Advanced Manufacturing Technology

Presented By: John Fikes

January 2017
<table>
<thead>
<tr>
<th>Technology</th>
<th>Performance</th>
<th>Cost</th>
<th>Schedule</th>
<th>Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Cost Upper Stage Class Propulsion</td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
</tr>
<tr>
<td>Additive Construction with Mobile Emplacement (ACME)</td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
</tr>
</tbody>
</table>

Technical is yellow due to the EBF³ process to add an inconel structural jacket to the GRCop-84 liner is producing cracks along forward and aft ends at the inconel/GRCop-84 interface. Currently implementing trial on Unit 2.1 as part of the approved recovery plan.

Cost is yellow due to the new recovery plan requiring more resources at LaRC. Project is carrying as a “threat” for now. Actual increase will not be realized until later in FY17.

Schedule is yellow due to minimum schedule reserves in current plan approved by change request.

Technical is yellow due to on-going challenges to meet the U.S. Army Corp of Engineers (USACE) requirements with their current material (3/8th inch aggregate). Schedule is yellow due to minimum schedule reserves for meeting ACES 3 hardware deliverables.
Resources: Non-Labor Obligations and Cost

FY 2017 Non-Labor Financial Status

Note: Carry-In is the unobligated/uncosted portion of PY11-16 funding end of FY16

<table>
<thead>
<tr>
<th>YTD Status</th>
<th>Explanation required for YTD Variance in excess of 5% from Phasing Plan (shaded red)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'17 Obs</td>
<td></td>
</tr>
<tr>
<td>Phasing</td>
<td>Current operating under CR thru April 2017. Contractual commitments/obligations are on-going and are expected to start catching up during the 2nd quarter of FY2017. Project activities on-going and there have been no impact to project milestones.</td>
</tr>
<tr>
<td>Actuals</td>
<td>$ 830</td>
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<tr>
<td>Variance</td>
<td>$ 107</td>
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<tr>
<td></td>
<td>(723)</td>
</tr>
<tr>
<td>'17 Cost</td>
<td></td>
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<tr>
<td>Phasing</td>
<td>Current operating under CR thru April 2017. Project utilizing uncosted FY2016 carryover for management support activities. Project activities on-going and no impact to project at this time.</td>
</tr>
<tr>
<td>Actuals</td>
<td>$ 183</td>
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<tr>
<td>Variance</td>
<td>$ 24</td>
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<td></td>
<td>(159)</td>
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</tbody>
</table>

Currently operating under CR thru April 2017. Contractual commitments/obligations are on-going and are expected to start catching up during the 2nd quarter of FY2017. Project activities on-going and there have been no impact to project milestones.

Currently operating under CR thru April 2017. Project utilizing uncosted FY2016 carryover for management support activities. Project activities on-going and no impact to project at this time.
Resources: Total Project Workforce
FTEs/WYE

FY 2017 Workforce Status

<table>
<thead>
<tr>
<th>Incremental</th>
<th>2015</th>
<th>2016</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>2017 Avg</th>
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<tr>
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<tr>
<td>Phasing Plan (RLP)</td>
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<td>24.0</td>
<td>24.0</td>
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<tr>
<td>Phasing Plan (RLP)</td>
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<td>24.0</td>
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<tr>
<td>Forecast</td>
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</table>

YTD Status

<table>
<thead>
<tr>
<th>Phasing</th>
<th>Actuals</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.0</td>
<td>32.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Explanation required for YTD Variance in excess of 5% from Phasing Plan (shaded red)

Currently overrun by 15% mainly due to WBS Labor Code turn-offs in October timeframe at MSFC. Since October, Labor Codes have been turned off and labor charges are decreasing. AMT expects to charge more FTE during 1st and 2nd quarters to support ACME activities. Charges will be decreased during 3rd and 4th quarters.
## AMT Milestones and Forward Plans

<table>
<thead>
<tr>
<th>FY17 Q1 (Oct 1 through Dec 31)</th>
<th>FY17 Q2 (Jan 1 through March 31)</th>
<th>FY17 Q3 (Apr 1 through June 30)</th>
<th>FY17 Q4 (Jul 1 through Sep 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FY17 Key and Controlled Milestones</strong></td>
<td><strong>Baselined or Current Approved Completion Date</strong></td>
<td><strong>Actual Completion Date</strong></td>
<td><strong>Estimated Completion Date</strong></td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>ACME (Zero Launch Mass In-Situ (ZLM) Construction) Materials Development (KSC &amp; MSFC)</td>
<td>12/30/16</td>
<td>12/30/2016(A)</td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>Completion of Environmental Modeling Analyses</td>
<td>12/31/16</td>
<td>12/31/2016(A)</td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>ACME (Zero Launch Mass In-Situ (ZLM) Construction) Material Print Head Demonstration</td>
<td>1/31/17</td>
<td>3/31/17</td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>Feedstock Processing/Transport Hardware Demonstration</td>
<td>1/31/17</td>
<td>3/31/17</td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>Print Head Integration with Mobility System (KDP 3)</td>
<td>3/31/17</td>
<td></td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>Full Scale Optimized Planetary Structure Demos with Integrated Systems at a Lab or Planetary Analog (local) Site</td>
<td>3/31/17</td>
<td></td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>Integrated Excavation and Handling System Test</td>
<td>3/31/17</td>
<td></td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Mechanical Testing Complete - SLM Deposited GRCop-84 (2nd Buy)</td>
<td>3/31/17</td>
<td></td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Standardized NDE Techniques for Flight HW Documented</td>
<td>3/31/17</td>
<td></td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Standardized SLM Process for Flt HW Documented</td>
<td>3/31/17</td>
<td></td>
</tr>
<tr>
<td><strong>FY17 Q3 (Apr 1 through June 30)</strong></td>
<td><strong>FY17 Q4 (Jul 1 through Sep 30)</strong></td>
<td><strong>FY17 Q3 (Apr 1 through June 30)</strong></td>
<td><strong>FY17 Q4 (Jul 1 through Sep 30)</strong></td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Mechanical Testing Complete - SLM Deposited GRCop-84 for Orientation &amp; Size Study*</td>
<td>6/22/17</td>
<td></td>
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<tr>
<td><strong>LCUSP</strong></td>
<td>Begin Hot Fire Test - Chamber</td>
<td>7/26/17</td>
<td>Per Change Request submitted to GCD on 12/16/16.</td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Complete Chamber Hot Fire Test</td>
<td>8/15/17</td>
<td>Per Change Request submitted to GCD on 12/16/16.</td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Hot Fire Test (Integrated Assembly)</td>
<td>8/16/17</td>
<td>Per Change Request submitted to GCD on 12/16/16.</td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Integrated Hot Fire Test</td>
<td>8/16/17</td>
<td>Per Change Request submitted to GCD on 12/16/16.</td>
</tr>
<tr>
<td><strong>LCUSP</strong></td>
<td>Complete Integrated Hot Fire Test</td>
<td>9/12/17</td>
<td>Per Change Request submitted to GCD on 12/16/16.</td>
</tr>
<tr>
<td><strong>ACME</strong></td>
<td>Complete Full Scale Demonstrations</td>
<td>9/30/17</td>
<td></td>
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</table>
## Risk Summary

