A Thermochemical Regenerative Energy Storage System (TRESS)

Presented by:
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This system concept is protected by US provisional patent 61/092,358
Acknowledgements

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  • Al Sullivan, Headwaters Technology Innovation
  • Bing Zhou, Headwaters Technology Innovation
Program Manager – Dr. Ighor Uzhinsky (ATK)

Principal Engineer and Scientist – Dr. Tony Castrogiovanni (ACEnT Labs)

Key Subsystem Principal Investigators:

• Florin Girlea, Joe Alifano (ATK)
  – Provided engineering design data for H$_2$ generation reactor and 3D models of system

• Chris Kogstrom (ATK)
  – Investigated SOFC, turbine, and MgO recycling systems
  – Supported by Acumentrics, M-DOT Aerospace, and Boston University

• Dr. Akiva Sklar (ATK)
  – Led H$_2$O$_2$ synthesis efforts supported by Headwaters Technology Innovation
TRESS Night and Day Cycles

Night – Power Out

Day – Power In
Concept based on efficient energy storage in hydrogen peroxide and magnesium hydride and in leveraging reaction heat release to generate hydrogen, oxygen, and steam for solid oxide fuel cell/steam microturbine power units.

\[
2H_2O_2 \rightarrow O_2 + 2H_2O
\]

\[
MgH_2 + H_2O \rightarrow MgO + 2H_2
\]
Reactant Volume Comparison

MgH2
H2 (liquid)
H2 (2000psi)

H2O2 (75%)
O2 (liquid)
O2 (2000psi)
Pod configuration:

- Sealed from lunar environment in dome (radiation shield)
- Readily deployable from lander
- Electrical interfaces:
  - Power in from PV array
  - Power out
- Total system mass ≈ 2,000 kg
- Materials consumption:
  - MgH₂ powder: ~500 gram/hour
  - H₂O₂ (75% in water): ~1,800 gram/hour
- Fully regenerative closed system
TRESS Processes Benefits Summary

• High temperature chemical processes
  – High efficiency thermal energy conversion
  – High grade heat used to generate additional power

• High volumetric and gravimetric energy density
  – High efficiency storage of H₂ and O₂
  – Scaling-up storage (duration) increases overall system energy density

• Low material flow rates
  – Simplifies material supply subsystem components
  – Compact energy generation modules

• No maintenance required for materials stored for extended time periods
  – Opportunity to generate and store materials in advance for later use
  – Materials are safe and easily transportable

• Efficient material recycling technologies
  – System based on tested processes – need to develop lunar-specific designs
  – Experimental data are available to support system performance estimates

• Recycling process synergy with ISRU
  – Hydrogen peroxide may be used as a compact /storable water/oxygen source
  – MgO availability on the Moon
TRESS Unit Design Essentials

• Compact size
  – The system can be delivered in one module to the Moon ready for operations after integration with the solar array
  – Most components (e.g. turbine/SOFC/H$_2$ and O$_2$ reactors) are small
  – The unit is transportable to other lunar locations
• Encapsulated fueling options
  – Provide opportunity to fuel mobile/remote units
  – May be readily transported via hoppers to any lunar location
  – Standardized recycling interface enables centralized recycling (recharging) pod

• System is ~18-in. Φ x 32-in. H + heat rejection panels

• Mass ≈ 80 kg (0.5 kWh/kg)
TRESS Mobile (Rover/Remote Outposts) Applications

- Mobile units use encapsulated MgH$_2$ powder and peroxide cartridges that can be easily exchanged from a central depot or remote supply caches
- No need for on-board recharging
- Modular power cartridges may be distributed to any place on the lunar surface where common power generator interfaces are provided
- The cartridges are safe for long-term storage and may be delivered to the areas of interest in advance of particular missions
Applications/Variations of TRESS Technology

