PAST, PRESENT AND FUTURE ADVANCED ECLS SYSTEMS FOR HUMAN EXPLORATION OF SPACE

Kenny Mitchell
MSFC Manager for Advanced ECLSS/New Space Exploration Initiative

This paper will review the historical record of NASA's regenerative life support systems flight hardware with emphasis on the complexity of spiral development of technology as related to the International Space Station program. A brief summary of what constitutes ECLSS designs for human habitation will be included and will provide illustrations of the complex system/system integration issues. The new technology areas which need to be addressed in our future Code T initiatives will be highlighted. The development status of the current regenerative ECLSS for Space Station will be provided for the Oxygen Generation System and the Water Recovery System. In addition, the NASA is planning to augment the existing ISS capability with a new technology development effort by Code U/Code T for CO2 reduction (Sabatier Reactor). This latest ISS spiral development activity will be highlighted in this paper.
Past, Present and Future Advanced ECLSS
( Strategic Planning for Participation in New Initiatives of NASA HQ/Code T and Code U)

Taking the Journey Together

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NASA has Vast Experience in Human Space Exploration Programs

Saturn/Apollo

Skylab

Space Shuttle

Spacelab

Shuttle/Mir

International Space Station
# Historical Driving Mission Requirements for Human Exploration

<table>
<thead>
<tr>
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<th>Mission Length</th>
<th>Crew Size</th>
<th>Habitat Atmosphere</th>
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<tr>
<td><strong>Saturn/Apollo</strong></td>
<td>&lt; 14 days</td>
<td>3</td>
<td>5 Pisa (pure oxygen)</td>
</tr>
<tr>
<td><strong>Skylab</strong></td>
<td>28 – 84 days</td>
<td>3</td>
<td>5 Pisa (N2/02, 70%/30%)</td>
</tr>
<tr>
<td><strong>Space Shuttle</strong></td>
<td>&lt; 14 days</td>
<td>2 - 7</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
</tr>
<tr>
<td><strong>Spacelab</strong></td>
<td>&lt; 14 days</td>
<td>3 - 4</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
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<tr>
<td><strong>Mir</strong></td>
<td>~ 15 years</td>
<td>2 - 6</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
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<tr>
<td><strong>International Space Station</strong></td>
<td>15 -20 years Planned</td>
<td>2 - 6</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
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*Regenerative life support systems on-board*
### Basic ECLSS Functions for Human Support

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<tr>
<td>• CO2 Removal</td>
<td>• O₂ Storage Systems</td>
<td>• Potable H₂O Storage</td>
<td>• Smoke Detection</td>
<td>• Cabin Air Temperature</td>
<td>• Urine Collection</td>
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<tr>
<td>• CO₂ Reduction</td>
<td>• N₂ Storage Systems</td>
<td>• Waste H₂O Processing</td>
<td>• Fire Detection</td>
<td>Control</td>
<td>and Pre-treatment</td>
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<tr>
<td>• Oxygen Generation</td>
<td>• O₂/N₂ Atmosphere Pressure Control</td>
<td>• Urine Processing</td>
<td>• Fire Suppression</td>
<td>• Habitable Volume Air</td>
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<tr>
<td>• Trace Contaminant Control</td>
<td>• Negative &amp; Positive Pressure Relief of Habitat</td>
<td>• Water Distribution</td>
<td>• Emergency Breathing Support</td>
<td>Ventilation</td>
<td>&amp; Processing</td>
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<tr>
<td>• Trace Contaminant Monitoring</td>
<td>• Purge and pressurant supply gases</td>
<td>• Hygiene H₂O Supply</td>
<td></td>
<td>• Air Filtration</td>
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</tr>
<tr>
<td>• Atmosphere Composition Monitoring</td>
<td>• EVA Support</td>
<td>• Water Quality Monitoring</td>
<td></td>
<td>• Air Circulation</td>
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<td></td>
<td>• O₂/N₂ Distribution</td>
<td>• Biocide and Sterilization</td>
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<td>• Humidity Control</td>
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<tr>
<th>Water Management Systems</th>
<th>Fire Detection &amp; Suppression</th>
<th>Temperature &amp; Humidity Control</th>
<th>Waste Management Systems</th>
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Human Friendly ECLSS Features

• Habitable noise level satisfies NC-50 Criteria (*MPLM and Node 2 met on ISS*)

• Low maintenance requirements (planned or unplanned)

• Personal hygiene support is simple and effective

• Comfortable environmental control (temperature/humidity/ventilation)

• Water management is “earth-like”.