### 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

### CONSEQUENCES

<table>
<thead>
<tr>
<th>ID</th>
<th>Trend</th>
<th>Approach/ Affinity</th>
<th>Risk Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC15</td>
<td>↓</td>
<td>W/Sc</td>
<td>Facility Operating Space</td>
</tr>
<tr>
<td>AC19</td>
<td></td>
<td>M/T</td>
<td>Safety Keep Out Zones CLOSED</td>
</tr>
<tr>
<td>AC20</td>
<td></td>
<td>M/Sc</td>
<td>Integration, Testing Space (Weather Impacts) CLOSED</td>
</tr>
<tr>
<td>AC21</td>
<td></td>
<td>M/T</td>
<td>Hose Management CLOSED</td>
</tr>
<tr>
<td>AC22</td>
<td></td>
<td>Sc/C</td>
<td>Logistics for Fabrication, Assembly, Integration</td>
</tr>
<tr>
<td>AC23</td>
<td></td>
<td>T</td>
<td>Nozzle Development and Test</td>
</tr>
<tr>
<td>AC24</td>
<td></td>
<td>T</td>
<td>Accumulator Development and Test</td>
</tr>
<tr>
<td>LC1*</td>
<td></td>
<td>M/T,C,Sc</td>
<td>EBF3 weld technology</td>
</tr>
<tr>
<td>LC8*</td>
<td></td>
<td>M/T</td>
<td>GRCop-84 and Inconel625 Interface flaws</td>
</tr>
</tbody>
</table>

*LCUSP risks currently under revision*

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*only high and medium risks are shown on summary chart*
Low Cost Upper Stage-Class Propulsion
The LCUSP will demonstrate the ability to produce a low cost upper stage-class propulsion component system using additive manufacturing technologies. LCUSP will do this by (1) developing a copper alloy additive manufacturing design process, (2) developing a new Nickel Jacket additive manufacture/application process (3) additive manufacture of a 35K-class regenerative chamber/nozzle, (4) testing chamber and then chamber/nozzle system in a hot fire resistance test.

<table>
<thead>
<tr>
<th>Integration with other projects/programs and partnerships</th>
<th>Technology Infusion Plan:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Propulsion System (LPS) Test Bed (being developed at MSFC with additive manufactured components such as injectors, LOx and H₂ Turbopumps plans to utilize the LCUSP Combustion Chamber or utilize the capability established under this project to fabricate a chamber. Test and Fabrication Data infused into Lander Technology Office methane thruster work. Follow-on regen Methane Engine Thrust Assembly for 4K lbf (META4) chamber design utilized SLM GRCop-84 process developed by LCUSP and incorporates LCUSP chamber mid-line weld design to enable required length. LCUSP printed faceplate provided strength, conductivity, and oxidation resistance needed for staged combustion testing in a much shorter time than it would have taken to procure stock and machine a traditionally fabricated GRCop faceplate, allowing MSFC to provide the first US data to USAF SMC. Industry partners are investigating possible partnerships with LCUSP for possible opportunities for fabrication of SLM combustion chambers to reduce cost of engine development.</td>
<td>PC, Propulsion, HEOMD, Potential use in manufacturing process of flight engines 2017. Military &amp; Industry, SpaceX, Aerojet-Rocketdyne, Orbital-ATK, ULA, Blue Origin, ASRC Federal, numerous copper machine shops, suppliers, and electronics manufactories.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key Personnel:</th>
<th>Key Facts:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Manager: John Fikes</td>
<td>GCD Theme: LMAM, Lightweight Materials and Advanced Manufacturing</td>
</tr>
<tr>
<td>Project Element Manager: Eric Eberly</td>
<td>Execution Status: Year 3 of 3</td>
</tr>
<tr>
<td>Lead Center: MSFC</td>
<td>Technology Start Date: April 2014</td>
</tr>
<tr>
<td>Supporting Centers: LaRC &amp; GRC</td>
<td>Technology End Date: September 2017</td>
</tr>
<tr>
<td>NASA NPR: 7120.8</td>
<td>Technology TRL Start: 3</td>
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<tr>
<td>Guided or Competed: Guided</td>
<td>Technology TRL End: 6</td>
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<tr>
<td>Type of Technology: Push</td>
<td>Technology Current TRL: 4/5</td>
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<td>Technology Lifecycle Phase: Implementation (Phase C/D)</td>
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</table>
LCUSP Component and System
TRL Quarterly Assessment

- Cu Alloy material Characterization
- Cu Alloy manufacturing process development
- Ni Alloy deposition to Cu Alloys
- Additive Manufacturing of upper stage components

- Use in applicable environment
- Material testing & analysis
- Fabrication process development

SLM & EBF3 Process Refinements (TBD)
Chamber & Nozzle Hot Fire Test

Goal
Actual Value
Predicted Value

2017 GCD 1st Quarter Review
### Advanced Manufacturing Technology

**LCUSP Performance**

- **Technology Advancements**
  - Selective Laser Melting (SLM) fabrication with GRCop-84 powder for rocket components (combustion chamber).
  - 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.

- **This is push technology**
  - Missions that require new propulsion systems can take advantage of this technology.

