, catastrophic failure

NEW INSIGHTS

- Sought manufacturing process to eliminate welds and efficiently use material
- Identified commercial automotive manufacturing process for transition to aerospace structures and materials

PROBLEM / NEED BEING ADDRESSED

Machined/welded construction for launch vehicles structures is expensive, heavy and risky

PROJECT DESCRIPTION/APPROACH

- Develop the Integrally Stiffened Cylinder (ISC) process for fabrication of launch vehicle structures
- Adapt proven technology from automotive steel to aerospace Al and Al-Li alloys
- Scale-up and optimize process for launch vehicle stiffened cryotank structure
- Conduct trade studies to optimize integrally-stiffened tank structure
- Demonstrate process by fabrication and testing of intermediate scale (0.5-2 meter diameter) barrel
- Validate process by fabrication and testing of large scale (2-5 meter diameter) barrel

QUANTITATIVE IMPACT

- Eliminate longitudinal welds in cryogenic tank barrel; Shuttle External Tank has half a mile of welds
- Reduce weight by >30%
- Reduce cost by >40% by reduced touch labor, material scrap rate &NDE

PROJECT GOAL

- Efficient manufacturing methods for robust full-scale one-piece integrally-stiffened launch vehicle structures

Revolutionizing Metals Forming- Low Risk, Big Payoff

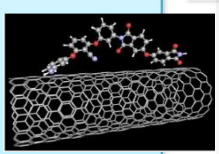
Materials Genome Initiative (MGI) Penta Chart

STATUS QUO

- Current materials development based on empirical design approaches results in incremental material improvements and long maturation and insertion time. For example, carbon fibers were invented in 1958 yet significant use of carbon fiber composites in aerospace applications has required 50 years of development.
- Existing material certification approach inhibits the utilization of new processing methodology.

NEW INSIGHTS

- Physics-based models for the characterization of materials processing and structure-property relationships are maturing.
- Synergistic efforts in multiscale modeling, information management,



experimental characterization and materials processing will accelerate design, development and sustainment of ultra-durable material systems.

PROBLEM / NEED BEING ADDRESSED

Development of new materials for aerospace applications is too costly and time intensive. Computational design of materials will enable accelerated insertion.

PROJECT DESCRIPTION:

Develop integrated computational / experimental / processing methodologies for accelerating discovery and insertion of materials to satisfy NASA's unique mission demands.

- The challenges:
  - Validated design tools that incorporate materials properties, processing and design requirements
  - Materials process control to rapidly mature emerging manufacturing methods to industry ready
- Approach:
  - Physics-based modeling to guide material design e.g. matrix composition, crosslinking between CNTs, grain size and texture
  - Multiscale modeling influence of materials design on mechanical properties and durability
  - Process modeling to determine processing parameters required to produce as-designed material nano-/micro-structures and enable advanced manufacturing methods utilization
  - Utilize material data management to support robust material design methodology

Computational material design is enabling to NASA's aerospace needs.

QUANTITATIVE IMPACT

- Reduce time between discovery and technology insertion by >50%.
- Shorter maturation and insertion translates to lower costs, greater affordability and lower risk of failure.
- Computational materials design will reduce time and cost to certify new flight hardware (50% reduction in time and cost, long-term national goal; 25% reduction in time to certify , current NASA MGI goal).

PROGRAM GOAL

- Cross-center effort including computational, experimental and processing expertise to develop emerging material systems including multifunctional materials.
- Define path for compressed materials maturation and insertion through multiscale modeling to reduce materials testing and shorten iterative cycle for materials optimization.
- Capability for materials "designers" to assess the trade-off between various material properties of interest and enable rapid prototyping.