- MgH₂ + O₂ system (instead of H₂O₂)
  - Eliminates most complex synthesis process (and contaminants)
- Interplanetary Lunar Network (ILN)
  - <100 W systems for remote applications
- Emergency oxygen, water, or heat delivery
- Rocket propulsion using ISRU + TRESS derived propellants
  - MgH₂ + H₂O₂ rocket has Isp > 300 sec
- Terrestrial vehicle applications – compact H₂ for fuel cells and energy generators
- Underwater applications (or other sealed environments)
<table>
<thead>
<tr>
<th>Category</th>
<th>Objective ID Number</th>
<th>Name</th>
<th>TRESS Technology Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life Support &amp; Habitat</td>
<td>mLSH2</td>
<td>Develop and deploy closed loop life support systems to increase self-sufficiency of future long-duration human exploration missions and minimize the impact of humans on the environment.</td>
<td>TRESS technology of MgH2 and H2O2 generation from regolith and water should enable lunar base life support system for long-duration human exploration missions. Being recyclable these materials need only solar power for their reproduction in the originally available quantities minimizing regolith mining requirements and environmental impact. TRESS energy generation system may become a universal modular solution for lunar base energy and life support.</td>
</tr>
<tr>
<td>General Infrastructure</td>
<td>mGINF1</td>
<td>Emplace support services on the Moon, including emergency response, to enable increased lunar activities.</td>
<td>As a result of &quot;no-maintenance&quot; storability of MgH2 and H2O2 and potential for delivery of capsules with these energetic materials and their universal use in energy generation/life support systems - emergency response may be provided even in remote locations during lunar expeditions.</td>
</tr>
<tr>
<td></td>
<td>mGINF3</td>
<td>Deploy a Moon-based infrastructure that can service space-based assets to reduce the cost and increase the lifetime of space system operations.</td>
<td>With development of MgH2/H2O2 propulsion systems (e.g. &quot;Cold&quot; solid rocket boosters) the lunar base may enhance its support for servicing of Moon orbiting and Earth/Moon space systems.</td>
</tr>
<tr>
<td>Operations, Testing &amp; Verification</td>
<td>mOPS3</td>
<td>Establish crew-centered, real-time mission planning and control to enable self-sufficiency of lunar operations.</td>
<td>Because energetic materials in discussion may be generated in necessary quantities using regolith, water and solar energy then lunar base crew may plan activities and expeditions with less reliance to Earth-based resources and controls.</td>
</tr>
<tr>
<td>Power</td>
<td>mPWR1</td>
<td>Develop lunar power generation, storage, and distribution systems to satisfy the energy demands of lunar operations.</td>
<td>This is primary application for the TRESS system. We see this system as complimentary to RFC power units. Advantages of the TRESS energy storage and generation solution is in low-maintenance storage of the energetic materials that should be beneficial for long-term out-of-grid, shadowed locations.</td>
</tr>
<tr>
<td>Transportation</td>
<td>mTRANS3</td>
<td>Develop cryogenic fluid management, storage, and distribution systems to extend the lifetime and reduce the launch mass of exploration systems.</td>
<td>If TRESS energetic materials would have been produced and available in large quantities for use for long-term energy generation, intra-lunar transportation including hoppers and rovers, emergency deliveries, and, potentially, propulsion - then requirements for cryogenic storage and distribution systems may be significantly reduced and simplified.</td>
</tr>
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<tr>
<td>Surface Mobility</td>
<td>mSM1</td>
<td>Provide surface mobility capabilities to move crew outside the local area of a lunar outpost.</td>
<td>TRESS-based infrastructure and energy generation units should provide a compact/high power propulsion systems for moon rovers and other lunar outpost vehicles. Encapsulated materials can be easily delivered to remote locations. Hydrogen peroxide alone is a perfect life-support material suitable for emergency needs providing energy, water, and oxygen.</td>
</tr>
<tr>
<td></td>
<td>mSM2</td>
<td>Provide surface mobility capabilities to move cargo and equipment outside the local area of a lunar outpost.</td>
<td>See above.</td>
</tr>
<tr>
<td></td>
<td>mSM3</td>
<td>Provide surface mobility capabilities for local operations within a lunar outpost complex.</td>
<td>See above.</td>
</tr>
<tr>
<td>Lunar Resource Utilization</td>
<td>mLRU3</td>
<td>Develop and validate tools, technologies and systems that extract lunar resources, to enable lunar resource utilization.</td>
<td>Recycling technologies and equipment, being essential parts of the TRESS technology, should provide a compact and high efficiency units for processing of lunar technology materials (regolith and water). SLM process is suitable for separation of oxygen and metals from a variety of oxides that are available on the Moon.</td>
</tr>
<tr>
<td></td>
<td>mLRU4</td>
<td>Develop and validate tools, technologies and systems that process lunar resources, to enable lunar resource utilization.</td>
<td>TRESS technology is an example of development and validation of tools, software, components and systems that perform various engineering processing of extracted lunar resources. TRESS processes and technologies being implemented, reduce the mass of materials and products that must be launched from Earth for activities on the Moon and other destinations.</td>
</tr>
<tr>
<td></td>
<td>mLRU6</td>
<td>Develop, validate, and incorporate new products and associated technologies and systems that effectively utilize lunar resources and products, to support further lunar resource utilization.</td>
<td>See above. “Cold” solid rocket boosters that potentially may be fabricated on the Moon with TRESS energetic materials may enhance launch capabilities from the Moon base that are essential for the Mars program.</td>
</tr>
<tr>
<td></td>
<td>mLRU7</td>
<td>Produce propellants and life support and other consumables from lunar resources, to improve the productivity of lunar operations.</td>
<td>TRESS concept, technologies, and equipment, being implemented, should ensure energy independence and life support to the whole cycle of lunar base operations and generationg of a significant stock of energetic materials for variety of applications (see above).</td>
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</table>
## TRESS Relevance to Lunar Exploration Objectives

