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Strategic Research to Enable NASA’s Exploration Missions Conference Program
We are developing nanoscale biosensors and bioactuators for use in astronaut health and safety monitoring. This involves nanoscale polymer structures less than 20 nm in diameter as the basis of the sensor/actuators. The structures would be designed to target into specific cells of an astronaut and be able to monitor health issues such as the exposure to radiation or infectious agents. These molecules would also be able to administer therapeutics in response to the needs of the astronaut, and act as actuators to remotely manipulate an astronaut as necessary to ensure their safety. A multidisciplinary team, involving disciplines including nanotechnology-based materials science, bioengineering, bioinformatics and medical sciences, performs these studies. We will use these different disciplines to converge on the design and manipulation of the nanosensors, and the development of a non-invasive system to interact with the sensors through multi-spectral fluorescence analysis. Because of these broad requirements, the research involves a multidisciplinary team from the Medical, Engineering and LS&A schools at the University of Michigan, and is funded to train multidisciplinary scientists at the pre-graduate level.
Gas-Liquid Packed Bed Reactors in Microgravity

Vemuri Balakotaiah, University of Houston
Brian J. Motil, NASA Glenn Research Center
Mark J. McCready, Notre Dame University
Yasuhiro Kamotani, Case Western Reserve University
Why Packed Bed Reactors in Microgravity?

Motivation

- Packed Bed is the ‘workhorse’ of the Chemical Industry.
  - Used to carry out many single and multiphase reactions
  - Used in many Unit Operations (Gas Absorption/Purification, Extraction/Leaching, Adsorption/Chromatography, etc.)

- Considered an “enabling technology” for long duration manned space flights
  - Water Recovery (catalytic beds/biological reactors) Critical Technology
  - Air Revitalization (CO₂ absorption) Severely Limiting


NASA funded grants and projects

- University of Houston, V. Balakotaiah (Principal Investigator).
  - M. McCready, U. of Notre Dame,
  - B. Motil, NASA GRC; Y. Kamotani, CWRU

- Purdue University, S. Revankar (Principal Investigator).
- AHLS-1 flight definition experiment.
Flow Regimes in 1-g co-current downflow

- **Trickle Flow**
  - Continuous Gas Phase
  - Solid packing coated with Liquid Film
- **Spray Flow**
  - Liquid Droplets
  - Alternating Gas/Liquid Phases
- **Pulse Flow**
  - Continuous Liquid Phase
- **Bubbly Flow**
  - Bubbles

**Legend**
- Continuous Gas Phase
- Liquid Droplets
- Alternating Gas/Liquid Phases
- Continuous Liquid Phase
- Bubbles
Similarities and Differences Between 1-g and 0-g Cocurrent Downflow Through Packed Beds

- Low Interaction Regime (trickle flow) does not exist without gravity.
- All fluid flow is driven by pressure gradient with capillary and shear forces playing a more significant role. No steady countercurrent flow.
- Pulse flow occurs at a much lower flow rate and enhances interaction.
- Liquid holdup in 0-g is 100%
- Pressure drop measured in 0-g is the true frictional pressure drop
- Spray flow is inertia driven and not effected by change in gravity.
First Experiments in 0-g

- 12 flights - over 300 test conditions flown on NASA KC-135 aircraft (20 sec/run)
- Rectangular cross section
  - 2.5 cm x 5 cm x 60 cm long
- 5 differential pressure trans. (1000 Hz)
- 2 mm and 5 mm spherical glass beads
- High speed video (500 fps)
- Air and Water-Glycerin (1 to 20 cP)
- $0.03 < G < 0.8 \text{ kg/(s m}^2\text{)}$
- $3 < L < 50 \text{ kg/(s m}^2\text{)}$
- $0.18 < \text{Re}_{LS} < 100$
- $8.5 < \text{Re}_{GS} < 175$
- $4 \times 10^{-4} < \text{We}_{LS} < 0.2$
- $900 < \text{Su}_L < 365,000$

\[
\text{Re}_{LS} = \frac{\rho_L U_{LS} d_p}{\mu_L} \quad \text{We}_{LS} = \frac{\rho_L U_{LS}^2 d_p}{\sigma} \quad \text{Su} = \frac{d_p \rho_L \sigma}{\mu_L^2} = \frac{\text{Re}_{LS}^2}{\text{We}_{LS}} \quad \text{Re}_{GS} = \frac{\rho_G U_{GS} d_p}{\mu_G}
\]
Identification of Flow Regime Transitions

Bubble flow

Bubble flow “near” transition

Pulse flow “near” transition

Pulse flow
Microgravity Experimental Results Compared to Talmor Map

\[ X = \frac{\text{inertia} + \text{gravity}}{\text{interface} + \text{viscous}} = \frac{1 + \frac{1}{Fr}}{\frac{1}{We} + \frac{1}{Re}} \]

\[ We = \frac{D^* (L + G) \nu_{LG}}{\sigma} \quad Re = \frac{D^* (L + G)}{\mu_{LG}} \quad Fr = \frac{[(L + G) \nu_{LG}]^2}{gD^*} \]

\[ \nu_{LG} = \frac{\nu_1 (L / G) + \nu_G}{1 + (L / G)} \]

Packed Bed in Microgravity

- Bubbly Flow
- Bubbly/Pulse Transition
- Pulse Flow

Upper and Lower Boundary for Bubbly/Pulse Flow Predicted by Talmor

Upper and Lower Boundary Observed for Bubbly/Pulse Flow in Microgravity
Bubble-Pulse transition is a function of gas and liquid Reynolds numbers and the liquid Suratman number, where:

$$Su_L = \frac{Re_{LS}}{Ca_{LS}} = \frac{Re_{LS}^2}{We_{LS}} = \frac{d_p \rho_L \sigma}{\mu_L^2}$$
Comparison of average pressure drop for normal and microgravity conditions.
Pressure Drop

Lockhart-Martinelli Correlation

- Scatter is increased in the microgravity environment, an indication of the degree to which the capillary or surface tension effects are masked by hydrostatic head.
Pressure Drop

- Dimensionless pressure drop:

\[ \frac{-\Delta P}{Z} \frac{d_p}{\rho L U_{LS}^2} = f \left[ \frac{S u_L}{Re_{LS}^2}, \frac{1}{Re_{LS}}, Re_{GS}, \varepsilon \right] \]

- Apply limiting cases in terms of the Ergun equation:
  1. In limit of zero interfacial tension between fluids, reduces to single phase.
  2. In the limit of zero gas flow, reduces to single phase.
  3. In the inertia dominated limit, the friction factor should be independent of the interfacial and viscous terms.

\[ f_{TP} - f_{SP} = \gamma \left( \frac{Re_{GS}}{1 - \varepsilon} \right)^a \left( \frac{1 - \varepsilon}{Re_{LS}} \right)^b \left( \frac{(1 - \varepsilon)^2 S u_L}{Re_{LS}^2} \right)^c \]

- Determining parameters by regression, reduces to (two-phase friction factor):

\[ f_{TP} = \frac{-\Delta P}{Z} \frac{d_p}{\rho L U_{LS}^2} \frac{\varepsilon^3}{1 - \varepsilon} = \frac{1 - \varepsilon}{Re_{LS}} \left[ 180 + 0.8 \left( \frac{Re_{GS}}{1 - \varepsilon} \right)^\frac{1}{2} \left( \frac{S u_L (1 - \varepsilon)}{Re_{LS}} \right)^\frac{2}{3} \right] + 1.8 \]
Single Phase Ergun Equation

\[
\frac{Re_{GS}}{1 - L} = 33
\]

\[
\frac{Re_{GS}}{1 - L} = 65
\]

\[
\frac{Re_{GS}}{1 - L} = 99
\]

\[
\frac{Re_{GS}}{1 - L} = 131
\]

\[
\frac{Re_{GS}}{1 - L} = 180
\]

\[
\frac{Re_{GS}}{1 - L} = 267
\]

\[Su = 900\]

---

\[
\frac{Re_{GS}}{1 - L} = 14
\]

\[
\frac{Re_{GS}}{1 - L} = 27
\]

\[
\frac{Re_{GS}}{1 - L} = 40
\]

\[
\frac{Re_{GS}}{1 - L} = 55
\]

\[
\frac{Re_{GS}}{1 - L} = 74
\]

\[
\frac{Re_{GS}}{1 - L} = 114
\]

\[Su = 9200\]

---

\[
\frac{Re_{GS}}{1 - L} = 13
\]

\[
\frac{Re_{GS}}{1 - L} = 35
\]

\[
\frac{Re_{GS}}{1 - L} = 67
\]

\[
\frac{Re_{GS}}{1 - L} = 100
\]

\[
\frac{Re_{GS}}{1 - L} = 135
\]

\[
\frac{Re_{GS}}{1 - L} = 180
\]

\[
\frac{Re_{GS}}{1 - L} = 270
\]

\[Su = 23,000\]

---

\[
\frac{Re_{GS}}{1 - L} = 13
\]

\[
\frac{Re_{GS}}{1 - L} = 26
\]

\[
\frac{Re_{GS}}{1 - L} = 40
\]

\[
\frac{Re_{GS}}{1 - L} = 53
\]

\[
\frac{Re_{GS}}{1 - L} = 72
\]

\[
\frac{Re_{GS}}{1 - L} = 106
\]

\[Su = 146,000\]
Pulse amplitude decreases with increasing gravity.

<table>
<thead>
<tr>
<th></th>
<th>Microgravity (10-18 s)</th>
<th>High Gravity (32-40 s)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Pressure Drop</td>
<td>4.15 psi</td>
<td>4.75 psi</td>
<td>.6 psi</td>
</tr>
<tr>
<td>Pulse Amplitude</td>
<td>2.22 psi</td>
<td>1.69 psi</td>
<td>.5 psi</td>
</tr>
</tbody>
</table>
Summary

- Flow regime and pressure drop data was obtained and analyzed
- Pulse flow exists at lower liquid flow rates in 0-g compared to 1-g
- 1-g flow regime maps do not apply in microgravity
- Pressure drop is higher in microgravity (enhanced interfacial effects)

Work in Progress

- Flow Regimes and Pressure Drop with Alumina/Catalyst Particles [Summer, 2004]
- Flow Regimes and Pressure Drop with Structured Packed Beds (2-D beds and monoliths) [Summer/Fall 2004]
- Mass Transfer Studies in Microgravity
  - Gas-liquid interfacial area
  - Gas to liquid mass transfer coefficient
  - Solid-liquid mass transfer coefficient
- Modeling/Computational and Scale-up Studies

Granular materials present a host of challenging questions that must be addressed if mankind is to successfully deal with locomotion on uncertain soils and to process soils from lunar or Martian surfaces for key life-sustaining materials. Here, we are particularly concerned with the behavior of dense granular materials, and the way in which such materials change from effective solids to fluids. It is critical that we understand this type of behavior in particular if we are to have rovers that do not get stuck and handling systems that do not jam or break. We begin by noting that granular handling systems on earth are sources of significant problems for industry. Failures of granular devices occurs on the order of 100 times more often than fluid-related devices. And granular processing facilities typically operate well below design. Unlike fluid flows, the basic equations for describing dense granular flow are still a matter of open debate. It is crucial to have careful well-designed experiments and simulations that provide the basis for theory. The Gravity and Granular Materials Flight project involves such a study. In particular, it focuses on the transition between dense and more fluid-like states. A key point here is that earth's gravity consistently compacts granular materials, so that it is impossible to provide a true characterization of the rheological properties of granular materials. Nevertheless, a ground based study has shown that this transition has a particularly novel character. The experimental part of this project is carried out in an annular channel that allows shearing from above and vibration from below. The latter feature gives us the ability both to partially compensate for gravity and to provide a kind of 'thermalization'. The fluid-solid transition see in these experiments is particularly striking because the system freezes--becomes an ordered solid, as a result of increasing the effective temperature due to vibration. A parallel aspect of these studies are Molecular Dynamics (MD) simulations in both 2D and 3D. These simulations provide insights into the expected behavior of a flight experiment--information that cannot be easily accessed with earth-based experiments. And it also provides key insight into new ways of modelling granular systems. In particular, in these studies, we have investigated the role played by order-disorder associated with the elastic energy stored in the grains. This work is in collaboration with Drs. O. Baran, K. Daniels, and L. Kondic.
Gravity and Granular Materials

O. Baran, R. P. Behringer, K. Daniels, and L. Kondic

Support: NASA NAG3-2372, NNC04GA98G
Outline

• Practical problems
• Basic properties of granular materials
• 2D shear—insight into role of force chains…
• 3D shear—structural phase transition
• Conclusions
Practical Problems—Dense Granular Materials

- Commercial granular systems operate at only 63% of design (Rand Corp. Study, Rept. R-3216-DOE/PSSP, 1986)
- Granular devices fail 100 to 1000 times more often than other building structures (J. Eibl, 1984)
- Examples—
Some Examples of Granular Catastrophes
Catastrophes, Continued
Relevance to Martian and Lunar Exploration

- Rovers and other vehicles must negotiate uncertain terrain
- Mining for essential life support materials (e.g. water...) must function without fail
- Landings, including effects from rocket exhaust depend critically on soil conditions
Examples—Rovers in the News

**Silent Beagle could be stuck in large crater**

ALASTAIR DALTON SCIENCE CORRESPONDENT

FIRST they admitted that communications between Beagle 2 and the nearest spacecraft had never been tested. Now scientists leading Britain’s Mars mission have revealed that the probe may be stranded in a deep crater, which was only spotted 90 minutes after the craft was due to land.

The latest potential setback for the Open University-led team was revealed yesterday, as the fate of the $143m probe continued to elude astronomers.

However, Lord Sainsbury, the science minister, suggested the government would back a Beagle 2 mission if it failed.

- NASA icy as Europe finds water on Mars (24-Jan-04)
- Final bid to contact Beagle 2 (24-Jan-04)
- Mars probe hits ‘serious problem’ (23-Jan-04)
- NASA fears for Mars Spirit rover as signal fades to a faint beep (23-Jan-04)
- Mud on the ‘magic carpet’ could prove that there’s life on Mars (22-Jan-04)
- Bush calls for manned flights to Moon and Mars (19-Jan-04)
- Beagle 2 probe still silent (10-Jan-04)
- Mars mission is next giant step for Bush (09-Jan-04)
- Beagle lies low (08-Jan-04)
- Fresh attempt to contact Beagle 2 (08-Jan-04)
- Pictures capture the spirit of Mars (07-Jan-04)
- NASA probe lands safely on Mars and sends back ‘outstanding’ pictures (06-Jan-04)
Rovers in the News

23 April 2004

MARS ROVER STUCK IN CRATER

From correspondents in Pasadena, California.

THE Opportunity rover slipped down a sandy uphill slope as it tried to leave the crater it has explored since landing on Mars nearly two months ago, mission scientists said.

The six-wheeled robot tried driving out of the crater yesterday, but the soft martian terrain prevented it from doing so, NASA's Jet Propulsion Laboratory said. Controllers planned to try a second way out of the crater today.

Opportunity landed inside the 21-metre diameter crater on January 24.

Halfway around Mars, Opportunity's twin rover, Spirit, has been exploring the rim of a far larger crater.

NASA launched the $US820 million ($1.1 billion) mission to search Mars for evidence the planet once was a wetter place. Opportunity already has uncovered such evidence.
Rovers in the News
Complications of Martian soil

Images from Mars rover reveal mysterious clumps

Scientists baffled by sandpaper-like patches on surface

Publication:
Author: By David Perlman, Chronicle Staff Editor

Short description: The images that Spirit sent down from its Martian parking spot, a few feet in front of its landing pad, was a flat patch of fine- and coarse-grained sand--much of it stuck together in clumpy patches that scientists conceded they did not yet understand.

Article:
Pasadena -- Ecstatic scientists used the Mars rover's powerful camera Friday to take the first close-up images ever made of the Martian surface and immediately confronted a new mystery over what they saw. The images that Spirit sent down from its Martian parking spot, a few feet in front of its landing pad, was a flat patch of fine- and coarse-grained sand--much of it stuck together in clumpy patches that scientists conceded they did not yet understand.
Some Basic Properties of Dense Granular Materials

- Forces are carried preferentially on force chains
- Deformation leads to large spatio-temporal fluctuations
- Preparation history of granular samples matters a lot
- Gravity compacts most materials, making discovery of their true behavior impossible
Example of Force Chains—Shear Experiment
Example of Stress Fluctuations

4mm Beads, 2cm Fill Height
20mHz Rotation Rate
Example of Force Network Evolution
Force chains evolve and break under vehicles
Force chains form and break—making “avalanches”
Stress avalanches can predict slip/failure

Stick-Slip Motion

![Diagram showing stick-slip motion with force vs. time and delta time events]

- ΔF (slip)
- ΔF (build-up)
- Δt (slip)
- Δt (build-up)

- Slip events
- Build-up events
2D Couette Shear Experiments
Data for Variance of Particle Positions vs. Time: Diffusion is affected by mean velocity and force network
3D Shear + Vibration: Experiments and Simulations
Computations show need for zero g
Clips from Experiments
Freezing by Heating—Competition between shearing and vibration ($\Gamma = 2.0$)
Spatial Autocorrelations show disorder with shear (a, b, d, e) and more quantitatively, c.

\[ \Omega = 0.0167 \text{ Hz} \]

\[ \Omega = 0.167 \text{ Hz} \]
Force Probability Distributions: Singular behavior in the Kurtosis
Phase Diagram in Shear Rate ($\Omega$) and Shaking Amplitude ($\Gamma$)
Conclusions

• Granular materials offer many challenges
• Low-g is very important for uncovering basic science
• This science will be crucial for manned exploration of Mars and the moon
• Dense granular materials: force chains, large fluctuations, novel phase transitions
• Understanding these phenomena will advance us towards more reliable earth-bound and extra-terrestrial granular engineering
The low per-unit cost of microfabricated devices along with the ability to integrate multiple components on a single device allows for the construction of a variety of complex chemical analysis systems. These complex systems can be only a squared centimeter or less in size but can perform functions normally associated with benchtop equipment. Such devices can, in essence, function as micron-scale intelligent sensors. We are constructing such devices on silicon, glass, and polymer substrates for the analysis of saliva, blood, and other medically relevant fluids. The devices consist of a combination of micron-scale fluidic channels, reaction chambers, and/or electrophoresis units. The devices can also include electronic control and sensing systems such as resistive heaters, temperature sensors, and fluorescence detectors. Liquid samples are injected into these devices and moved between components by a variety of techniques including hydrophobic/hydrophilic patterning, pressure manifolds, and/or phase-change valves. The output from these devices can then be used to determine physical and/or chemical properties of the liquid sample and ultimately the medical condition of the patient from which the sample was obtained. Results will be presented for the analysis of both physical (e.g., viscosity) and chemical (e.g., DNA) properties.
Advanced Life Support

Joe Chambliss EC1
281-483-9204
http://advlifesupport.jsc.nasa.gov
June 22, 2004
Advanced Life Support Topics

1. Fundamental Need for Advanced Life Support
2. ALS organization
   • Areas of research and development
   • Project management techniques
3. Requirements and Rationale
4. Past Integrated tests
5. The need for improvements in life support systems
6. ALS approach to meet exploration goals
   • Candidate groups of systems
7. ALS Projects showing promise to meet exploration goals
8. GRC involvement in ALS
## Human Life Support System Requirements

<table>
<thead>
<tr>
<th>Consumables</th>
<th>Kilograms per person per day</th>
<th>Wastes</th>
<th>Kilograms per person per day</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gases</strong></td>
<td></td>
<td><strong>Gases</strong></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.84</td>
<td>Carbon Dioxide</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>23.4</td>
<td><strong>Water</strong></td>
<td>23.7</td>
</tr>
<tr>
<td>Drinking</td>
<td>1.62</td>
<td>Urine</td>
<td>1.50</td>
</tr>
<tr>
<td>Water content of food</td>
<td>1.15</td>
<td>Perspiration/respiration</td>
<td>2.28</td>
</tr>
<tr>
<td>Food preparation water</td>
<td>0.79</td>
<td>Fecal water</td>
<td>0.09</td>
</tr>
<tr>
<td>Shower and hand wash</td>
<td>6.82</td>
<td>Shower and hand wash</td>
<td>6.51</td>
</tr>
<tr>
<td>Clothes wash</td>
<td>12.50</td>
<td>Clothes wash</td>
<td>11.90</td>
</tr>
<tr>
<td>Urine flush</td>
<td>0.50</td>
<td>Urine flush</td>
<td>0.50</td>
</tr>
<tr>
<td>Solids</td>
<td>0.6</td>
<td>Humidity condensate</td>
<td>0.95</td>
</tr>
<tr>
<td>Food</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>24.8</td>
<td><strong>TOTAL</strong></td>
<td>24.9</td>
</tr>
</tbody>
</table>
Human Life Support System Requirements

Open-Loop Life Support System
Resupply Mass - 12,000 kg/person-year
(26,500 lbs/person-year)

- Water 89%
- Oxygen 2.5%
- Food (dry) 2.2%
- Crew Supplies 2.1%
- Gases lost to space 2.1%
- Systems Maintenance 2.1%

Water 10,680 kg
(23,545 lbs)
(2827 gallons)
Mass Cost of Human Mars Mission Using Today’s Technologies

- Advanced Avionics [7%]
- Maintenance & Spares [18%]
- Advanced Materials [17%]
- Closed life Support [34%]
- Advanced Propulsion [EP or Nuclear] [45%]
- Aerobraking [42%]

The NASA Exploration Team [NExT]
Advanced Life Support (ALS)

ALS research and technology development provides technology options that either address:

- Bioastronautics Critical Path Roadmap (BCPR) risk
- Improved efficiency (lower mass, power and volume)
  - Closure of the air, and water loops is critical
    - Solid Waste, Thermal Control improvements contribute to efficiency
  - Technology development is undertaken after rigorous systems analysis including the current baseline (ISS and Shuttle) systems.
  - Technology maturation is accomplished through validation and demonstration in integrated test beds and flight experiments
    - ALS takes technologies from very low Technology Readiness Level concepts (TRL 1-3) to mature technologies at TRL 6 via test and analysis
    - Make the technology available for consideration in an exploration vehicle
WHY MUST WE DEVELOP NEW ALS SYSTEMS?