Low Cost Upper Stage-Class Propulsion (LCUSP) Penta

STATUS QUO

- Rocket Engine Propulsion Elements are typically high cost and have long manufacturing times
- No data exist for Additive Manufacturing of Cu alloys
- US government is sole user of engines from sole provider

NEW INSIGHTS

- AM can significantly reduce development time and cost of complex rocket propulsion hardware
- GRCop material shows high promise for engine component use

PROBLEM / NEED BEING ADDRESSED

Current rocket propulsion manufacturing techniques are costly and have lengthy development times

PROJECT DESCRIPTION/APPROACH

- Develop materials properties and characterization for SLM manufactured GRCop
- Develop and optimize SLM manufacturing process for a full component GRCop chamber and nozzle
- Develop and optimize the Electron Beam Freeform Fabrication (EBF3) manufacturing process to direct deposit a nickel alloy structural jacket and manifolds onto an SLM manufactured GRCop chamber and nozzle
- Demonstrate the process for integrating the engine system by performing a hot fire, resistance test.

QUANTITATIVE IMPACT

- Order of magnitude savings of cost and schedule
- New competitive markets for Cu Alloys
- New material property database and processes to implement AM into manufacturing processes

PROJECT GOAL

- Develop material properties and characterization of GRCop
- Optimize SLM for GRCop
- Optimize EBF3 to deposit Ni onto GRCop
- Demonstrate the integrated process via hot fire test

Additive Construction with Mobile Emplacement (ACME) Penta

STATUS QUO

- *Large structures for habitats and infrastructure on Earth require substantial form work and /or manual labor*
- *Terrestrial applications of this technology are being investigated by the Army Corps of Engineers*
- *Space Habitats and infrastructure must be transported from Earth at high cost and low packaging volume*
- *3D additive construction has been completed in the lab using terrestrial materials (TRL 4)*
- *Regolith based materials Additive Construction is at TRL 3*

NEW INSIGHTS

- **New regolith based structural materials** can be created in-situ using sintering, sulfur binding, polymer binders, thermite self sintering, synthetic biology binders and more methods, to be developed.
- **New robotic technologies** and digital manufacturing allow additive construction on a large scale

PROBLEM / NEED BEING ADDRESSED

NASA lacks in-space construction capabilities and cannot fabricate Deep Space mission infrastructure. This technology directly addresses the NASA Advanced Manufacturing **subject matter areas of additive manufacturing, robotics and non-metallic materials processes.** (TA 12, TA04, TA07, TA09)

PROJECT DESCRIPTION/APPROACH

- Several ***construction tasks*** will be necessary to achieve safe and productive conditions for extended robotic & human presence at extraterrestrial sites
  - Roads, landing pads, berms
  - Unpressurized shelters for protection of rovers, etc.
  - Pressurized shelters for long-term crew protection

- The proposed work will establish the body of knowledge required for co-robotic Additive Construction ***of in-space radiation shielding (flight & surface)*** and ***infra -structure for human settlement***, with research in 3 major categories:
- ***Robotic control & coordination***
- ***Materials, processes, and system modeling***
- ***Construction tooling and robot testbeds***