• Fire and smoke detection is reliable

• Robust (handles anomalies with minimal crew attention)

• Significant safety features for crew life support
Typical ECLSS Functions Including Regenerative
Environmental Control and Life Support Systems

Human Needs and Effluents Mass Balance (per person per day)

**Needs**
- Oxygen = 0.84 kg (1.84 lb)
- Food Solids = 0.62 kg (1.36 lb)
- Water in Food = 1.15 kg (2.54 lb)
- Food Prep Water = 0.76 kg (1.67 lb)
- Drink = 1.62 kg (3.56 lb)
- Metabolized Water = 0.35 kg (0.76 lb)
- Hand/Face Wash Water = 4.09 kg (9.00 lb)
- Shower Water = 2.73 kg (6.00 lb)
- Urinal Flush = 0.49 kg (1.09 lb)
- Clothes Wash Water = 12.50 kg (27.50 lb)
- Dish Wash Water = 5.45 kg (12.00 lb)
- Total = 30.60 kg (67.32 lb)

**Effluents**
- Carbon Dioxide = 1.00 kg (2.20 lb)
- Respiration & Perspiration Water = 2.28 kg (5.02 lb)
- Food Preparation, Latent Water = 0.036 kg (0.08 lb)
- Urine = 1.50 kg (3.31 lb)
- Urine Flush Water = 0.50 kg (1.09 lb)
- Feces Water = 0.091 kg (0.20 lb)
- Sweat Solids = 0.018 kg (0.04 lb)
- Urine Solids = 0.059 kg (0.13 lb)
- Feces Solids = 0.032 kg (0.07 lb)
- Hygiene Water = 12.58 kg (27.68 lb)
- Clothes Wash Water Liquid = 11.90 kg (26.17 lb)
- Latent = 0.60 kg (1.33 lb)
- Total = 30.60 kg (67.32 lb)

Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 BTU/person/day) and a respiration quotient of 0.87. The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO₂ generated to O₂ consumed.
Water recycling is essential for human space exploration missions to be cost effective.

*Current ISS requirements lower than this.*
Significant Water Storage Required on ISS without Regenerative System On-Board

Water Stowage Containers on ISS
- Requires habitat volume
- Crew time
- Inventory Mgt.
Human Exploration Begins with the International Space Station

Space operations to the Moon

Space operations to another planet

International Space Station

Lunar Outpost

Humans on Another Planet

Partial-g

u-g

CEV
Partial-Gravity Environments Benefit ECLSS Design/Operations

**Design Simplications**
- Eliminates need for liquid/gas phase separation
- Fire suppression easier
- Smoke detection easier
- Ventilation systems more “Earth-like”
- Water distribution systems utilize gravity
- Human hygiene functions more “Earth-like”

**Benefits**
- Saves development costs, power, mass, volume, and reduces contribution to noise.
- Suppressant “falls” on fire
- Integrate detectors for natural convection
- Easier to design/integrate air flow for thermal comfort, CO2 removal, etc. and reduces noise production associated with fans.
- Simplifies water management hardware.
- Urine/fecal collections systems lower weight, volume, power. Easier to recycle waste.
Regenerative ISS ECLSS Architecture Overview

(Water Recovery System (WRS))

URINE PROCESSOR ASSEMBLY (UPA)
- Vapor Compression Distillation (VCD)
- Distillate

WATER PROCESSOR ASSEMBLY (WPA)
- Gas Separator
- Particulate Filter
- Multifiltration Beds
- Volatile Removal Ass’y (VRA)

OXYGEN GENERATOR ASSEMBLY (OGA)
- Solid Polymer Electrolysis (SPE)

CO2 REDUCTION SYSTEM (CRS)
- Sabatier Reactor Sub. (SRS)
- CO2 Mgmt Sub. (CMS)

Legends:
- flight experiment subjects
- scars

Legend:
- overboard

Legend:
- overboard

USOS CABIN
- CREW
- BIOLOGICAL PAYLOADS
- scars

Pathways:
- Urine
- Wastewater
- Distillate
- Potable water
- Water
- Oxygen
- Carbon Dioxide
- Methane
- Hydrogen

NASA/CP—2004-213205/VOL1
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**ISS Node 3**

**Regenerative ECLSS Racks**

- **Oxygen Generation System Rack (Rack #3)**
  - Deionizer Bed (H)
  - N₂ Purge ORU (H)
  - Power Supply Module (M)
  - Electrolysis Cell Stack (H)
  - Water Processor Delivery Pump (H)

- **Water Recovery System Rack #1**
  - Reactor Health Sensor ORU (H)
  - Particulate Filter (H)
  - Pumps, Valves (H)
  - Firmware Controllers (H)
  - Water Processor Pump & Separator (H)

