Astrobiology Technology Branch
Advanced Life Support Research and Technology Development

Dr. Mark Kliss, Chief
Astrobiology Technology Branch (Code SSR)

Presented at the
International Advanced Life Support Working Group Meeting
Guelph, Ontario
May 12–16, 2001
Enterprise
Human Exploration and Development of Space (HEDS)

“We will conduct R&TD for advanced life support systems which will be validated on the ISS.”

“We will develop revolutionary advanced technologies that will support future national decisions regarding human missions beyond Earth orbit.”

The HEDS Enterprise relies on the Space Science Enterprise missions to demonstrate the feasibility of utilizing local resources to “live off the land.”

http://www.hq.nasa.gov/office/hsps/NST PTOC.html
GOAL: Provide life support self-sufficiency for human beings to carry out research and exploration productively in space, to open the door for planetary exploration, and for benefits on Earth.
Role of NASA Ames in Advanced Life Support

- Provide innovative ALS technology development for ISS, crewed transit vehicles, and surface habitats.
- R&TD focus: Physicochemical Technologies (TRL 1-5)
  - Regenerative Air, Water & Solid Waste Processing
  - Systems Integration, Modeling and Analysis
## Contractors / University COOPs 19

<table>
<thead>
<tr>
<th>Dr. Mark Kliss, Chief</th>
<th>Eric Litwiller</th>
</tr>
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<tbody>
<tr>
<td>Karen Bunn</td>
<td>Mark Moran</td>
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<tr>
<td>Dr. Cory Finn</td>
<td>Dr. Les Montgomery</td>
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<td>Dr. John Finn</td>
<td>Lila Mulloth</td>
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<td>John Fisher</td>
<td>Greg Pace</td>
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<td>Michael Flynn</td>
<td>Dr. Chris Pawlowski</td>
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<td>Dr. Harry Jones</td>
<td>Suresh Pisharody</td>
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<tr>
<td>Richard Lamparter</td>
<td>Maher Temmat</td>
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<tr>
<td>Julie Levri</td>
<td>Sunita Verma</td>
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<td>Dr. Andrew McMillan</td>
<td>Barbara Walton</td>
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<td>Dr. Jonathan Trent</td>
<td>Dr. Wiggy Wignarajah</td>
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<tr>
<td>Richard Wisniewski</td>
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### Dr. K. R. Sridhar

<table>
<thead>
<tr>
<th>Suzanne Chan</th>
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<tr>
<td>Joshua Coe</td>
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<td>Janice Cregan</td>
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<td>Kindall Forrest</td>
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<td>Chris Knoell</td>
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<td>Amber Sanford</td>
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<td>Kerry Wooding</td>
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Total FY01 ALS Funding (Direct & Indirect)

- ARC Portion
  - $3,429K
  - $670K

Total FY01 ALS Funding at ARC (Direct & Indirect)

