Overview

• National Aeronautic and Space Administration
• Definitions
• NASA Near Term Activities
• Energy Storage and Power
  • Batteries
  • Fuel Cells
  • Regenerative Fuel Cells
  • Electrolysis
• ISRU
• Cryogenics
• Review
NASA has many development activities supported by a number of high quality people across the country. This list only includes the most significant contributors to the development of this presentation.

**Headquarters**
- Lee Mason, Space Technology Mission Directorate, Deputy Chief Engineer
- Gerald (Jerry) Sanders, Lead for In-Situ Resource Utilization (ISRU) System Capability Leadership Team

**Jet Propulsion Laboratory**
- Erik Brandon, Ph.D, Electrochemical Technologies
- Ratnakumar Bugga, Ph.D, Electrochemical Technologies

**Marshall Space Flight Center**
- Kevin Takada, Environmental Control Systems

**Kennedy Space Center**
- Erik Dirschka, PE, Propellant Management

**Glenn Research Center**
- William R. Bennett, Photovoltaic and Electrochemical Systems
- Fred Elliott, Space Technology Project Office
- Ryan Gilligan, Cryogenic and Fluid Systems
- Wesley L. Johnson, Cryogenic and Fluid Systems
- Lisa Kohout, Photovoltaic and Electrochemical Systems
- Dianne Linne, ISRU Project Manager
- Phillip J. Smith, Photovoltaic and Electrochemical Systems
- Tim Smith, Chief, Space Technology Project Office
Electrochemical System Definitions

**Primary Power**
Discharge Power Only

**Description**
- Energy conversion system that supplies electricity to customer system
- Operation limited by initial stored energy

**Examples**
- Nuclear (e.g. RTG, KiloPower)
- Primary Batteries
- Primary Fuel Cells

**NASA Applications:**
Missions without access to continuous power (e.g. PV)
- All NASA applications require electrical power
- Each primary power solution fits a particular suite of NASA missions

**Energy Storage**
Charge + Store + Discharge

**Description**
- Stores excess energy for later use
- Supplies power when baseline power supply (e.g. PV) is no longer available
- Tied to external energy source

**Examples**
- Rechargeable Batteries
- Regenerative Fuel Cells

**NASA Applications:**
Ensuring Continuous Power
- Satellites (PV + Battery)
- ISS (PV + Battery)
- Surface Systems (exploration platforms, ISRU, crewed)
- Platforms to survive Lunar Night

**Commodity Generation**
Chemical Conversion

**Description**
- Converts supplied chemical feedstock into useful commodities
- Requires external energy source (e.g. thermal, chemical, electrical, etc.)

**Examples**
- ISS Oxygen Generators (OGA, Elektron)
- ISRU Propellant Generation

**NASA Applications:**
Life-support, ISRU
- Oxygen Generation
- Propellant Generation
- Material Processing
- Recharging Regenerative Fuel Cells
Electrochemical System Definitions

**Primary Fuel Cell**
Discharge Power Only
\[ 2H_2 + O_2 \rightarrow 2H_2O + 4e^- + \text{Heat} \]

**Regenerative Fuel Cell**
Charge + Store + Discharge
\[ Q_{TH} \]
\[ \Delta P \]
\[ Q_{ELE} \]

**Electrolysis**
Chemical Conversion
\[ 2H_2O + 4e^- \rightarrow 2H_2 + O_2 + \text{Heat} \]

Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

[Diagram showing the systems and their components]
Each power technology contributes to an integrated Regenerative Fuel Cells (RFCs) for Lunar Exploration

- Batteries meet energy storage needs for low energy applications
- RFCs address high energy storage requirements where nuclear power may not be an option (in locations near humans)
- Nuclear and radio isotope power systems provide constant power independent of sunlight
Current energy storage technologies are insufficient for NASA exploration missions.

Availability of flight-qualified fuel cells ended with the Space Shuttle Program.

Terrestrial fuel cells not directly portable to space applications:
- Different wetted material requirements (air vs. pure O₂)
- Different internal flow characteristics

No space-qualified high-pressure electrolyzer exists:
- ISS O₂ Generators are low pressure electrolyzers
- Terrestrial electrolyzers have demonstrated >200 ATM operation
Battery Activities in Support of NASA Missions

- Low temperature electrolytes to extend operating temperatures for outer planetary missions
- High temperature batteries for Venus missions
- Non-flammable separator/electrolyte systems
- Solid-state high specific energy, high power batteries
- Li-air batteries for aircraft applications
  