Shuttle/ISS life support technologies are mass, power and resupply intensive.

Lunar and Mars missions
- a high degree of closure of oxygen and water regeneration loops and efficient low mass thermal management is required.
- subsequent closure of the food loop along with containment and recycling of solid wastes must be pursued.

Lunar or planetary bases - greater autonomy of life support system reduces the dependency on resupply missions, thereby increasing safety and reducing cost.

Pertinent Connections to BCPR

<table>
<thead>
<tr>
<th>Risk #</th>
<th>Risk Title</th>
<th>ISS</th>
<th>Moon</th>
<th>Mars</th>
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<tbody>
<tr>
<td>43</td>
<td>Maintain Acceptable Atmosphere</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>44</td>
<td>Maintain Thermal Balance in Habitable Areas</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>45</td>
<td>Manage Waste</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>46</td>
<td>Provide and Maintain Bioregenerative Life Support Systems</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>47</td>
<td>Provide and Recover Potable Water</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>48</td>
<td>Inadequate Mission Resources for the Human System</td>
<td>Y</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>

Many enabling questions are addressed in the seven principal risks listed above
This effort also addresses enabling questions for shared risks of other Bioastronautics disciplines.
ALS IMPLEMENTATION

Coordinating Center: JSC

The JSC EC Advanced Life Support Manager administers the overall
Advanced Life Support Budget for JSC, ARC, KSC, MSFC, (GRC in 05)

Participants
– NASA Field Centers, including ARC, GRC, JPL, JSC, KSC, MSFC and their
affiliated institutes.
– NASA Research Partnership Centers including BST, CAMMP, CSP, ES-CTSC,
FTCSC, and WCSAR.
– Principal investigators with research and technology offerings sponsored through
other programs such as EPSCoR and congressional earmarks.
– Contractors and small business concerns who respond to competitive contracts
and SBIR/STTR program solicitations.
– Assistance and collaboration will be sought by experts within existing flight
programs including ISS, Shuttle, and Project Constellation.

Funding
– Funding for tasks is implemented through the most appropriate method.
– Funding methods include: NASA Research Announcements, Technology
Development Proposals, Technical Task Agreements, Competitive Procurements.

Leveraging
– SBIR, STTR, EPSCoR, GSRP, NRC, Code R/T/M, SFF, NASA CO-OP Program
Advanced Life Support (ALS) Areas

- Air Revitalization Systems
- Crop Systems
- ALS Flight Experiments
- Advanced Thermal Control Systems
- Advanced Water Recovery Systems
- Systems Integration Modeling & Analysis
- Solid Waste Management
- Integration & Test

<table>
<thead>
<tr>
<th>Research Center</th>
<th>Manpower</th>
</tr>
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<tbody>
<tr>
<td>JSC (38)</td>
<td>9</td>
</tr>
<tr>
<td>ARC (39)</td>
<td>5</td>
</tr>
<tr>
<td>KSC (46)</td>
<td>4</td>
</tr>
</tbody>
</table>

NRA (26)

TDP (39)
Augmentation Major Products

**Air**
- Gas Supply (2)
- CO\textsubscript{2} Removal (3)
- Advanced CO\textsubscript{2} Reduction
- Regenerative Trace Contaminant Control
- Efficient, Low Noise Air Flow System

**Water**
- Advanced Biological Primary Water Processor
- Ultrafiltration
- Next Generation Phys/Chem Primary Water Processor
- Reverse Osmosis
- Brine Dewatering
- Post Processors
- Alternative Disinfection Technologies

**Bioregenerative Systems**
- Sustained Crop Production Testing
- Hypobaric Plant Test Chambers
- Mineral and Water Recycling Testing
- Vegetable Production Unit EDU
- Microbial Risk Assessments

**Thermal**
- Advanced Coldplate Development
- Humidity Control Device
- Structural Radiator Prototype
- Evaporator Prototype
- Sublimator Prototype

**Solid Waste**
- Compactor
- Stabilization & Containment
- Water Recovery Technology
- Mineralization Technology

**Ground Test**
- 20’ Chamber Certified for Reduced Pressure Testing.
## Past ALS Testing
### Lunar Mars Life Support Test Project

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase IIA</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration</strong></td>
<td>15-days</td>
<td>30-days</td>
<td>60-days</td>
<td>91-days</td>
</tr>
<tr>
<td><strong>Dates</strong></td>
<td>Completed August '95</td>
<td>Completed July '96</td>
<td>Completed March '97</td>
<td>Completed December '97</td>
</tr>
<tr>
<td><strong>Crew Size</strong></td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Technologies</strong></td>
<td>Air revitalization using crops with P/C</td>
<td>Regenerative P/C technologies</td>
<td>ISS life support technologies</td>
<td>Integration of physicochemical &amp; biological technologies</td>
</tr>
<tr>
<td><strong>Regeneration</strong></td>
<td>Air</td>
<td>Air &amp; water</td>
<td>Air &amp; water</td>
<td>Air, water, solid waste, food</td>
</tr>
</tbody>
</table>
Lunar Mars Life Support Test Project

Phases III: 91-day, 4-Person Tests

- Biological Water Recovery System
- Carbon Dioxide Removal System
- Oxygen Generation System
- Carbon Dioxide Reduction System
- Solid Waste Incinerator
- Control Room

Phase III Crew (left to right, Nigel Packham, Laura Supra, John Lewis, Vickie Kloeris)

VPGC Wheat Harvest
ALS Integrated Test Plans Support the Exploration Timeline


First Uncrewed CEV Flight

1st Crewed CEV Flight

1st Human Mission to Moon

Lunar landing outpost

Last year for lunar landing

CEV ECLSS Tech Test System A

6 year prime contractor lead-time

Lunar Outpost Tech. Test System B&C

6 year prime contractor lead-time

Lunar Outpost Bioregenerative Test System C

6 year prime contractor lead-time
Advanced Life Support Approach for Supporting NASA Exploration

- Preliminary analysis shows the exploration program will require at least three different environmental control systems architectures
  - A) a short duration, open-loop system architecture;
  - B) a zero-g, medium duration system architecture; and
  - C) a partial-g, long duration system architecture.

- Technologies for these systems need to be matured to technology readiness level (TRL) 6, to lower program risk and to provide mature technology selections for the vehicles’ integrating contractors.

- A technology development program that will demonstrate these technologies on the ground in an integrated fashion prior to committing to flight designs is essential.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>System A</th>
<th>System A</th>
<th>System C</th>
<th>System B</th>
<th>System A</th>
<th>System C</th>
<th>System A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration (Human Tended)</strong></td>
<td>7 – 14 days (Roundtrip)</td>
<td>1 – 5 days</td>
<td>1 – 18 months</td>
<td>12 – 24 months (Roundtrip)</td>
<td>1 – 45 days</td>
<td>17 – 20 months</td>
<td>1 – 7 days</td>
</tr>
<tr>
<td><strong>Air Revitalization</strong></td>
<td>Open</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Closed ISRU</td>
<td>Open</td>
</tr>
<tr>
<td><strong>Water Recovery</strong></td>
<td>Collection and Storage</td>
<td>Collection and Storage</td>
<td>Closed ISRU</td>
<td>Closed</td>
<td>Collection and Storage</td>
<td>Closed ISRU</td>
<td>Collection and Storage</td>
</tr>
<tr>
<td><strong>Waste Management</strong></td>
<td>Stored</td>
<td>Stored</td>
<td>Volume Reduction</td>
<td>Volume Reduction</td>
<td>Volume Reduction</td>
<td>Volume Reduction</td>
<td>Stored</td>
</tr>
<tr>
<td><strong>Food Systems</strong></td>
<td>Conventional Stored</td>
<td>Conventional Stored</td>
<td>Conventional Stored with Fresh Food</td>
<td>Extended Shelf Life with Fresh Food</td>
<td>Extended Shelf Life</td>
<td>Extended Shelf Life</td>
<td>Extended Shelf Life</td>
</tr>
<tr>
<td><strong>Thermal Systems</strong></td>
<td>LP-BR</td>
<td>LP-DR</td>
<td>HP-DR</td>
<td>HP-DR</td>
<td>LP-BR</td>
<td>HP-DR</td>
<td>LP-BR</td>
</tr>
<tr>
<td><strong>System Configuration</strong></td>
<td>System A</td>
<td>System A</td>
<td>System C</td>
<td>System B</td>
<td>System A</td>
<td>System C</td>
<td>System A</td>
</tr>
</tbody>
</table>

Closed Air is 75% by Mass
Closed Water is 90% by Mass
ISRU –Investigate and utilize as appropriate
Regenerative Systems will be selected over consumable systems

System A: Short-duration, micro-g
System B: Long-duration, micro-g
System C: Long-duration, planetary surface, partial-g
Mars Mission Concepts

Mars Planetary Base – A Sustainable Presence

- Permanent presence
- Power and volume: significantly more is available
- Hypoogravity environment
- Types of systems:
  - Integration of physicochemical and biological technologies
  - Closure of air & water loop
- Food: staple foods grown, processed by food system, contribute substantially to caloric requirements and to air and water regeneration
- Solid waste management:
  - may be processed to recover resources
- EVA: Extensive with overnight stays
- Communication:
  - highest degree of crew autonomy
ALS Projects Showing Promise for Exploration

• ALS Proposed Projects show great promise to meet exploration goals
  – Sabatier- CO2 reduction
  – Advanced Trace Contaminant Control
  – Advanced CO2 removal and reduction system
  – Biological Water Processor
  – Rotating Reverse Osmosis
  – Vapor Phase Catalytic Ammonia Removal System
  – Cascade Distillation System
  – Low power two-phase Active Thermal Control System
  – Advanced thermal and humidity control
  – Multi application gravity insensitive heat pump
  – Solid waste management compaction
  – Dry and Wet Pyrolysis
  – Lyophilization (Freeze Drying)
  – Vegetable Production Unit

• Ground and Flight experimentation is needed to establish capabilities
• To evaluate technologies Systems Integrated Modeling and Analysis and integrated testing is needed
Glenn Research Center
Contribution to ALS

- FY05 ALS plans call for GRC support to provide expertise in assessing microgravity and fluid physics areas related to ALS technologies
  - GRC to provide design tools, experimentally validated components, trade studies and trouble shooting
    - Two-phase separation processes
      - Gas tolerant pumping assemblies
      - Evaporative cooling techniques
      - Condensing HXs
      - Gas/Liquid separation devices
      - Liquid/Solid Separation of waste products
    - Reactor bed processes in micro and partial gravity
      - Design tools and techniques to address fine generation
      - Fluid flow processes in filtration assemblies
  - GRC to serve as technical monitor for NSCORT effort related to biofilters for trace contaminant removal
    - Related to water distribution, choking or channeling and nutrient supply
Acronyms

- BST – Bioserve Space Technologies NASA Research Partnership Center, University of Colorado.
- BWP – Biological Water Processing
- CAMMP – Center for Advanced Microgravity Materials Processing. Northeastern University, Boston, Massachusetts.
- CSP – Center for Space Power. Texas A&M University.
- EPSCoR – Experimental Program to Stimulate Competitive Research.
- FTCSC – Food Technology Commercial Space Center. Iowa State University.
- GSRP – Graduate Student Researchers Program
- LTV – Lunar Transit Vehicle
- LLV – Lunar Landing Vehicle
- LO – Lunar Outpost
- MTV – Mars Transit Vehicle
- MLV – Mars Landing Vehicle
- MH – Mars Habitat
- NRC – National Research Council Fellowships
- PR – Pressurized Rover
- P-C – Physiochemical
- SBIR/STTR – Small Business Innovative Research/Small Business Technology Transfer
- SFF – Summer Faculty Fellowships
- WCSAR – Wisconsin Center for Space Automation & Robotics
Overview and Status of the Bioastronautics Critical Path Roadmap (BCPR)

Presented at Conference Workshop “Strategic Research to Enable NASA’s Exploration Missions”
By John Charles, NASA Johnson Space Center
June 22, 2004
BCPR Objectives

• Identify and assess risks for human space exploration
• Prioritize research and technology and communicate those priorities
• Guide solicitation, selection, and development of NASA research (ground and flight) and allocation of resources
• Assess progress toward reduction and management of risks
• Define operating bands (acceptable levels of risk)
BCPR History
- Initiated by the Johnson Space Center (JSC) Space and Life Sciences Directorate in 1997
- Expanded to include National Space Biomedical Research Institute (NSBRI) in 1998
- BCPR has guided research solicitation and selection since 2000

BCPR Revisions (Rev. E, 2004)
- Expanded set of Reference Missions (ISS, Moon, & Mars)
  - Previous BCPR based only on a 30-month Mars mission
- Greater representation of NASA Advanced Human Support Technology (AHST) and NASA Space Medicine programs
- Improved statements of risks and questions
  - Previous BCPR had 55 risks; Rev. E has 50 risks
  - Rev. E eliminated redundancy but added new autonomous medical care and AHST risks
  - Rev. E includes enabling research and technology questions (EQ) that are more specific and measurable

- 25 Intramural Scientists + 25 NSBRI leads
- 10-20 on each team
- Total of 300 attended each NSBRI retreat
- Presented at OBPR Biennial Symposia & NSBRI Biennial Retreats
- On web since 2000
BCPR and OBPR
Program Management

- BCPR provides framework for Codes U, M and Z Bioastronautics Strategy and for Bioastronautics components of Code U Enterprise Strategy (Bioastronautics Strategy aligns with NASA Strategic Plan)
- Code UB research portfolio is tied to BCPR
- BCPR has been revised to align with new vision for space exploration
- Revised BCPR content and processes now under review by Committee on Aerospace Medicine and Medicine in Extreme Environments of the Institute of Medicine, National Academy of Sciences and National Academy of Engineering
- Bioastronautics Science Management Team (BSMT) was chartered by Codes U, M and Z to lead current revision of the BCPR (temporarily replaced CPCP)
BCPR Disciplines & Cross-Cutting Areas

Human Health & Countermeasures
- Bone loss
- Muscle alterations & atrophy
- Neurovestibular adaptation
- Cardiovascular alterations
- Immunology, infection & hematology
- Environmental effects

Autonomous Medical Care
- Clinical capabilities

Behavioral Health & Performance
- Psychosocial adaptation
- Sleep & circadian rhythms
- Neuropsychological
- Space human factors – cognitive capabilities

Radiation Health
- Radiation effects

Advanced Human Support Technologies
- Advanced life support
- Advanced environmental monitoring
- Advanced food technology
- Advanced EVA
- Space human factors – physical capabilities
## Characteristics of BCPR Reference Missions

<table>
<thead>
<tr>
<th>DRM</th>
<th>1 Year ISS</th>
<th>Lunar</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew Size</td>
<td>2 +</td>
<td>4 – 6</td>
<td>6</td>
</tr>
<tr>
<td>Launch Date</td>
<td>2005?</td>
<td>NET 2015-2020</td>
<td>NET 2025 – 2030</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>12 months</td>
<td>10 – 44 days</td>
<td>30 months</td>
</tr>
<tr>
<td>Outbound Transit</td>
<td>2 days</td>
<td>3 – 7 days</td>
<td>4 – 6 months</td>
</tr>
<tr>
<td>On-Site Duration</td>
<td>12 months</td>
<td>4 – 30 days</td>
<td>18 months</td>
</tr>
<tr>
<td>Return Transit</td>
<td>2 days</td>
<td>3 – 7 days</td>
<td>4 – 6 months</td>
</tr>
<tr>
<td>Communication lag time</td>
<td>0+</td>
<td>1.3 seconds +</td>
<td>3 – 20 minutes +</td>
</tr>
<tr>
<td>G-Transitions (assumes no artificial g)</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hypogravity</td>
<td>0 g</td>
<td>1/6g for up to 30 days</td>
<td>1/3 g for up to 18 months</td>
</tr>
<tr>
<td>Internal Environment</td>
<td>~ 14.7 psi</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>EVA</td>
<td>0 – 4 per mission</td>
<td>2 – 3/week; 4 – 15/person</td>
<td>2 – 3/week; 180/person</td>
</tr>
</tbody>
</table>
Bioastronautics Timetable
(notional)

2004: Announcement of new vision for space exploration
2005: Countermeasure hardware requirements (Phase A)
2006: Initial flight experiments; countermeasure hardware design & prototype development (Phase B)
2007-8: First unmanned test flight of CEV
2010: STS to be retired, end heavy lift/return
2010-13: Final ground demo of countermeasures
2013-16: In-flight demo/validation of integrated countermeasure suite(s)
2015-20: Moon human landing/exploration testbed
2016: End ISS validation of countermeasures
2025-2030: First piloted Mars mission
BCPR Processes
Risk Identification, Assessment, and Management

• Original list of risks, research issues culled from advisory committee reports & other sources, deliberated among discipline experts
  – All BCPR risks & questions were compared with recent advisory committee reports (e.g., CSBM Strategies Report) and revisions made where necessary
• Starting in 1997 with over 100 risks, list reduced to 55 risks in 1998 and current 50 risks in 2004 by continued deliberations, eliminating redundancy, incorporating new advisory committee reports and space flight research findings
• Discipline teams assessed risks within own disciplines, prioritized own enabling research and technology questions for each risk
• Second group of experts assessed relative priority of risks across all disciplines
• Configuration Control (CPCP - Critical Path Control Panel)
  – 2000-2003: BCPR was under configuration control (currently Bioastronautics Science Management Team controls the process)
  – Will return to configuration control in 2005
Types of BCPR Risks

- Risk: conditional probability of adverse event or system-related inefficiency
  - Human health & medical risks from exposure to hazardous conditions of space flight (e.g., microgravity, radiation, confinement)
    - Thirty-five risks classified as human health or medical
  - System performance & efficiency risks involve technologies required for providing safe & habitable environment
    - Fifteen risks classified as system performance and efficiency-related

- Different criteria employed to assess and rate risks
  - Human health & medical risks used traditional risk assessment criteria of estimated likelihood of risk occurrence & its severity of impact on crew health or performance
  - System performance & efficiency risks rating scheme based on improved efficiency
  - Both types used risk mitigation status (readiness levels)