QUANTITATIVE IMPACT

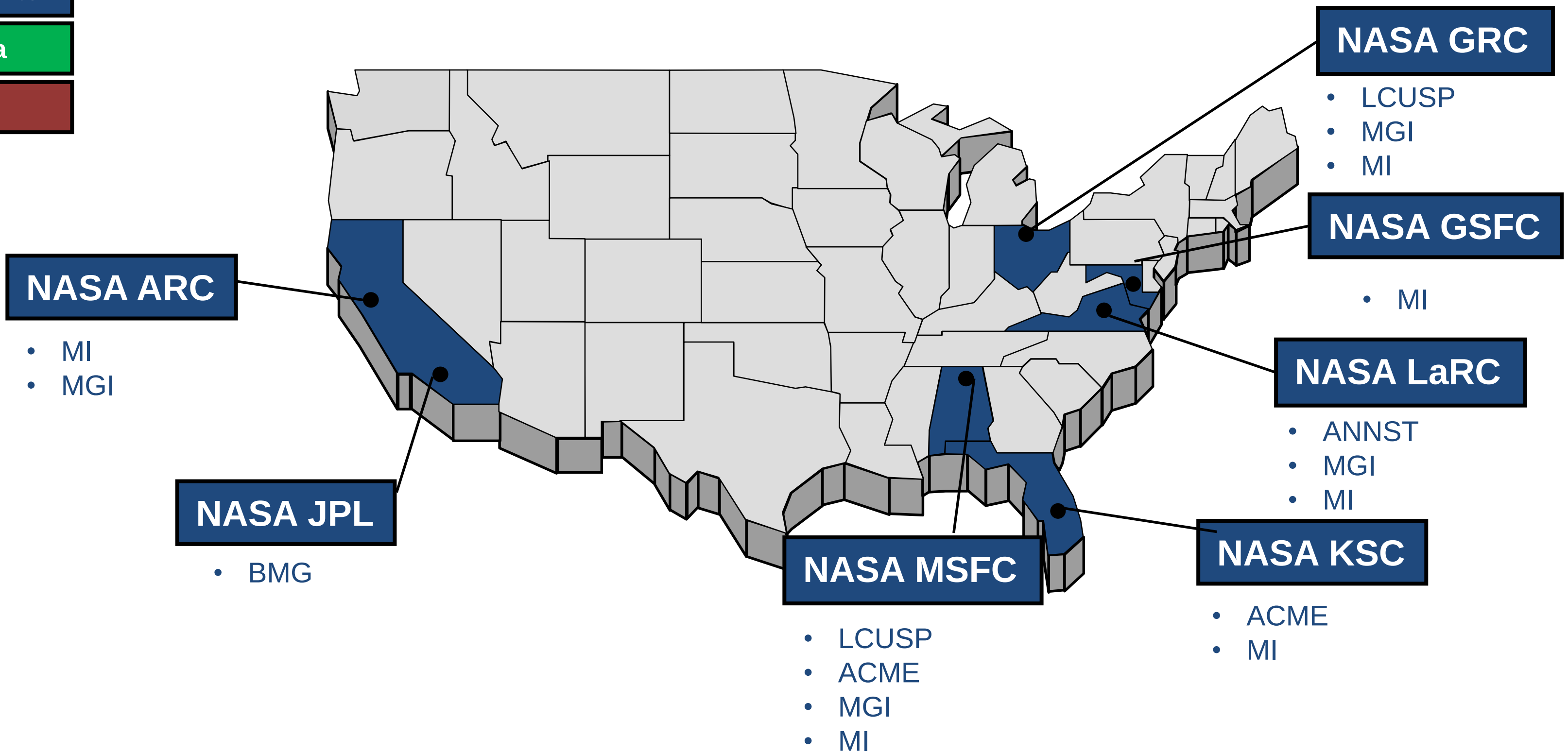
- ***Reduce mass of materials*** that must be transported to the space destination by a factor of 2,000:1
- ***Mitigate space radiation effects on humans*** full (SPE/GCR) protection while in a regolith shielded shelter in-space & surface
- ***Reduce cost*** of large scale Earth construction by 10:1

PROJECT GOAL

- ***Construct a 4 meter diameter demonstration domed structure (habitat, radiation shelter, heat shield) on terrestrial and planetary analog sites***
- Develop regolith based structural materials & print process combinations functional in space environment analog & vacuum testing (TRL 6)
- Prototype a regolith print head for emplacement
- Use existing NASA GCD robots to position and follow tool paths with the regolith print head end effector

AMT Organization and Key Members

- NASA Center
- Academia
- Industry



Industry Partners

ANNST	MI	MGI	LCUSP	ACME
• MT Aerospace • Leifeld Metal Spinning • Lockheed Martin • International Technologies			• Allegheny Technologies Inc.	• PISCES - Hilo, HI • USACE – Champaign, IL • CCC – Marina del Rey, CA

Technical Accomplishment: Thermal Modeling of Additive Manufacturing

Milestone: Develop data schema for process parameters of SLM development part. *Completed September 2015*

Deliverable: Provide a detailed data schema highlighting the critical data parameters for collection for SLM processing and a proposed method to utilize this data for process improvements.

Problem: Selective laser manufacturing is a complex process, with many variables associated with the machine, processing parameters, initial material, and build geometry. To develop a certifiable process, accurate information must be stored and evaluated critically.

Objective: Develop a data schema for a complex data management system that can be used to track the process configuration and identify uncertainties and potential issues in the process.

Approach: NASA worked closely with the Materials Data Management Consortium to develop the data schema for an existing materials data management system specific for additive manufacturing.