  Improved cathode and electrolyte stability in Lithium-Oxygen batteries

- Multi-functional load-bearing energy storage
- X-57 Maxwell distributed electric propulsion flight demonstration
- Safe battery designs and assessments for aerospace applications
Energy Storage System Needs for Future Planetary Missions

- **Primary Batteries/Fuel Cells for Surface Probes:**
  - High Temperature Operation (> 465°C)
  - High Specific Energy (>400 Wh/kg)
  - Operation in Corrosive Environments

- **Rechargeable Batteries for Aerial Platforms:**
  - High Temperature Operation (300-465°C)
  - Operation in Corrosive Environments
  - Low-Medium Cycle Life
  - High Specific Energy (>200 Wh/kg)
  - Operation in High Pressures

- **Primary Batteries/Fuel Cells for planetary landers/probes:**
  - High Specific Energy (> 500 Wh/kg),
  - Long Life (> 15 years),
  - Radiation Tolerance & Sterilizable by heat or radiation

- **Rechargeable Batteries for flyby/orbital missions:**
  - High Specific Energy (> 250 Wh/kg)
  - Long Life (> 15 years)
  - Radiation Tolerance & Sterilizable by heat or radiation.

- **Low temperature Batteries for Probes and Landers:**
  - Low Temperature Primary batteries (< -80°C)
  - Low Temperature Rechargeable Batteries (< -60 C)

All images are Artist’s Concepts
Lunar RFC Trade Study Results

10 kW $\text{H}_2/\text{O}_2$ RFC Energy Storage System for Lunar Outpost

- Reactants
- Batteries
- RFCs enable missions to survive the lunar night

RFC specific energy dependent on location.
Battery specific energy independent of location.
A solar array powers the probe at high altitude and generates H₂ and O₂ with Solid Oxide Electrolysis Cell (SOEC) using water carried from ground as a closed-system. Metal hydride H₂ storage and compressed gas O₂ storage. Solid Oxide Fuel Cell (SOFC) will powers the probe at low altitudes from the stored H₂ and O₂. H₂-filled balloon will be used for buoyancy and altitude control (60-15 km).
Electrolysis within NASA

**Fundamental Process**
- Electrochemically dissociating water into gaseous hydrogen and oxygen
- Multiple chemistries – Polymer Electrolyte Membrane (PEM), Alkaline, Solid Oxide
- Multiple pressure ranges
  - ISRU & Life support = low pressure
  - Energy storage = high pressure

**Life Support:** Process recovered H$_2$O to release oxygen to source breathing oxygen
- Redesign ISS Oxygen Generator assembly for increased safety, pressure, reliability, and life
- Evaluate Hydrogen safety sensors

**Energy Storage:** Recharge RFC system by processing fuel cell product H$_2$O into H$_2$ fuel and O$_2$ oxidizer for fuel cell operation

**ISRU:** Process recovered H$_2$O to utilizing the resulting H$_2$ and O$_2$
- Hydrogen Reduction – Hydrogen for material processing
- Life Support – Oxygen to source breathing oxygen
- Propellant Generation – Oxygen for liquefaction and storage
In-situ Resource Utilization (ISRU)

Modular Power Functions/Elements
- Power Generation
- Power Distribution
- Energy Storage (O₂ & H₂)

Support Functions/Elements
- ISRU
- Life Support & EVA
- O₂, H₂, and CH₄ Storage and Transfer

Shared Hardware to Reduce Mass & Cost
- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility

**In-Space Construction**

**Civil Engineering, Shielding, & Construction**

**Parts, Repair, & Assembly**

**In-Space Manufacturing**

**Life Support & EVA**

**Pressurized Rover**

**Surface Hopper**

**Used Descent Stage**

**Propellant Depot**

**Lander/Ascent**

**Regenerative Fuel Cell**

**Solar & Nuclear**

**CO₂ & Trash/Waste**

**H₂O, CO₂ from Soil/Regolith**

**Water/Volatile Extraction**

**Regolith Crushing & Processing**

**Regolith/Soil Excavation & Sorting**

**Regolith/Soil Transport**

**Resource & Site Characterization**

**CO₂ from Mars Atmosphere**

**H₂O, CO₂ from Soil/Regolith**

**Cryogenic Storage**

**Reactant Storage**

**Water Electrolysis**

**Solar arrays/nuclear reactor**

**Shared Hardware to Reduce Mass & Cost**

**Modular Power Systems**
Lunar ISRU Mission Capability Concepts

- Resource Prospecting – Looking for Polar Ice
- Excavation & Regolith Processing for O$_2$ Production
- Carbothermal Processing with Altair Lander Assets
- Thermal Energy Storage Construction
- Landing Pads, Berm, and Road Construction
- Consumable Depots for Crew & Power
ISRU is Similar to Establishing Remote Mining Infrastructure and Operations on Earth