- **Water Recovery System Rack #2**
  - Urine Processor Firmware Controller (M)
  - Urine Processor Pumps (M)
  - Storage Tanks (M)
  - Multi-Filtration Beds (H/M)
  - Product Water Tank (H)
  - Water Processor Pump & Separator (H)
  - Water Processor Waste Water Tank (H)
  - Sensor ORU (H)


**VCD Flight Experiment successfully flown on STS-107, January 2003**

(H) = Hamilton Sundstrand provided hardware
(M) = MSFC provided hardware

Hamilton Sundstrand responsible for rack analytic integration for WRS#1
MSFC responsible for rack analytic integration for WRS#2 & OGS racks; physical integration for all 3.
ISS Node 3 Architecture
(MSFC Manages Node 3 DDT&E)
Node 3 Plumbing/Harnesses/Ducting Integrated with Primary/Secondary Structure
How Did ISS ECLSS Get To Where It Is?

- Comparative Testing of Technologies
- Down Selecting Technologies
- Integrated System Testing
- Integrated System/System Testing
- Proceed with Flight Hardware Development
ECLSS Test Facility at NASA/MSFC

North Bay

MSFC Building 4755
ECLSS DEVELOPMENT TESTBED RESOURCES
History of MSFC ECLSS Test Beds


MSFC Building 4755 in 2004 for International Space Station ECLSS/Thermal Test Beds
Focused Technology Testing for C/D Milestones
(Illustrates Technology Development Supporting Program Needs)

**Water Reclamation**
- Multi-filtration (MF)
- Reverse Osmosis (RO)
- TIMES
- Vapor Compression/ Distillation (VCD)

**Oxygen Generation**
- Static Feed Electrolysis
- Solid Polymer

**CO₂ Reduction**
- Sabatier
- Bosch

**CO₂ Removal**
- Molecular Sieve

**Trace Contaminant Cont.**
ECLSS Comparative Technology Test Bed

(MSFC testing for Space Station application)
WATER RECOVERY TEST HISTORY
(Illustrates Technology Development Supporting Program Needs)
End-Use Equipment Facility (EEF)
Space Station ECLSS
Water Recovery Testing Area

Vapor Compression Distillation (VCD) Unit

Facility Water Storage

End-Use Equipment Facility (EEF)

Water Processor (WP) and Process Control Water Quality Monitor (PCWQM)

Waste Water Storage Tanks

North Bay of Building 4755
Space Station ECLSS Air Revitalization Test Area

Oxygen Generator Assembly/
Static Feed Water Electrolyzer

Control Room

Core Module Simulator

Carbon Dioxide
Removal Assembly

Major Constituent
Analyzer

North Bay of
Building 4755

Trace Contaminant
Control Subassembly
Space Station ECLSS
Life Testing Area

Trace Contaminant Control Subassembly

Vapor Compression Distillation Unit

Carbon-dioxide Removal Assembly/
Four-Bed Molecular Sieve

Water Degradation Study

TCCS  VCD

CDRA

WDS

North Bay of Building 4755
The following charts give the technology development status of the current ISS Program regenerative ECLSS Water Management System and Oxygen Generation System hardware.
UPA Development History

- **Technology Selection**: based on comparative testing & analysis conducted during Space Station Freedom program

- **Process Demonstration**: thousands of hours of ground testing (bench & integrated system).

- **Flight Demonstration**: full size unit delivered for micro-gravity demonstration on STS-107

- **Life Demonstration**: Distillation Assembly compressor, Purge Pump, Fluids Pump life demonstrated during 3,000-17,000 hr life-test programs during SSF.

- **ISS Development Testing**:
  - DA Stationary Bowl condensate control: developed & demonstrated heater-based controls
  - Materials compatibility: bearings & seals with pretreated urine
  - Acoustic Testing: analytical flight predictions based on ORU-level test data show that planned attenuation measures will meet rack acoustic requirements
  - Micro-gravity Disturbance: identified and quantified major disturbers (pumps and DA); data is being used to refine ISS micro-g model predictions; candidate materials received for testing to finalize micro-g isolators design
  - Hose Gas Permeation: characterize gas introduction through flex hoses & impacts on UPA pressure control/operability
Urine Processor Assembly Technology Development Status

Development Concerns Legend:

Red: Significant unresolved issues
Yellow: Open validation remaining
Green: Ready to proceed for flight

Microgravity Sensitivities

Distillation Assy, Purge Pump, Fluids Pump

- performance demonstrated in 1000s of hours of bench tests & 2 yrs of integrated systems testing
- life of most suspect parts demonstrated in 3000-17,000 hours of life testing
- 0-g performance demonstrated on STS-107

Wastewater Tank

- Urine from Node 3

Recycle Filter Tank Assy.