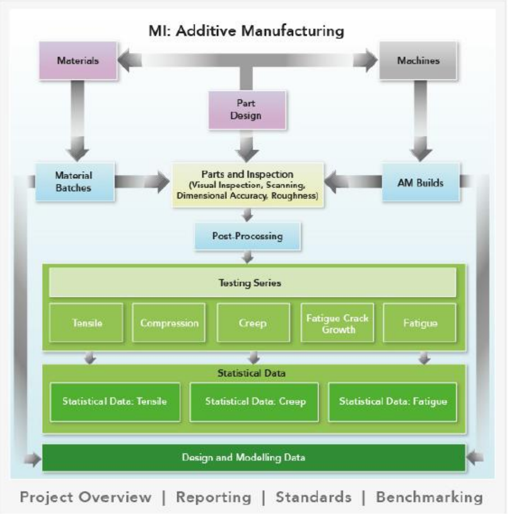
Results: The proposed schema will be shared with the manufacturing team and MSFC and the MI Granta software will also be supplied.

Inputs for an AM data schema

Machines	Materials	Part Design
General Information	General Information	General Information
Calibration	General Properties	Original Design
Machine Specifications	Composition overview	Re-Design
Material	Bulk Mechanical Properties	Dimensions
Machine Properties	Bulk Thermal Properties	General Material Properties
Build Environment	Bulk Electrical Properties	Processing
Laser Properties	Biological	Static Tensile Properties
Electron Beam Properties	Chemical	High-cycle fatigue properties
	Eco	Fracture Toughness
	Cost	Fatigue Crack Growth
	Safety and Handling	Surface Roughness Requested
	General Information	Other Requested Properties
	Requirements	Final Part Details
	Composition	Quality Assurance
	Physical Properties	Key Benefits
	Further Information	

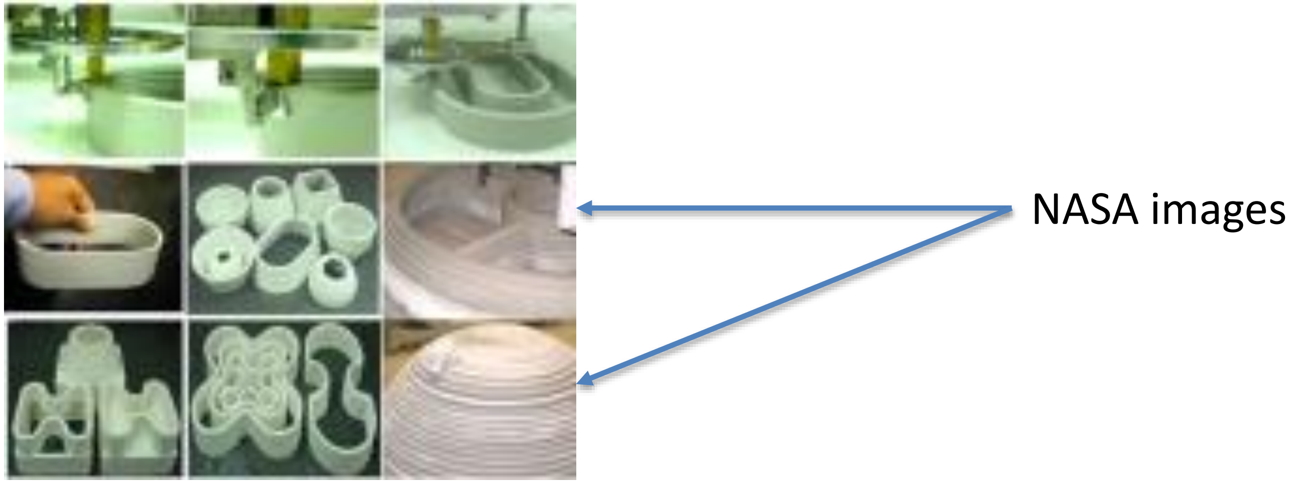
Material Batches	Builds	Parts
Project Information	Project Information	Project Information
General Batch Information	General Information	Part Information
Manufacturing	Build Information	Part Specifications
Material Quality	General Build Parameters	Samples
Particle Properties and Size Distribution	Build Atmosphere	Visual Inspection
Interstitial contamination	Material Used	Accuracy Testing
Flowability	Support	NDT Testing
Wire Properties	Filament Information	Post Processing
Chemical Analysis and Composition	Substrate	Heat Treatment
	Quality of Welding Consumables	HIP
	Build Alarms	Machining
	Themes Used	Laser Polishing
	Powder Build Parameters	Other Post Processing
	Wire Build Parameters	
	Laser Properties	
	Electron Beam Properties	
	Arc Properties	
	In-Process Rolling	
	In-Process Analysis	