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>State of the Art</th>
<th>Threshold Value</th>
<th>Project Goal</th>
<th>Estimated Current Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process control of using Copper via SLM</td>
<td>SLM demonstrated with Inconel 718, Inconel 625, and Al 357, and CoCr by MSFC, but not with copper</td>
<td>Demonstrate parameter set that allows fabrication of monolithic structures to be used for mechanical properties and surface finish testing</td>
<td>Develop an optimized parameter set to maximize build speed, control surface finish, and maximize mechanical properties of SLM copper</td>
<td>GRCop SLM process yielding &gt;99% dense parts with properties comparable to traditionally manufactured GRCop84 samples. External vendor has extended process to commercial application.</td>
</tr>
<tr>
<td>Copper alloy material characterization using SLM</td>
<td>Not established for copper</td>
<td>SLM’d GRCop-84 thermal conductivity at 90% of baseline extruded GRCop and remaining material properties at or greater than those of OFHC Copper</td>
<td>90% of baseline extruded GRCop-84 material properties</td>
<td>GRCop SLM process yielding &gt;99% dense parts with properties comparable to traditionally manufactured GRCop84 samples.</td>
</tr>
<tr>
<td>Deposition of nickel alloy to SLM Copper</td>
<td>Demonstrated for pure nickel to pure copper, but not for nickel alloys to copper alloys</td>
<td>Deposition of nickel alloy to copper alloy that remains intact at the bond through a thermal cycle and with minimum defects</td>
<td>Deposition of nickel alloy onto copper alloy with a ductile transition zone and mechanical properties equivalent to cast annealed condition</td>
<td>Deposition process developed. Joint samples microscopy inspection and pull tests with no initial cracking show sufficient bond strength for design application. Further properties samples and process improvements to remove cracking being developed and tested.</td>
</tr>
<tr>
<td>Manufacture of AM upper stage engine components</td>
<td>SLM upper stage engine components demonstrated with Inconel 718, Inconel 625 by MSFC, but not with Copper (GRCop) chambers</td>
<td>Demonstrate build of subscale components or subassemblies with properties and geometry sufficient to be utilized in initial subscale testing</td>
<td>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</td>
<td>Full scale H2 chamber go forward path developed. Successful methane tests of SLM printed chamber occurred 08/10/2016.</td>
</tr>
</tbody>
</table>
Technical Accomplishments:

- Held Design Checkpoint Review on 10/14/2016 to communicate recovery plan and design changes based on lessons learned.

- Manufacturing Readiness Review (MRR) completed for the Electron Beam Free Form Fabrication (EBF³) on 11/15/2016.
  - Reverting back to process used on Unit 1.
  - Minor EBF³ adjustments based on Design of Experiments.

- Unit 2.1 short chamber, 2.2 short chamber & Unit 3.0 Aft section GRCop-84 liners completed Select Laser Melting (SLM) production at MSFC.
  - Unit 2.1 is at LaRC for EBF³ deposition.
  - Unit 2.2 is at MSFC for inspection after powder removal.
  - Unit 3.0 Aft is at HIP vendor.

- Hot-fire milestones Change Request (CR) sent to GCD for review and approval.

- Mechanical Testing: GRCOP-84 low cycle fatigue testing completed. In-625 cryogenic tensile testing completed.
Technical Challenges:

- **During Unit 2 Recovery, significant channel blockage was found in the Forward and Aft closeouts.**
  - New Recovery Plan Developed.
  - Change Request submitted to GCD.

- **The technical tall pole over the course of the project and for FY2017**
  - Inconel 625 jacket application using the Electron Beam Free Form Fabrication process.
  - Applying Structural Jacket over the intermediate manifold. The previous units used Inconel scaffolding. The new units will use GRCop-84 Closeout Ring.

Revised Joint
Includes GRCop-84 Split Ring Closeout
Select Laser Melting Productions Completed

- Unit 2.1 for EBF$^3$ process validation
- Unit 2.2 for Ebeam weld process trial and backup hot-fire unit
- Unit 3.0 for primary hot-fire test article
LCUSP
Plans for FY2017

GRCop-84/Inconel 625 Chambers

- Complete Unit 2.1 test chamber
  - EBF3 Inconel 625 onto GRCop-84 liner to verify process
  - Visual and CT scan inspection
  - Leak/pressure check
  - Destructive testing
- Complete Unit 2.2 chamber
  - EBF3 Inconel 625 onto GRCop-84 liner
  - Visual and CT scan inspection
  - Weld manifolds to Unit 2.2
  - Leak/pressure check
- Complete Unit 3.0 chamber
  - Weld Unit 3 halves together
  - EBF3 Inconel 625 onto GRCop-84 liner
  - Visual and CT scan inspection
  - Weld manifolds to Unit 3.0
  - Leak/pressure check

Chamber Hot Fire Testing (Unit 2.2 or Unit 3)

- Begin in late July
- Complete in August
- Complete integrated test in September

Materials Work

- Mechanical Testing
  - SLM Deposited GRCop-84 for Orientation & Size Study. Estimated completion in June 2017
Additive Construction with Mobile Emplacement
### Advanced Manufacturing Technology

**ACME Project Overview**

- Additive Construction with Mobile Emplacement (ACME) is 2D and 3D printing on a large (structure) scale using in-situ resources as construction materials to help enable on-location surface exploration.
- 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

- Current partnership between MSFC, KSC, the USACE, Contour Crafting Corporation (CCC), and the Pacific International Space Center for Exploration Systems (PISCES).
- 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, University of Mississippi).
- In-Situ Resource Utilization (ISRU) project integration & uses.

### Technology Infusion Plan:

- Potential Customer: HEOMD, USACE and Industry (Caterpillar Inc.).
- Phased approach for maturation of hardware: ACME units intended to serve as prototypes for the USACE devices which will be used in domestic and international venues.
- 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 Fikes
- **Project Element Managers:** John Fikes and Rob Mueller
- **Lead Center:** Co-led by MSFC and KSC
- **Supporting Centers:** None

### Key Facts:

- **GCD Theme:** LMAM
- **Execution Status:** Year 3 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
**Technology Advancement**
- Developed a continuous feed system for construction materials.
- Integrated ACME 2 training nozzle into system.