- Direct NRA's 30% ($1,231K)
- Direct TTA's 54% ($2,198K)
- Indirect SBIR's 16% ($670K)
<table>
<thead>
<tr>
<th>COMPANY</th>
<th>TITLE</th>
<th>FY99</th>
<th>FY00</th>
<th>FY01</th>
<th>CONTRACT STATUS</th>
<th>INNOVATION</th>
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</thead>
<tbody>
<tr>
<td>Phytron Instruments, Inc.</td>
<td>Clean Water: ElectrN Beam Water Treatment</td>
<td></td>
<td>70,000</td>
<td></td>
<td>99-1 started FY00</td>
<td>X-ray optic spectrometer</td>
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<tr>
<td>EnerTech Environmenta, Inc.</td>
<td>Wet Carbonization of Space Mission Generated Wastes</td>
<td></td>
<td>70,000</td>
<td></td>
<td>99-2 Started FY00</td>
<td>Make pumpable slurries out of inedible biomass</td>
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<tr>
<td>Reaction Engineering Intl</td>
<td>Integration of a Metal Fluoride Type Catalyst in a Low Temperature Fluidized Bed Incinerator into a Biomass Waste Management System</td>
<td>100,000</td>
<td></td>
<td>300,000</td>
<td>95-2 Phase II Completed 6/99</td>
<td>Unique catalyst for resource recovery system</td>
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<tr>
<td>Umpqua Research Co.</td>
<td>Electrochemically Generated, Hydrogen Peroxide Boosted Aqueous Phase Catalytic Oxidation</td>
<td>100,000</td>
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<td>95-2 Del 4-99 Phase II Completed 9/99</td>
<td>Direct generation of H2O2 and catalyst selection for reaction promotion</td>
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<td>Materials and Electrochemical Res Corp</td>
<td>Novel Fullerene bed for Low Pressure Oxygen Storage</td>
<td>100,000</td>
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<td>95-2 Del 10-99 Phase II Completed 10/99</td>
<td>High density oxygen storage</td>
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<tr>
<td>Umpqua Research Co.</td>
<td>Microwave Regenerable Air Purification Device</td>
<td>100,000</td>
<td></td>
<td></td>
<td>98-1 contract initiated Dec 98 No Phase II Completed FY99</td>
<td>Efficient continuos feed system for making high solids pumpable biomass slurry</td>
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<tr>
<td>Umpqua Research Company</td>
<td>Biomass Slurry Production</td>
<td>70,000</td>
<td></td>
<td></td>
<td>98-2 contract Phase II Awarded 10/99</td>
<td>Pyrolyze waste without producing undesireable byproducts</td>
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<td>Advanced Fuel Research, Inc.</td>
<td>Pyrolysis Processing for Solid Waste Resource Recovery in Space</td>
<td>70,000</td>
<td>300,000</td>
<td></td>
<td>97-2 initiated 1/99</td>
<td>Remove N0x and SO2 contaminants from flue gas</td>
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<td>TDA Research, Inc.</td>
<td>System for Removal of the Oxides of Nitrogen and Sulfur from Incinerator Effluents</td>
<td>200,000</td>
<td>300,000</td>
<td>300,000</td>
<td>00-1 Started FY01</td>
<td>Efficient stabilization of waste and recovery of water</td>
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<td>Nanotechnology, Inc.</td>
<td>Sublimation-based Water Reclamation and Purification from Solids</td>
<td></td>
<td>70,000</td>
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Focused Research Areas

Air Regeneration Research at NASA Ames

- Characterization of adsorption in the 4BMS (CO₂ removal for ISS)
- Support of NASA Missions (such as ISS)
- Prediction of effects of water co-adsorption with trace contaminants
- Study of physical chemistry of adsorbed CO₂/H₂O solutions

Low-power hybrid membrane/adsorption unit for CO₂ removal

New Concepts and Technology for Advanced Life Support
- Temperature swing adsorption for utilization of Mars atmosphere gases
- Solid State CO₂ Compressor for ISS (closes air loop)
- Regenerable Trace Gas-Phase Contaminant Control

Basic Physical and Chemical Research

Adsorption-based gas separation and purification
Why Develop Advanced CO₂ Removal Technologies?

- The International Space Station (ISS) CO₂ removal subsystem has the highest power penalty of any ISS life support subsystem (~ 3200 W-hr/kg CO₂). Current technology has a thermodynamic efficiency of about 3%.

- Current CO₂ removal & reduction technology in closed-loop mode (with Sabatier/oxygen recovery) will require ~ 5400W-hr/kg CO₂.

- Life scientists are calling for lower CO₂ levels on International Space Station.
  - ISS requirement is 7000 ppm, compared to ~400 ppm Earth-normal
  - Confounding influence on gravity-response experiments; blood chemistry effects
  - Achieving lower concentrations translates directly into more energy consumption.

- Power will be an extremely critical resource for a Mars transit vehicle.
  - The Mars Reference Mission would use a solar-powered transit vehicle with total estimated available power of 30 kW; 12 kW for ECLS

★ Develop CO₂ removal technology that consumes 10x less power than current Space Station technology for same performance. (or maintains substantially lower concentrations of CO₂ for no increase in power)
1. Hybrid Membrane/Adsorption CO₂ Removal

State of the Art (ISS): Four-Bed Molecular Sieve
(4BMS, AlliedSignal/Honeywell)

**PROS**
- Mature technology (*Skylab*)
- Fully regenerable
- High removal efficiency (100%)
- High-purity CO₂ for reduction

```
cabin air
  desiccant bed (adsorbing) → CO₂ scrubber (desorbing) → to vacuum
  desiccant bed (desorbing) → blower/cooler
```

**CONS**
- High power consumption
  (860 W avg in open-loop mode), mostly needed for water desorption
Hybrid Membrane/Adsorption CO₂ Removal

Proposed Technology: WAter Recuperated CO₂ Sorbed
(WARCS, NASA Ames Research Center)

**PROS**
- Lower power than 4BMS due to reduced/eliminated need for water desorption
- Uses similar materials to existing life support equip.