Flow for an AM data management system



3rd Party Image Information

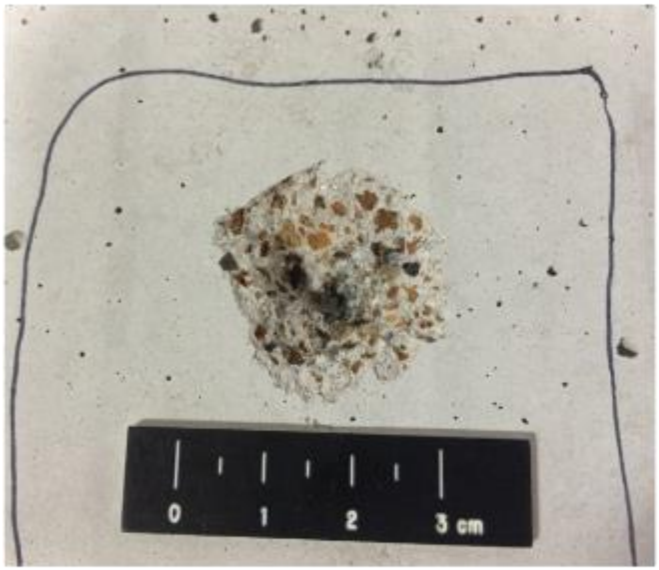
If 3rd Party Images were utilized, please provide the details of which image and the details of the location of the image.



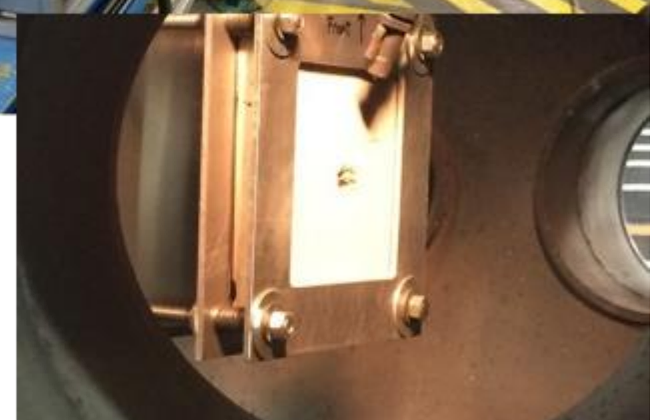
Found on the Penta chart for ACME

All images (with the exception of the two NASA images highlighted above) are courtesy of Dr. Behrokh Khoshnevis the University of Southern California.

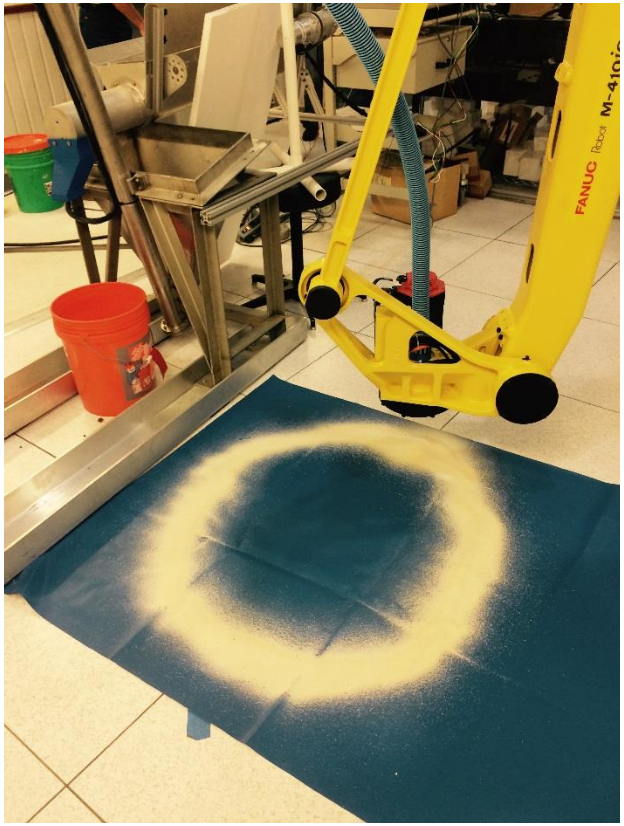
- **Hypervelocity impact testing (HVIT) of martian simulant concrete, White Sands NM 8/19/15, in collaboration with JSC HVIT team.**