**Technology advance means**
- Moving from batch processing to continuous feed; need further understanding of how feedstock viscosity, pump speed, and nozzle speed affect printing.
- Ability to print structures continuously; no start/stop due to refilling with feedstock

**Technology push and pull**
- Impacts future planetary missions, in-situ resource utilization, and terrestrial applications (includes US Army and potentially industry)

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### Key Performance Parameters

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>State of the Art</th>
<th>Threshold Value</th>
<th>Project Goal</th>
<th>Estimated Current Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPP-1 Construction Material</td>
<td>Contour crafting with water-based concrete</td>
<td>Use in-situ regolith materials for manufacturing feedstock using imported binders</td>
<td>Use in-situ regolith materials for manufacturing feedstock using no imported feedstock materials</td>
<td>Demonstrated fabrication of construction material using regolith simulant and multiple binders (polymers, cements), as well as sintered regolith simulant. Performed compression tests and hypervelocity impact tests.</td>
</tr>
<tr>
<td>KPP-2 Emplacement</td>
<td>Subscale gantry mechanisms that are fixed in locations</td>
<td>Full scale gantry mechanisms in fixed locations</td>
<td>Mobile-ready print system</td>
<td>Developed continuous feed capability. (ACES 2) Design near complete for large scale mobile gantry system. (ACES 3) Gantry versus robot trade study complete. Report due 1/31/2017.</td>
</tr>
<tr>
<td>KPP-3 Construction Scale</td>
<td>Small concrete dome: ~1m high</td>
<td>In-situ regolith structure pad and curved wall; subscale optimized planetary structure</td>
<td>In-situ regolith structure pad and curved wall; full scale optimized planetary structure</td>
<td>Contour crafted martian simulant concrete straight and curved wall segments constructed. USACE additive printed guard shack (trials on 3/24, 5/5, 5/24 and final full size of 6'x8' on 7/6/16)</td>
</tr>
<tr>
<td>KPP-4 Print Head Construction Speed (1cm thick layers material)</td>
<td>30cm/minute</td>
<td>60cm/minute</td>
<td>100cm/minute</td>
<td>ACME 2 – 206 cm/minute ACES 2 – 508 cm/minute ACES 3 goal- 1270 cm/minute</td>
</tr>
</tbody>
</table>
Advanced Manufacturing Technology
ACME Technical Accomplishments and Technical Challenges

Technical Accomplishments:

• The ACES-2 DGFS was delivered to the United States Army Construction Engineering Research Laboratory (CERL) the first week of November 2016. Mods are currently taking place in preparation for a new motor installation for the weigh bin. A KSC software engineer is planning to be on-site at CERL the week of 2/6/2017 to assist with the install and testing.

• ACES-3 Liquid Delivery System Preliminary Design Review (PDR) was successfully completed at KSC on 11/29/2016. The ACES-3 Liquid Goods Delivery System (LGDS) Critical Design Review (CDR) is scheduled for 1/26/17 at KSC. Internal team review is complete.

• ACES-3 System Critical Design Review (CDR) was successfully completed on 12/8/2016.

• The energy chain concept was successfully tested on 12/5/2016, demonstrating the viability of this technique for hose management.

• Environmental Modeling analysis report that includes materials development work is complete (176 pages).

Technical Challenges:

• Meeting the U.S. Army Corp of Engineers (USACE) requirements with their current material (3/8th inch aggregate). ACME 2 runs were held on 11/10, 11/23, 11/28, 12/9. Work continues on characterizing the effects of material viscosity (standard mix and Martian simulant mix), pump speed, and the accumulator on concrete flow rate at the nozzle and overall nozzle performance.
The ACME team ran tests on 11/23/16, 11/28/16 and 12/9/16 with the Mars simulant mix to continue to understand the ACME-2 system variables.

The 12/9 test utilized the ACME-2 “training nozzle” and the ACME-2 accumulator. The purpose of the test was to demonstrate the capability to pump a batch of concrete with 17% of the stucco-based aggregate replaced with JSC Mars 1A regolith simulant through the modified ACME-2 system. Material flowed through both nozzle outlets. “Tearing” of the concrete during extrusion was witnessed. This phenomenon has only been seen while running the JSC Mars 1A regolith simulant through the ACME-2 “training nozzle”. The team is working to understand this phenomenon in order to better mitigate this issue.
ACES 3 System

Dry Good Storage Subsystem

Continuous Feedstock Mixing Delivery Subsystem (CFDMS)

Liquid Storage Subsystem

<table>
<thead>
<tr>
<th>Mixer</th>
<th>Pump</th>
<th>Compressor w/ Accumulator</th>
<th>Gantry</th>
<th>Nozzle</th>
</tr>
</thead>
</table>

Hose
ACES-3 Dry Goods Delivery System

- The ACES-2 DGFS was delivered to the United States Army Construction Engineering Research Laboratory (CERL) the first week of November 2016.
  - Mods are currently taking place in preparation for a new motor installation for the weigh bin. A KSC software engineer is planned to be on-site at CERL the week of 2/6/17 to assist with the install and testing.
- Several enhancements requested by the customer have been added to the design, including a bumper underneath the weigh bin exit chute, crane lifting points, and a Palletized Loading System (PLS) compatible interface on the structure.
- The bulk of the Liquid Goods Delivery System (LGDS) will be colocated underneath the dry good hoppers.
ACES-3 Liquid Goods Delivery System

- ACES-3 Liquid Goods Delivery System Preliminary Design Review (PDR) with Chief Engineers completed at KSC on 11/29/16.
- ACES-3 Liquid Goods Delivery System Critical Design Review (CDR) with Chief Engineers scheduled at KSC for 1/26/17.
- Modeling of Liquid Goods Delivery System complete, drawings and analysis to be completed by 1/24/17.
- Procurement of components in work.

Liquid goods delivery system will be controlled by the same software as the dry goods delivery system for ease of operator use.

Closed system: All tanks’ relief valves go back into tanks.

The additive tanks and pumps will be housed in an enclosure that can be heated when temperature nears freezing to ensure proper functionality.