<table>
<thead>
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<th>TRESS Technology Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mLRU8</td>
<td>Construct facilities and manufacture hardware, materials, and other infrastructure growth products and capabilities from lunar resources, to improve the productivity of lunar operations.</td>
<td>See above.</td>
</tr>
<tr>
<td></td>
<td>mLRU9</td>
<td>Repair, fabricate and assemble parts and products using extracted and processed in-situ resources to support self-sustained, long duration missions.</td>
<td>See above.</td>
</tr>
<tr>
<td></td>
<td>mLRU10</td>
<td>Produce products from lunar resources that can be used for missions to other destinations, to enable and support future exploration.</td>
<td>See above.</td>
</tr>
</tbody>
</table>
• ATK and ACEnT Laboratories propose a phased program for the development of a TRESS system with a TRL of 6 by 2015 to 2018. The program is divided into 3 phases as follows:

  – Phase I: Electrical Energy Generating Module Demo and TRESS System Analysis

  – Phase II: TRESS Small Scale Prototype Demo Fabrication and Testing


• Detailed schedules have been developed for each of the program phases using Microsoft Project software

• All work is expected to be conducted in close cooperation with NASA
TRESS System Design and Concept of Operation
TRESS Pod with Heat Rejection Arrays

5 kW, 2,000 kWh System Depicted

5 ft 9 in. person for scale
TRESS System Isometric (Peroxide Tank Removed)
TRESS System Isometric (Peroxide Tank Removed)

- MgH2 Synthesis Reactor
- H2O2 Synthesis Reactor
- H2O2 Reactor
- SOFC
- High Pressure Electrolyzer
- Turbine
- MgO Hopper
- Condenser
- SOM Reactor
- Support Structure
- H2O2 Pump
- H2O Pump
A premier aerospace and defense company

Only TRESS Power Generation Components Required for Mobile Applications

Mobile TRESS Block Diagram with Orientation
Regeneration Station for Mobile System

Mobile Cartridges are Inserted into Regeneration Pod
Subsystems Overviews
Aqueous Peroxide Storage

- Toroid-cylinder with bladder
- $\text{H}_2\text{O}_2 + \text{H}_2\text{O}$ on inside, $\text{H}_2\text{O}$ collection on outside
- Largest volume component
- Key issue = compatibility with HBr and HCl (from synthesis reactor) and thermal management
Magnesium Hydride Storage

- Dry powder hopper
- Ultrasonic micro-dispenser
- Vibration-assisted flow
- Key issues – low gravity and dispense to pressurized reactor
Peroxide Decomposition System