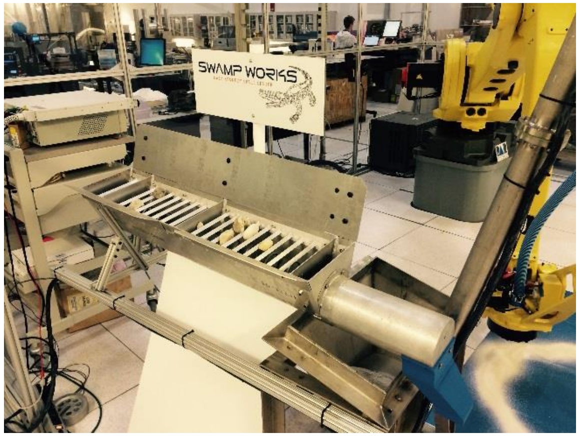
Martian simulant concrete was hypervelocity impact tested at White Sands on 8/19/15. An aluminum sphere of 1.99mm diameter struck the 25.4mm-thick concrete block at 6.83km/s. The crater was roughly 30mm in diameter, the maximum crater depth was measured at 10.3mm, and there was no damage or evidence of microcracking on the back side of the block.



- **Regolith Size Sorting & Feed System for 3D Printing Feedstock (KSC Swamp Works, completed 9/28/15)**



Emplacement of fines with a robot arm

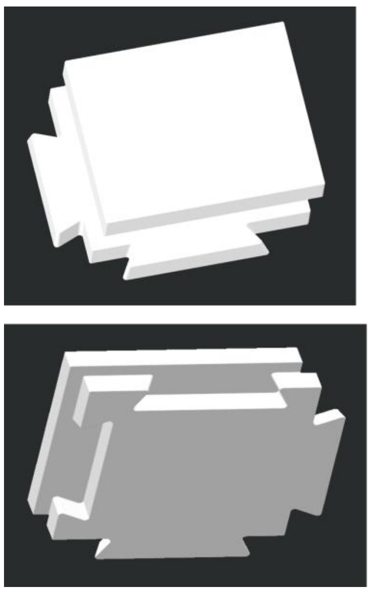


Size Sorting and Auger Feed

ACME Year-End Review
VTVL Pad Paver System

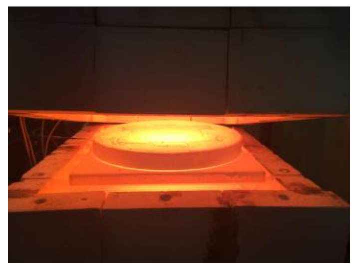
- **Design and Fabrication of an in-situ sintered basalt inter-locking paver system for Vertical Takeoff, Vertical Landing (VTVL) pad to protect against rocket plume impingement and intrusion**