Water Tank

Additive Tanks

Water Pump

Pumps underneath tanks
ACES 3 Design

ACES 3 Major Components

Accumulator
Pump Trolley

Gantry

Hose Management

Nozzle

Electrical & Software
Tests were performed on 12/5/2016 to demonstrate the use of an energy chain to assist with hose management. As part of the tests, a 2” hose was filled with wet sand and was bent, extracted, and inserted into the energy chain.
Milestone: Select a construction material that can be produced on Mars and used in additive construction technology. 
*Completed December 29, 2016*

Deliverable: Notification of the use of a polyethylene-regolith mixture, as well as compression and flexure test results, of the proposed material. This material will be pursued for the future print head development milestone.

**PROBLEM:** The use of in-situ resources is necessary to reduce the cost of missions. Planetary construction material development is still in its infancy. Additive construction on planetary surfaces requires a material that can be produced in-situ, but still work with additive construction technology.

**Objective:** Determine a material that can be produced in-situ and serve as a planetary construction material to be used in additive construction.

**Approach:** Use current knowledge of available surface and atmosphere resources and binders that can be produced from those resources to identify a combination that can be produced 100% in-situ on Mars. Optimize the mixture for additive construction.

**Results:** Selection of a polyethylene (produced from the atmosphere of Mars) regolith mixture. The mixture requires heating and mixing for extrusion and use in additive construction; a print head is in development.

---

Standard 2-inch cube compression test specimens with varying ratios of polyethylene to regolith.
Objective:
Record work completed to date in the study of candidate planetary construction materials specific to the environment of use: Mars atmosphere tests, compression load tests, hypervelocity impact tests, and radiation protection modeling.

Milestone completed on 12/30/16. This is a living document updated monthly.

Key Accomplishment/Deliverable/Milestone:

• Summarized experiments to date involving curing of planetary construction materials in a Mars environment (CO₂ gas and ~7 Torr pressure).

• Summarized compression testing data used to optimize the strength of material mixtures.

• Summarized hypervelocity impact test results applicable to both NASA and the Army Corps.

• Summarized radiation modeling parameters and modeling completed to date on single point spherical (dome) geometry for both Galactic Cosmic Rays and Solar Particle Events. Future work includes geometries more likely to be built on planetary surfaces and additional materials.

Significance:

• Established a living document to record analyses completed on planetary construction materials relative to their environment of use.

• Records planetary construction materials development, strengthening of these materials through experimentation, resistance of the material to hypervelocity impact, and the potential for radiation protection for future Mars habitats.
ACME
Plans for FY2017

- **FY17 Plans**
  - Completion of mobility trade study report.
  - Deliver third generation ACME and ACES hardware. (Nozzle, accumulator, wet goods subsystem, gantry)
  - Fabricate a representative planetary structure. (NASA)
  - Fabricate an expeditionary structure. (USACE)

- **FY17 Threats**
  - Deliver third generation ACES hardware by April 1, 2017.
## Project Summary Performance

<table>
<thead>
<tr>
<th>Project</th>
<th>Summary Performance</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technical</td>
<td>Cost</td>
</tr>
<tr>
<td>Quarter 1</td>
<td>AMT is yellow overall due to challenges utilizing the EBF³ process to add an inconel structural jacket to the GRCop-84 liner without producing cracks. (LCUSP) &amp; due to on-going challenges to meet the U.S. Army Corp of Engineers (USACE) requirements with their current material (3/8th inch aggregate). (ACME)</td>
<td>Technical- AMT is yellow overall due to challenges utilizing the EBF³ process to add an inconel structural jacket to the GRCop-84 liner without producing cracks. (LCUSP) &amp; due to on-going challenges to meet the U.S. Army Corp of Engineers (USACE) requirements with their current material (3/8th inch aggregate). (ACME)</td>
</tr>
<tr>
<td>Quarter 2</td>
<td>AMT is yellow overall due to the new recovery plan requiring more resources at LaRC. (LCUSP)</td>
<td>Cost- AMT is yellow overall due to the new recovery plan requiring more resources at LaRC. (LCUSP)</td>
</tr>
<tr>
<td>Quarter 3</td>
<td></td>
<td>AMT is yellow overall due to technical challenges resulting in lack of schedule reserves for project deliverables. (LCUSP &amp; ACME)</td>
</tr>
<tr>
<td>Quarter 4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Significant Challenges

**LCUSP**
- Understanding the failure modes and root cause of the EBF³ inconel to copper interface is required to successfully demonstrate objectives of the LCUSP project. Team working to understand process variability.

**ACME**
- Delivering the ACES 3 system to the USACE that meets their requirements by April 1, 2017.
Back Up Charts

<These charts feed Quarterly Reporting. All charts are required. >
**Risk Statement:** Given that this project involves developing new processing parameters in an effort to deposit a Ni-alloy onto the GRCop liner, there is the possibility that the combined jacket/liner part does not meet the structural or geometric requirements resulting in impacts to project schedule and technical objectives.

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

**Status:** The 2.5” plugs (pre and post HIP) were examined on Unit 1 and inspection thru electron microscope showed good results to proceed. The interface samples have been fabricated and machined and will be tested in May. A bigger issue has arisen with leaks identified in Unit 2. The leaks were found post HIP at the ends of the chamber and is suspected to have occurred during tooling extraction or HIP. Fault analysis and Unit 2 fix are being investigated at this time. CT scans show majority of the EBF3 application was done well, the end effects/crack can be mitigated and Unit 1 forward section was successful and had no leakage. The risk has been realized and likelihood has changed from 2 to 5 and the schedule has been impacted.

**Mitigation Steps**

<table>
<thead>
<tr>
<th>Mitigation Steps</th>
<th>Dollars to implement</th>
<th>Trigger/Start date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td></td>
<td></td>
<td></td>
<td>12/2014</td>
<td>3/4</td>
</tr>
<tr>
<td>2. Experiments are planned on a C18150 Chamber Simulator to assess the effect of higher strength and hoop stresses in a cylindrical geometry</td>
<td></td>
<td>7/2015</td>
<td></td>
<td>skipped</td>
<td>2/4</td>
</tr>
<tr>
<td>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</td>
<td></td>
<td>7/2015</td>
<td></td>
<td>10/2015</td>
<td>2/4</td>
</tr>
<tr>
<td>4. Metallurgical analyses are planned to examine the microstructures and precipitate morphologies at the interface between the GRCop and In625</td>
<td></td>
<td>On going as samples are made</td>
<td></td>
<td>12/2015</td>
<td>2/4</td>
</tr>
<tr>
<td>5. Examine 2.5” plugs (pre and post HIP) to understand the GRCop/Inconel Interface. Also tensile test of material interface and subsequent analysis show structural integrity</td>
<td></td>
<td>Interface looked very good</td>
<td></td>
<td>5/2016</td>
<td>1/4</td>
</tr>
<tr>
<td>6. The Hot Fire Test article passes Proof Pressure Test and Cold Flow Test</td>
<td></td>
<td></td>
<td></td>
<td>6/2016</td>
<td>close</td>
</tr>
</tbody>
</table>
### Risk Statement:

Given observations of flaws produced by the fabrication process as it has been developed to date and the lack of characterization for the critical flaw size and the lack of developed measurement techniques specific to this new manufacturing technique and geometry there exists the possibility of catastrophic failure of the part and loss of project objectives.