- Overlap across the different types of risk
  - As mitigations are validated, increased efficiency is important
  - System performance & efficiency risks can have health-related effects
## Enabling Questions Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Health and Countermeasures</td>
<td>Risk Assessment &amp; Acceptability</td>
</tr>
<tr>
<td></td>
<td>Mechanisms and Processes</td>
</tr>
<tr>
<td></td>
<td>Countermeasure Strategies</td>
</tr>
<tr>
<td>Behavioral Health &amp; Performance</td>
<td>Medical Diagnosis &amp; Treatment</td>
</tr>
<tr>
<td></td>
<td>Prevention (selection and countermeasures)</td>
</tr>
<tr>
<td></td>
<td>Monitoring</td>
</tr>
<tr>
<td></td>
<td>Diagnosis</td>
</tr>
<tr>
<td></td>
<td>Treatment</td>
</tr>
<tr>
<td></td>
<td>Informatics (cross cutting)</td>
</tr>
<tr>
<td>Radiation Health</td>
<td>Advanced Human Support Technology</td>
</tr>
<tr>
<td></td>
<td>Research Requirements/Specifications</td>
</tr>
<tr>
<td></td>
<td>Design Tools</td>
</tr>
<tr>
<td></td>
<td>Technologies</td>
</tr>
<tr>
<td></td>
<td>Operations and Training</td>
</tr>
<tr>
<td>Autonomous Medical Care</td>
<td></td>
</tr>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Risk Mitigation Status

### Technology Readiness Level (TRL) & Countermeasures Readiness Level (CRL)

<table>
<thead>
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<td>System flight proven through mission operations</td>
<td>9</td>
<td>Countermeasure fully flight-tested and ready for implementation</td>
<td>Countermeasure operations</td>
</tr>
</tbody>
</table>
Defining Levels of Accepted Risk

• Tolerance limits (desirable operating bands) for human system
  – For example
    • How much bone loss (or muscle atrophy, etc.) is acceptable?
    • Units? %? Functionality?
  – Derived from available data, expert opinion and consensus
  – Decisions require selecting best mitigation options
  – Mitigate to the best level possible (risk never zero)

• Five month effort initiated by NASA Chief Medical Officer, now underway
  – Focused NASA JSC/NSBRI team to document currently accepted risk levels
  – “Acceptable” vs. “accepted” risks
BCPR Integration

- Risks initially derived (identified, assessed) at discipline level, but risk reduction and management requires integrated approach
  - Effective and efficient risk mitigation solutions result from:
    - Collaborations across traditional disciplines
    - Coordination among intramural and extramural researchers
    - Cooperative efforts of key players – flight surgeons, astronauts, researchers, and technology developers
  - Adoption of project management tools and practices facilitates risk reduction solutions
  - Ground-based integration sites (e.g., advanced integration matrix - AIM) are essential for demonstrating & validating readiness for meeting requirements of exploration missions
    - technology components
    - human systems
- Cross cutting areas lend themselves to “projectized” approach
BCPR Implementation, Integration, and Validation

• Projects as implementing and integrating tools
  – Projects impose discipline on the research activities and help focus on schedule and deliverables
  – Project plans force forward and integrated planning
  – Project plans reviewed (NAR) and approved to assure management concurrence
  – Project teams should include the best experts
    • Draw on NASA and non-NASA sources
  – Project teams can also help with integration (physicians, scientists, engineers, managers and astronauts)
BCPR Refinement Schedule

• BSMT prepared materials for IOM/NAS/NAE Review, briefed JSC & HQ
• April 1
  – BSMT delivered BCPR content and processes to CAMMEE for review
  – posted revised document to website for public comment
• April 12: CAMMEE briefing on study request
• May 25-26: Risk Rating workshop
• In preparation for delivery to CAMMEE
  – Draft operating bands, accepted risk levels (SLSD)
  – Final risk assessment
  – Web tool
• October 1: Interim Report from CAMMEE
• October 1, 2005: Final Report from CAMMEE
Academy Review

- **Study Title:** “Assessing the Bioastronautics Critical Path Roadmap”
- **Study Sponsors:** Code Z, Code U, Code M
- **Actionees:** Committee on Aerospace Medicine and Medicine in Extreme Environments (CAMMEE)—IoM (primary), NAS, NAE, with NRC coordinating
- **Statement of Work**
  - Independent review of BCPR content and processes with respect to clinical issues and bioastronautics research for the missions in new exploration initiative.
    - Assessment of strengths and weaknesses.
    - Identification of unique challenges.
  - Interim report in 6 months.
  - Final report in 12 – 18 months.
- **Recommended committee composition**
  - Representative experts (e.g., discipline areas, risk assessment, medical decision-making, public health, epidemiology).
  - Exclude currently funded Bioastronautics researchers.
Academy Review
(continued)

• **Statement of Work**
  – Conduct an independent review of the content and processes currently used for communication, assessment, and implementation of the BCPR with respect to clinical issues and bioastronautics research for the missions contemplated in the President’s exploration initiative
    • Assessment and report of the strengths and weaknesses
    • Identification of unique challenges
  – Interim report 6 months after initiation of study
  – Final report at completion of study approximately 12 – 18 months

• **Recommended committee composition**
  – Representative experts (e.g., discipline areas, risk assessment, medical decision-making, public health, epidemiology)
  – Exclude currently funded Bioastronautics researchers
Rating Bioastronautics Risks

- Rating is important for programmatic reasons (allocation of resources, etc.)
- Each of the 50 risks is important and needs to be addressed for human health, safety and performance during or after space flight
- The risk is determined by the likelihood of occurrence, the severity of the consequence should it occur, and the current status of mitigation
Risk Rating Exercises

• Repeated Risk Rating exercises since 2000
• Different participants (subcommittee; steering committee; joint astronaut / space medicine / science management workshop; senior managers)
• Generally in agreement, including highest priority risks (radiation health, clinical care, human performance & fracture risk)
• Reconciling of recent (3 @ 2004) sets of ratings now in work
• The results of one of the risk rating exercises is contained in Rev. E
### Human Health Risk Assessment
#### Criteria (examples)

#### Severity of Consequences (for example)

<table>
<thead>
<tr>
<th>Types of Consequences</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crewmember Health In-flight</td>
<td>No more than temporary discomfort</td>
<td>Short-term incapacitation or impairment</td>
<td>Death, significant health issue requiring mission abort or long-term incapacitation or impairment</td>
</tr>
<tr>
<td>Crewmember Performance In-flight</td>
<td>Delays of mission objectives</td>
<td>Loss of some mission objectives</td>
<td>Inability to perform critical mission functions, or total loss of mission objectives</td>
</tr>
<tr>
<td>Crewmember Health Post-mission</td>
<td>Limited increase in post-mission rehabilitation</td>
<td>Impairment but no long term reduced quality of life</td>
<td>Significant permanent disability or significantly reduced lifespan, or significant long term impairment or reduced quality of life</td>
</tr>
</tbody>
</table>

#### Likelihoods (for example)

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood</td>
<td>&lt;0.001</td>
<td>0.001-0.01</td>
<td>&gt;0.01</td>
</tr>
</tbody>
</table>
A Recent Risk Rating Exercise

• Consensus workshop participants: representatives of Astronauts, Space Medicine and Researchers
• Participants answered two questions for each BCPR risk:
  – If the US committed to sending humans to Mars today how worried would you be?
    • Scale 0 (not worried) to 10 (very worried)
  – How important is the International Space Station to reducing or eliminating the worry (for each risk)?
    • Scale 0 (not at all) to 10 (very important)
• Risk rating methodology for this exercise
  – The 3 groups independently rated 35 risks (not including 15 Advanced Human Support Technology risks)
  – Group discussion to reach consensus
Consensus Workshop

Background

• The process for evaluating & incorporating changes into BCPR is still being developed
• Position statements from the astronauts and recommendations from the flight surgeons are currently being drafted (due end of June)
• The recommendations that follow have not been fully reviewed by the workshop participants and should be considered preliminary
Consensus Workshop
Rating Analysis

• Human Health and Countermeasure Risks
  – Most microgravity physiology risks are moderate
  – ISS should be used to mitigate those risks
• Autonomous Medical Care Risks
  – Clinical risks are substantial
  – ISS important for many clinical risks
• Behavioral Health and Performance Risks
  – Critical for exploration
  – ISS only moderately useful to mitigate risks
  – Research should be done in integrated test facilities
• Radiation Risks
  – Radiation protection is essential for exploration
  – Most research should be done on Earth
Consensus Workshop Selected Preliminary Recommendations

• “Bioastronautics Critical Path Roadmap” may not be the most appropriate title
• ISS research is important, but ground models should be emphasized
• Reword risk titles, descriptions to more accurately reflect actual risk
• Certain overarching risks should be combined
  – Need for reliable medical support hardware (including exercise equipment) for effective risk mitigation
• Further discussion of enabling questions is needed
• Incorporate integrated approach where needed
  – E.g., return to gravity rehabilitation

Other programmatic issues were also identified
Access to BCPR Content

http://research.hq.nasa.gov/code_u/bcpr/index.cfm
(revised baseline document)

http://criticalpath.jsc.nasa.gov/beta/
(revised searchable website—beta version!)
Overview

Transitioning to The Vision for Space Exploration

June 2004
Strategic Directives Guiding the Human Support Technology Program

- Vision for Space Exploration (February 2004)
“The Commission finds that successful development of identified enabling technologies will be critical to the attainment of exploration objectives within reasonable schedules and affordable costs”
Progressive Capabilities

Earth’s Neighborhood Capability
- Current launch systems
  Payload: 40mt
- In-space propulsion, Isp>1000 sec, high thrust
- Power systems, >200 w/kg
- Integrated Human/robotic capabilities
- Crew countermeasures for 100 days
- Closure of water/air systems
- Materials, factor of 9
- IVHM - Integrated Vehicle Health Monitoring

Accessible Planetary Surface Capability
- ETO $/kg (under review)
  Payload: ~100mt
- In-space propulsion, Isp>3000 sec, high thrust
- Power systems, >500 w/kg
- Robotic aggregation/assembly
- Crew countermeasures for 1-3 years
- Complete closure of air/water; options for food
- Materials, factor of 20
- Micro-/Nano- avionics

Sustainable Planetary Surface Capability
- ETO $/kg (under review)
  Payload: 100+mt
- In-space propulsion, Isp>3000 sec, high thrust
- Sustainable power systems
- Intelligent systems, orbital and planetary
- Crew countermeasures for indefinite duration
- Closure of life support, including food
- ISRU for consumables & spares
- Materials, factor of 40
- Automated reasoning and smart sensing
• The Commission identified 17 areas for initial focus. Among them are:

  – Advanced Power and Propulsion
  – Cryogenic fluid management
  – Closed-loop life support and Habitability
  – Extravehicular activity systems
  – Scientific data collection and analysis
  – Planetary in-situ resource utilization
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Refining Bioastronautics “Critical Path Roadmap (CPR)” in light of recently established and configuration controlled Level 0 Exploration Requirements/Level 1 Objectives
http://research.hq.nasa.gov/code_u/bcpr/index.cfm
• Roadmap initiated in 1997 -- focuses research and technology solutions on:
  • Reduction or elimination of identified risks to humans during space flight
  • Increased efficiencies of systems supporting humans in space
  • Current activities:
    • Assessed risks in light of Vision for U.S. Space Exploration
      • Under independent review by National Research Council (joint review by Institute of Medicine, Space Studies Board and Aerospace Engineering Board)
      • Updated CPR publicly released for comment, consolidated comments to be provided to NRC
    • Reassessing countermeasure validation requirements and strategy
      • Joint Bioastronautics/Fundamental Space Biology workshop held April 13-15 to determine appropriate animal models.
      • Human Subjects Strategy Workshop, May 12-13, JSC
      • Review with Astronaut Office and Flight Surgeons, May 25-26, JSC
      • Results to be incorporated as appendix to CPR, subjected to the NRC (IOM/SSB/ASEB) review
<table>
<thead>
<tr>
<th>Design Reference Mission</th>
<th>1 Year ISS</th>
<th>Lunar</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew Size</td>
<td>2 +</td>
<td>4 – 6</td>
<td>6</td>
</tr>
<tr>
<td>Launch Date</td>
<td>2005?</td>
<td>NET 2015, NLT 2020</td>
<td>NET 2025 – 2030</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>12 months</td>
<td>10 – 44 days</td>
<td>30 months</td>
</tr>
<tr>
<td>Outbound Transit</td>
<td>2 days</td>
<td>3 – 7 days</td>
<td>4 – 6 months</td>
</tr>
<tr>
<td>On-Site Duration</td>
<td>12 months</td>
<td>4 – 30 days</td>
<td>18 months</td>
</tr>
<tr>
<td>Return Transit</td>
<td>2 days</td>
<td>3 – 7 days</td>
<td>4 – 6 months</td>
</tr>
<tr>
<td>Communication lag time</td>
<td>0+</td>
<td>1.3 seconds +</td>
<td>3 – 20 minutes +</td>
</tr>
<tr>
<td>G-Transitions (assumes no artificial g)</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hypogravity</td>
<td>0 g</td>
<td>1/6g for up to 30 days</td>
<td>1/3 g for up to 18 months</td>
</tr>
<tr>
<td>Internal Environment</td>
<td>~ 14.7 psi</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>EVA</td>
<td>0 – 4 per mission</td>
<td>2 – 3/week; 4 – 15/person</td>
<td>2 – 3/week; 180/person</td>
</tr>
</tbody>
</table>
### Rating Risks

- Stoplight format adopted as a communication and decision-making tool:
  - R/Y/G rating used to communicate relative priorities and to guide decisions about research program resource allocation

### Criteria for Assigning Red/Yellow/Green Risk Rating

<table>
<thead>
<tr>
<th>Risk Rating</th>
<th>Human Health Risk</th>
<th>System Performance/Efficiency Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>Unacceptable risk of serious adverse health or performance consequences; there is no mitigation strategy that has been validated in space or demonstrated on Earth.</td>
<td>Considerable potential for improvement in mitigation efficiency in many areas; proposed missions may be infeasible without improvements.</td>
</tr>
<tr>
<td>Yellow</td>
<td>High risk of serious health or performance consequences; there is no mitigation strategy that has been validated in space.</td>
<td>Considerable potential for improvement in mitigation efficiency in a few areas.</td>
</tr>
<tr>
<td>Green</td>
<td>Health and performance consequences are known or suspected, but will not affect mission success due to effective mitigation strategies that have been validated in space.</td>
<td>Minimum or limited potential for improvement in mitigation efficiency.</td>
</tr>
</tbody>
</table>
## Current Critical Path Roadmap (Draft) Rating Risks: Human Health

### Risk Categories

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>ISS (1yr)</th>
<th>Moon (30d)</th>
<th>Mars (30m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unacceptable risk of serious adverse health or performance consequences; there is no mitigation strategy that has been validated in space or demonstrated on earth.</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>High risk of serious health or performance consequences; there is no mitigation strategy that has been validated in space.</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Health and performance consequences are known or suspected, but will not affect mission success due to effective mitigation strategies that have been validated in space.</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Risk #</th>
<th>Theme</th>
<th>Discipline</th>
<th>Risk Category</th>
<th>ISS (1yr)</th>
<th>Moon (30d)</th>
<th>Mars (30m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HH&amp;C</td>
<td>Bone</td>
<td>Accelerated Bone Loss and Fracture Risk</td>
<td>Y</td>
<td>G</td>
<td>R</td>
</tr>
<tr>
<td>2</td>
<td>HH&amp;C</td>
<td>Bone</td>
<td>Impaired Fracture Healing</td>
<td>G</td>
<td>G</td>
<td>R</td>
</tr>
<tr>
<td>3</td>
<td>HH&amp;C</td>
<td>Bone</td>
<td>Injury to Joints and Intervertebral Structures</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>4</td>
<td>HH&amp;C</td>
<td>Bone</td>
<td>Renal Stone Formation</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>5</td>
<td>HH&amp;C</td>
<td>Cardio</td>
<td>Occurrence of Serious Cardiovascular Dysrhythmias</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>HH&amp;C</td>
<td>Cardio</td>
<td>Diminished Cardiac and Vascular Function</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>7</td>
<td>HH&amp;C</td>
<td>Env Health</td>
<td>Define Acceptable Limits for Contaminants in Air and Water</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>8</td>
<td>HH&amp;C</td>
<td>IH</td>
<td>Immunodeficiency / Infection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>9</td>
<td>HH&amp;C</td>
<td>IH</td>
<td>Virus-Induced Lymphomas and Leukemias</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>10</td>
<td>HH&amp;C</td>
<td>IH</td>
<td>Anemia, Blood Replacement &amp; Marrow Failure</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>11</td>
<td>HH&amp;C</td>
<td>IH</td>
<td>Altered Host-Microbial Interactions</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>12</td>
<td>HH&amp;C</td>
<td>IH</td>
<td>Allergies and Autoimmune Diseases</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>13</td>
<td>HH&amp;C</td>
<td>Muscle</td>
<td>Skeletal Muscle Atrophy Resulting in Reduced Strength and Endurance</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>14</td>
<td>HH&amp;C</td>
<td>Muscle</td>
<td>Increased Susceptibility to Muscle Damage</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>15</td>
<td>HH&amp;C</td>
<td>Neuro</td>
<td>Vertigo, Spatial Disorientation and Perceptual Illusions</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>16</td>
<td>HH&amp;C</td>
<td>Neuro</td>
<td>Impaired Movement Coordination Following G-Transitions</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>17</td>
<td>HH&amp;C</td>
<td>Neuro</td>
<td>Motion Sickness</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>18</td>
<td>HH&amp;C</td>
<td>Nutrition</td>
<td>Inadequate Nutritional Requirements</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>19</td>
<td>AMC</td>
<td>Clin</td>
<td>Monitoring &amp; Prevention</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>20</td>
<td>AMC</td>
<td>Clin</td>
<td>Major Illness &amp; Trauma</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>21</td>
<td>AMC</td>
<td>Clin</td>
<td>Pharmacology of Space Medicine Delivery</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>22</td>
<td>AMC</td>
<td>Clin</td>
<td>Ambulatory Care</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>23</td>
<td>AMC</td>
<td>Clin</td>
<td>Return to Gravity/Rehabilitation</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>24</td>
<td>AMC</td>
<td>Clin</td>
<td>Insufficient Data/Information/Knowledge Management &amp; Communication</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>25</td>
<td>AMC</td>
<td>Clin</td>
<td>Skill Determination and Training</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>26</td>
<td>AMC</td>
<td>Clin</td>
<td>Palliative, Mortem, and Post/Mortem Medical Activities</td>
<td>Y</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>27</td>
<td>BH&amp;P</td>
<td>HBP</td>
<td>Human Performance Failure Due to Poor Psychosocial Adaptation</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>28</td>
<td>BH&amp;P</td>
<td>HBP</td>
<td>Human Performance Failure Due to Neurobehavational Problems</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>29</td>
<td>BH&amp;P</td>
<td>SHFE</td>
<td>Mismatch between Crew Cognitive Capabilities and Task Demands</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>30</td>
<td>BH&amp;P</td>
<td>HBP</td>
<td>Human Performance Failure Due to Sleep Loss and Circadian Rhythm</td>
<td>G</td>
<td>G</td>
<td>Y</td>
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<tr>
<td>31</td>
<td>RH</td>
<td>Rad</td>
<td>Carcinogenesis</td>
<td>G</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>32</td>
<td>RH</td>
<td>Rad</td>
<td>Acute and Late CNS Risks</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>33</td>
<td>RH</td>
<td>Rad</td>
<td>Other Degenerative Tissue Risks</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>34</td>
<td>RH</td>
<td>Rad</td>
<td>Heredity, Fertility and Sterility Risks</td>
<td>G</td>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>35</td>
<td>RH</td>
<td>Rad</td>
<td>Acute Radiation Syndromes</td>
<td>G</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>
### AHST Risk Rating Criteria for System Performance Risks