Communications
- To/From Site
- Local

Transportation to/from Site:
- Navigation Aids
- Loading & Off-loading Aids
- Fuel & Support Services

Power:
- Generation
- Storage
- Distribution

Maintenance & Repair

Living Quarters & Crew Support Services

Construction and Emplacement

Planned, Mapped, and Coordinated Mining Ops:
Areas for: i) Excavation, ii) Processing, and iii) Tailings

Roads
Reactant Processing and Storage

Oxygen

MOXIE O₂ Generator

O₂ Exhaust

CO₂ Feed

O₂ Exhaust

Endplate (-)

Midplate (+/-)

Endplate (+)

Oxygen Concentrators

Tank-to-Tank Transfer

Radio Frequency Mass Gauge (RFMG)

CryoFILL Liquefaction and Storage

Hydrogen

Zero Boil-Off Tank (ZBOT) Experiment

Purification and Recovery

H₂

He
Zero Boil-off Cryogenics

Zero Boil-Off Tank (ZBOT) Experiment: Hardware in MSG Aboard ISS

1g (1W), 90%, Self-Pressurization

Micro-g (0.5W), 70%, Self-Pressurization

ZBOT Experiment During Jet Mixing
Thank you for your attention.

Questions?
Major Challenges of Solar System Missions

- Some missions require high radiation resistant power systems
- Outer planetary surface missions require low temperature power systems
- Some outer planetary missions require power systems that can operate in deep space and in dense or tenuous atmospheres

Extreme Environments in Planetary Missions

Some missions require high radiation resistant power systems.

Outer planetary surface missions require low temperature power systems.

Some outer planetary missions require power systems that can operate in deep space and in dense or tenuous atmospheres.

Inner planetary missions require power systems that can operate in very high temperature environments.
## Representative Examples of Aeronautics Mission Requirements

<table>
<thead>
<tr>
<th>Mission</th>
<th>Number of Passengers</th>
<th>Typical Range</th>
<th>Power Level</th>
<th>Specific Energy</th>
<th>EAP Configurations</th>
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</thead>
<tbody>
<tr>
<td>Urban Mobility</td>
<td>≤ 4</td>
<td>&lt; 50 miles</td>
<td>200-500 kW</td>
<td>250 – 400 Whr/kg</td>
<td>• All electric</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Hybrid Electric</td>
</tr>
<tr>
<td>Thin Haul</td>
<td>≤ 9</td>
<td>&lt; 600 miles</td>
<td>200-500 kW</td>
<td>300 – 600 Whr/kg</td>
<td>• Hybrid Electric</td>
</tr>
<tr>
<td>Short Haul Aircraft</td>
<td>40-80</td>
<td>&lt; 600 miles</td>
<td>500-1500 kW</td>
<td>300 – 600 Whr/kg</td>
<td>• Hybrid Electric</td>
</tr>
<tr>
<td>Single Aisle</td>
<td>150-190</td>
<td>900 mile typical mission, 3500 mile maximum range</td>
<td>1000-5000 kW</td>
<td>750 – 1000 Whr/kg minimum</td>
<td>• Hybrid Electric</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Turbo Electric</td>
</tr>
</tbody>
</table>
The Need for In-Situ missions:
Despite years of exploration, major questions remain:
• What is the precise chemical composition of the atmosphere and how does it vary with location and altitude?
• When and How did the Greenhouse effect occur on Venus
• How did the atmosphere of Venus form and evolve?
• What are the morphology, chemical make-up, and variability of the Venusian clouds and their impact on the climate?
• What are the processes controlling the atmospheric super-rotation?
• What are the processes governing Venus seismicity and its interior structure?
• How have the interior, surface, and atmosphere interacted as a coupled system over time?

The Problem
• Hostile environment of high temperature and pressure (465°C and 92 atm of CO₂) makes surface and low-altitude missions challenging.
• Cloud opacity limits orbital/balloon observations
• Conventional power sources, PV or RTG may not be applicable. New power technologies desired to enable missions

Battery Options Non-Existent

Thermal Batteries
Li-FeS2
Na-S or Na-MCl2
Li-Ion
Li Primary

Fig. 1 Venus temperature/pressure vs. altitude.
New Power Concept for Variable Altitude Venus Balloon Operation

Altitude Control
- H₂-filled balloon for buoyancy and altitude control (60-15 km)
- To Ascend: move H₂ from hydride into balloon
- To Descend: move H₂ from balloon into hydride