### Context:

Advancement of TRL from 3 to 6 as well as current GCD philosophy of higher risk with potential high gain opportunity is being utilized for this project. This is not flight hardware and there is minimal risk to the test stand. “Good Enough” instead of “Perfect” approach is being utilized control schedule. With schedule constraints and given that the flaws were recently observed in the samples, the quality control of EBF3 of Inconel on GRCop for material integrity throughout will be difficult. Perfection of method with multiple statistical samples in various configurations are not possible within schedule or cost constraints.

### Status:

Testing and Analysis of samples are part of the current process for learning good fabrication process. An additional HIP after application of the Inconel625 Jacket has been incorporated to close up cracks or gaps or flaws in material interface. Sample Trials on 3” section has been analyzed and evaluated. CT scans look good except at fore and aft ends and with the evaluation of the plugs from unit 1 looking good, the likelihood was reduced from 2 to 1. The end effect cracks are addressed in Risk 1 Mitigation Steps.

### Mitigation Steps

<table>
<thead>
<tr>
<th>Step Description</th>
<th>Dollars to implement</th>
<th>Trigger/Start Date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Initial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3x5</td>
</tr>
<tr>
<td>2. Additional thickness incorporation into Inconel625 Jacket and HIP entire Chamber after Jacket application</td>
<td></td>
<td></td>
<td></td>
<td>10/2015</td>
<td>2x5</td>
</tr>
<tr>
<td>3. Material Interface Inspection &amp; Analysis at sample points. Also material strength testing.</td>
<td></td>
<td></td>
<td></td>
<td>12/2015</td>
<td>2x5</td>
</tr>
<tr>
<td>4. Pathfinder 1st Unit will go thru the same application process for identifying improvements as well as for analysis and testing. Plugs from 1st Unit will be inspected and additional interface samples made to improve analysis.</td>
<td></td>
<td></td>
<td></td>
<td>3/2016</td>
<td>1x5</td>
</tr>
<tr>
<td>5. NDE of Chamber (X-ray or CT scans)</td>
<td></td>
<td></td>
<td></td>
<td>5/16</td>
<td>1x5</td>
</tr>
<tr>
<td>6. First order analysis of key geometries with representative flaws for minimum crack length allowable for crack propagation and chamber failure will be performed as test data is available.</td>
<td></td>
<td></td>
<td></td>
<td>5/2016</td>
<td>1x5</td>
</tr>
<tr>
<td>7. Proof Pressure check and Cold Flow prior to hot fire</td>
<td></td>
<td></td>
<td></td>
<td>9/2016</td>
<td>1x5</td>
</tr>
</tbody>
</table>
## ACME Risk Assessment

### 5 X 5 Risk Assessment Matrix

<table>
<thead>
<tr>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

### Risk Log

<table>
<thead>
<tr>
<th>Risk ID</th>
<th>Risk Definition</th>
<th>Approach</th>
<th>Est. Closure Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Facility Operating Space</td>
<td>Mitigate</td>
<td>1/25/2017</td>
</tr>
<tr>
<td>19</td>
<td>Safety Keep Out Zones</td>
<td>Mitigate</td>
<td>01/18/2017</td>
</tr>
<tr>
<td>20</td>
<td>Integration, Testing Space (Weather Impacts)</td>
<td>Mitigate</td>
<td>1/11/2017</td>
</tr>
<tr>
<td>21</td>
<td>Hose Management</td>
<td>Mitigate</td>
<td>12/15/2016</td>
</tr>
<tr>
<td>22</td>
<td>Logistics for Fabrication, Assembly, Integration</td>
<td>Mitigate</td>
<td>1/31/2017</td>
</tr>
<tr>
<td>23</td>
<td>Nozzle Development and Test</td>
<td>Mitigate</td>
<td>01/31/2017</td>
</tr>
<tr>
<td>24</td>
<td>Accumulator Development and Test</td>
<td>Mitigate</td>
<td>02/14/2017</td>
</tr>
</tbody>
</table>

### Consequences

<table>
<thead>
<tr>
<th>Risk ID</th>
<th>Risk Definition</th>
<th>Approach</th>
<th>Est. Closure Date</th>
</tr>
</thead>
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<tr>
<td>15</td>
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<tr>
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<td>Integration, Testing Space (Weather Impacts)</td>
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<tr>
<td>21</td>
<td>Hose Management</td>
<td>Mitigate</td>
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</tr>
<tr>
<td>22</td>
<td>Logistics for Fabrication, Assembly, Integration</td>
<td>Mitigate</td>
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</tr>
<tr>
<td>23</td>
<td>Nozzle Development and Test</td>
<td>Mitigate</td>
<td>01/31/2017</td>
</tr>
<tr>
<td>24</td>
<td>Accumulator Development and Test</td>
<td>Mitigate</td>
<td>02/14/2017</td>
</tr>
</tbody>
</table>

### Risk Assessment Scores

- **R, Y, G** 3 13 8 2 1* 0 1 0 2 1 1 2 1 11 4
- **Open** 18 3 3 4 10
- **Closed** 13

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

15

Trend

Criticality

Med

Current L/C

3x4

Affinity Group

Schedule,
Performance

Planned Closure

01/25/2017

Open Date

02/16/2016

Risk Statement

Given that the ACME team must relocate all resources (i.e. hardware) to another facility and an appropriate facility is not identified, resulting in not having the needed facility space to build and operate the ACME system, there is a possibility that the ACME team will not be able to operate the system, resulting in not meeting GCD and USACE milestones.