<table>
<thead>
<tr>
<th>Rating</th>
<th>Considerable potential for improvement in efficiency in many areas, or proposed missions may be infeasible without improvements.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Considerable potential for improvement in efficiency in a few areas</td>
</tr>
<tr>
<td>G</td>
<td>Minimum or limited potential for improvement in efficiency.</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>RISK NUMBER</th>
<th>Theme</th>
<th>Discipline</th>
<th>Risk Category</th>
<th>ISS (1yr)</th>
<th>Moon (30d)</th>
<th>Mars (30m)</th>
</tr>
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<tbody>
<tr>
<td>36</td>
<td>AHST</td>
<td>AEMC</td>
<td>Monitor Air Quality</td>
<td>Y</td>
<td>R</td>
<td>R</td>
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<tr>
<td>37</td>
<td>AHST</td>
<td>AEMC</td>
<td>Monitor External Environment</td>
<td>Y</td>
<td>R</td>
<td>R</td>
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<tr>
<td>38</td>
<td>AHST</td>
<td>AEMC</td>
<td>Monitor Water Quality</td>
<td>Y</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>39</td>
<td>AHST</td>
<td>AEMC</td>
<td>Monitor Surfaces, Food and Soil</td>
<td>Y</td>
<td>R</td>
<td>R</td>
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<tr>
<td>40</td>
<td>AHST</td>
<td>AEMC</td>
<td>Provide Integrated Autonomous Control of Life Support Systems</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>41</td>
<td>AHST</td>
<td>AEVA</td>
<td>Provide Space Suits and Portable Life Support Systems</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>42</td>
<td>AHST</td>
<td>AFT</td>
<td>Maintain Food Quantity and Quality</td>
<td>Y</td>
<td>G</td>
<td>R</td>
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<tr>
<td>43</td>
<td>AHST</td>
<td>ALS</td>
<td>Maintain Acceptable Atmosphere</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<td>44</td>
<td>AHST</td>
<td>ALS</td>
<td>Maintain Thermal Balance in Habitable Areas</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<td>45</td>
<td>AHST</td>
<td>ALS</td>
<td>Manage Waste</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>46</td>
<td>AHST</td>
<td>ALS</td>
<td>Provide and Maintain Bioregenerative Life Support Systems</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>47</td>
<td>AHST</td>
<td>ALS</td>
<td>Provide and Recover Potable Water</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>48</td>
<td>AHST</td>
<td>AHST</td>
<td>Inadequate Mission Resources for the Human System</td>
<td>Y</td>
<td>R</td>
<td>R</td>
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<tr>
<td>49</td>
<td>AHST</td>
<td>SHFE</td>
<td>Mismatch between Crew Physical Capabilities and Task Demands</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>50</td>
<td>AHST</td>
<td>SHFE</td>
<td>Mis-assignment of Responsibilities within Multi-agent Systems</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
</tbody>
</table>
• Developing medical operating bands within which level of risk can be accepted for Moon/Mars
  – Initiated by NASA Chief Medical Officer
  – Focused NASA/National Space Biomedical Research Institute team assessing currently accepted risk levels (target completion June)
  – Will be subjected to external review

• Examining current Enterprise research portfolio to determine degree of alignment with Vision
  – Determining specific product lines (countermeasures, technologies, research results) and developing associated work breakdown structures
  – Aligned with Critical Path Roadmap

• Evaluating mechanisms to stabilize funding to external research community
  – Alternative approaches to soliciting research, including increased focus in product line areas of interest, higher funding levels per effort, increased emphasis on teaming
  – Working with Biological and Physical Research Advisory Committee to consider methods for employing ground based research and flight opportunities in combination so as to streamline process and provide greater funding stability for research community.
Aligning with the Vision:  
Exploration Research Areas of Emphasis

- Research areas of emphasis include:
  - Human Health and Countermeasures Research – predominant areas of emphasis include:
    - Radiation health effects
    - Loss of bone density and muscle strength
    - Behavioral health
    - Trauma (injury and illness)
  - Technology development – predominant areas of emphasis include:
    - Real-time medical diagnosis and treatment
    - Human habitability technologies
      - Life support systems
      - Environmental safety
      - Nutrition
      - Machine-human interfaces
  - Research which supports the development of lower mass, lower volume, more efficient and reliable exploration systems

- Recognized need to:
  - Maintain a fundamental research base to seed future endeavors
  - Continue to deliver and communicate Earth benefits of space research
Code U Efforts To Align With The Vision For U.S. Space Exploration

- Through FY06 budget development effort, we will adjust research portfolio to meet exploration agenda
- Working closely with the Office of Space Flight and the International Space Station Program to adjust research manifest
  - Considering employing free flying spacecraft to complement ongoing ISS research activities
Summary

- Code U is aggressively aligning its efforts to support the Vision for U.S. Space Exploration
  - Refining Bioastronautics “Critical Path Roadmap”
    - Defining accepted risk criteria and developing medical operating bands within which the level of risk can be accepted for Moon/Mars (initiated by the Agency Chief Medical Officer)
    - Countermeasure Validation Requirements and Strategy development
      - Informs crew size/increment duration
  - Examining Enterprise research portfolio to determine degree of alignment with Vision
    - Adjusting research portfolio and developing ‘product line’ framework to meet Vision needs
  - Considering alternative approaches for engaging the research community
  - Establishing relationships with other Enterprises
  - Working closely with the Office of Space flight to address associated requirements for the International Space Station
Backup
Types of Critical Path Roadmap Risks

- A risk is the conditional probability of an adverse event occurring or a system-related inefficiency
  - Human health and medical risks arise from exposure to the hazardous conditions of space flight (e.g., microgravity, radiation, confinement)
    - Thirty-five risks classified as human health or medical
  - System performance and efficiency risks involve the technologies required for providing a safe and habitable environment
    - Fifteen risks classified as system performance and efficiency-related
- Different criteria employed to assess and rate the risks
  - Human health and medical risks use traditional risk assessment criteria of estimated likelihood of a risk’s occurrence and its severity of impact on crew health or performance, should the risk occur
  - System performance and efficiency risks use a rating scheme based on improved efficiency
  - Both types use risk mitigation status (readiness levels)
Examples of Specific Products or Projects on the ISS:

- Performance/reliability testing of a Sabatier reactor (to recycle CO2, and diminish need for resupply for ISS crew – informs closed loop life support for Moon/Mars) – may transition from RD&D into operations during ISS lifetime [Node 3 already scarred]
- Validation of system stability and new design tools for low mass, reduced gravity performance of thermal control subsystems and components -- primarily for advanced life support and with additional applicability to nuclear propulsion thermal control [requires FIR]
  - Examples: phase separators, passive thermal loops, evaporation/condensation systems for heating and cooling systems of lesser mass than now used
- Characterization of flammability and smoke from spacecraft materials in candidate atmospheres (reduced pressure, enriched oxygen concentration) for Moon and Mars [requires CIR]
  - Examples: 0g testing of polyethylene, plastics, and other materials; will verify a new test method(s) in 1g for materials’ selection
- Characterization and verification of performance of onboard and advanced smoke detectors and suppression systems [requires CIR]
  - Examples: False smoke alarm on ISS today occurs; first test of CO2 suppression system
Examples of Specific Products or Projects on the ISS (continued):

- Experimental demonstration of rapid prototyping technology for in-space fabrication of spare parts or fabrication / recycling of medical instruments [requires MSRR]
- Experimental demonstration of granular media for guidance for particulate control during EVA surface operations and for materials’ handing for ISRU [requires FIR]
- Demonstration of microbial technologies for water recycling methods for advanced ECLSS [location TBD – either FIR or Express Rack]
- Demonstration of new technologies for oxygen generation [location: TBD, likely Express Rack]
- Demonstration of 0g fabrication of useful materials from regolith simulants [requires SpaceDrums]

- The range of products have associated requests for ISS resources
  - Capacity to meet requests dependent upon several factors -- Shuttle Return to Flight requirements, ISS vehicle health and maintenance needs, post-Shuttle vehicle capabilities, etc.
  - Actively working with the Office of Space Flight to identify ways to address requirements in light of available capacity
A DUAL TRACK TREADMILL IN A VIRTUAL REALITY ENVIRONMENT AS A COUNTERMEASURE FOR NEUROVESTIBULAR ADAPTATIONS IN MICROGRAVITY

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Jay G. Horowitz Ph.D., Philip A. O’Connor M.S.
NASA Glenn Research Center, Cleveland, OH

INTRODUCTION
While the neurovestibular system is capable of adapting to altered environments such as microgravity, the adaptive state achieved in space is inadequate for 1G [1]. This leads to gait and postural instabilities when returning to a gravity environment and may create serious problems in future missions to Mars. New methods are needed to improve the understanding of the adaptive capabilities of the human neurovestibular system and to develop more effective countermeasures [2]. The concept behind the current study is that by challenging the neurovestibular system while walking or running, a treadmill can help to readjust the relationship between the visual, vestibular and proprioceptive signals that are altered in a microgravity environment. As a countermeasure, this device could also benefit the musculoskeletal and cardiovascular systems and at the same time decrease the overall time spent exercising. The overall goal of this research is to design, develop, build and test a dual track treadmill, which utilizes virtual reality, VR, displays (Figure 1).

PILOT STUDIES
Pilot studies were performed to evaluate the potential of the system to stimulate the neurovestibular system. Twenty subjects were tested running on a dual-track treadmill in simulated curve walking scenes. Subjects also participated in an extended trial consisting of walking 30 minutes in one randomly assigned condition. Before and immediately following testing, subjects ran a timed obstacle course. Results revealed that the combination of visual and proprioceptive stimuli provided by the VR system and the movement of the treadmill respectively, will significantly increase the stimulus to the neurovestibular system.

TREADMILL DESIGN
The proposed treadmill has been designed to function with two belts and four actuators to both elevate and incline the tracks independently (Figure 2). Along with dual speed control, this arrangement will enable the system to replicate motion found during ascending and descending hills, going over rough terrain, turning corners and climbing stairs. Working in conjunction with the VR display, the treadmill system will provide an immersive environment for testing effects on the neurovestibular system.
The system’s motion is governed by six independently controlled axes: two AC motor-driven treads and four servo-driven linear actuators. The system can be simplified as a hierarchical structure composed of three levels and ten components (Figure 3). The highest level of the hierarchy is the main user interface which governs all functions of the system, including manual control, programmed control, and path generation. It is also responsible for synchronizing the system’s motion with its visual display. The user interface level communicates directly with the motor controller and visualization application. The visualization application, created by NASA, uses a “morphing hallway” algorithm to create a visual environment that simulates motion in three dimensions, as well as a variety of terrains including stairs. This application outputs the visual effects to a display unit. The motor controller is responsible for the motion of the motors. This component is linked to the user interface via component object model (COM) interface. The controller is responsible for the PID control of the servomotors and the translation of the user interface’s mnemonic code to machine code. The lowest level of the hierarchy represents the hardware of the system. This level is responsible for providing the physical stimulation to the subject. It is composed of the visual display and the actuation devices working through the treadmill frame.

Biomechanical testing will concentrate on establishing the extent to which the treadmill will stimulate the neurovestibular system. This will include motion analysis, electromyography, accelerometry and pupil tracking data. It is expected that these biomechanical parameters indicating neurovestibular response will differ significantly while walking and running on a standard treadmill from those recorded using the novel virtual reality dual track system.

REFERENCES

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A Dual Track Actuated Treadmill in a Virtual Reality Environment

A Countermeasure for Neurovestibular Adaptation in Microgravity

Susan E. D’Andrea PhD, Jay G. Horowitz PhD, Philip A. O’Connor MS and Michael W. Kahelin BS

The Cleveland Clinic Foundation

NASA Glenn Research Center
Research Objectives

- To design and develop an exercise countermeasure
  - Challenge the postural control system
  - Exercise balance and locomotor reflexes
  - Alleviate adverse adaptations to the neurovestibular system
- Address multiple physiological systems
  - Neurovestibular
  - Musculoskeletal
  - Cardiovascular
Neurovestibular Adaptations in Microgravity

- Space motion sickness, visual reorientation illusions, inversion illusions
- Post flight modifications to posture, balance, locomotion, head-eye coordination
Challenging the Neurovestibular System

- Balance reflexes are supported by vestibular, visual and proprioceptive sensory systems.
- Design a countermeasure which can adjust the relationship between the visual, vestibular and proprioceptive signals.
- Facilitate the re-adaptation of neurovestibular system to a gravity environment.
Disorientation and inability to perform landing, egress or other physical tasks

Impaired neuromuscular coordination and/or strength

Impaired cognitive and/or physical performance due to motion sickness

Possible chronic impairment of orientation or balance function due to microgravity

Vestibular contribution to cardio-regulatory dysfunction

Risk Level

HIGH

LOW
Earth Applications

- In the US, 2 million adults have balance disorders or impairment from dizziness
- Eighty million adults have experienced clinically significant dizziness problems at some point in their lives
- Balance related falls account for one half of accidental deaths in the elderly
- Countermeasures can help physicians diagnose and treat patients with neurovestibular diseases
System Components

- Virtual Reality Display
- Dual Track Treadmill
- Software Interface
- Motion Control System
Dual Track Treadmill

- Independently operated tracks
  - Speed
    - Curves
  - Elevation
    - Stairs
    - Rough terrain
  - Inclination
    - Hills
Virtual Reality System

- Visualization was developed with state-of-the-art virtual reality techniques at NASA Glenn Research Center.
- To optimize for performance and flexibility, the illusion of motion was created by morphing a single segment of hallway and sliding textures along the walls.
- Graphics will port easily to immersive display devices, such as stereoscopic Head Mounted Display.

Click here to play movie
Hardware Configuration

- Gemini Motor Drives
- Tread Motor Controllers
- 6k Motor Controller
- D/A Card
- Tread Motors
- Linear Actuators
- Gemini Motor Drives
- Motion Control Process
**Software Overview**

- **Master Control Console – Setup File**
  - Tuning Parameters, Scaling Factors Home Position

**Pre-Runtime**

- Array of VR Commands
- Tab Delimited Text File
- VR Visual Display Program
- 6k Controller – Motion Control
- Tread Motor Controller

**Load Path Created In Matlab Path Generation Tool**

**Runtime**

- Array of Actuator Positions and Tread Velocities
- Tab Delimited Text File
- Master Control Console

**Synchronization Via TCP**
Path Generation

Matlab® Path Generation Program

- Select Points On XZ Plane and Spline
- Select Points On XY Plane and Spline
- Pick Points On Mean Velocity Profile and Spline
- Insert Intervals of Stairs and Rough Terrain
- Input Sample Rate And Duration of Trial
- Output Array With 4 Actuator Positions And 2 Tread Speeds
- Output Array With Curvature and Inclination

Hill Simulation Program

- Duration (min) 1
- Speed t
- Degree of Inclination

Time (min)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 -5 -10

Plot

LEFT 4deg

Path plot

Time (min)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 -40 -80

Plot

RIGHT 4deg

Fast Speed

Time (sec)

3.75 4.0 4.25 4.5 4.75 5.0 5.25 5.5 5.75

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

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Pilot Studies

- Biomechanical Testing
  - 20 subjects
    - 7F, 13M
    - Average age 25
  - Obstacle course
  - Tested in 4 conditions for 3 minutes each
    - Control
    - Visual only
    - Treadmill only
    - Treadmill and visual
  - Extended trial
    - 30 minutes at one randomly assigned condition
Neurovestibular Adaptation Results

Comparison of the range of gaze velocity in four experimental conditions

Timed Obstacle Course Results
Treadmill Construction
Acknowledgements

- Ed Eucker
- Samantha Lane
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- Brian Sauer
NUCLEATE BOILING HEAT TRANSFER
UNDER MICROGRAVITY CONDITIONS
-POOL AND FLOW BOILING

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Henry Samueli School of Engineering and Applied Science
University of California, Los Angeles

Presented at
Strategic Research to Enable NASA’s Exploration Missions
Cleveland, Ohio, June 23, 2004
MULTIPHASE AND PHASE CHANGE PROCESSES IN MICROGRAVITY

- Wastewater recovery systems
  - Distillation systems
  - Evaporation systems
  - Phase separators

- Thermal management
  - Radiators
  - Energy storage - Phase change materials

- Propulsion systems

- Space power systems
  - Rankine cycle - Liquid metal reactors, heat exchangers, phase separators,
GAPS IN KNOWLEDGE

- No mechanistic or empirical models are available to describe all the observed phasic behavior and related heat transfer during pool nucleate and film boiling.

- Some of the difficulties in developing correlations and models is due to the lack of understanding of the coupling between the test heater and the test chamber as the bubble size becomes comparable to both. The duration of the experiments in another important variable.

- Only a few studies of forced flow boiling of ordinary liquids under reduced gravity condition have been reported. However the flow velocity above which gravity becomes unimportant is not known as a function of independent variables.

- No studies of the phasic behavior and heat transfer during pool or forced boiling of liquid metals in reduced gravity have been reported.

- Not much is known about quenching behavior in reduced gravity of an overheated surface.
RESEARCH OBJECTIVES

- Since pool boiling is the limiting condition of flow boiling, a need exists to understand heat transfer and vapor removal processes during pool nucleate boiling from a well characterized surface under microgravity.

- Develop a mechanistic numerical models to predict bubble dynamics and heat transfer during pool and flow boiling in partial and microgravity environments. Extend to liquid metals.

- Use two liquids with distinctly different properties (water and FC-72). Some properties of FC-72 (e.g., wetting characteristics) are similar to liquid metals.

- Subsequently extend the effort to simulate boiling and dryout in the boiler of two-loop Rankine cycle power plant.
APPROACH

- Building block type approach
  - Single bubble
  - Two – Three bubbles
  - Five bubbles on a two-dimensional grid
  - Multiple cavities on a heater surface

- Experiments at Earth normal gravity

- Experiments in the low gravity environment of the KC-135 aircraft

- Numerical simulations

- Experiments in the microgravity environment of the space station
EXPERIMENTS IN THE LOW GRAVITY ENVIRONMENT OF THE KC-135 AIRCRAFT

POOL NUCLEATE BOILING

Bubble Growth – Lift off Cycle

\[ \Delta T_{\text{sub}} = 0.3 \, ^\circ \text{C}, \quad \Delta T_{\text{w}} = 4.2 \, ^\circ \text{C}, \quad g_z = 0.02 \, \text{g}/\text{g}_e \]
POOL NUCLEATE BOILING (contd.)

Single Bubble – Numerical Simulations

Comparison between measured and predicted bubble shapes for $\Delta T_w = 3.8^\circ C$, $\Delta T_{sub} = 0.4^\circ C$ and $g_z = 0.02\ g_e$
POOL NUCLEATE BOILING (contd.)

Scaling of the Effect of Gravity on Bubble Lift-off Diameter and Growth Period

![Graphs showing scaling of lift-off diameter and growth period with gravity ratio](image)
POOL NUCLEATE BOILING (contd.)

Bubble Merger


Two bubble merger for water, $\Delta T_w = 5.0 \, ^\circ\text{C}$, $\Delta T_{sub} = 3.0 \, ^\circ\text{C}$, $g_z = 0.0033g_e$, spacing $= 7 \, \text{mm}$
Bubble Merger – Heat Transfer

Five bubble merger for saturated water, $\Delta T_w = 7.0 \, ^\circ C$, $g_z = 0.01g_e$, spacing = 7 mm
**POOL NUCLEATE BOILING (contd.)**

*Boiling eXperiment Facility (BXF)*

BXF is a multi-use apparatus designed to accommodate two fluid physics experiments

*Nucleate Pool Boiling eXperiment (NPBX)*

Intends to use BXF to develop a basic understanding of heat transfer and vapor removal processes that take place during nucleate boiling from a well characterized surface under microgravity conditions.
POOL NUCLEATE BOILING (contd.)

VIEW OF FLIGHT HARDWARE IN MSG

- HSC camera
- Microscopic lens
- HSC processor
- Avionics box
- CV
- Test chamber
- Viewing window
POOL NUCLEATE BOILING (contd.)

NPBX Test Chamber

Heater (85 mm dia.) with 5 cavities spaced 27 mm apart

Bellow

Test chamber

114 mm

228 mm

114 mm

114 mm
POOL NUCLEATE BOILING (contd.)

Single Bubble – Numerical Simulations

Saturated FC-72, $\Delta T_w = 10 \, ^\circ C$
$\phi = 10^\circ$

Saturated Water, $\Delta T_w = 10 \, ^\circ C$
$\phi = 54^\circ$

$g = 10^{-5} \, g_e$
POOL NUCLEATE BOILING (contd.)

Three Bubble Merger – Numerical Simulations

\[ g_z = 10^{-5} g_e \]

Fluid: Sat. FC-72

Click here to play movie

Click here to play movie

Click here to play movie
POOL NUCLEATE BOILING (contd.)

Five Bubble Merger – Numerical Simulations

\( g_z = 10^{-5} \, g_e \)

Time lag = 0.5 sec

Fluid: Sat. FC-72

Click here to play movie
TRANSITION FROM POOL TO FLOW BOILING

Low Velocity Flow Boiling

- Stainless steel hose assembly
- Silicon wafer
- Preheater
- Turbine flowmeter
- Gear pump
- Drain
- Tank (0.3 m³)
- Heaters (12 kW)
- Traversing Thermocouples
- Test section
- Developing section
FLOW BOILING (Contd.)