**CONS**
- Low technical maturity
Conclusions — Low Power CO₂ Removal

- ARC research focuses on developing CO₂ removal technology that has significantly lower power requirements for the same performance of current processors.

- Vanderbilt University will perform modeling and optimization work, supported by experimental testing at NASA Ames.

- If the concept has sufficient merit in terms of its power and mass trade (ESM) with existing technology, we will propose further development. Alan Drysdale (SIMA group) is collaborating on system metrics.

- In addition, characterization and development of sorbent materials continue to play an essential and fundamental role in the research.
2. ISRU Technologies for Mars Life Support

Self-Sufficiency Options for Life Support

- Complete regeneration
  - No leaks
  - Total closure (100%)

- Relatively relaxed closure and leakage requirements
  - Reliance on local resources

Design Drivers are
- Reduced mass and power
- Increased safety and reliability
Atmospheric Resources of Mars

Mars atmosphere composition
- Pressure: ~1% of Earth's
- Temperature: 180 – 290 K (equatorial)
- Dusty, windy

CO₂
95.3%

N₂
2.7%

Ar
1.6%

Other
0.4%

Mars Pathfinder, 1997
**Transit Leakage Losses:**
0.1 kg/day leakage,
260 days = 26 kg $N_2$

**Surface Leakage Losses:**
0.1 kg/day leakage,
619 days = 62 kg $N_2$

**Surface/Airlock Losses:**
1 kg/cycle, 2 cycles/day,
619 days = 1200 kg $N_2$

**Total Mission $N_2$ Losses:**
~1.3 tonnes $N_2$ lost
(2x safety factor = 2.6 tonnes)

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*Figure 3-4 Fast-transit mission profile*

**N$\text{$_2$}_2$, Consumables / Make-up for Mars Life Support**

Mars Atmosphere Separation and Compression
NASA Ames Research Center

Basic research on adsorption separations of Mars atmospheric gases at Mars local conditions.

NASA Ames Research Center

Mars In-situ Carrier Gas Generator (MICAGG) will produce compressed N₂-Ar for science payloads at no electrical cost.

NASA Ames Research Center/University of Arizona
Solid-state CO₂ compressor produces 13 g CO₂ per cycle at 1 bar for 35 W-h electrical energy.

All hardware is tested under simulated Mars conditions of pressure, gas composition, and diurnal temperature cycle.
3. Absorption-Based Compressor for International Space Station Oxygen Recovery

- ISRU research demonstrated low power technology which effectively separated and compressed N₂ and CO₂. Perhaps other applications?

- Until oxygen recovery on the International Space Station is implemented, all CO₂ removed from the cabin air and H₂ generated through water electrolysis will be vented.

- Venting of H₂ and oxygen (in the form of CO₂) represents a water resupply penalty. Water loss is minimized when no H₂ is vented. Total venting difference is about 0.37 kg H₂O per HEU per day, (2000 lb or $20M per year)

### BASIS: one Human Equivalent Unit = 1 kg CO₂ generated / day

<table>
<thead>
<tr>
<th>Current ISS Approach</th>
<th>Evolutionary ISS Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>cabin air</strong></td>
<td><strong>cabin air</strong></td>
</tr>
<tr>
<td><strong>vent to space</strong></td>
<td><strong>vent to space</strong></td>
</tr>
<tr>
<td><strong>excess H₂ is vented also</strong></td>
<td><strong>vent to space</strong></td>
</tr>
<tr>
<td>1.0 kg CO₂ / day</td>
<td>0.5 kg CO₂ / day</td>
</tr>
<tr>
<td>(about 0.05 kg / day)</td>
<td>0.18 kg CH₄ / day</td>
</tr>
<tr>
<td><strong>Sabatier</strong></td>
<td><strong>H₂O</strong></td>
</tr>
<tr>
<td><strong>CH₄, H₂O</strong></td>
<td><strong>electrolyzer</strong></td>
</tr>
<tr>
<td><strong>H₂</strong></td>
<td></td>
</tr>
</tbody>
</table>
### CDRA and CRA Characteristics