Approach: Mitigate

Context: ACME was allowed to operate in an older machine shop building knowing that at some point the “owner” of the building would need the building again. The owner of the machine shop building has started updating the building and will need the building around mid-April/ early-March. 2016 This risk affects meeting the milestones associated with ACME-3. Facility needs water, drainage to outside, storage space, electricity and a 80’x80’ foot print.

Status 01/12/2017 The LxC was updated from a 5x4 to a 3x4 resulting in a decreasing trend. Updated closure date from 01/18/2017 to 01/25/2017. A facility space has been located on-site (building 4757A). Building 4757A has some items that will need to be moved out before it is usable. There are issues that need to be addressed. Additional 110V power needs to be supplied, 3 -phase power needs to be available, additional lighting inside needs to be added. Solutions for drainage, water supply, and 3-phase power need to be developed as well.

12/21/2016 There are further issues with facilities locating a space and providing information about procuring a tent. The need for a usable facility is 01/18/2017. After this date, schedule delays are very likely to occur (one-for-one).

Mitigation Steps

<table>
<thead>
<tr>
<th>Step</th>
<th>Dollars to implement</th>
<th>Trigger/Start date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Evaluate off-site options. (Dynetics).</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Request assistance from MSFC management to find an outside space and use a tent or some other temporary shelter with a generator and water supply.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Develop an alternate plan to store procured hardware until assembly is needed.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2017 GCD 1st Quarter Review
Risk Statement

Given that the design of the hardware and software for ACES-3 includes fabrication, assembly, and control of large structural pieces, there is a possibility that certain logistics could be overlooked or underestimated, resulting in schedule loss and increased technical costs due to not planning the right resources prior to fabrication, assembly, and integration.

Approach: Mitigate

Context ACES-3 system is a large system (at least 30’x20’x15’) and will require the use of equipment for assembly. Machine shops need to be identified and confirmed that they can accommodate fabrication requests. Any transportation needs should be identified. Secondary equipment needed for the assembly and integration need to be identified and confirmed or bought.

Status 01/12//2017 Updated LxC from 1x4 to 3x4 resulting in an increasing trend. The closure date was updated from 01/18/2017 to 01/31/2017. The new facility space does not have water. The project will need to supply water tanks (approx. 500 gallons per tank) and a pump. At least one tank will be needed to hold clean water and at least three will be needed to hold used water. Used water cannot be drained on-site. Used water tanks will need to be hauled away by the heavy lift organization. Heavy lift could be prioritized to assist with SLS and cause a delay with hauling away the water tanks. Used water tanks will need to be cleaned and brought back. Three-phase power for operation of the ACES-3 system will need to be brought in. USACE is providing an M100 power distribution panel but the project will need to locate a power source. These issues could impact cost and schedule. The project would like to begin fabrication based on preliminary drawings. EV is suggesting to wait until issued drawings are released before any fabrication. This could greatly impact schedule.

Mitigation Steps

<table>
<thead>
<tr>
<th>Mitigation Steps</th>
<th>Dollars to implement</th>
<th>Trigger/ Start date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Develop an AI&amp;T plan to identify resources needed at critical times.</td>
<td></td>
<td></td>
<td></td>
<td>12/06/2016</td>
<td></td>
</tr>
</tbody>
</table>
ACES-3 Nozzle Development and Test

Risk Statement
Given that the Contour Crafting nozzle has proven to be difficult on both ACES-2 and ACME-2, there is a possibility that a poorly-designed nozzle for ACES-3 can result in not having the ability to sculpt the concrete and stop flow of the concrete when needed.

Approach: Mitigate

Context
Neither the ACME-2 or ACES-2 nozzles have worked as intended. There have been issues with concrete only flowing out one side of the nozzle, poor bead width consistency, the cutters not extending correctly to stop flow, and parts easily broken. Proper testing to identify the causes of these issues is needed.

Status  01/12/2017 The planned closure date was updated from 01/18/2017 to 01/31/2017. CCC has fabricated a plastic prototype of the ACES-3 nozzle. CCC provided analytical models for the team to review. The team has provided feedback to CCC. The current design and fabrication method for the ACES-3 nozzle requires additive manufacturing (AM). Using AM may require the material of the nozzle to be changed to better suit the fabrication process. A material change will result in a requirements change, but this is a minimal impact. Planned testing using the ACES-2 nozzle that would generate potential design data may be impacted by available resources (e.g. workforce).

12/05/2016 Updated closure date from 12/05/2016 to 01/18/2017. There were issues with the material mix on 12/02/2016, so the run was cancelled and has been rescheduled for 12/09/2016.

Mitigation Steps

<table>
<thead>
<tr>
<th>Mitigation Steps</th>
<th>Dollars to implement</th>
<th>Trigger/Start date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Develop a fault tree analysis for ACME-2 nozzle to identify potential variables.</td>
<td></td>
<td>11/17/2017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Test potential design solutions.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Pending results, incorporate nozzle design solutions.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Trend

Med

Criticality

Current L/C
2x4

Affinity Group
Technical

Planned Closure
01/31/2017

Open Date
11/17/2016
Risk Statement
Given that the accumulator has proven to be difficult on ACES-2, there is a possibility that a poorly-designed accumulator for ACES-3 can result in not having the ability to control and stop flow of the concrete.

Approach: Mitigate

Context
There are unknowns associated with the ACES-3 accumulator since there has been limited testing of the ACES-2 accumulator. The accumulator for ACME-2 does work as intended. The materials used for ACES-2 and ACME-2 are different, so it is unknown if a one-for-one comparison can be assumed.

Status 01/12/2017 Planned testing using the ACES-2 accumulator that would generate potential design data may be impacted by available resources (e.g. workforce). The same resources required for the fabrication and assembly of ACES-3 are the same resources required to operate the ACES-2 system. There is no testing currently planned.

12/21/2016 The ACES-2 accumulator was delivered to MSFC on 12/20/2016 for testing.