- Filter is oversized and should minimize any gravity sensitivity of internal filter loading (& hence tank change out frequency)

Recycle Filter Tank

Distillation Assembly (DA)

- Purge Pump
- Coolant

Purge Gas to Node 3 cabin

Separator

- Performance demonstrated over 1000s of hours of bench tests & 2 yrs of integrated systems testing
- 10x performance margin demonstrated in bench tests
- System schematic modified to mitigate impact of failure

Recycle Filter Tank Assy.

- Product water to Water Processor Assembly

- External heaters added to prevent condensation in stationary bowl
- Design finalized; release complete 8/02

Distillation Assembly Condensate Control

- Full-scale DA
- Steady state & transient ops
- STS-107
- Functionality confirmed

- KC-135 "flow visualization" testing Feb '02
- Observed flow patterns & fluid distribution

VCD Flight Exp’t
Urine Processor Assy (UPA) Flight Hardware

- **Urine Processor Assy (UPA)**
- **Flight Hardware**

**Urine from Node 3**
- **Wastewater Tank**
- **Distillation Assembly** (Distills wastewater)
- **Purge Pump** (removes gases from Distillation Assy.)
- **Coolant** (promotes condensation within purge pump)
- **Separator** (separates water from purge gases)
- **Recycle Filter Tank Assy.** (accumulates & stores brine for disposal)
- **Purge Gas to Node 3 cabin**
- **Product water to Water Processor Assembly**
VCD Flight Experiment
STS-107

VCD FE Schematic

Flight Experiment in Spacehab Rack (prior to acoustic treatment)

“Successful Demo”
ISS Water Processor Development History

- **Technology Selection:** based on comparative testing & analysis conducted during SSF
- **Process Demonstration:** 1000’s of hours of ground testing (bench & integrated system).
- **Flight Demonstration:** multiphase catalytic reactor performance demonstrated in Volatile Removal Assembly Flight Experiment, STS-96 (May ’99) & KC135 tests;
  - extent of gas occlusion in micro-g shown to be same as in 1-g
  - O₂ utilization less in micro-g due to differences in gas distribution; factored into final flight sizing and performance predictions
- **Life Demonstration:**
  - Pumps: Ceramic gear pumps; 17,733 hours on process pump to date (vs. 8,000 hr.goal); 18,626 hours and 560,000 on/off cycles on delivery pump to date (vs. 8,760 hour/1 year life requirement)
  - Tanks: Dev. bellows tested 560,000 cycles (delivery tank) and 35,000 cycles (waste tank) = 4 x life
  - GLS: 1200 hrs on modules (=150 days operation); 6 mo. life demonstrated w/ 90 ppb reactor fines (expect 10 ppb actual fines); integrated flight-like GLS operated 2 months at max O₂ flow w/ no degradation
  - Catalyst: > 1 yr demonstrated w/o performance degradation; testing continuing
- **ISS Development Testing:**
  - MLS: optimized to work w/ foaming soaps; demonstrated operation in various 1-g orientations
  - GLS: demonstrated robustness of hollow fiber membranes against degradation due to fine particulates released from upstream reactor
  - Catalyst: Monometallic catalyst developed to replace original bimetallic– reliable performance achieved w/ repeatable manufacturing process
  - Pumps: Redesign after qual cycle life failures to eliminate gear wear caused by axial load. Redesign complete, pumps in final integration. Qualification tests Aug-Sep ’03
  - pH Adjuster (MgO): Material selection and chemical performance characterization.
ISS Water Processing Assembly (WPA) Flight Hardware

Wastewater Tank
- from Node 3 wastewater bus
- to Node 3 cabin

Particulate Filter
- removes particulates

Multifiltration Beds
- remove dissolved contaminants

Gas/Liquid Separator
- removes oxygen

Preheater
- heats water to 275F

Ion Exchange Bed
- removes reactor by-products

Reactor
- oxides organics

Regen. HX
- recovers heat

Heat Exchanger
- to/from Node 3 MTL

Product Water Tank
- connects to Node 3 cabin

Microbial Check Valve
- provides isolation
- reject line (allows reprocessing)

To Node 3 cabin

O2 from Node 3

Delivery Pump
- to Node 3 potable water bus

Accumulator

Cabin

 reactor health sensor
- verifies reactor is operating w/n limits
ISS OGA Development History (page 1)

- **Technology Selection**: based on comparative testing & analysis conducted during Space Station Freedom program

- **Process Demonstration**: membrane electrolyzers investigated & tested since 1960s and now used commercially (laboratories, utilities) and by Navy.