Low Velocity Flow Boiling – Earth Normal Gravity

Departure and lift off diameters as a function of velocity and angle of inclination

![Graph showing departure and lift off diameters as a function of velocity and angle of inclination.](image)
FLOW BOILING (Contd.)

Experimental Setup (KC-135)
FLOW BOILING (Contd.)

KC-135 Experiments

Fluid: water, $\Delta T_w = 6^\circ C$, $\Delta T_{sub} = 0.5^\circ C$, $g_z = 0.023g_e$
Low Velocity Flow Boiling - Numerical Simulation

Fluid: water, $\Delta T_w = 6 \, ^\circ\text{C}$, $\Delta T_{\text{sub}} = 0.2 \, ^\circ\text{C}$, $v = 0.08 \, \text{m/s}$

$g_z = 1.0g_e$

$g_z = 0.02g_e$
FLOW BOILING (Contd.)

Low Velocity Flow Boiling - Numerical Simulation

Fluid: water, $\Delta T_w = 6 \, ^\circ C$, $\Delta T_{sub} = 0.2 \, ^\circ C$, $v = 0.08 \, m/s$

$g_z = 0.02g_e$
CONCLUSIONS

Pool Boiling
- For single bubbles, the departure diameter scales as $g_z^{-0.5}$ for water and as $g_z^{-0.43}$ for FC-72.
- For single bubbles, the growth period scales as $g_z^{-0.93}$ for water and as $g_z^{-0.82}$ for FC-72.
- Bubble merger leads to a “lift” force normal to the surface. As a result of this force, the bubble departure diameter is smaller than that for a single bubble. The lift force weakens the dependence of bubble departure diameter on gravity.

Flow Boiling
- The departure and lift off diameters have a weaker dependence on gravity.
- The magnitude of gravity normal and along the surface are found to affect the dynamics of bubble departure.
Development of a Portable Unit for Metabolic Analysis


R.D. Pettigrew, NCMR

R.W. Valentine and M.E. Cabrera, CWRU

June 21, 2004
Objective

Develop, test and calibrate a prototype portable device that will measure human metabolic activity; namely time resolved measurements of gas temperature, pressure and flow-rate, and oxygen and carbon dioxide partial pressure during inhalation and exhalation.
Motivation

- Rate of metabolic activity is a better measure of fitness than heart rate and workload.
- Need for a unit to measure metabolic rate during varied activities (including EVA).
  - Cardiovascular Alteration.
  - Muscular Alteration.
  - Nutrition Fitness and Rehabilitation.
- Evaluation of fitness and training programs.
ISS Gas Analyzer System for Metabolic Analysis Physiology
Design Goals

- Breath by breath analysis and within breath analysis
  - Design goal is 10 Hz (minimum)
- Eliminate timing issues with existing fixed and portable units (sampling at mask instead of remotely)
- Utilize better oxygen sensor technology than exists with existing portable units (electrochemical cell)
- Integrate PUMA with other Glenn BEC projects
Specific Technologies

- Pressure (used indirectly)
  - Use COTS technology
- Temperature (used indirectly)
  - PUMA-1 uses COTS technology
  - Next generation may use different technique
- Flow
  - PUMA-1 uses COTS technology (ultrasonic sensor)
  - Also looking at GRC-developed thin film sensors
- Carbon Dioxide
  - Infrared absorbance (custom developed system)
- Oxygen
  - Fluorescence quenching (custom developed system)
Carbon Dioxide Subsystem

- Technology similar to commercial $CO_2$ sensors

- Modulated IR source (currently incandescent-chopped)

- PbSe photoconductive detector (cooled)
Oxygen Subsystem

- Commercial sensor uses absolute intensity
- Modulated blue light source
- Custom detection electronics/algorithm

Measuring phase shift is:
- More stable/repeatable
- Less temperature dependent
- Not as sensitive to ambient light
PUMA-1 Overview

- First generation $CO_2$ and second generation $O_2$ sensor
- First unit to incorporate simultaneous measurement of all quantities
- $CO_2$ unit working, but needs modification

- Current sample rate is 2.5 $Hz$
- Unit is 22” $\times$ 15” $\times$ 7” and approximately 22 lbs
Future Work

- Complete characterization of PUMA-1 (Summer ’04)
- Get IRB approval for Human Subject Testing (Summer ’04)
- Human Subject Testing on PUMA-1 (Fall/Winter ’04)
- Begin design work on PUMA-2
  - Battery powered
  - 10 Hz minimum sample rate
  - Suitable for use on a belt pack
- Software to allow use as a digital spirometer
Design for microgravity has traditionally not been well integrated early on into the development of advanced life support (ALS) technologies. NASA currently has a many ALS technologies that are currently being developed to high technology readiness levels but have not been formally evaluated for microgravity compatibility. Two examples of such technologies are the Vapor Phase Catalytic Ammonia Removal Technology and the Direct Osmotic Concentration Technology. This presentation will cover the design of these two systems and will identify potential microgravity issues.
NASA Workshop on Strategic Research to Enable NASA’s Exploration Missions

June 22-23, 2004
Cleveland Ohio

Michael Flynn
Ames Research Center
Moffett Field CA, 94035
650-604-1153
mflynn@mail.arc.nasa.gov
Advanced Life Support

Water Recycling

- One of the “tall poles” in the development of a viable human Mars Exploration program is the development of applicable Advanced Life Support System.

- Of all the metabolic requirements water is the most significant

- Water accounts for 89% 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, flow=3.18kg/hr, duration=960 days, launch Cost= $150,000/kg
Advanced Life Support

• The ALS program supports fundamental research into the development of new technologies.

• It supports the development of these technologies to high technology readiness levels (TRL 5-6).

• It has not adequately supported the validation of the microgravity performance of these technologies (TRL 7 to 8).
Rule of Thumb Approach
Alternative Approaches?

- Integrate technology development and microgravity design early on in the design process.

- Complete a set of fundamental microgravity fluid physics experiments that will have broad applicability to ALS.
  - Workshop on Critical Issues in Microgravity Fluids, Transport and Reaction Processes in Advanced Human Support Technology

- Form teams with microgravity community to begin to generate answers to questions associated with existing technologies.
Case Study Examples

• Vapor Phase Catalytic Ammonia Removal
  – Currently a TRL 5 technology being developed for advancement to TRL 6

• Direct Osmotic Concentration
  – Currently a TRL 3 technology being developed for advancement to TRL 6
Vapor Phase Catalytic Ammonia Removal (VPCAR)
The VPCAR is designed to accept a combined waste stream (urine, condensate, and hygiene) and produce potable water in a single step.

- The system is designed to require no re-supply or maintenance.
- The technology is modular and can be packaged to fit into a volume comparable to a single Space Station rack.
- The technology has been the subject of many NASA trades studies and peer reviews.
WFRD Components
Rotor Assembly
Wiper Blades
Microgravity Evaporator
VPCAR Systems
Flight Verification
Topics

• Thermal properties of thin fluid films
• Two phase flow in open chambers
• Three phase flow
• Splashing in liquid/gas boundaries
• Centrifugal separations, what occurs during start and stop events
• Wiper blade fluid application
VPCAR Systems
Flight Verification
Topics (Cont.)

- Pumping of saturated fluids
- Surface tension directed flow stability
- Reaction kinetics in packed beds, effects of channeling and condensation
- Stability of packed beds during launch
- Deterioration of packed beds during operation
- Lubrication of rotating gears
Direct Osmotic Concentration (DOC)
DOC Description

- The DOC technology is a highly integrated membrane / distillation / oxidation based water processor.

- It incorporates a novel direct osmosis step, an osmotic distillation step, a reverse osmosis step, and a catalytic reactor post treatment step.

- The DOC technology is designed to accept separate hygiene and urine + condensate streams and produces potable water while requiring little re-supply or maintenance for a 3 year mission.
DOC Simplified Flow Diagram

Waste Water Feed

Feed Tank

Permeate Tank

Waste Side

Multistage RO

Product Water

Recycle Bleed To Solid Waste Treatment

Waste Recycle
DOC Complete
Flow Diagram

Hygiene Waste Stream

Urine Waste Stream

Feed Tank

DO Module

Osmotic Distillation Module

Feed Tank

Permeate Tank

Recycle

Permeate

OA Recycle

RO Module

Preheater

Gas/Liquid Separator

Catalytic Reactor

Regenerative HX

Ion Exchange Bed

O2 & CO2

Product Water

Recycle Bleed
To Solid Waste Treatment

O2
DOC Flight Verification

Topics

• Three phase flow
• Two and three phase flow in membrane elements
• Stability of packed beds
• Two phase flow in packed beds
• Multi Phase flow separation and mixing
• Cavitation control
Investigations of pulmonary epithelial cell damage due to air-liquid interfacial stresses in a microgravity environment

Donald P. Gaver III
Department of Biomedical Engineering, Tulane University, New Orleans, LA, USA
A.M. Bilek, S. Kay and K.C Dee
Department of Biomedical Engineering, Tulane University, New Orleans, LA, USA

Pulmonary airway closure is a potentially dangerous event that can occur in microgravity environments and may result in limited gas exchange for flight crew during long-term space flight. Repetitive airway collapse and reopening subjects the pulmonary epithelium to large, dynamic, and potentially injurious mechanical stresses. During ventilation at low lung volumes and pressures, airway instability leads to repetitive collapse and reopening. During reopening, air must progress through a collapsed airway, generating stresses on the airway walls, potentially damaging airway tissues. The normal lung can tolerate repetitive collapse and reopening. However, combined with insufficient or dysfunctional pulmonary surfactant, repetitive airway collapse and reopening produces severe lung injury. Particularly at risk is the pulmonary epithelium. As an important regulator of lung function and physiology, the degree of pulmonary epithelial damage influences the course and outcome of lung injury. In this paper we present experimental and computational studies to explore the hypothesis that the mechanical stresses associated with airway reopening inflict injury to the pulmonary epithelium.

Experimental Investigations
Experiments were performed in a parallel plate chamber lined with pulmonary epithelial cells, which was constructed as an idealized model of a collapsed segment of an airway where the walls are held in opposition by a viscous fluid. These experiments were conducted to determine whether air-liquid interfacial stresses can cause damage to epithelial cells, and to provide response behavior that can be correlated to the mechanical stimuli determined from computational investigations (below).

In a first set of experiments, a fetal rat pulmonary epithelial cell line (CCL-149, ATCC) was cultured to confluence on a small (1 cm²), square region of the upper plate. The narrow channel was filled a model airway lining fluid. Phosphate buffered saline including 0.1 mg/mL CaCl₂ and MgSO₄ (PBS) was used to model a surfactant-deficient airway lining fluid. A surfactant-containing airway lining fluid was approximated using Infasurf (ONY, Inc.) diluted to 1 mg/mL phospholipid concentration in PBS. Airway “reopening” was generated by the steady progression of a semi-infinite bubble of air down the length of the channel using a constant rate infusion pump (7 or 70 ml/min). A digital camera mounted above the channel collected sequential overhead images of the progressing bubble, which were used to calculate bubble velocity. Once removed from the apparatus, the slide was incubated with 1.2 μM Ethidium homodimer-1 (Eth-1) and 1.2 μM calcine AM (Molecular Probes). For each slide, the number of injured cells was recorded as the average number of Eth-1 stained nuclei counted in fluorescence microscopic images.

In a second experimental study, we attempted to discriminate the stress magnitude from the stimulus duration. To do so, the stress magnitude is modified by varying the viscosity of the
occlusion fluid while fixing the reopening velocity across experiments. This approach causes the stimulus duration to be inversely related to the magnitude of the pressure gradient. We also explore the mechanism for acute damage and demonstrate that repeated reopening and closure is shown to damage the epithelial cell layer even under conditions that would not lead to extensive damage from a single reopening event.

**Fluid Dynamic Simulations**

The bubble and parallel-plate flow chamber was modeled as a semi-infinite bubble progressing within a Hele-Shaw cell. In this model the walls were separated by a distance $2H$, with the semi-infinite bubble progressing in the $x$-direction with tip velocity $U$. The surface tension, $\gamma$, was constant. The capillary number, $Ca = \mu U/\gamma$, representing the relative importance of viscous to surface tension effects on the bubble determines the dynamic response of the system. Stokes equations, $\nabla \cdot \mathbf{u} = 0$, were solved using the boundary element method. The interfacial stress condition applied at the air-liquid interface was $|\sigma \cdot \hat{n}| = \gamma \kappa \hat{n}$, where $\sigma = -\mathbf{p} I + \mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T)$ was the stress tensor, $\hat{n}$ was the unit normal, and $\kappa$ was the interfacial curvature. For a given $Ca$, the system was simulated until a steady-state meniscus had developed and the stress-field and bubble geometry were determined.

Three potentially injurious components of the stress cycle associated with bubble progression – the shear stress, the shear stress gradient, and the pressure gradient – were analyzed. Regression relationships describing the behavior of these components as a function of $Ca$ were determined for very small $Ca$ ($5 \times 10^{-4} \leq Ca \leq 2 \times 10^{-3}$). Additionally, the thickness of the thin film deposited by bubble progression was estimated. Dimensionless values for the experimental flow conditions were extrapolated from the regression equations and redimensionalized.

**Results and Discussion**

For each condition the average number of injured cells per square centimeter was measured. For the saline-occluded channels, bubble progression at both velocities produced significantly increased numbers of injured cells when compared to the control. The slow velocity resulted in a 66-fold increase in the number of injured cells and the fast velocity produced a 20-fold increase. The addition of Infusurf to the occlusion fluid reduced the number of injured cells to a level similar to the control. These results support the hypotheses that mechanical stresses associated with airway reopening injure pulmonary epithelial cells and that pulmonary surfactant in the normal lung protects the epithelium from injury due to airway reopening.

The stress component that best agrees with the experimentally observed trauma is the maximal pressure gradient. Pressure gradients create a force imbalance on the cell membrane over the length of the cell. In addition, cell damage remains directly correlated with the pressure gradient, not the duration of stress exposure. For a low profile predominately flat cell (or region of a cell), the non-uniformly distributed load can depress the cell and stretch the membrane. For high profile cells or regions of a cell, such as the protrusion cause by the nucleus, where the normal forces of the cell surface are nearly opposite, the pressure gradient will pinch that region. The pinching can tear the membrane at the base of the protrusion or force fluid upward rupturing the top surface of the cell. The present study thus provides additional evidence that the magnitude of the pressure gradient induces cellular damage in this model of airway reopening.
Investigations of Pulmonary Epithelial Cell Damage Due to Air-Liquid Interfacial Stresses in a Microgravity Environment

Donald P. Gaver
Anastacia M. Bilek
Sarina Kay
Anne-Marie Jacob
Kay C Dee

Department of Biomedical Engineering
Tulane University
New Orleans, LA
Critical Path RoadMap

**Cardiovascular Alterations**
- Impaired Response due to Modified Orthostatic Mechanical Stress
- Diminished Cardiac Function
- Impaired Response to Exercise Stress

**Pulmonary Alterations**
- Airway Closure Becomes more Homogeneous
- Potentially Impaired Pulmonary Function
- Impaired Response to Exercise Stress
Gravity Effects on Ventilation Distribution

- (A) At FRC the lower region is less expanded, but more compliant so it receives larger portion of ventilation
- (B) At RV the lower lung regions experience airway closure

**Airway Closure in Microgravity**

**MICROGRAVITY CAUSES:**

- Regional Modification of Ventilation
- Changes of Blood Perfusion
- Variation in Lung Capacity

- ‘Patchy’ regions of airway collapse
Related Terrestrial Syndromes

- Infant Respiratory Distress Syndrome
- Acute Respiratory Distress Syndrome
- Ventilator-Induced Lung Injury
Pulmonary Multiscale Interactions
Motivation

Our goal is to determine the cause of reopening-induced damage, and the surfactant properties and airway reopening strategies that will allow pulmonary airways to be opened with minimal damage to the lung.
Stresses in Airway Reopening

Direction of Bubble Progression

Air Bubble

Collapsed Airway

Mechanisms of Cell Mechanotransduction and Damage

3-D Surface Topography Influences Stress Distribution

Luminal Transmembrane Proteins

Cell-cell proteins

Force Transmission

Nuclear Membrane

Nucleus

Focal Adhesion Sites

Matrix

Adapted from Davies, *Physiol. Rev.*, 1995
Lung epithelial cells were:

- Cultured in an idealized model of small airways,
- Exposed to a moving finger of air under reopening conditions,
- Examined for cellular trauma.
Methods – Variable Velocity

- Lung epithelial cells (CRL-149, ATCC) cultured to confluence on glass microscope slides.

- The channel dimensions were 2.5 x 7.0 x 0.17 cm.

- **Two velocities** (0.27 and 2.7 cm/s) were assessed.

- Two occlusion fluids were assessed:
  - phosphate buffered saline (PBS) and
  - 1 mg/mL Infasurf (ONY, Inc., Buffalo, NY) in PBS.

- Cellular trauma was quantified using fluorescent staining (Live/Dead Kit, Molecular Probes).
Injury by a Single Bubble Progression

(L2 cells, Live/Dead Kit)

Control

Bubble Velocity

0.27 cm/s 2.7 cm/s

PBS Infasurf

Occlusion Fluid

Air Bubble

Glass Plate

Pulmonary Epithelial Cells (L2 or A549)

Occlusion Fluid (PBS or Infasurf)

Glass Plate

(~ 0.25 - 2.5 cm/s)

L2 or A549
Injury by a Single Bubble Progression
(L2 cells, Live/Dead Kit)

Injured Cells [cells/mm²]

Control 0.27 2.7

Bubble Velocity [cm/s]

PBS Infasurf (1 mg/mL in PBS)

n = 5
* p < 0.01
Mechanisms of Cell Membrane Wounding

- Shear Stress
- Shear Stress Gradient
- Pressure
- Pressure Gradient
The Flow Model

Steady Flow of a Semi-Infinite Bubble in a Channel

Surface Tension, $\gamma_{eq}$

$2H$

Newtontian Fluid, $\mu$

Q = Constant

Governing Parameter:

$$Ca = \frac{\mu U}{\gamma_{eq}}$$
## Predictions

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Speed</th>
<th>$\tau_s$ (dyn/cm²)</th>
<th>$\Delta \tau_s$ (dyn/cm²)</th>
<th>$\Delta P$ (dyn/cm²)</th>
<th>$f$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>Slow</td>
<td>15.5</td>
<td>9.2</td>
<td>340</td>
<td>1.4</td>
</tr>
<tr>
<td>Saline</td>
<td>Fast</td>
<td>34.3</td>
<td>10.1</td>
<td>170</td>
<td>6.0</td>
</tr>
<tr>
<td>Infasurf</td>
<td>Slow</td>
<td>7.9</td>
<td>3.4</td>
<td>89</td>
<td>2.7</td>
</tr>
<tr>
<td>Infasurf</td>
<td>Fast</td>
<td>17.5</td>
<td>3.8</td>
<td>44</td>
<td>11.6</td>
</tr>
</tbody>
</table>

### Control Bubble Velocity [cm/s]
- 0.27
- 2.7
1. Film Thickness decreases with decreasing velocity

2. The pressure gradient on the cell surface increases with decreasing velocity
Investigations of the Applied Stress Duration

The variable velocity experiments induce stresses on cells that are not of constant duration.

Hypothesis:
The slow velocity experiments may induce greater damage because of the increased exposure time.
Methods – Constant Velocity

- Human Pulmonary Epithelial Cells (A549, ATCC) cultured to confluence on glass microscope slides.

- The channel dimensions were 2.5 x 7.0 x 0.17 cm.

- A single velocity (0.34 cm/s) was applied.