<table>
<thead>
<tr>
<th>Carbon Dioxide Removal Assembly (CDRA)</th>
<th>CO₂ Reduction Assembly (CRA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 4BMS adsorption separation (AlliedSignal/Honeywell)</td>
<td>• Sabatier methanation (Hamilton Sundstrand)</td>
</tr>
<tr>
<td>• Removes CO₂ from cabin air</td>
<td>• Uses CO₂ (and H₂) to make CH₄ and H₂O</td>
</tr>
<tr>
<td>• Operates on a 155-minute “half-” cycle</td>
<td>• Operates on a 90-minute cycle</td>
</tr>
<tr>
<td>• Produces CO₂ at vacuum (&lt; 4 psia)</td>
<td>• Needs CO₂ at pressure (~ 14 psia)</td>
</tr>
</tbody>
</table>

Interface equipment is required that

- Can remove CO₂ (4 kg/day) from the CDRA at vacuum
  (To react all available H₂, 4 kg CO₂ needs to be extracted & compressed from the CDRA)
- Compresses the gas
- Stores it at pressure until it can be used by the CRA
- Fits within the OGS rack
- Requires no modifications to existing hardware/software
<table>
<thead>
<tr>
<th>Resource</th>
<th>Mechanical compressor</th>
<th>Temperature Swing Absorption (TSA) compressor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>500 W nominal, 900 W peak</td>
<td>150 W nominal, 300 W peak</td>
</tr>
<tr>
<td>Volume buffer tank volume</td>
<td>31 liters (1.1 cubic feet)</td>
<td>25 liters (0.9 cubic feet)</td>
</tr>
<tr>
<td>Mass</td>
<td>27 kg (60 lbs)</td>
<td>n/a</td>
</tr>
<tr>
<td>Heat rejection to cold water</td>
<td>up to 500 W</td>
<td>22.5 kg (50 lbs)</td>
</tr>
<tr>
<td>Heat rejection to avionics air</td>
<td>up to 200 W</td>
<td>150 W</td>
</tr>
<tr>
<td>Operating life</td>
<td>3.1 yr</td>
<td>comparable to 4BMS</td>
</tr>
</tbody>
</table>
• A single-bed partial unit was developed and tested with the MSFC 4BMS hardware in FY00.

• Development and testing of a complete four-bed brassboard unit is ongoing in FY01.

• The TSA compressor is expected to be capable of providing 4 kg CO₂ per day from the CDRA with
  - lower power
  - quieter and vibration-free operation
  - expected better reliability and lifetime than the mechanical compressor alternative

• If successful, this technology would solve one of the key technical challenges to closing the air loop for the first time on International Space Station.
Justification

- Water accounts for 87% of the total metabolic resupply requirements to keep an astronaut alive in space.

- Using the Mars Reference Mission as a baseline and Mars Pathfinder launch cost data, the cost of supplying water for this mission in the open loop case is over $11 Billion.

Assumptions: 6 astronauts, duration = 960 days, launch cost = $150,000/kg,
State-of-the-Art Water Recovery

- The International Space Station (ISS) uses a water recycling system (WRS) which all but eliminates this open loop penalty.

- However, the ISS WRS system has a significant processor-related resupply requirements (primarily adsorption beds, filters, and makeup water).

- Using the Mars Reference Mission as a baseline and the Mars Pathfinder cost data, the cost for resupplying an ISS type WRS for such a mission would be in excess of $1 Billion.

Assumptions: 6 astronauts, duration = 960 days, launch cost = $150,000/kg, WRS resupply = 1.19kg/person-day, flow rate = 3.18kg/hr
The Advanced Life Support (ALS) water treatment technology development program is focused on developing fully regenerative water recycling solutions for nearer term missions.