- **Flight Demonstration**: VRA FE (& ground tests) highlighted susceptibility of membrane gas separators to contamination-induced fouling in micro-g; system configuration changed to cathode feed to eliminate separators

- **Life Demonstration**: 
  - Electrolytic Cells: Ongoing single cell tests >12,000 hours, integrated anode feed system >20,000 hours, integrated cathode feed system >2985 hours in OGA test bed
  - Pump: (common with WPA pump). >2.4x required life demonstrated w/o degradation
  - Hydrogen Sensor: confirmed required operational life of 90 days (dry gases)

- **ISS Development Testing**: 
  - see next page
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<th>Test</th>
<th>Finding</th>
<th>Resolution</th>
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<tr>
<td>VRA Flight Experiment/OGA Life Test</td>
<td>Established sensitivity of membranes to particulate and microbial contamination, exacerbated by micro-G</td>
<td>Eliminated membrane phase separators-cathode feed cell stack and rotary phase separator</td>
</tr>
<tr>
<td>Venturi Testing</td>
<td>Established performance and performed acoustic measurements to compare to specification</td>
<td>Testing Complete – Unit to Dev Test Bed</td>
</tr>
<tr>
<td>Absorber Development Unit</td>
<td>Established performance and life, and compared to calculated requirements.</td>
<td>Testing Complete – Unit to Dev Test Bed</td>
</tr>
<tr>
<td>Cathode Feed Cell Stack</td>
<td>Development cell stack successfully assembled and tested.</td>
<td>Testing Complete on Rig 275 - Unit to Dev Test Bed</td>
</tr>
<tr>
<td>Cathode Feed Single Cell Testing</td>
<td>Characterized cell voltage rise and life under controlled conditions: Temperature, pressure, cycling, MSFC development processed water</td>
<td>Compatibility verified, all MSFC product water consumed, testing continues with DI water.</td>
</tr>
<tr>
<td>Water Diffusion (Cell Stack Vacuum Test)</td>
<td>Verified analysis predicting diffusion of water, hydrogen, and oxygen through the edges of the cell stack membranes. Correlated results between anode feed vs cathode feed (18 cells vs 28 cells).</td>
<td>Testing Complete.</td>
</tr>
<tr>
<td>H2 Sensor Challenge Test</td>
<td>Established operational life using 2 sensor assemblies containing 3 sensors each. Gases flowing through the sensors was dry.</td>
<td>Operational life of 90 days confirmed. (dry gases)</td>
</tr>
<tr>
<td>Rotary Separator Development Unit</td>
<td>Fabricated/tested proof-of-concept and development units. Established performance and verified critical design characteristics: separation and level sensing.</td>
<td>Testing Complete. Unit to Dev Test Bed.</td>
</tr>
<tr>
<td>TFS Sensor (optical gas bubble sensor)</td>
<td>Established performance in detecting bubbles of various sizes over the specified flow range.</td>
<td>Bench testing, vibration, and thermal cycling complete - Unit to Dev Test Bed.</td>
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International Space Station Oxygen Generator System (OGS) Description

- **Core Technology**: Solid Polymer Electrolysis (cathode feed)

**Cell Stack**

**Electrolysis Cell Reactions**

- Hydrogen electrode (cathode) + Solid polymer electrolyte + Oxygen electrode (anode)
- $2H_2O \rightarrow 4H^+ + 4e^- + O_2$
- $4e^- + 2H_2O \rightarrow 4H_2 + O_2$
- DC Power
- Water diffusion
- Water electro-osmotic flux
Integrated Process

1. Oxygen & hydrogen produced in 28-cell stack
2. \( \text{O}_2 \) delivered to cabin
3. \( \text{H}_2 \) mixed with excess recirculated water, separated dynamically, and vented overboard (ISS baseline)
4. Makeup water periodically added and stored within rotary separator
5. Oxygen lines purged with nitrogen for safety after shutdowns
ISS Oxygen Generator Assembly Technology Development Status

Nitrogen from Node 3

Feed water from Node 3

Feed water with air returned to Node 3

To Node 3 vent

Nitrogen

O₂

O₂ to cabin

H₂ & H₂O

H₂ & H₂O

O₂ to cabin

H₂ Sensor
✓ general performance demonstrated in bench tests & test bed
○ Transient performance & contamination susceptibility open issues

Cell Stack
✓ 48K cell hours on aircraft O₂ generators
✓ 126K cell hours in bench top H₂ generators
✓ 10-12K hours on OGA single cells, equivalent to 15-25 yrs operating life
✓ >3500 hours on OGA cell stack, equivalent to > 10 yrs operating life