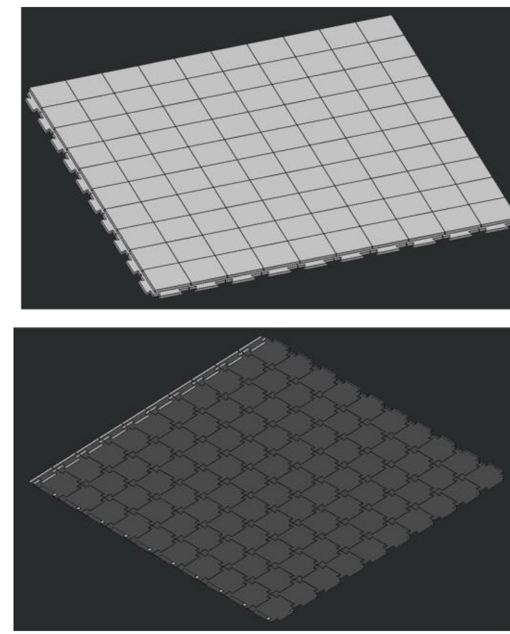
(KSC Swamp Works & PISCES, completed 9/30/15)



Top View

Bottom View





Top View

Bottom View

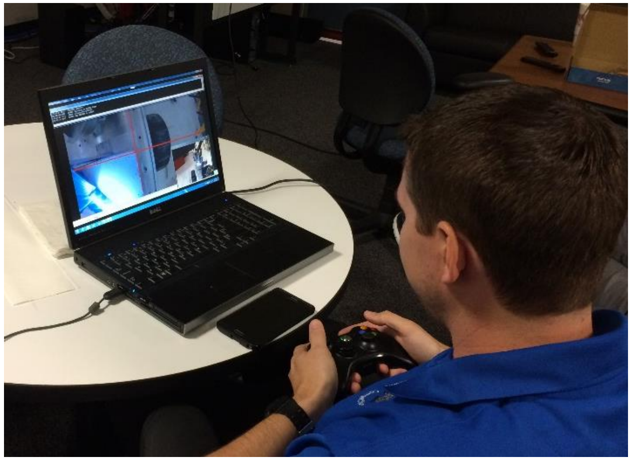
Paver System

Basalt Inter-locking Paver – modular design

Tele-robotic Paver Deployment Mechanism

- **Design and Fabrication of an Paver Deployment Mechanism (PDM) for tele-robotically laying inter-locking pavers to remotely construct a Vertical Takeoff, Vertical Landing (VTVL) pad.**

(KSC Swamp Works, completed 9/30/15)

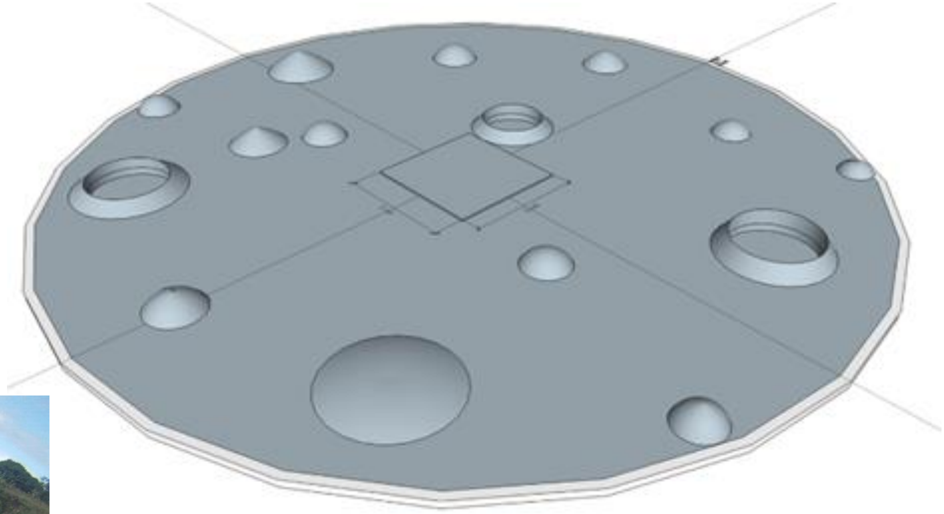


Tele-Operation of PDM

Paver Deployment Mechanism (PDM) robotic arm assembly, with pavers stack, on a Rover Mockup