- Passive transition metal catalyst bed similar to peroxide monopropellant rockets
- Exothermic decomposition reaction
- At < 67% concentrations, temperature is limited to saturation at set pressure
- Product (<67%) is O₂ and high quality steam
- Gravity-based liquid/water separator

\[
\text{H}_2\text{O}_2 \xrightarrow{\text{Isolation valve and liquid pump}} \text{Catalyst Bed} \xrightarrow{\text{O}_2 (v) + \text{H}_2\text{O} (v) + \text{H}_2\text{O} (l)} \text{Liquid Separator} \xrightarrow{\text{O}_2 (v) + \text{H}_2\text{O} (v)} \text{SOFC}
\]
• Based on powder/flame spray gun technology
• Key is mixing efficiency and residence time to complete reaction
Accumetrics cylindrical configuration is baseline.
• Microturbine has highest power to weight

• We need Pin/Pout = 270 to maximize power output

• 40% efficiency today, but we can sacrifice weight for more efficiency for TRESS

• M-DOT 500 W product is selected departure point
Other Power Generation Options Considered

- Scroll expander offers 70% efficiency, however pressure ratio is limited
- Multiple units in series possible
- NASA Stirling engines for radioisotope systems
- 38% efficiency for 850°C to 90°C demonstrated
High Pressure Water Electrolyzer

- Giner Electrochemical Systems 1,200 psi high pressure electrolyzer is baseline point of departure
  - NASA GRC and DARPA funding
  - Eliminates need for O₂ and H₂ compressors for H₂O₂ synthesis system

<table>
<thead>
<tr>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specific power (W/kg)</strong></td>
</tr>
<tr>
<td><strong>Pressure (kPa gage)</strong></td>
</tr>
<tr>
<td><strong>Efficiency at design point (at Higher Heat Value basis)</strong></td>
</tr>
<tr>
<td><strong>Efficiency at 25% Imax (HHV basis)</strong></td>
</tr>
<tr>
<td><strong>Efficiency at 50% Imax (HHV basis)</strong></td>
</tr>
<tr>
<td><strong>Efficiency at 75% mA/cm² (HHV basis)</strong></td>
</tr>
</tbody>
</table>
Aqueous Hydrogen Peroxide Synthesis

- Headwaters Technology Innovations direct synthesis process is baseline
  - Industrial process uses methanol as substrate, TRESS uses supercritical CO₂
• Boston University solid oxide membrane (SOM) process is baseline for MgO decomposition
• ORC bottoming cycle may be used to extract additional energy from H₂O₂ synthesis reactor cooling loop

• Use of second fluid and temperature difference from reactor (1,150°C) to shaded lunar heat sink

• Low efficiency expected due to indirect heat exchange (~20%), but small system does not add significant weight
• NASA CR – 2006-214388\(^1\) describes a potential system for heat rejection of temperatures in the range \(\sim 450K\) (177°C)

• A ~6 meter diameter single-wing UltraFlex unit of 14 to 18 kW will be able to provide the necessary power for the daytime regeneration cycle of TRESS
## Top Subsystem Risks

<table>
<thead>
<tr>
<th>Risk Items</th>
<th>Effect(s)</th>
<th>Proposed R&amp;D Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contamination of H₂O₂ with trace quantities of HBr and HCl</td>
<td>Corrosion of catalyst and reduced life of subsystem.</td>
<td>Experimental verification of material life with trace quantities of the additives</td>
</tr>
<tr>
<td>Ineffective gas phase MgH₂ synthesis</td>
<td>Incorrect chemistry</td>
<td>Not typically done with gas phase Mg – bench-scale tests to verify</td>
</tr>
<tr>
<td>Inefficient mixing of powder and steam</td>
<td>Incorrect chemistry results in low H₂ yield and undesired products</td>
<td>Extensive design and test of system. Leverage experience from flame spray industry</td>
</tr>
<tr>
<td>Accurate control of powder dispense in reduced gravity and low temperature</td>
<td>Non-uniform dispensing results in incorrect chemistry and thermal balance for system</td>
<td>Leverage experience from pharmaceutical industry. Carefully calibrate system</td>
</tr>
<tr>
<td>Backflow of steam due to powder dispense to pressurized reactor</td>
<td>Reaction in powder hopper</td>
<td>Backpressure hopper to above steam pressure (not desired). Supersonic injection (ejector) similar to HVOF flame spray.</td>
</tr>
<tr>
<td>HBr + HCl contaminants in MgH₂ reactor</td>
<td>Potential creation of unwanted compounds (e.g. MgCl₂ and MgBr₂)</td>
<td>Assess with bench-scale tests</td>
</tr>
<tr>
<td>SOM Containment Vessel Corrosion</td>
<td>maintenance, life</td>
<td>Investigate alternatives- material optimization, coatings, alloys..; surface temp.</td>
</tr>
<tr>
<td>SOM YSZ Membrane Durability</td>
<td>Life, efficiency, maintenance, durability</td>
<td>Examine post-exposure mechanical and physical characteristics</td>
</tr>
</tbody>
</table>
## Top System Level Risks