- Two viscosities were used
  - $\mu = 8 \times 10^{-3}$ g/(cm s) (PBS)
  - $\mu = 8 \times 10^{-2}$ g/(cm s) (PBS + 14% Dextran)

- Cellular trauma was quantified using fluorescent staining (Live/Dead Kit, Molecular Probes).
Traveling-Wave Behavior

Film Thickness Increases as Ca Increases

Lubrication Film

Ca = 0
Ca > 0

Pressure Field Near Contact Line

Pressure Gradient Decreases as Ca Increases

\[ Ca = \frac{\mu U}{\gamma} \]
Traveling-Wave Behavior

\[ Ca = \frac{\mu U}{\gamma} \]

\( \Delta t_{\text{exp}} = \frac{L_{\text{wave}}}{U} \propto \frac{H \mu^{0.29}}{U^{0.71} \gamma^{0.29}} \)

\( \Delta P \sim \gamma/H \)

|dP/dx| Decreases as Ca Increases

Increases as Ca Increases
Pressure Gradient, not Exposure Duration, Determines Damage

\[ U = 0.34 \text{ cm/s}, \mu_{\text{Dextran}} = 10\mu_{\text{PBS}} \]

Kay et al., JAP, 2004
Investigations of Topography

- Our system is modeled to isolate the influence of epithelial topography on the following components of the stress cycle during airway reopening:
  - shear stress and shear stress gradient
  - normal stress and normal stress gradient
Computational Model

Geometric Parameters: \( \varepsilon = a/H \), \( \Lambda = \lambda/H \)
Computational Model

Boundary Element Method

Interfacial Stress
\[ \tau^* = \gamma \kappa^* n \]

Kinematic Boundary Condition
\[ \frac{\partial Y^*}{\partial t^*} \cdot n = u^* \cdot n \]

Stokes Flow
\[ \nabla^* P^* = \mu \nabla^2 u \]

Lubrication Theory

Governing Parameter:
\[ Ca_Q = \frac{Q^* / 2H}{\gamma / \mu} \]
Normal Stress Distribution

\[ \lambda/H = 2, \; Ca = 0.01 \]

\[ \epsilon = a/H = 0.00 \]
\[ \epsilon = a/H = 0.05 \]
\[ \epsilon = a/H = 0.10 \]

increasing cell height

bubble
epithelial cell
Normal Stress Distribution

\( a/H = 0.1, \lambda/H = 2, Ca = 0.01 \)
Tangential Stress Distribution

\[ \lambda/H = 2, \ Ca = 0.01 \]

Increasing cell height

\[ \epsilon = a/H = 0.00 \]

\[ \epsilon = a/H = 0.05 \]

\[ \epsilon = a/H = 0.10 \]
Tangential Stress Distribution

\( \frac{a}{H} = 0.1, \frac{\lambda}{H} = 2, \frac{Ca}{H} = 0.01 \)

Click here to play movie
Ca_Q vs. Tangential Stress and Stress Gradient \( \varepsilon/\Lambda = 0.05 \)

\[ Ca_Q = \frac{Q^*/(2H)}{(\gamma/\mu)} \]

- Increasing \( \varepsilon/\Lambda \)
- Increasing \( \varepsilon/\Lambda \)

\[ Ca_Q = \frac{Q^*/(2H)}{(\gamma/\mu)} \]

- \( \varepsilon/\Lambda = a/\lambda = 0.05 \)
- \( \varepsilon/\Lambda = a/\lambda = 0.00 \)
\( Ca_Q \) vs. Normal Stress Gradient

\[ \varepsilon/\Lambda = 0.05 \]

Normal Stress Gradient

\[ (d\tau_n/dx)_{\text{max}} \]

Increasing \( \varepsilon/\Lambda \)

\[ Ca_Q = \left[ Q^*/(2H) \right]/(\gamma/\mu) \]
Surfactant Effects
Equilibrium Equation of State (Infasurf)


Influence of Surfactant Concentration

(A549 cells, Live/Dead Kit, 0.25 cm/s)

Population Injury [cells/cm$^2$]

Infasurf Concentration [mg/mL]

0 0.01 0.1 1

0 10,000 20,000 30,000 40,000 50,000

CBC

Surface Tension [dyn/cm]

Influence of Surfactant Concentration
## Correlation of Stress and Injury

<table>
<thead>
<tr>
<th>Infasurf (mg/mL)</th>
<th>Speed (cm/s)</th>
<th>Injury (cells/cm²)</th>
<th>$\tau_s$ (dyn/cm²)</th>
<th>$\Delta\tau_s$ (dyn/cm²)</th>
<th>$\Delta P$ (dyn/cm²)</th>
</tr>
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<td>0</td>
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<td>++</td>
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<td>4.8</td>
<td>163</td>
</tr>
<tr>
<td>0.01</td>
<td>0.25</td>
<td>++</td>
<td>12.8</td>
<td>4.6</td>
<td>154</td>
</tr>
<tr>
<td>0.1</td>
<td>0.25</td>
<td>++</td>
<td>7.1</td>
<td>1.9</td>
<td>48</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
<td>-</td>
<td>6.7</td>
<td>1.8</td>
<td>44</td>
</tr>
</tbody>
</table>
Influence of Non-Equilibrium Behavior of Infasurf

Non-equilibrium behavior:
- produces dynamic surface tensions that are greater than the equilibrium surface tension,
- creates non-equilibrium surface tension that causes film-thinning.
Dynamic Surface Tension of Infasurf


Conclusions

• Combined experiments and computational investigations allows us to estimate the mechanical stresses that damage epithelial cells during reopening.

• The damaging effects from reopening are likely to be due to a large pressure gradient from the traveling air-liquid interface.

• Topological effects can increase the magnitude of deleterious stresses.

Non-equilibrium surface-tension effects may increase damage unless concentrations are large.

NASA: NAG3-2734
NIH: P20 EB001432
NSF: BES-9978605
COLORIMETRIC SOLID PHASE EXTRACTION: A METHOD FOR THE RAPID, LOW LEVEL DETERMINATIONS OF BIOCIDES LEVELS IN SPACECRAFT WATER

Daniel B. Gazda, James S. Fritz, Robert J. Lipert, and Marc D. Porter
Institute for Combinatorial Discovery, Ames Laboratory-U.S.D.O.E. and Department of Chemistry
Iowa State University
Ames, IA 50011

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Wyle Laboratories
Houston TX 77058

Monitoring and maintaining biocide concentrations is vital for assuring safe drinking water both in ground and spacecraft applications. Currently, there are no available methods to measure biocide concentrations (i.e., silver ion or iodine) on-orbit. Sensitive, rapid, simple colorimetric methods for the determination of silver(I) and iodine are described. The apparatus consists of a 13-mm extraction disk (Empore® membrane) impregnated with a colorimetric reagent and placed in a plastic filter holder. A Luer tip syringe containing the aqueous sample is attached to the holder and a predetermined volume of sample is forced through the disk in ~30 s. Silver(I) is retained by a disk impregnated with 5-(p-dimethylaminobenzylidene)-rhodanine (DMABR), and iodine is retained as a yellow complex on a membrane impregnated with polyvinylpyrrolidone (PVP). After passage of a water sample, the colorimetric response generated by the interaction between analyte and reagent is measured by use of a hand-held, commercial reflectance spectrophotometer. This simple solid-phase extraction (SPE) method gives a high concentration factor. The sensitivity for both measurements is excellent: 0.005 mg/L for Ag(I) and 0.1 mg/L for I2. Furthermore, the methodology minimizes sample handling and potential contamination events, produces only a small volume of waste, and requires only ~60 s for completion. Details related to membrane impregnation, calibration, and interferences are presented, as well as the results of ground-based analysis of samples of actual Space Shuttle and International Space Station (ISS) drinking water. Findings from KC-135 microgravity flight simulations and challenges for the eventual deployment on ISS will also be described.
NASA Bioscience and Engineering Institute
at The University of Michigan

www.umnbei.umich.edu
PISTONS NBA CHAMPS!!!
Goals of NBEI

- High-quality, state-of-the-art research
- Dissemination of advances in knowledge
- Undergrad and grad cross-training programs
- Seminars & workshops; courses; national needs ID
- K-12 education, diversity and public/industry outreach
- Information repository
- Development of a new generation of Bioengineers
HISTORY

Cooperative Agreement Notice (CAN) released Oct. 2001

13 Proposals received in response narrowed to 2 finalists for site visits

On site visits conducted May 2002

Award September 2003

(Funding for 5 years with a renewal provision not to exceed 5 more years)
U of Michigan Components in NBEI

UM+NASA

Medical School

College of Engineering

Lit Sci & Arts

Dental School

Industry Partners

Kinesiology

Life Sciences Institute

Public Health

NASA Bioscience and Engineering Institute

University of Michigan
DIRECTOR

James Grotberg, Ph.D., M.D.

OBJECTIVE: Enable world-class research and development in bioscience and engineering related to NASA’s overall missions with emphasis on human exploration and development of space

RESEARCH THEMES AND LEADERS

- BioMEMS and Biomaterials  
  Daryl Kipke, Ph.D.
- Transport Phenomena in Biology and Devices  
  Ron Larson, Ph.D.
- Tissue Bioscience and Engineering  
  Laurie McCauley, D.D.S., Ph.D.
- Molecular Biophysics and Bioengineering  
  Matthew O’Donnell, Ph.D.

INCEPTION

September, 2003
Research Theme: Molecular Biophysics & Engineering

Theme Leader: Matt O’Donnell, PhD  BME (Chair), EECS

Project MB1: Molecular Nanosystems to Monitor Astronaut Radiation Sickness

Retinal flow cytometry to detect astronaut radiation exposure by apoptosis of lymphocytes.

Jim Baker, Med; Matt O’Donnell, BME; Raoul Kopelman, Chem; Ted Norris, EECS

NASA Bioscience and Engineering Institute
University of Michigan
MB1: Molecular Nanosystems to Monitor Astronaut Radiation Sickness

PI  James Baker, M.D.

NBEI Goal  Develop a device to quantify radiation effects and other physiological states in astronauts

Research Details

• Develop a polymer that will monitor functionality using cell-binding ligands
• Test biologic adherence of polymer both in vitro and in vivo
• Characterize precision and accuracy of assays developed
Project MB2: Single-Molecule Biosensor in the Search for Life

Engineered RNA binds to specific amino acid, causing conformational change detected by light, a single molecular biosensor

Chris Meiners, Physics; Nils Walter, Chem

NASA Bioscience and Engineering Institute
University of Michigan
MB2: Single-Molecule Biosensor in the Search for Life

PI Jens-Christian Meiners, PhD

NBEI Goal Chip to detect life on other planets

Research Details

- Develop and validate a single molecule analysis system based on a TIRF microscope
- Adapt TIRF technology to a BioMEMS chip
- Validate single RNA molecule analysis with the TIRF microscope
- Complete a fully-functional biosensor chip to detect life
Research Theme: Tissue Bioscience & Engineering

Theme Leader: Laurie McCauley, DDS, PhD  Perio/Prev/Geri (Chair)

Project TB1: Effects of hind-limb unweighting on muscle function.

Impact of microgravity or unweighted-disuse on muscle satellite cell self-organization to functional muscle tissue.

Bob Dennis, Mech E; Sue Brooks, Med

Use of engineered muscle, from cells to tissue construct, to examine unweighting response

NASA Bioscience and Engineering Institute

University of Michigan
TB1: Effects of Hind-Limb Unweighting on Muscle Function

PI    Robert G. Dennis, Ph.D./Susan Brooks, Ph.D.

NBEI Goal Determine the ability of muscle satellite cells to effect muscle remodeling following exposure to modeled microgravity deconditioning

Research Details

• Determine number of myogenic precursor (satellite) cells as a function of the duration of modeled microgravity due to hind limb suspension of rats.

• Assess effects of microgravity on satellite cells by observing growth dynamics in two dimensional cultures

• Grow in vitro functional muscle tissue from satellite cells that have experienced microgravity and compare the properties of this tissue with tissue where the precursors had not been exposed to microgravity.
Project TB2: Anabolic parathyroid hormone: A countermeasure for bone loss in space

PTH Implantable Delivery Strategy: Multilayered scaffolds will release PTH intermittently as drug implant dissolves.

Model: subcutaneous bone ossicles in rats: fatty center (no added PTH); bony center (PTH added)

No added PTH

PTH added

Laurie McCauley, Dent; Peter Ma, Dent

NASA Bioscience and Engineering Institute

University of Michigan
TB2: Local Delivery of PTH to Counter Microgravity-Associated Bone Loss

PI Laurie McCauley, D.D.S., Ph.D.

**NBEI Goal** Eliminate microgravity-induced bone loss

**Research Details**

- Develop a polymer of sufficiently high molecular weight for layer-by-layer degradation. Currently polymers with this feature are too soft for devices and, in some cases, are almost liquid.

- Verify surface erosion features required for drug delivery

- Develop multilayer constructs to test pulsatile release of PTH

- Provide a bone loss countermeasure based on pulsed release of PTH from layered poly(lactic-co-glycolic acid) microspheres
Project TB3: Mechanical signal transduction in bone under microgravity conditions.

A novel *in vivo* model for signal cascades from mechanical stimuli using hydraulically loaded bone development.

Steve Goldstein, Med & BME; Barbara McCreadie, Med

NASA Bioscience and Engineering Institute

University of Michigan
TB3: The Influence of Physical Forces on Bone Adaptation

PI Steven A. Goldstein, Ph.D.

NBEI Goal Guide development of optimal countermeasures to prevent bone loss during spaceflight by determining the mechanical signal transduction pathways regulating bone formation and resorption.

Research Details

- Identify short and long term cellular and molecular events associated with mechanical stimulation from a hydraulically-controlled *in vivo* device
- Measure integrin-mediated signal transduction as a function of applied force and rate of force application
- Adapt *in vivo* rodent model for investigating mechanotransduction in a space flight environment
Research Theme: Transport Phenomena in Biology & Devices
Theme Leader: Ron Larson, PhD

Project TP1: Neural & neurovascular changes in simulated microgravity

Study brain fluid shifts during head-down-tilt using fMRI, examine fluid shear effects on neural and endothelial cells

Rachael Seidler, Kines; Doug Noll, BME; Shu Takayama, BME; Jim Grotberg, BME
TP1: Neural and Neurovascular changes in Simulated Microgravity

PI  Rachael Seidler, Ph.D.

NBEI Goal  Understand human deficits in motor coordination and sensory abilities in microgravity by studying changes at the system and cellular levels.

Research Details

- Begin by developing microfluidic devices to vary fluid flow rates in the cell culture chamber to change shear stress and rate of nutrient delivery
- Include pulsatile flow to mimic physiological conditions and study how proliferation, differentiation, shape and death are affected by stress and nutrient transport
- Systems level studies will use functional MRI to determine how the brain responds to a head-down tilt challenge, which is similar to microgravity insertion, and whether different parts of the neural system respond differently to this challenge.
- Correlate cellular and system level results
Project TP2: An Earth-based model of microgravity pulmonary physiology

Simulating weightless lungs for Pulmonary Function Tests by use of liquid ventilation with perfluorocarbon in submerged sheep to remove the usual density gradients (gravity effects) between lung tissue and lung air.

Ron Hirschl, Med; Joe Bull, BME; Jim Grotberg, BME

Rat breathing perfluorocarbon liquid spontaneously

Photograph courtesy of Alliance Pharmaceutical Corp., 1999
TP2: An Earth-Based Model of Microgravity Pulmonary Physiology

PI Ronald B. Hirschl, M.D.

NBEI Goal
Develop an experimentally verified model of microgravity respiration and incorporate with digital astronaut effort

Research Details

• Compare results of modeled microgravity respiration to 1G respiration in an animal model including cardiac output, arterial venous pressure, lung volume and mechanics

• Compare results of modeled microgravity respiration to previous actual microgravity data from animal models

• Use radiographic imaging to measure pulmonary blood flow distribution, distribution of ventilation and other quantities that have not been previously measured

• Incorporate data into a model for human performance in microgravity

NASA Bioscience and Engineering Institute
University of Michigan
Project TP3: Lab-on-Chip devices: Portable medical diagnosis, initial studies on saliva to monitor astronaut health

Ron Larson, Chem E; Margaret Terpenning, Med; Bill Schultz, Mech E; Mark Burns, Chem E
TP3: Lab-on-Chip Devices for Bio-Medicine in Space with Focus on Saliva Analysis

PI Mark Burns, Ph.D.

NBEI Goal Use MEMS techniques to measure radiation damage and bone loss in astronauts

Research Details

• Use cravicular fluid (saliva between teeth) because it has many serum markers present in blood and collection is non-invasive

• Characterize rheological properties of saliva for chip level analysis

• Study droplet evaporation and associated DNA stretching as a method of preparing the DNA for scission

• Use results to quantify radiation damage to in flight astronaut DNA

• Leverage grants with NIH and Sandia and apply the work to saliva markers characteristic of bone loss
Research Theme: BioMEMS and Biomaterials

Theme Leader: Daryl Kipke, PhD

Project BM1: “Skin-patch” polymer MEMS device for physiological sensing and environmental monitoring

Phase I: Develop prototype polymer-based microsystem placed under skin for sensing biopotentials. Work to include wireless communication and embedded processing.
BM1: Integrated Microsensors for Environmental and Physiologic Monitoring

PI Daryl Kipke, Ph.D.

NBEI Goals
Develop a polymer-based skin patch sensor to monitor both physiological and environmental systems
Evolve probe to include drug and fluid delivery systems

Research Details
• Develop a polymer substrate so the probe better conforms to the body
• Advance device electronics to include wireless communication
• Design both epidermal and implantable devices
• Wound healing isolates implants: determine how to overcome this reaction
• Collaborate with NASA to measure signaling pathways associated with neurovestibular adaptation to space
NBEI Education and Outreach

- Undergraduate Education
- Graduate Education
- Interns & Scientists
- Public Outreach
  - Women & Under-Represented Minorities
  - K-12
- Outreach to Societies and Agencies
Phase Change
by
Mohammad M. Hasan

Strategic Research to Enable NASA’s Exploration Missions
June 22-23, 2004
Cleveland, Ohio

Glenn Research Center
at Lewis Field
Phase Change Processes in Space Systems

- Recent workshops to define **strategic research** on critical issues in microgravity fluids and transport phenomena in support of **mission orientated needs** of NASA and many technical conferences over the years in support of **fundamental research** targeting NASA’s long range missions goal have identified several phase change processes needed to design advanced space and planetary based systems for long duration operations

- Recommendation noted that phase change processes are profoundly affected by gravitational environment
Space Systems Requiring Phase Change Processes

- Closed loop life support systems: Humidity control, drying, wastewater processing
- Thermal management: Heat rejection systems (heat pipes, radiators) for power generating units, habitats, vehicles
- Power generation using Rankine cycle
- Thermal energy storage, transient thermal management using phase change materials
- In space depot: Storage, acquisition and transport of cryogenic fluid in space
- In situ production, liquefaction and storage of cryogenic fluids (life support, propellants)
Phase change processes affected by gravitational environment

- **Boiling**: Pool and flow boiling in geometrical configurations and surfaces of practical applications, flow boiling in conduits from inception to post dry-out conditions, boiling in porous media and from prepared surfaces

- **Condensation**: Drop wise and film condensation on surfaces, conduits, porous media, screened surface, membranes; direct contact condensation on subcooled droplets and agitated interface

Glenn Research Center at Lewis Field
Phase change processes affected by gravitational environment

- **Evaporation**: Evaporation from plane and screened surfaces, porous media, at solid-liquid-vapor contact line with and without forced flow

- **Melting and solidification**: Void formation, void location, growth and migration of void bubble as function of material properties, thermal conditions and geometric configurations
State of Knowledge of Phase Change Processes in Microgravity

- Presentations by leading experts in the afternoon sessions will provide most current state of information on respective topics.

- Visual and quantitative data from numerous experiments on pool boiling in short and long durations reduced and microgravity environments. Findings are often contradictory. Useful information but it could not be compiled into a form useful for design purposes.
State of Knowledge of Phase Change Processes in Microgravity

- Limited number of flow boiling experiments in short duration microgravity. High velocity results are insensitive to microgravity. Need to define quantitative criteria for high and low velocities. Need to describe flow boiling independent of pool boiling in microgravity.

- A good number of short duration two phase flow experiments to identify and characterize flow regimes and experiments involving liquid vapor interface configurations

- Number of short and long durations experiments with systems utilizing phase change processes (mostly with heat pipes) some fluid mixing and interface condensation
Strategic Research on Phase Change Processes

• Phase change heat and mass transfer processes are very efficient but complicated. Except for a few idealized cases they cannot be solved from first principles. Resolution of critical issues associated to these phenomena through comprehensive understanding has been the goal of fundamental research supported by OBPR. This goal may or may not be realized in time to support NASA’s current mission plans.