<table>
<thead>
<tr>
<th>Mitigation Steps</th>
<th>Dollars to implement</th>
<th>Trigger/Start date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Incorporate design changes to accommodate higher pressures.</td>
<td></td>
<td></td>
<td></td>
<td>12/08/2016</td>
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<tr>
<td>2. Modify the current ACES-2 accumulator with the current Aces-3 design.</td>
<td></td>
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<td>01/18/2017</td>
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<tr>
<td>3. Test the ACES-2 accumulator with the ACES-2 nozzle on the ACME-2 system.</td>
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<td>01/31/2017</td>
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</tbody>
</table>
Risk Statement
Given that the ACES-3 mobility system will utilize several high voltage motors and power supplies designed to move large masses very rapidly, and that there is a tendency for personnel on the project to work within the construction volume even during construction, there is a possibility of personnel being struck by rapidly moving hardware or being electrically shocked, resulting in significant injury or death.

Approach: Mitigate

CLOSED 12JAN2017

Context
Historically to date, there have been many instances where both ACME and ACES personnel have worked within the construction volume while the hardware was operating.

Status 01/12/2017 CLOSED A design to inhibit people from entering the work area while the ACES-3 system is being used was addressed during the CDR on 12/08/2016. The risks of entering the work area will also be called out in the operation manual.

12/01/2016 Updated the closure date from 12/15/2016 to 01/18/2017. Separated out the mitigation step 2 into design and fabrication steps. Completion dates for those reflect what is in the integrated schedule. The team is awaiting OSHA and other safety requirements to incorporate into a revision of the requirements.

Mitigation Steps

<table>
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<tr>
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<tbody>
<tr>
<td>1. Modify the requirements to include safety keep-out zones.</td>
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<tr>
<td>2a. Design physical barriers (tied to a power “kill” switch to keep people out.</td>
<td>10/27/2016</td>
<td>12/15/2016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b. Fabricate physical barriers (tied to a power “kill” switch to keep people out.</td>
<td>12/15/2017</td>
<td>02/14/2017</td>
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<td></td>
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<tr>
<td>3. Modify all existing or future operating procedures to define this new protocol.</td>
<td>10/27/2016</td>
<td>02/14/2017</td>
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Risk Statement
Given that the ACES-3 project is on a very tight schedule and that hardware integration is scheduled to occur in the Dec-Feb timeframe and that all locations identified by MSFC for integration and test are outdoors and that the average historical % of days below freezing for Dec-Jan-Feb is 20-27-21% and average days with measurable precipitation is 40-45-45%, there is a possibility of between 20 and 45% of workdays being unworkable due to weather, resulting in significant schedule delays.

Approach: Mitigate

Context The assembly/integration area required for ACES-3 is approximately 50’ x 30’, 15-20’ high. MSFC has been looking for possible indoor locations on-site, with no luck. Several outdoor locations have been identified and are under evaluation. This is not a requirement for operation, but a requirement for assembly.

Status 01/12/2017 CLOSED An enclosed facility location has been found and secured.
12/01/2016 Assessing another building, but have started the process to acquire a tent if needed.
11/17/2016 Added additional context “this is not a requirement for operation, but a requirement for assembly.”

Mitigation Steps

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<tbody>
<tr>
<td>1</td>
<td>Continue to look for indoor locations, preferably close to 4739.</td>
<td>10/27/2016</td>
<td>1x4</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>Evaluate options of renting or buying a tent and other environmental enclosure elements to cover the structure during assembly/test</td>
<td></td>
<td>1x4</td>
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</tbody>
</table>
Risk Statement
Given that concrete hose management has proven to be difficult on both ACES-2 and ACME-2, there is a possibility that improper or poorly-designed hose management techniques for ACES-3 can result in clogging, binding, or difficulty in extraction/removal of hoses for cleaning.

CLOSED 12JAN2017

Approach: Mitigate

Context
When a two-inch diameter hose is filled with concrete, the weight of the hose is significant. The extra weight makes it more difficult to manage the movement of the hose. This can affect the printing process because of complications like clogging or binding. Having a design that allows for easy extraction and removal of the hose for cleaning purposes is ideal. The CDR for the gantry system that encompasses the hose design will occur in early December.

Status 01/12/2017 CLOSED Testing was performed using the energy chain that will be used for hose management. The hose movement will meet the project requirements. Testing of the energy chain with hose to meet cleaning requirements was observed with no expected complications.

12/21/2016 Updated closure date from 12/15/2016 to 01/10/2017. Awaiting comments from the ACES-3 Critical Design Review board before closing to address any concerns of the board.

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<tr>
<td>1</td>
<td>Test hose configuration concepts in the lab.</td>
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Resources: Total Obligations and Cost

FY 2017 Financial Status

- Currently operating under CR thru April 2017. Contractual commitments/obligations are on-going and are expected to start catching up during the 2nd quarter of FY2017. Project activities on-going and there have been no impact to project milestones.
Excel File: STMD and GCD Data Request

- Milestone Completion and Burndown
- Technology Transfer or Infusion
- EPO: Activities, Conferences, and Students
- Economic Development

- Post Excel File to the following link on NX: https://nx.larc.nasa.gov/dsweb/View/Collection-95546

Use Excel file sent with the template and located on NX
Low Cost Upper Stage-Class Propulsion (LCUSP) Penta

**Problem / Need Being Addressed**

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

**Project Goal**

- 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 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.

**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

- 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 for Mobile Emplacement (ACME) Penta

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

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

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

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

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 MSFC
- LCUSP
- ACME

NASA GRC
- LCUSP

NASA LaRC
- LCUSP

NASA KSC
- ACME

Contour Crafting Corp

PISCES

US Army Corp Engineers

Allegheny Tech.

Industry Partners

<table>
<thead>
<tr>
<th>MI</th>
<th>MGI</th>
<th>LCUSP</th>
<th>ACME</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>• Allegheny Technologies Inc., Pennsylvania (GRCop Powder)</td>
<td>• PISCES - Hilo, HI</td>
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<td></td>
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<td>• USACE – Champaign, IL</td>
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<td>• CCC – Marina del Rey, CA</td>
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• AMT projects were represented at the NASA Innovation Day held at MSFC on 11/1/2016.

• The ACME materials work was presented at the Advanced Materials for Transformative Changes to the Defense, Aerospace, and Civil Environments conference at the University of Mississippi on 11/16/2016.

• LCUSP presented papers at Joint Army-Navy-NASA-Air Force (JANNAF) in Phoenix, AZ. (Dec 5-8)