Solar array powers the probe at high altitude and generates H₂ and O₂ with Solid Oxide Electrolysis Cell (SOEC) from stored H₂O

At low altitudes, the SOEC operates reversibly as a Fuel Cell to power the probe from the stored H₂ and O₂ and stores the byproduct H₂O
## Portability of Terrestrial Technology to Aerospace Applications

<table>
<thead>
<tr>
<th>Component</th>
<th>Aerospace TRL Level</th>
<th>Portability of Terrestrial Technology to Aerospace Applications</th>
<th>Remaining Technical Challenge</th>
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<tbody>
<tr>
<td>Electrochemistry</td>
<td>9</td>
<td>High</td>
<td></td>
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<tr>
<td>Materials</td>
<td>5+</td>
<td>High</td>
<td>High Pressure, Mass</td>
</tr>
<tr>
<td>Seals</td>
<td>5+</td>
<td>High</td>
<td>High Pressure, Mass</td>
</tr>
<tr>
<td>Gas Management</td>
<td>5+</td>
<td>Moderate</td>
<td>High Pressure, Mass</td>
</tr>
<tr>
<td>Flow Fields</td>
<td>5+</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Bipolar Plates</td>
<td>5+</td>
<td>Moderate</td>
<td>O₂ vs air</td>
</tr>
<tr>
<td>Materials</td>
<td>5+</td>
<td>Moderate</td>
<td>O₂ vs air</td>
</tr>
<tr>
<td>Electrochemistry</td>
<td>5+</td>
<td>Low</td>
<td>O₂ vs air, Performance</td>
</tr>
<tr>
<td>Water Management</td>
<td>5+</td>
<td>Low</td>
<td>Flow Rate, µg</td>
</tr>
<tr>
<td>Fluidic Components</td>
<td>8+</td>
<td>Moderate</td>
<td>O₂ vs air</td>
</tr>
<tr>
<td>Procedures</td>
<td>5</td>
<td>Moderate</td>
<td>O₂ vs air, Performance</td>
</tr>
<tr>
<td>Thermal</td>
<td>8+</td>
<td>Moderate</td>
<td>µg, Vacuum</td>
</tr>
<tr>
<td>Materials</td>
<td>8+</td>
<td>Low</td>
<td>O₂ vs air</td>
</tr>
<tr>
<td>Water Management</td>
<td>5+</td>
<td>Low</td>
<td>O₂ vs air, µg</td>
</tr>
<tr>
<td>Hardware/PCB</td>
<td>8+</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Power Management</td>
<td>8+</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>8+</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>8+</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Instrumentation</td>
<td>8+</td>
<td>Moderate</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** Not all relevant technologies exist within the same application nor are at the same TRL. Elements of multiple terrestrial applications are required to meet specific NASA mission requirements.
In-situ Resource Utilization (ISRU)

**Water**
- **Moon**
  - Icy Regolith in Permanently Shadowed Regions (PSR)
- **Mars**
  - Hydrated Soils/Minerals: Zypsum, Jarosite, Phylosilicates, Polyhydrated Sulfates
- **Asteroids**
  - Subsurface Regolith on C-type Carbonaceous Chondrites

**Oxygen**
- Solar wind hydrogen with Oxygen
- Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite
  - CO, CO₂, and HC’s in PSR
  - Solar Wind from Sun (~50 ppm)
  - Minerals in Lunar Regolith
    - Iron/Ti: Ilmenite
    - Silicon: Pyroxene, Olivine, Anorthite
    - Magnesium: Mg-rich Silicates
    - Al: Anorthitic Plagioclase

**Metals**
- Minerals in Lunar Regolith
  - Iron/Ti: Ilmenite
  - Silicon: Pyroxene, Olivine, Anorthite
  - Magnesium: Mg-rich Silicates
  - Al: Anorthitic Plagioclase
- Minerals in Mars Soils/Rocks
  - Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smeectite
  - Silicon: Silica, Phylosilicates
  - Aluminum: Laterites, Aluminosilicates, Plagioclase
  - Magnesium: Mg-sulfates, Carbonates, & Smeectites, Mg-rich Olivine
- Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids
- Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites

**Uses**
- Drinking, radiation shielding, plant growth, cleaning & washing
- Making Oxygen and Hydrogen
- Breathing
- Oxidizer for Propulsion and Power
- Fuel Production for Propulsion and Power
- Plastic and Petrochemical Production
- In situ fabrication of parts
- Electrical power generation and transmission

**Note:** Rare Earth Elements (REE) and Platinum Group Metals (PGM) are not driving Resources of interest for Human Exploration