• Phase change processes are highly gravity dependent but we must make use of these efficient processes to design essential subsystems, such as evaporators, condensers for Advanced Closed Loop Life Support Systems, thermal management and power generation systems.
Strategic Research on Phase Change Processes

- Performance and operation of these units may be significantly affected by the microgravity and partial gravity environments if these units are not designed, either to be gravity insensitive or the effects of gravity on processes are accounted for through appropriate scaling parameters and validated design equations.
Useful Design Specific Information

- **Pool boiling**: Analytical description of pool boiling in microgravity, prediction of critical heat fluxes if they exist, liquid superheat excursion (on-orbit start up failure of CPL due to high liquid superheat), boiling in the presence of vapor or gas bubble.

- **Flow boiling**: Saturated/subcooled flow boiling in single and multiple channels, with and without porous wicking materials for fluid properties encompassing range of cryogenic to liquid metals to quantify:
  - Inception of boiling
  - Critical heat fluxes and the wall superheats at critical conditions
  - Boiling heat transfer coefficients (Flow regime specific)
  - Minimum flow velocity needed to sustain the boiling process
  - Effect of dissolved gas
Useful Design Specific Information

- **Condensation**: Condensation on hydrophobic and hydrophilic surfaces, condensation on porous media and propagation of condensation front, steady and transient direct contact condensation including the effects of non-condensable, stability of condensation in multiple channels.

- **Evaporation**: Evaporation from screened surface, porous media; from interface due to sudden depressurization.

- Phase change materials for thermal management: Melting and solidification, void formation, growth and departure in confined geometry in microgravity.
Strategic Research Questions on Phase Change Processes

- Can we develop design equations or compile information into system specific design guides valid for a limited range of operating parameters of practical applications in time to support NASA’s current mission plans even though the necessary fundamentals are not understood to a desired level?

- Can we design systems utilizing phase change processes from existing body of knowledge based on normal gravity experience and limited microgravity data in a way such that their performance in microgravity will remain unaffected or if affected it can be described by appropriate scaling parameters, equations?
Strategic Research Questions on Phase Change Processes

- Can we make use of unique geometrical configuration that eliminates gravity dependence and makes effective utilization of capillary and inertia forces?

- Can we establish limiting design criteria?

- How can we conclusively verify the gravity insensitivity and certify performance in microgravity without experimental validation in microgravity?
Strategic Research Questions on Phase Change Processes

• If flight experiment is a must how can we optimized the need for microgravity data?

• Do we need to develop experiment protocol (e.g. well defined procedure for surface preparation for boiling experiment) to obtain much needed data?

• Multi-scale, multi-dimensional numerical models for multiphase systems make use of mechanistic models for CHF, boiling inception, dry-out conditions, interface transfer etc. If microgravity data is needed should we follow a well defined experiment protocol?

Uday Hegde
National Center for Microgravity Research
Cleveland, Ohio
Solid Waste Management

- **Current**
  - Segregation (manual)
  - Drying (exposure to space vacuum) and/or Compaction (human waste)
  - Storage

- **Future**
  - Mission objectives and factors (e.g., crew safety, planetary protection, mission cost) drive the functional requirements of waste management systems
    - Stabilization
    - Decrease volume
    - Resource recovery
    - Microbial control
  - Transition to life support system closure to reduce upmass, resupply
Solid Waste Processing / Resource Recovery

**GOAL**

**Long missions, with little or no food production**

**Destroy hazardous or noxious wastes**

**Long missions using biological processors**

**Reclaim CO₂ and nutrients from waste for biological processors**
<table>
<thead>
<tr>
<th>Waste Component</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feces</td>
<td>114 g/person-d</td>
</tr>
<tr>
<td>Urine</td>
<td>1562 g/person-d [Composition: 59 g solids, 1503 g water]</td>
</tr>
<tr>
<td>Toilet paper</td>
<td>28 g/person-d</td>
</tr>
<tr>
<td>Miscellaneous (skin cells, hair, sweat, etc.)</td>
<td>10.75 g/person-d</td>
</tr>
<tr>
<td>Menus</td>
<td>113.4 g/female for each day of menstruation.</td>
</tr>
<tr>
<td>wipes</td>
<td>185 g/person-d</td>
</tr>
<tr>
<td>Paper documentation</td>
<td>77 g/person-d [Moisture content of 6%]</td>
</tr>
<tr>
<td>Clothing, towels and wash cloths</td>
<td>486 g/person-d [Moisture content of 8.5%]</td>
</tr>
<tr>
<td>Food packaging - adhered food</td>
<td>508 g/person-d</td>
</tr>
</tbody>
</table>

**Others:**
- Wasted grown food
- Tape
- Inedible biomass
- Wasted EVA food sticks and packaging
- MAG's (diaper, feces & urine)

Planetary mission with crew of six is expected to generate solid waste at the rate of (NASA TM-2003-210785):
- 10-12 kg/day (dry)
- 25-30 kg/day (wet)
Closed Loop Life Support

People

Plants

Air, Water, Waste Processing

Waste disposal

Food

Nutrients

CO2, minerals

CO2

contaminated air, water, waste

Biomass contaminated air, water

clean air, water
### Potential Resource Recovery Objectives

<table>
<thead>
<tr>
<th>Water recovery</th>
<th>Plant nutrient recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>- from wet wastes</td>
<td>- recycle nutrients to growth chambers</td>
</tr>
<tr>
<td>- from brines</td>
<td></td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; recovery</td>
<td>Transform to beneficial products</td>
</tr>
<tr>
<td>- supply photosynthetic requirements</td>
<td>- activated carbon</td>
</tr>
<tr>
<td>- O&lt;sub&gt;2&lt;/sub&gt; generation/recovery</td>
<td>- food production substrate</td>
</tr>
<tr>
<td></td>
<td>- structural materials - paper</td>
</tr>
<tr>
<td></td>
<td>- fuel production (CH&lt;sub&gt;4&lt;/sub&gt;, C&lt;sub&gt;2&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;)</td>
</tr>
</tbody>
</table>
Example Technologies

- Based on systems analysis, many technologies can meet functional requirements efficiently and are in various stages of development.
  - e.g., Lyophilization (freeze drying)
  - Chemical oxidation
  - Bio-oxidation
Gravity Related Issues

• Among the development challenges for waste management technologies are gravity related issues that require research, development, and flight testing

• Final Report

  Workshop on Critical Issues in Microgravity Fluids, Transport, and Reaction Processes in Advanced Human Support Technology

  NASA/ TM -2004-212940

Top Level Functional Operations

- Collection/Segregation
- Transport
- Processing (include pre- and post-processing)
- Storage
- Disposal

Complexity of these operations and gravity related issues will depend upon the overall Solid Waste Management system.
Collection and Transport

- Pneumatic transport of dry solids, liquid waste and slurries
- Transport of liquid-solid slurries with or without gas entrainment
- Material containment during transfer to storage systems

Characterize flow pattern, phase distribution, pressure drop, slurry properties
Storage

- Packing and distribution within storage vessels
- Flow through, and emptying from, temporary storage vessels
- Phase positioning within tanks with respect to feed line to reactor and filling port
- Gas movement to accommodate volume changes during filling and emptying process
Processing

- Drying
  - water removal
  - water condensation

- Size reduction and classification
  - pretreatment of biomass, paper, plastic (e.g., gas-solid separation, solid-solid separation for size classification)
  - dust explosion hazards
Processing (continued)

- Solid, Liquid, Gas Feeding Systems
  - active feed
  - liquid/solid slurry feed
  - gas-solid slurry

- Reactor
  - material containment
  - feed variability
  - multiphase heating, mixing, and distribution of species
  - material residence time control
Processing (continued)

- Phase separation
  - gas-solid separation (e.g., ash)
  - condenser and water removal

- Monitoring and control
  - sensor design and placement
High Priority Issues Summary

- Transport of moisture bearing solids with associated gases both external to and within the reactor
- Solids containment - reaction bed, size reduction, drying
- Mixing/distribution of chemical species and phases in reactor
- Multiphase separations - gas/solid, gas/liquid, solid/liquid, three phase
Acknowledgements

John Fisher- NASA ARC
John Hogan- Rutgers University
Robert Davis- University of Colorado
Jay Garland- Dynamac Corporation
Otis Walton- Grainflow Dynamics
John McQuillen- NASA GRC
Moderate Priority Issues Summary

- Dry solids feed mechanism
- Monitoring and control related to possible system instability issues
- Monitoring and control related to process control
- Dust explosion hazards
Gravity Effects in Condensing and Evaporating Films

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University of Washington, Seattle, WA

J.S. Allen
National Center for Microgravity Research, Cleveland, OH

P.C. Pedersen
Worcester Polytechnic Institute, Worcester, MA

Strategic Research to Enable NASA’s Exploration Missions
June 23, 2004
Research Overview

• Objective
  - Understand film condensation/evaporation behavior (and implications for heat transfer) in variable gravity environments

• Problems studied
  - Film condensation and evaporation on planar surfaces at normal gravity (+1g, -1g) and reduced gravity ≈ 0.01g (aircraft)
  - 2-3 minutes of low-gravity testing desirable
NASA Recognizes Critical Need for Condensation & Evaporation Research to Enable Human Exploration of Space


Condensation and Evaporation Research in Reduced Gravity is Enabling for AHST Technology Needs

- **Humidity Control**
  - Mechanisms which inhibit or exacerbate liquid film motion
  - Condensate control in ducts
  - Condensers/evaporators for crew atmosphere

- **Air Revitalization (O₂ production via electrolysis)**
  - Control of water transport
  - Separation of dissolved gases from water

- **Water Purification (Potable Water via VCD)**
  - Stability of large area condensed liquid films
  - Mechanisms for shedding condensed films in reduced gravity

- **Environmental Control and Heat Rejection**
  - Evaporation and condensation heat transfer
  - Stability of evaporating/condensing films
Differing Role of Surface Tension on Condensing/Evaporating Film Stability

Evaporating film - surface tension variations de-stabilizing

Condensing film - surface tension variations stabilizing
Fluid Mechanisms in Condensing and Evaporating Films in Reduced Gravity

- Condensing film in low-g
  - Cooled surface
  - Lower condensation rate (stabilizing)
  - Surface tension force (stabilizing)
  - Higher condensation rate (de-stabilizing)
  - Body force/perturbation (de-stabilizing)
  - Saturated vapor

- Evaporating film in low-g
  - Heated surface
  - Lower evaporation rate (de-stabilizing)
  - Higher evaporation rate
  - Lower surface tension
  - Higher surface tension (de-stabilizing)
  - Saturated vapor
Research Plan

- 1-g (normal gravity) laboratory experiments (UW/WPI)
- Reduced gravity experiments on board NASA parabolic-trajectory aircraft (NASA Glenn Research Center)
- Numerical modeling using unsteady Navier-Stokes equations by a finite element method based on a front tracking technique (Prof. A.N. Alexandrou, University of Cyprus)
Experimental Configurations for Condensing Films

- **Geometries**
  1) Stabilizing gravitational body force (+1g, condensing surface “upwards”)
  2) De-stabilizing gravitational body force (-1g, “downwards”)
  3) Reduced gravity with external perturbation

- **Fluid configurations**
  1) Condensing film (thermal plus mass addition effects)
  2) “Pumped” film with isothermal mass addition through porous substrate
Experimental Configurations for Evaporating Films

- **Geometries**
  1) Stabilizing gravitational body force (+1g, evaporating surface “upwards”)
  2) De-stabilizing gravitational body force (-1g, “downwards”)

- **Fluid configurations**
  1) Evaporating film (thermal and mass removal effects)
  2) Heated, non-volatile film (thermal effects only)
Laboratory Condensation Test Cell

Schematic

Actual
Aircraft Experiment

Aircraft rig with volume control system

A/C rig test cell with dual thermoelectric elements
Condensation Study
Current Test Conditions

- **Condensation experiments**
  - 10 cm diameter cooled brass plate
  - Fluids: Methanol and n-pentane
  - Enclosed test cell, typical operating pressure 50-70 kPa
  - Subcooling range $T_{sat} - T_{wall} = 4 - 16$ C

- **“Pumped film” experiments**
  - 10 cm diameter perforated stainless plates
  - Fluids: Silicone oil (125 and 50 cSt)
  - Pumping rates 2-12 ml/min
Diagnostics

- **Double-pass shadowgraph imaging**
  - Synchronized with data acquisition
  - Disturbance wavelengths
  - Time to drop formation/break off (condensation) or dry-out (evaporation)

- **Thermal measurements**
  - Thermocouples (surface, vapor temperatures)
  - Imbedded heat transfer sensors
  - Numerical inverse method employed to determine surface heat flux

- **Ultrasound gauging**
  - Single and multiple sensors
  - Film thickness and growth rate
Shadowgraph Images of Condensing \textit{n}-pentane Film in Unstable (-1g) Configuration

\[ T_{\text{wall}} = 11 \text{ C}, \quad T_{\text{sat}} = 17 \text{ C}, \quad P_{\text{sat}} = 50 \text{ kPa} \]

At start of condensation 37 s after the start of condensation
Condensing n-Pentane Film in Normal Gravity (-1g) at Constant Pressure

$P_{sat} = 50$ kPa, $T_{sat} = 16.5$ C, $T_{wall} = 11$ C

Video real time
Condensing n-Pentane Film in Normal Gravity (-1g) with Cyclic Pressure

$P_{\text{sat}} = 36-48 \text{ kPa} \quad T_{\text{sat}} = 8.8-15.5 \text{ C}, \quad T_{\text{wall}} = 11 \text{ C}$

Cycle period 180 s; video rate 2.4 x real time
Non-condensing “Pumped” Film in Normal Gravity (-1g)

50 cSt Silicone Oil

Pumping rate 4 ml/min
→ average film growth rate = 8.2 µm/s
Video rate 0.4 x real time
Non-condensing “Pumped” Film in Normal Gravity (-1g)

50 cSt Silicone Oil

Pumping rate 12 ml/min
→ average film growth rate = 24.7 µm/s
Video rate 0.4 x real time
Non-condensing “Pumped” Film in Normal Gravity (-1g)

Silicone Oil

Time to first droplet break-off decreases with increasing pumping rate

Film thickness at first droplet break-off increases with increasing pumping rate
Unstable (-1g) condensing n-pentane film

$T_{\text{wall}} = 11 \, \text{C}, \quad T_{\text{sat}} = 17 \, \text{C}, \quad P_{\text{sat}} = 50 \, \text{kPa}$
Heat Transfer for Unsteady Condensing Film (-1g)

$P_{sat} = 36-48$ kPa, $T_{sat} = 8.8-15.5$ C, $T_{wall} = 11$ C
Ultrasound Measurement of Film Thickness

N-pentane Film, Stable (+1g) Configuration

![Graph showing film thickness over time with two transducers.](image)

- Transducer 1
- Transducer 2
Ultrasound Measurement of Film Thickness

N-pentane Film, Unstable (-1g) Configuration
Summary

- Condensation and evaporation research is critical to meeting the technology needs of the AHST development effort
  - Evaporation and condensation heat transfer and film stability and phase separation phenomena are strongly dependent on gravity level
  - Development of empirical correlations, theoretical models, CFD codes for these processes are all important to the success AHST technology development

- Research conducted to date in the current project includes
  - Film imaging and heat transfer measurements of steady and unsteady condensing films in the laboratory
  - Ultrasound gauging to determine the thickness of stable condensing and non-condensing films and in recording fluctuations in unstable films
  - The use of non-condensing, mechanically pumped films which simulate the growth and instability associated with unstable condensing films in the absence of thermal effects
Questions?

Research supported by NASA OBPR Cooperative Agreements NAG3-2395 and NNC04GA76G
FLEX - Flammability and Extinction Investigations

Michael C. Hicks
NASA Glenn Research Center

June 23, 2004
Acknowledgements:

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- Frederick Dryer, Princeton
- Vedha Nayagam, NCMR
- Benjamin Shaw, UCD
- Forman Williams, UCSD
- Craig Myhre & NASA Engineering Team
Diffusive and Radiative Extinction of Diffusion Flames

\[ \delta = \frac{\text{Flow time}}{\text{Reaction time}} = \frac{\tau_{fl}}{\tau_{ch}} \]

Similar extinction scenarios for different flow configurations:

* Counter-flow
* Cup-burners
* Droplet combustion

Nayagam and Williams, 28th Combustion Symposium 2000
What role can "droplet combustion" investigations play in spacecraft and/or extra-terrestrial Fire Safety Research?

Droplet combustion is a well-characterized fundamental experimental configuration where extinction conditions can be precisely measured ...

- the results obtained can be generalized
- chemistry is well characterized
- numerical scheme is well in hand
- many runs can be made
- coupling of condensed fuel is present
Organizing questions where "droplet combustion" may play a significant role:

1. What is the O₂ mole fraction and total pressure below which a fire cannot exist?

- flammability assessments in terms of the environment's propensity to support fire ... not a "material flammability" assessment
- droplet testing allows for a greater range of environmental conditions ... the entire range of atmospheres could be assessed with "precursor droplet tests"
- use results obtained from FLEX tests to identify test boundaries for follow-on material flammability studies using the FEANICS insert
Organizing questions where "droplet combustion" may play a significant role:

2. What is the relative effectiveness of candidate suppressants to extinguish a fire in reduced gravity, including high \( \text{O}_2 \) mole fraction low pressure environments?

   - compare performance of suppressants in microgravity using a droplet flame configuration ... spherical (quiescent) and axisymmetric (flow) geometries.
   - results will extend modeling capabilities to practical fire configurations in both microgravity and partial gravity environments.

3. What effect does gas-phase radiative absorption play in the overall fire and post-fire environments ... particularly when a radiatively participating suppressant is employed?

   - extend scope of existing ground-based investigations currently using droplet configuration to assess gas phase radiation effects in post-fire \( \text{CO}_2 \) enriched environments.
FLEX - Flammability and Extinction Investigations

1. Limiting Oxygen Index (LOI) Investigation:

Rationale:

- Previous work suggests that the droplet LOI is substantially less in microgravity than is found in normal gravity.
- Slow convective flows tend to lower this LOI even further.
- The droplet test configuration allows an opportunity for a clearer understanding of the physical phenomena controlling the LOI and is useful in extrapolating results to more complex systems.
- Droplet configuration is a reasonable approximation to a very real fire hazard found in burning particles which may become dislodged (either by extinguisher deployment or fuel bubbling (Skylab tests)) from a primary fire site and float undetected to inaccessible regions of the spacecraft.
1. Limiting Oxygen Index (LOI) Investigation (cont):

Approach:

- using n-heptane and methanol fuels provide a map of droplet extinction diameters (De) for different ambient O₂ concentrations
- tests initially performed in quiescent conditions (freely deployed droplet) using N₂ or other inerts as diluent and then repeated with slow convective flows, induced by translating droplet at speeds up to 1.5 cm/s.
- repeat tests with reduced total pressures (O₂ partial pressures similar to those used for a 1 atm total chamber pressure)
- extrapolate results to different flame configurations for follow-on flammability studies using FEANICS insert
FLEX - Flammability and Extinction Investigations

1. Limiting Oxygen Index (LOI) Investigation (cont):

Typical Test Matrix:

- Test number: 50
- Diluent: N₂ or other
- Fuel types: methanol, n-heptane
- Droplet Sizes: 2.0 mm - 5.0 mm
- Total pressures: 0.5 atm, 0.75 atm, 1.0 atm
- Flow: 0 cm/s - 3 cm/s

Diagnostics:

- backlit images of droplet
- OH-emission and color flame images
- wide band and narrow band radiometric measurements

Science Data:

- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions
1. Limiting Oxygen Index (LOI) Investigation (cont):

- simplified theory (AEA) predicts extinction Damköhler number ($D_a$)
- Results of this nature can be extrapolated to other configurations
2. **Suppressant Effectiveness Studies:**

**Rationale:**

- Effectiveness of passive suppressant agents (e.g., gaseous CO$_2$, N$_2$, He) in microgravity environments has not been systematically quantified.
- In certain flame configurations, particularly in microgravity environments where buoyant forces no longer provide a contributing "blow-off" mode of extinction, increased suppressant concentrations, compared to that necessary for 1-g flames, may be necessary.
- Effect of suppressant on the extinction Damköhler number can be used to relate results to other geometries (Hamins et al. C&F 1994).
- Effects on changing flame temperature can be assessed through changes in burning rates and radiant output.
2. *Suppressant Effectiveness Studies (cont)*:

**Approach:**

- chamber will be filled with various concentrations of suppressant and/or suppressant blends (both passive and chemical suppressant agents may be considered) and sufficient levels of O\(_2\) to support a flame.
- droplet extinction diameters (De) [and possibly the droplet regression rates; (D(t)/Do)^2] will be used as a "figure-of-merit" in comparing suppressant effectiveness.
- a range of ambient pressures (0.5 atm to 1.0 atm) and flow conditions (up to 3 cm/s) will used.
FLEX - Flammability and Extinction Investigations

2. Suppressant Effectiveness Studies (cont):

Proposed Test Matrix:
Test number: 178 Diluent: N$_2$ and other
Fuel types: methanol, n-heptane Droplet Sizes: 2.0 mm - 5.0 mm
Total pressures: 0.75 atm, 0.85 atm, 1.0 atm Flow: 0 cm/s - 3cm/s
Suppressants: He, CO$_2$, Halon, etc.