<table>
<thead>
<tr>
<th>Risk Items</th>
<th>Effect(s)</th>
<th>Importance/Likely-hood</th>
<th>Technical Risk</th>
<th>Proposed R&amp;D Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inaccuracy in flow control, particularly during system transients</td>
<td>Reduced efficiency, offset thermal balance, unwanted products can accumulate contaminants</td>
<td>High</td>
<td>High</td>
<td>Comprehensive closed-loop control architecture development. Extensive testing and sensitivity examination</td>
</tr>
<tr>
<td>Thermal balance variations, particularly during transients</td>
<td>System efficiency, weight, life</td>
<td>High</td>
<td>Med</td>
<td>Thermal controls development and testing – sensitivity assessment. Environmental tests</td>
</tr>
<tr>
<td>Accumulation of contaminants</td>
<td>Efficiency, life reduction</td>
<td>High</td>
<td>High</td>
<td>Subsystem testing to insure purity, system testing to assess impacts</td>
</tr>
</tbody>
</table>
# TRL Assessment

## System

<table>
<thead>
<tr>
<th>System</th>
<th>TRL Today (on Earth)</th>
<th>TRL Today (lunar)</th>
<th>Risk to TRL 6 by 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O$_2$ Storage</td>
<td>9</td>
<td>2</td>
<td>L</td>
</tr>
<tr>
<td>MgH$_2$ Storage</td>
<td>9</td>
<td>2</td>
<td>L</td>
</tr>
<tr>
<td>H$_2$O$_2$ Decomposition Reactor</td>
<td>9</td>
<td>3</td>
<td>L</td>
</tr>
<tr>
<td>MgH$_2$ + H$_2$O Reactor</td>
<td>4</td>
<td>2</td>
<td>L</td>
</tr>
<tr>
<td>SOFC and Turbine</td>
<td>5</td>
<td>3</td>
<td>M</td>
</tr>
<tr>
<td>Water Electrolysis</td>
<td>9</td>
<td>6</td>
<td>L</td>
</tr>
<tr>
<td>MgH$_2$ Synthesis</td>
<td>3</td>
<td>1 - 2</td>
<td>M/H</td>
</tr>
<tr>
<td>H$_2$O$_2$ Synthesis</td>
<td>9</td>
<td>1 - 2</td>
<td>M/H</td>
</tr>
<tr>
<td>System Integration and Operation</td>
<td></td>
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<td>H</td>
</tr>
</tbody>
</table>
Figure of Merit Sensitivity Analysis

- Variables used in parametric analysis:
  - Percent hydrogen peroxide concentration in water (50% and 75%)
  - System power level (2, 3.5, and 5 kW)
  - System energy storage (100 kWh to 2,000 kwh) or up to 400 hours
  - Regeneration time as a function of power generation time (1X and 2X)
  - SOFC efficiency (45% to 60%)
  - Nighttime waste heat efficiency

- Key figures of merit:
  - System flow rates
  - Overall TRESS system mass
  - Energy-in/energy-out “round trip” efficiency
  - Power-in requirements
  - System mass distribution by major subsystem
System Energy-Out/Energy-In Efficiency versus Nighttime Waste Heat Utilization Efficiency