Candidate Technologies:

* Vapor Phase Catalytic Ammonia Reduction (VPCAR)
* Wiped-Film Rotating-Disk Evaporator
* Lyophilization
* Direct Osmotic Concentration
Aqueous Phase Catalytic Oxidation
In situ hydrogen peroxide generation
Electrochemical Oxidation
Vapor Phase Catalytic Ammonia Removal (VPCAR)

- The VPCAR is a distillation based/catalytic oxidation water processor:
  - Designed to accept a combined waste stream (condensate, hygiene and urine) and produce potable water in a single step.
  - Designed to require no re-supply or maintenance for 3 yrs.

- The technology is modular and can be packaged to fit into a volume comparable to a single Space Station rack.
## Comparison Between ISS Baseline and VPCAR

<table>
<thead>
<tr>
<th></th>
<th>ISS Water Recycling System</th>
<th>VPCAR System</th>
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<tbody>
<tr>
<td>Re-supply (equipment)</td>
<td>413 Kg/year</td>
<td>0 Kg/year</td>
</tr>
<tr>
<td>Number of Independent Processors</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Feed Streams</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Weight</td>
<td>193 Kg</td>
<td>68 Kg</td>
</tr>
<tr>
<td>Volume</td>
<td>1.1 m³</td>
<td>0.39 m³</td>
</tr>
<tr>
<td>Power – Water Processor Only</td>
<td>55 W-hr/kg</td>
<td>300 W-hr/kg</td>
</tr>
<tr>
<td>Oxidant Feed</td>
<td>2 g/hr</td>
<td>&gt;30 g/hr</td>
</tr>
<tr>
<td>Oxidant Consumption</td>
<td>0.67 g/hr</td>
<td>&gt;30 g/hr</td>
</tr>
<tr>
<td>Oxidant Energy Penalty</td>
<td>0.7 W-hr/kg feed</td>
<td>0.7 W-hr/kg feed</td>
</tr>
<tr>
<td>CO₂ Generation Rate</td>
<td>0.47 g/hr</td>
<td>0.47 g/hr</td>
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<tr>
<td>CO₂ Energy Penalty</td>
<td>0.6 W-hr/kg feed</td>
<td>0.6 W-hr/kg feed</td>
</tr>
<tr>
<td>Lyophilization Power **</td>
<td>5.2 W-hr/kg feed</td>
<td>10.4 W-hr/kg feed</td>
</tr>
<tr>
<td>Total Subsystem Power</td>
<td>61.5 W-hr/kg feed</td>
<td>311.7 W-hr/kg feed</td>
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<tr>
<td>Recovery Rate</td>
<td>99%</td>
<td>97%</td>
</tr>
<tr>
<td>Scheduled Maintenance</td>
<td>every 50 days</td>
<td>0</td>
</tr>
<tr>
<td>TRL</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Mass Metric</td>
<td>2463</td>
<td>434 (332)</td>
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</table>
The Development of a Lyophilization-based Solid Waste Treatment Technology
A Stanford Univ.- Ames Research Center Collaboration

- The objective of this NRA research is to evaluate the use of a modified lyophilization technique to recover water from/stabilize spacecraft solid wastes.
  (food wastes, feces, general trash, and water treatment system byproduct streams)

- The lyophilization process is a process by which water contained within a solid sample is frozen and then sublimed thus leaving a dry solid material (usually 1-3% water content) and liquid water.

- This technology is ideally suited for an application such as a Mars Transit Vehicle (MTV) where water recovery rates approaching 100% are desirable, but the production of CO₂ (from conversion of solid wastes) is not.

<table>
<thead>
<tr>
<th></th>
<th>Mass (wet) Kg/person day</th>
<th>Water Content %</th>
<th>Mass Water Kg/person day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feces</td>
<td>0.132</td>
<td>84</td>
<td>0.11</td>
</tr>
<tr>
<td>Water Treatment System By-products*</td>
<td>0.27</td>
<td>71</td>
<td>0.19</td>
</tr>
<tr>
<td>Leftover food</td>
<td>0.10</td>
<td>70</td>
<td>0.07</td>
</tr>
<tr>
<td>paper</td>
<td>0.13</td>
<td>10.2</td>
<td>0.013</td>
</tr>
<tr>
<td>Other Trash</td>
<td>0.78</td>
<td>0.2</td>
<td>0.0016</td>
</tr>
<tr>
<td>Total</td>
<td>1.41</td>
<td></td>
<td>0.38</td>
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</table>