Pump
✓ pump: dev pump 2.4x life tested w/o degradation
○ pump: WPA qual pump cycle failures; redesign complete, retest in 6/03
✓ motor: 1.3x life tested w/o degradation

Water Absorber
✓ performance demonstrated in bench tests
✓ capacity validation ongoing in test bed

Deionizer Bed
✓ functionality demonstrated in ground test bed
✓ sizing based on standard calcs.
✓ gas occlusion characterized in 1-g & KC135 tests

Gas Sensor
✓ performance tested across wide range of bubble sizes

Rotary Separator Accumulator
✓ tested in all 1-g orientations
✓ rotating disks rather than pitots to reduce clogging potential & reduce carryover
✓ hydrodynamic bearings – avoids life-limiting wear

Heat Exchanger

Dome

Integrated Ops Risk Mitigation
✓ Full-scale cell stack & dev components integrated in ground test bed
✓ Steady & transient ops
✓ Software algorithm validation

Development Concerns Legend:
Red: Significant unresolved issues
Yellow: Open validation remaining
Green: Ready to proceed for flight

Microgravity Sensitivities
Life
Performance

Water Absorber

H₂ Sensor

Cell Stack

Pump

Deionizer Bed

Gas Sensor

Rotary Separator Accumulator
OGA Flight Hardware

Nitrogen Purge Manifold

Ion Exchange Bed
- (removes iodine)
- Feed water from Node 3

Absorber
- (traps liquid water)
- (detect cell stack leaks)

Two-phase Fluid Sensors
- (check for gas bubbles)

Feed water with air returned to Node 3

To Node 3 vent

H2 & H2O

Cell Stack
- (produces oxygen)
- (contains hydrogen leaks)

Rotary Separator/Accumulator
- (separates hydrogen, stores water)

Dome
- (contains hydrogen leaks)

Heat Exchanger
- (rejects waste heat)

Pump
- (recirculates water)

O2 to cabin

O2

H2

H2 & H2O

H2
What’s Next?

Advanced ECLSS for New Space Initiative
Strategic Roadmap to Success

THIS!

NOT THIS!
The Future

1. It’s essential that we all understand NASA/HQ program needs for advanced ECLSS.

2. It’s essential we communicate on common ECLSS technology interests. MSFC wants to work with HQ and other NASA centers/industry/universities to assure maximum return on investments and avoid duplication of efforts.

3. It’s essential we use common terminology to define what we’re doing and where we are in doing it.

4. Managing a technology development program is different than managing development of flight hardware.
H&RT Cycles of Innovation and Spiral Development
Code T/H&RT Strategic Technology/Systems Model

System Test, Launch & Mission Operations
- System/Subsystem Development
- Technology Demonstration
- Technology Development
- Research to Prove Feasibility
- Basic Technology Research

TRL 1
TRL 2
TRL 3
TRL 4
TRL 5
TRL 6
TRL 7
TRL 8
TRL 9

Basic Research
Supporting Advanced Space Technology Research
"Technology Push"

Technology Maturation Capability-Focused Technology and Demo Programs
"Applications Pull"

System Development Projects & Programs
(e.g. CEV Lunar Orbiter Mission)

Flight Mission Projects
(e.g. Lunar Orbiter Mission)

Specific Flight Missions...

e.g. T, S, Specific Flight Systems O-C/D Projects

e.g. T, S, Specific Flight Systems O-C/D Projects

e.g. T, U, Other Agencies

(e.g. T, U, Other Agencies

(e.g. S, U, NSF, NIH)
Technology Readiness Levels (TRLs)

- **TRL 1**: Basic principles observed and reported
- **TRL 2**: Technology concept and/or application formulated
- **TRL 3**: Analytical and experimental critical function and/or characteristic proof-of-concept
- **TRL 4**: Component and/or breadboard validation in laboratory environment
- **TRL 5**: Component and/or breadboard validation in relevant environment
- **TRL 6**: System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
- **TRL 7**: System prototype demonstration in a space environment
- **TRL 8**: Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)
- **TRL 9**: Actual system “flight proven” through successful mission operations

Levels below TRL 1 and above TRL 9 are not typically used.
Defining ECLSS Technology Development Terminology
(Calendar Year 2004)

- **Advanced Technology** = speaks to technology that is further than 6 years (2010) from reaching TRL 6.

- **Far-Term Technology** = speaks of technology that is required in the 6 – 20 year time frame. This technology will tend to be at very low TRL (0-3). This is an activity that requires long-term development and is usually discipline-oriented.

- **Mid-Term Technology** = speaks of technology that is required in the 3-6 year time frame. In general, this technology tends to be midTRL (3-5) that is oriented toward specific functional applications.