ACME Year-End Review
PISCES Simulated Planetary Landing Site

CAD Model of a Planetary Surface



Basalt Fines shaped to form the Planetary Surface in the CAD model

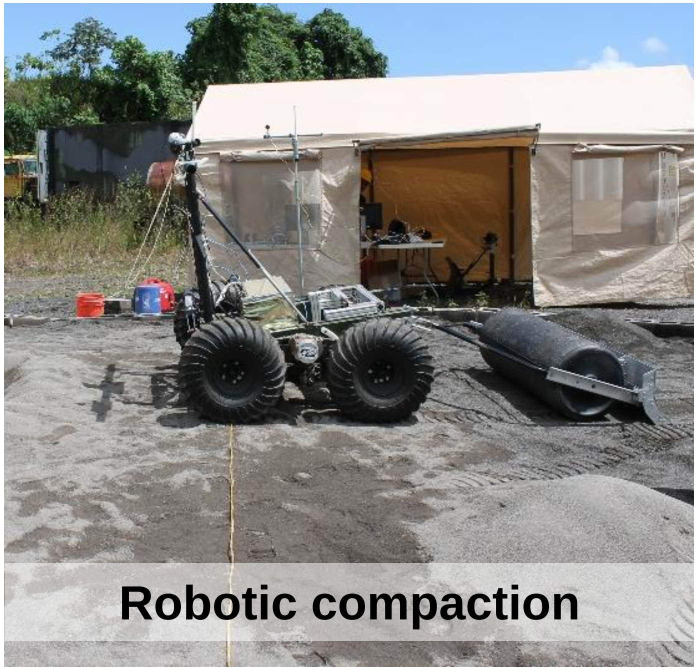
20 meter diameter simulated planetary terrain area shown in a basalt quarry in Hilo, Hawaii

Planetary Analog Site Preparation

- **Field demonstration of rover-mounted implement for site preparation. (PISCES, completed 9/30/15)**

PISCES Landing Pad location

Robotic leveling and grading

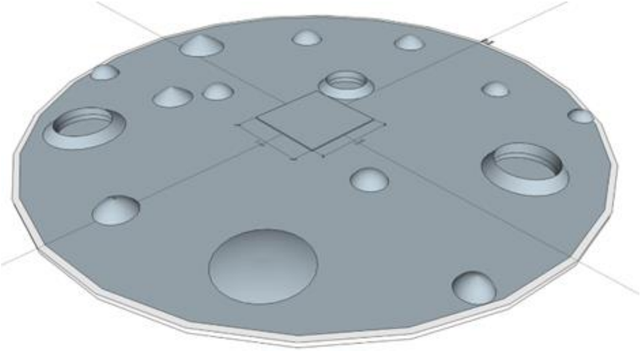


Robotic compaction

3rd Party Image Information

If 3rd Party Images were utilized, please provide the details of which image and the details of the location of the image.

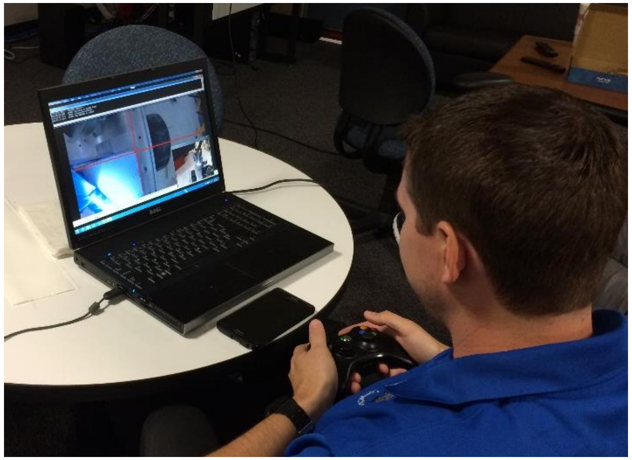
These four images are courtesy of PISCES.



Tele-robotic Paver Deployment Mechanism

- **Design and Fabrication of an Paver Deployment Mechanism (PDM) for tele-robotically laying inter-locking pavers to remotely construct a Vertical Takeoff, Vertical Landing (VTVL) pad.**

(KSC Swamp Works, completed 9/30/15)



Tele-Operation of PDM

Paver Deployment Mechanism (PDM) robotic arm assembly, with pavers stack, on a Rover Mockup