* Based on International Space Station water recovery rate of 99%.
Lyophilization vs. Other Drying Technologies

- **Low pressure, low temperature process** (potential for low power operation).
- **Complex solids pumping or handling techniques are not required.**
- **The technique should not produce CO₂, NOₓ, SOₓ, or any other undesirable oxidation byproducts** (gases generated are primarily water).
- **The final product is a stable dried material with from 1 to 3% H₂O.**
- **The approach is fully regenerable, meaning that the process requires no consumables, only energy.**
Focused Research Areas
Solid Waste Processing / Resource Recovery

Goal

Stabilize/Destroy hazardous or noxious wastes

Long missions, clarity, savings, solution

Reclaim CO₂ and nutrients from waste for biological processors
1. What are the mission scenarios and how do these scenarios affect the requirements on waste processing?

2. What are the desired products of waste processing?

3. What quality/quantity of reclaimed products are necessary?

4. What is the weight, power, volume, and reliability of the candidate processing technology?

5. What is the cost, time, and probability of success for the development effort?
## What are the Options? Promising Technologies

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<tbody>
<tr>
<td>Incineration</td>
<td>• Low pressure • Commercial applications&lt;br&gt;• NOx • Sulfur</td>
<td></td>
<td>+ But byprod</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td></td>
<td>Existing</td>
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<tr>
<td>Steam Reforming</td>
<td>• Low pressure • Clean syngas for oxidation&lt;br&gt;• Power and energy rec.</td>
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<td>-</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>+</td>
<td>+</td>
<td>?</td>
<td></td>
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<tr>
<td>SCWO</td>
<td>• One step processing&lt;br&gt;• Corrosion&lt;br&gt;• Sly pump&lt;br&gt;• Reactor Plug</td>
<td></td>
<td>+</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
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<td>-</td>
<td>?</td>
<td></td>
<td>+</td>
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<tr>
<td>Wet Ox</td>
<td>• Lower pres. than SCWO&lt;br&gt;• Post treatment for acetic acid</td>
<td></td>
<td>=</td>
<td>?</td>
<td>+</td>
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<tr>
<td>Biological</td>
<td>• Low power • Nutrient recovery&lt;br&gt;• Incomplete reaction&lt;br&gt;• Sludge control&lt;br&gt;• Large size</td>
<td></td>
<td>=</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>+</td>
<td>?</td>
<td>-</td>
<td>?</td>
<td></td>
<td>Existing</td>
</tr>
</tbody>
</table>

+ Likely Advantage  □ Neither Advantage, nor Disadvantage  - Maybe Disadvantage  = Likely Disadvantage  ? Unknown

**Incineration** - mature technology, complete oxidation, low pressure, but high temp and requires catalysts/resupply for flue gas clean up

**SuperCritical Water Oxidation (SCWO)** - 'ultimate' processor, complete oxidation, no catalysts/resupply, but high pressure/temp, pretreatment

**Biological Waste Treatment** - limited wastes, but potential 'front end' system to remove K+/organics for plant growth
INCINERATION R&TD EFFORTS

- Feed system development
- Improved energy efficiency
- Improved catalyst lifetime/robustness
- Waste Reutilization
  - Trace gas analysis of flue gas
  - CO, NO, SO₂, trace hydrocarbon dose response studies (plant sensitivity)
  - Ash analysis for plant nutrient solution make up
Incineration Resource Recovery Schematic

Inedible Biomass → NH₃ → Inincinerator

Approx 16psi
Approx 1100K

Gas Compression and Storage

Approx 10% CO₂
100 psi

Plant Volatiles Chamber
Approx 1000ppm CO₂, 14.7 psi

NO monitor
SO₂ monitor
CO₂ monitor
O₂ monitor
CO monitor
Total HydCarb
Grab sample analysis (GC/MS etc.)

Condensate → Feces collection

CO emission data from the incinerator

NOx emission data from the incinerator

NO & NO₂ emission data from the incinerator

SO₂ emission data from the incinerator
Reutilization of Incinerator Flue Gas and Ash

Lettuce Grown on Cleaned Flue Gas

General Recovery Factors for Inorganics in the Incinerator-Ash

- The inorganics represent about 7.5% of the original plant dry weight.
- About 90% of inorganics are retained in the incinerator ash.
- About 72% of the inorganics in the ash are water soluble.
- All of the ash is soluble in acid.