- **Near-Term Technology** = speaks of technology that is needed in the 1-3 year time frame. This technology, because of its time constraints, must be at least at midTRL (5-8) and must focus on tailoring the technology to program-specific requirements and on demonstration of technology at the component, subsystem, or system level through ground-based test beds and, if required, in space.

- **Technology Pull** = is that technology which has been accepted as an integral part of an Enterprise mission study or mission requirement. It is supported with a technology program.

- **Technology Push** = is that technology that is supported solely by a technology program. Potential for application to a mission problem. It is “push” until it is accepted by the mission, at which point it becomes a “pull” and remains “pull” until it is either successfully integrated into the mission architecture or rejected as unsuccessful.
Definition of ECLSS Hardware, Models, Concepts and Units

- **Proof of Concept** = Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and flight units.

- **Breadboard Unit** = A unit that demonstrates function only, without respect to form or fit. It has no flight hardware/software.

- **Brassboard Unit** = A unit that lies somewhere between a breadboard unit and prototype unit. It typically tries to make use of as much flight hardware/software as possible.

- **Development Unit** = Any series of units built to evaluate various aspects of form, fit, and function or combinations thereof.

- **Engineering Unit** = A unit that demonstrates critical aspects of the engineering processes involved in the manufacturing of the flight unit. In some cases, the engineering unit will become the prototype, the flight qualification unit or even a flight qualified unit.

- **Prototype Unit** = A unit which demonstrates form, fit and function. It is to every possible extent identical to flight hardware/software and is built to test the manufacturing and testing processes and is intended to be tested to flight qualification levels. The only difference from the flight unit is that it is realized from the start that elements of the prototype unit will in all probability be changed as a result of experiences encountered in its dev./test.

- **Flight Proven** = Hardware/software that is identical to hardware/software that has been successfully operated in a space mission.

- **Flight Qualification Unit** = Flight hardware that is tested to the levels that demonstrate the desired margins, typically 20 – 30%. Sometimes this means testing to failure. This unit is never flown.

- **Flight Qualified Unit** = Actual flight hardware/software that has been through acceptance testing.
Code T/H&RT Competitive/Portfolio
Approach to New Technologies and Systems

Starting Point: TRL 2/3

Many Diverse Competing Technologies at a Low Level of Funding -- All Addressing Approximately the same functional capabilities...

Technology Flight Experiment Where Necessary

Goal: TRL 4/5

Several Competing Technologies at a Moderate Level of Funding

Functionally-Focused Technology R&D

In Most Cases 1 or 2 “Best Candidate” Technologies at a Substantial Level of Funding

Systems-Oriented Technology Demos

Goal: TRL 6

Option: 1 or 2 “Best Candidate” Systems-Level Flight Demos at Significant Funding

Goal: TRL 7

Various Technologies Dropped of Deferred to Future Application Opportunities

Technology Ready to Support Decisions to Proceed with Development of a Desired Capability...

Number of Competing Technologies Being Funded

Total Resources Being Invested in a specific technology

TIME

e.g. Advanced Space Technology

e.g. Technology Maturation (Typical Case)

e.g. Tech. Maturation (By Exception)
Code T Implementing a Competition-Rich R&D Portfolio Phasing Approach
(Typical Life Cycle of a Technology Project within HR&T)

- **Round 1 “final” Gateway Recommendation?**
- **First Gateway**
  - Terminate current?
  - Add’l Options?

- **Year -1**

- **Year 0**
  - **Gateway:** Validation
  - **Gateway Project:** Develop/Demo

- **Round 1 Gateway**
  - Recommendation?

- **Year 1**
  - **Gateway:** Validation
  - **Gateway Project:** Develop/Demo

- **Pilot Program**

- **“Spiral N” – Round 1**

- **Year 2**

- **Year 3**
  - **Gateway:** Validation
  - **Gateway Project:** Develop/Demo

- **Round 2 “final” Gateway Recommendation?**

- **Year 4**
  - **Gateway:** Validation
  - **Gateway Project:** Develop/Demo

- **Second Gateway**
  - Terminate current?
  - Add’l Options?

- **Year 5**
  - **Gateway:** Validation

- **“Spiral N” – Round 2**

- **Year 6**

- **Margins and redundancy** in diverse subsystems, systems and systems-of-systems—but particularly those that must execute mission critical operations (such as transportation or life support) with the prospect of significant improvements in robustness in operations, reliability and safety.

- **Reusability** using vehicles and systems during multiple phases of a single mission, and/or over multiple missions instead of “throwing away” crew transportation, service modules, propulsion stages, and/or excursion systems after only a single mission.

- **Modularity** employing common, redundant components, subsystems and/or systems that can improve reliability and support multiple vehicles, applications and/or destinations—with the potential for significant reductions in cost per kilogram.