5kW - 2000kW-hr System with ORC (η=20%), 75% H₂O₂
SOFC efficiencies from 45% to 60%
Mass vs. Nighttime Waste Heat Utilization Efficiency
5kW - 2000kW-hr System, 75% H₂O₂
Day = Night, SOFC efficiencies from 45% to 60%
System Mass Sensitivity (2 kW, 75% Peroxide)

Mass vs. Nighttime Waste Heat Utilization Efficiency
2.0kW - 800kW-hr System, 75% H₂O₂
Day = Night, SOFC efficiencies from 45% to 60%
Daytime Waste Heat vs. Waste Heat Utilization Efficiency
5kW - 2000kW-hr System with ORC with η=20%, 75% H₂O₂
Day = Night, SOFC efficiencies from 45% to 60%

Nighttime Waste Heat Utilization Efficiency

Daytime Waste Heat vs. Waste Heat Utilization Efficiency
2.0kW - 800kW-hr System with ORC with η=20%, 75% H₂O₂
Day = Night, SOFC efficiencies from 45% to 60%
Daytime Waste Heat (55% Peroxide)

Daytime Waste Heat vs. Waste Heat Utilization Efficiency
5kW - 2000kW-hour System with ORC with $\eta=20\%$, 55% $H_2O_2$
Day = Night, SOFC efficiencies from 45% to 60%

Nighttime Waste Heat Utilization Efficiency
Daytime Waste Heat vs. Waste Heat Utilization Efficiency
2.0kW - 800kW-hour System with ORC with $\eta=20\%$, 55% $H_2O_2$
Day = Night, SOFC efficiencies from 45% to 60%
System Mass Distribution, Day = Night
(5kW, 2000kWh, 75% H₂O₂)

- SOM MgO decomp: 0.3%
- Electrolyzer: 1.7%
- MgO vessel: 0.6%
- Turbine: 0.1%
- Pumps, valves: 0.4%
- SOFC: 2.6%
- Separators: 0.3%
- Hydride reactor: 0.1%
- Peroxide reactor: 0.1%
- MgH₂ synth: 0.2%
- Peroxide synth: 10.4%
- MgH₂: 16.9%
- MgH₂ Tank: 0.8%
- Peroxide Tank: 1.7%
- Heat Rejection: 5.6%
- Peroxide Mixture: 58.2%
System Mass Distribution, Day = Night
(5kW, 100kWh, 75% H₂O₂)

- Peroxide Mixture: 11.3%
- Peroxide Tank: 0.3%
- MgH₂: 3.3%
- Hydride reactor: 0.4%
- Separators: 1.1%
- Pumps, valves: 1.7%
- SOFC: 10.1%
- Electrolyzer: 6.5%
- Peroxide synth: 40.4%
- Heat Rejection: 21.7%
- MgH₂ Tank: 0.2%
- MgO vessel: 0.6%
- MgO synth: 0.1%
- SOM MgO decomp: 1.3%
- MgH₂ synth: 0.6%
Reactants as a Percent of System Mass

Day = Night, 75% H₂O₂

Energy Stored (kWh)

Reactant (%)
Key Results Summary

• System is characterized by high energy density
  – ~1.1 kWh.kg for complete TRESS
  – ~1.4 kWh/kg for power generation only

• As expected, high concentrations of peroxide are favorable
  – Less water to store and regenerate in peroxide mixture

• Reactant storage is key mass and volume driver
  – Efficiency is key for power gen components – mass is secondary (or lower)
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100 W TRESS-derived Power Sources (ILN)

Operational Time 336 hours

**MgH₂/O₂ System**
Weight ~35kg; Volume ~140 l

**TCH/O₂ System**
Weight ~50kg; Volume ~220 l
100 W MgH2/O2 System Configuration

A premier aerospace and defense company
• Our Thermochemical Regenerative Energy Storage System (TRESS) is a promising candidate to meet NASA’s requirements in a highly compact, efficient package

• The system performance and form factor is superior to batteries and H₂ –O₂ regenerative fuel cell based systems

• TRESS is highly compatible with future in-situ resource utilization (ISRU) for added long-term benefits

• ATK has committed significant funding to the underlying CHOSS system development
Thank You!