Nutrients Available from Ash

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Lettuce hydroponic solution (LHS) (mM)</th>
<th>Elemental composition of Ash (mg/g)</th>
<th>% Supplied by ash alone</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>5</td>
<td>7.92</td>
<td>101</td>
</tr>
<tr>
<td>Mg</td>
<td>1.5</td>
<td>17.3</td>
<td>24</td>
</tr>
<tr>
<td>Ca</td>
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<tr>
<td>B</td>
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<td>Cu</td>
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<td>Fe</td>
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<tr>
<td>Mn</td>
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<td>0.5333</td>
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<tr>
<td>Mo</td>
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<td>0.1333</td>
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</tr>
<tr>
<td>Zn</td>
<td>0.0038</td>
<td>0.004</td>
<td>8</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
<td>28</td>
<td>60</td>
</tr>
</tbody>
</table>
Reactive Carbon for Flue Gas Cleanup

- **Background:** Catalysts and adsorbents (activated carbon) are typically used for clean up of combustion process gases.

- **NRA Goal:** convert inedible biomass to activated carbon to eliminate adsorbent resupply (adsorb NO\textsubscript{x}, SO\textsubscript{2}; reduce NO\textsubscript{x} to N\textsubscript{2}; SO\textsubscript{2} to S).

Effect of High Temperature on NO and SO\textsubscript{2} Adsorption/Removal

Removal efficiency for NO and SO\textsubscript{2} using char from rice hulls at 3% oxygen

Example of flow diagram of reactive carbon for flue gas cleanup
Focused Research Areas

SUPERCRITICAL WATER OXIDATION (SCWO)

Essence of the Process

Air or Oxygen
Aqueous Waste

Pure Products
($H_2O, CO_2, minerals$)

SCWO R&TD EFFORTS

- Demonstrated effectiveness on liquid waste streams (complete oxidation w/o catalysts)
- Determine kinetics of biomass particle oxidation
- Development of solid feed system
  - Feed pretreatment (slurry)
  - Feed delivery/pumping
- Investigate batch operation methods
- Evaluate carbonization process to fluidize waste
• Mission objectives drive the functional requirements of Advanced Life Support technology development.

• Systems Engineering (SIMA) enables R&TD efforts to meet the functional requirements the best way possible.
  - Identification and evaluation of feasible designs
  - Performance of technology/configuration trade studies
  - Optimization of operational strategies
  - Provide guidance for future R&TD efforts
Dynamic mass flow modeling of Bio-PLEX

- Model flow of material through BLSS over time
  - Crew
  - Air Revitalization
  - Water Recovery
  - Solid Waste Processing/Resource recovery
  - Biomass Production Chamber
  - Food Processing System

- Conduct candidate technology trades
  - Bioreactor or incinerator?
  - Grow all food or partial resupply?

- Compare candidate configurations
  - Separate or combined air loops for the crew and crops?
  - Recycle crop transpiration water to WRS or to nutrient solution?

- Optimize operational strategies
  - What is the best crop planting/harvesting schedule?
  - Adjust solid waste processing rate to maintain CO₂ level?
Dynamic System Modeling

Dynamic mass flow modeling of Bio-PLEX

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- Optimize operational strategies
  What is the best crop planting/harvesting schedule?
  Adjust solid waste processing rate to maintain CO₂ level?
• Develop schedules for crop production
  - Smooth crop gas exchange profiles (CO₂ usage)
    by altering planting/harvesting schedules

• Develop control system strategies
  - Design controllers that meet performance specifications (atmospheric oxygen level)

• Apply model-based Fault Detection, Isolation and Recovery (FDIR) system
  - Compare model predictions to real-time data for failure diagnosis (simulated 4BMS failure)

• Design appropriately sized processors and buffers
  - Select technologies based on systems trades
Power Reduction in ALS Systems - NRA

- Motivation
  The high power requirement associated with ALS is a key challenge.
  Optimization of total system efficiency (not individual processors) is required.

- Approach
  - Apply Pinch Analysis technique and Market-based Control strategy

Reduce total system power by optimized reuse of waste heat between hot and cold streams.

The market determines which processes receive the power they demand within the target limit (function of internal process state and power cost).