- **Autonomy**—making vehicles and other systems more intelligent to enable less ground support and infrastructure, including the goal of accelerating application of ‘COTS’ and COTS-like computing and electronics in space.

- **In-Space Assembly**—docking vehicles and systems together on orbit instead of launching pre-integrated exploration missions from Earth using very heavy launch vehicles, and including in-space manufacturing, servicing, reconfiguration, evolution, etc. for exceptionally long-duration deep space operations.

- **Robotic Networks**—robots that can work cooperatively to prepare landing sites, habitation, and/or resources and to extend the reach of human explorers.

- **Affordable Logistics Pre-positioning**—sending spares, equipment, propellants and/or other consumables ahead of planned exploration missions to enable more flexible and efficient mission architectures.

- **Energy-rich Systems and Missions**—including both cost-effective generation of substantial power, as well as the storage, management and transfer of energy and fuels to enable the wide range of other system-of-systems level challenges.

- **Space Resource Utilization**—manufacturing propellants, other consumables and/or spare parts at the destination, rather than transporting all of these from Earth.

- **Data-rich Virtual Presence**—locally & remotely, for both real-time and asynchronous virtual presence to enable effective science and robust operations (including tele-presence, tele-supervision, tele-science, etc.).

- **Access to Surface Targets**—that is precise, reliable, repeatable and global for small bodies, the Moon, Mars, and other destinations through the use of advanced mobility systems (accessible from orbit on other planetary surface).
Well-Planned Advanced ECLSS Technology Development Program for New Space Initiative

- Establish meaningful objectives and milestones for achieving goals
- Multiple paths to success for supporting lunar and Mars exploration
- Fallback positions when pursued technology efforts fail
- Quantifiable milestones for management of cost/schedules for technology
- Periodic “gates” for changing program directions when needed
- Maximize the probability of success
- Establish schedules that will maximize probability of success
- Live within the costs allocated to the program
- An integrated approach with other new space initiative efforts
- Agreed to metrics for assessing technology development progress
- Strong technical peer group for
  - conducting reviews of proposed technology pursuits
  - prioritizing technologies to pursue
  - conducting reviews of progress made in technology
  - also, an Independent Advisory Group to program manager
ECLSS Partnership with *In-situ Resource Utilization* Proposals
(Lunar and Planetary Surface Operations)

**ECLSS**
- Source of hydrogen for CO2 reduction
- Source of oxygen supply
- Source of CO2 (Mars) for water supply

**Potential relationships of In-situ Resource Utilization Technology**

**In-space Repair & Fabrication**
- Source of materials for Rapid prototyping

**Propulsion Systems**
- Hydrogen propellants
- Oxygen propellants
- Create methane from CO2 (Mars)

**Space Radiation Protection Shield Materials**
ECLSS Partnership with *In-space Repair & Fabrication* Proposals
(Surface Manufacturing and Construction Systems)

**Logistics/Spares**
- ECLSS ORU’s
- TCS ORU’s
- Propulsion systems
- Power systems

**In-situ Resource Utilization**
- Source of materials for Rapid prototyping

**Potential relationships of In-space Repair & Fabrication Technology**

**Maintenance**
- IVA tools
- EVA tools
- Plumbing

**Space Environment Protective Shields**
- Meteoroids
- Radiation
- Dust Storms
Potential benefits of Lab-on-a-chip Technology

- Advanced atmosphere monitoring
  - Habitable environments
  - Martian surface environments
- Microbial monitoring of TCS fluids
- Microbial monitoring of ECLSS water systems
- Specific trace contaminant monitoring
- Portable systems
- Reliable
- Lower weight
- Flexible applications (upgraded in-situ)
How Can NASA Use Ionic Liquids?

- In-Situ Resource Utilization or Analysis?
- CO2 Removal/O2 Release?
- Space Lubricants?
- Biomaterials Processing?
- New Materials?
- Thermal Fluids?
- Radiation Shielding?
- Fuel Cells?
- Batteries?
- Energetic Liquid Propellants?
- Ion Drive Propulsion?
ECLSS Partnership with *Ionic Fluid* Technology Proposals
(Advanced Materials)

**ECLSS**
- CO2 removal
- C02 reduction
- Regen. waste mgt.

**Potential relationships of Ionic Fluid Technology**

**In-situ Resource Utilization**
(Lunar or Martian missions)

**Space Radiation Protection Shield**
(Lunar or Martian missions)

**Thermal Control Systems**
- Active thermal control system fluid
- Tailored to mission environments on lunar and/or Martian surfaces
- Prometheus heat rejection system