Diagnostics:
• backlit images of droplet
• OH and color flame images
• wide band and narrow band radiometric measurements

Science Data:
• Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions and suppressant concentrations
2. ** Suppressant Effectiveness Studies (cont) :**

- simplified theory (e.g., AEA) correlates De with suppressant concentration with a range of O₂ partial pressures.

- location of local maximum dependant upon gas phase participation and radiative characteristics of flame (i.e., sooting flames easier to extinguish in non-participating gas suppressants ??).
3. **Gas Phase Radiative Absorption Investigation:**

**Rationale:**

- Gaseous CO₂ is the suppressant of choice on ISS; however, this is largely based on ground based experience where radiation losses are often minimal for most small scale fires.

- At elevated temperatures CO₂ becomes an effective thermal absorber and emitter ... effectiveness of suppressant may diminish in space applications.

- Earlier numerical work (Ju and Ronney, '98) showed a decrease in flammability limits of CH₄ when radiative reabsorption was considered (equivalence ratio, at the lean flammability limit, changed from 0.68 to 0.44).

- This is of particular concern in post-fire scenarios where large amounts of CO₂ may have been injected into inaccessible spaces (e.g., behind an experimental rack).

- Temperatures of the gaseous CO₂ would be elevated creating conditions where smoldering particles, dislodged from a primary fire site, would be kept at elevated temperatures and possibly re-ignite.
3. *Gas Phase Radiative Absorption Investigation (cont.)*:

**Approach:**

- droplets will initially be freely deployed in atmospheres of 21% O₂ with varying levels of diluent comprising mixtures of CO₂/N₂
- concentrations of CO₂ up to 75% (i.e., CO₂ displaces only N₂)
- measurements of extinction diameters (De), flame dimensions, and droplet burning rates
- since optical thickness in a participating gas is pressure dependent ... a series of tests will be performed at elevated pressures (up to 3 atm)
3. *Gas Phase Radiative Absorption Investigation (cont.):*

**Proposed Test Matrix:**

- **Test number:** 40
- **Diluent:** N₂
- **Fuel types:** methanol, n-heptane
- **Droplet Sizes:** 5.0 mm
- **Total pressures:** 1.0 atm, 2.0 atm, 3.0 atm
- **Flow:** 0 cm/s
- **Suppressants:** CO₂

**Diagnostics:**

- backlit images of droplet
- OH and color flame images
- wide band and narrow band radiometric measurements

**Science Data:**

- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions and suppressant concentrations
3. **Gas Phase Radiative Absorption Investigation (cont.):**

- preliminary results from recent testing show high concentrations of CO₂ (i.e., 0.74 mole fraction) yield lower burn rates, higher flame radiation, and similar flame dimensions

- results suggest lower flame temperature (possibly due to higher effective gas mixture Cp)

- increase in radiation due to thermal absorption and re-radiation from larger gas volume
FLEX - Flammability and Extinction Investigations

MDCA Capabilities (as currently configured):

- Provides for spherical and axisymmetric flame configurations using droplets
- Symmetric ignition and fuel deployment allows for un-tethered droplets.
- Slow convective flows (up to 3 cm/s) over the burning droplets can be obtained.
- Chamber pressures controllable from 0.02 atm to 3.0 atm with wide range of suppressant/oxidizer mixtures.
MDCA Capabilities (cont):

Potential exists for extended capabilities in MDCA hardware ...

  • PI specific hardware could add capabilities without the need to alter the existing hardware
  • dynamic environments to simulate a suppressant discharge
    ... addition of suppressant during combustion
  • reduction of pressure during combustion
  • solid particles (e.g., PMMA spheres) placed on a fiber and ignited
  • wider range of velocities and/or accelerations with the inclusion of small cameras moving with droplets
FLEX - Flammability and Extinction Investigations

Summary:

Benefits of FLEX testing...

- Hardware already exists (i.e., MDCA)
- Provides a reasonable geometric approximation of realistic spacecraft fire hazards floating embers, molten wire insulation, other ejected particles
- Strong modeling base already exists
  - ... simplified one- and two-dimensional geometry allows for refinements to modeling (detailed chemistry, gas-phase radiation, etc.)
- Easily reproducible and controlled test conditions
  - ... consistent initial droplet diameters, precisely controlled flow rates, ignition energy
- Allowance of a large test matrix with a range of parameters (on the order of 300 test points/investigation)
  - ... less up mass than other configurations, multiple tests per chamber fill
Spacecraft and Navy Materials
Flammability

Review of Some Concepts and Test Methods

David Hirsch
Agenda

- Concepts of spacecraft fire safety
- Spacecraft materials flammability test methods
- Evaluation of flight hardware flammability
- Review of flammability data in conditions of interest to the Navy
- Overview of some flammability test methods recommended for the Navy
Spacecraft Fire Safety

General strategy: prevent fires

- Materials control
- Minimizing potential ignition sources and materials that can propagate a fire
- Controlling the quantity and configuration of flammable materials to eliminate fire propagation paths
Spacecraft Fire Safety (Continued)

Risk management

- Accepted worst case
- Fire extinguishers

U.S. spacecraft fire history
Spacecraft Conditions
Maximum O₂ % and pressures for NASA spacecraft

■ Space Shuttle Orbiter Cabin
  – maximum during normal operations 25.9% O₂, 14.5 psia
  – during EVA preparation: 30% O₂, 10.2 psia

■ Space Shuttle Orbiter Payload Bay: 20.9% O₂, 14.7 psia (Ground)

■ Space Station Internal: 24.1% O₂, 14.5 psia

■ Space Station Airlock: 30% O₂, 10.2 psia

■ Space Station External: 20.9% O₂, 14.7 psia (Ground)
Spacecraft Conditions (Continued)

- Microgravity
- Forced convection
- Enclosed space
Flammability of Flight Hardware - Technical Requirements

- NASA-STD-6001
- NSTS 1700.7B - Safety Policy and Requirements for Payloads Using the Space Transportation System
- SSP 30233 - Space Station Requirements for Materials and Processes
Spacecraft Materials Flammability Assessment for Habitable Flight Compartments

Required materials tests are conducted per NASA STD 6001

- Test 1 - Upward flammability
- Test 2 - Heat and visible smoke release rates using a cone calorimeter
- Test 4 - Wire insulation flammability
- Test 18 - Arc-tracking
- Configurational flammability tests
NASA STD 6001 Test 1

- Upward flame propagation on vertical samples
- Quiescent environment. Worst environment conditions (% oxygen, pressure)
- Point ignition source provided by a chemical igniter
- Sample dimensions: 2.5 in. wide x 12 in. long x worst case thickness
Test 1 (Continued)
Test 1 (Continued)

Major measurements:
- burn length
- burn propagation time
- Ignition of K-10 paper
NASA STD 6001 Test 2
Heat and Visible Smoke Release Rates Using an Oxygen Consumption Calorimeter

- Test method based on the relationship between materials heat of combustion and the amount of oxygen required for combustion

- Test system similar with the system used by ASTM E 1354
Test 2 (Continued)

- 4 x 4 in. samples are exposed to a predetermined radiant energy (25, 50, or 75 kW/m²) under flowing oxygen/nitrogen mixtures

- Sample is autoignited, or burning can be initiated by a spark ignition
Test 2 (Continued)

- Soot collection filter
- Exhaust blower
- Controlled flow rate
- Gas samples taken here
- Load cell
- Laser photometer including temperature
- Temperature and pressure measurements taken
- Soot sample tube
- Exhaust hood
- Cone heater
- Spark igniter
- Specimen

Vertical orientation
Test 2 (Continued)

Major measurements:
- oxygen concentration
- combustion gas temperature and flow rate
- sample mass loss rate
- time to sustained flaming
- smoke obscuration
Test 2 (Continued)

Data obtained:
- Average heat release rate
- Peak heat release rate
- Total heat released
- Effective heat of combustion
- Ignition time
- Smoke obscuration
- CO and CO$_2$ in combustion products
NASA STD 6001 Test 4

- Upward flame propagation on a powered sample installed at 15 degrees from vertical
- Quiescent environment. Worst environment conditions (% oxygen, pressure)
- Point ignition source provided by a chemical igniter
- Sample test section: 12 in. long
Test 4 (Continued)
Test 4 (Continued)

Major measurements:
- burn length
- burn propagation time
- Ignition of K-10 paper
How is NASA test data used for materials selection?

- Pass/fail criteria
- Material usage agreements

Some issues

- Simulation by ground tests of spacecraft conditions (correlation between ground test data and real life)
  - Quiescent environment vs. forced convection
  - Normal gravity vs. microgravity
Extinction boundary for a diffusion flame stabilized over a condensed fuel
Experimental information on quiescent environments vs. forced convection flow effects on flammability

- Ground tests: free convection with gas linear velocity of 50 to 75 cm/s

- Spacecraft: forced convection with linear velocities of 10 to 15 cm/s
Experimental information on normal gravity vs. microgravity effects on flammability

- An upward flame propagation test performed under normal gravity would support flaming combustion under less severe oxygen concentration environments than those under which extinguishment would occur in a quiescent microgravity environment.

- Melting of thermoplastics could generate bubbles with increased bursting strength in microgravity, when burning gaseous and/or molten fuel could be ejected forcibly.
Flammability Tests on Flight Hardware

- A flammability configuration analysis is performed and/or flammability tests are conducted when components are flammable

- Example 1
- Example 2
Navy - Environments of interest

- ambient air - ships
- enclosed space - submarines
- possibility of oxygen depletion in a submarine fire. Note that sub-ambient oxygen concentrations may be worse environments than air for generation of toxic combustion products
- hyperbaric environments for diving; other diluents than nitrogen
Navy - additional flammability parameters of interest

- Spacecraft fire safety strategy focuses on prevention - by rigorous materials control. In microgravity environments, flammability is strongly dependent on oxygen availability; therefore, stopping free convection in a spacecraft is a strong deterrent to post-ignition flame development. Consequently, NASA’s interest in post-ignition fire properties is secondary to materials ignitibility.
Navy - additional flammability parameters of interest (continued)

- Due to its specific operating conditions, the Navy’s interest may well go beyond determining ignition characteristics.

- Post-ignition fire properties also could be of interest. Such properties include flame spread and burn rates; heat and smoke release rates; and toxicity of combustion products. Also, a developing fire could affect both ignition and post-ignition fire properties of surrounding materials through generation of radiant energy.
Flammability under hyperbaric conditions

- Oxygen partial pressure vs oxygen percentage
  Example:
  30.0% O₂, 10.2 psia (pO₂ = 3.06 psia)
  21.9% O₂, 14.7 psia (pO₂ = 3.08 psia)

- Effects of oxygen concentration and total pressures on ignition and flammability characteristics
Flame speed - total pressure relationship

![Graph showing flame speed-total pressure relationship with various oxygen concentrations and pressures.](image)
Flame speed - oxygen concentration relationship

![Graph showing the relationship between flame speed and oxygen concentration for different materials: PTFE, Vitron, Nylon 6/6, and PMMA. The graph plots flame speed (mm/min) against oxygen concentration (%).]
Autoignition temperature - oxygen concentration and pressure effects

![Graph showing AIT (°C) vs Pressure (psi) for different materials: Fluorel E-2160, Vespel SP-21, Nylon 6/6, Neoprene. The graph illustrates how the autoignition temperature decreases with increasing pressure for each material.]
Limiting oxygen index - pressure effects

![Graph showing the relationship between oxygen index and absolute pressure for different materials. The graph plots oxygen index (%) on the y-axis against absolute pressure (atm) on the x-axis. Different materials such as PTFE, Vitron, Neoprene, Nylon 6/6, Glass-Filled Nylon 6/6, and PMMA are represented with distinct markers and lines.]
MIL-STD-2031

- Oxygen-temperature index
- Flame spread index per ASTM E 162
- Ignitibility, heat release, combustion gas generation per ASTM E 1354
- Smoke obscuration per ASTM E 662
- Burn-through fire test
- Quarter-scale fire test
- Large scale open and pressurizable fire tests
- N-gas Model smoke toxicity screening test
Oxygen Index

D 2863

- PTFE > 99.5
- PCTFE > 99.5
- Silicone 45.4
- Zytel 42 31.8
- Viton A 31.5
- Neoprene 23.9
- PE 17.5
- Delrin 17.2
## Oxygen Index

<table>
<thead>
<tr>
<th>Material</th>
<th>D 2863</th>
<th>Upward LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>&gt; 99.5</td>
<td>49.0</td>
</tr>
<tr>
<td>PCTFE</td>
<td>&gt; 99.5</td>
<td>54.3</td>
</tr>
<tr>
<td>Silicone</td>
<td>45.4</td>
<td>23.5</td>
</tr>
<tr>
<td>Zytel 42</td>
<td>31.8</td>
<td>23.0</td>
</tr>
<tr>
<td>Viton A</td>
<td>31.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Neoprene</td>
<td>23.9</td>
<td>17.5</td>
</tr>
<tr>
<td>PE</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Delrin</td>
<td>17.2</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Hirsch et al.
Flame spread index per ASTM E 162

- Radiant heat energy source
- Downward burning on a sample inclined at 30 degrees from vertical
- Major measurements: Surface flame velocity and combustion gas temperature
- A flame spread index defined as a product of a flame spread factor and a heat evolution factor
Flame spread index per ASTM E 162

Some issues:

- Downward flame spread
- Thermocouple measurements
### E 1354 piloted ignition time (s)

<table>
<thead>
<tr>
<th>Material</th>
<th>20 kW/m²</th>
<th>50 kW/m²</th>
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<tbody>
<tr>
<td>Epoxy</td>
<td>337</td>
<td>62</td>
</tr>
<tr>
<td>Epoxy/fiberglass</td>
<td>320</td>
<td>57</td>
</tr>
<tr>
<td>Nylon 6/6</td>
<td>700</td>
<td>74</td>
</tr>
<tr>
<td>PEEK</td>
<td>NI</td>
<td>142</td>
</tr>
<tr>
<td>Phenolic/fiberglass</td>
<td>NI</td>
<td>165</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>403</td>
<td>58</td>
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<tr>
<td>Polypropylene</td>
<td>120</td>
<td>27</td>
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</table>

Scudamore et al
## E 1354 Autoignition time (s)

<table>
<thead>
<tr>
<th></th>
<th>25 kW/m²</th>
<th>50 kW/m²</th>
<th>75 kW/m²</th>
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<tbody>
<tr>
<td>polycarbonate</td>
<td>NI</td>
<td>99</td>
<td>44</td>
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<tr>
<td>polyethylene</td>
<td>141</td>
<td>70</td>
<td>35</td>
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<tr>
<td>PVC</td>
<td>485</td>
<td>421</td>
<td>69</td>
</tr>
<tr>
<td>Navy req (minimum)</td>
<td>300</td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>- assumed piloted?</td>
<td></td>
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</tbody>
</table>

*Holbrow et al*
Comparison of ignitibility in various tests

<table>
<thead>
<tr>
<th>Material</th>
<th>UL94V 1mm thick</th>
<th>UL 94 V 2 mm thick</th>
<th>Min heat flux, kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>V-0</td>
<td>V-0</td>
<td>33</td>
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<tr>
<td>PVC</td>
<td>V-1</td>
<td>V-2</td>
<td>8</td>
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<tr>
<td>PVC, FR</td>
<td>V-0</td>
<td>V-0</td>
<td>11</td>
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</tbody>
</table>

O’Neill et al.
### E 1354 results at 70 kW/m²

<table>
<thead>
<tr>
<th></th>
<th>TTI</th>
<th>PRHR</th>
<th>ARHR</th>
<th>TTI/RHR</th>
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</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>252</td>
<td>161</td>
<td>53</td>
<td>1.56</td>
</tr>
<tr>
<td>PCARB</td>
<td>75</td>
<td>342</td>
<td>115</td>
<td>0.22</td>
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<tr>
<td>PE</td>
<td>47</td>
<td>2735</td>
<td>911</td>
<td>0.02</td>
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<tr>
<td>XLPE</td>
<td>35</td>
<td>268</td>
<td>194</td>
<td>0.13</td>
</tr>
</tbody>
</table>

* Navy req @ 75 kW/m²

- Minimum: 90
- Maximum: 100

Babrauskas et al.
HRR vs. time for PTFE

The graph shows the heat release rate (HRR) in kW/m² as a function of time (in minutes) for different heat flux levels: 20 kW/m² (dashed line), 40 kW/m² (dotted line), and 70 kW/m² (solid line). The peak HRR occurs within the first few minutes, with a subsequent decline to a lower, more stable level.
HRR vs. time for PCARB

- --- 20 kW/m²
- -- 40 kW/m²
- ---- 70 kW/m²

HRR (kW/m²)

TIME (min)
HRR vs. time for PE

![Graph showing HRR vs. time for PE with different heat fluxes: 20 kW/m², 40 kW/m², and 70 kW/m².](image)
HRR vs. time for XLPE
Achieving non-flammability

- Using halogenated polymers
- Using polymers that upon decomposition leave more than 60% of their mass as char
- Incorporating flame retardant

Drawback:
- Toxicity and corrosivity of combustion products
MIL-STD 2031 - Combustion gas generation (per E 1354)

Maximum combustion gas produced at 25 kW/m²

- CO: 200 ppm
- CO₂: 4% by volume
- HCN: 30 ppm
- HCl: 100 ppm
Combustion gas generation (Continued)

Some issues:
- Generally a wider range of compounds are being sought - including HBr, HF, NO\textsubscript{x}
- Fires in enclosed environments would deplete the oxygen and thus create conditions for generation of different combustion products, perhaps more toxic
- E 1354 does not simulate this situation
Mil-Std-2223
Test Methods for Insulated Electrical Wires

- Preparing activity: Navy
- Method 3006 - Wet arc-propagation resistance
- Method 3007 - Dry arc-propagation resistance
## Arc tracking test methods comparison

<table>
<thead>
<tr>
<th>Ranks/Qualifies</th>
<th>Mil-Std-2223 - 3006/3007</th>
<th>NASA STD 6001</th>
<th>ASTM D 3032</th>
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</thead>
<tbody>
<tr>
<td>7-wire bundle</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>400 Hz, 3 phase, 120/208 V</td>
<td>X</td>
<td>X</td>
<td>X – allows alternates</td>
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<tr>
<td>Arc Tracking Test Methods Comparison (continued)</td>
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<tr>
<td>-----------------------------------------------</td>
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<tr>
<td><strong>Arc initiation</strong></td>
<td><strong>3006/3007</strong></td>
<td><strong>NASA STD 6001</strong></td>
<td><strong>ASTM D 2223</strong></td>
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<tr>
<td>Pre-damaged wires/RB</td>
<td>-</td>
<td>Reciprocating blade (RB)</td>
<td>X</td>
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<tr>
<td>Voltage proof test</td>
<td>X</td>
<td>-</td>
<td>X</td>
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<tr>
<td>Visual damage</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>CB's tripped</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>
SS800-AG-MAN-010/P-9290

- System Certification Procedures and Criteria Manual for Deep Submergence Systems

- Cat 3 - materials and components for which definitive information and experience is not available
SS800-AG-MAN-010/P-9290
Category 3 Materials

- Validation of acceptability must be provided
- SS800-AG-MAN does not specify acceptance tests for new components or materials
- Regarding flammability testing:
  Manufacturer’s flammability data is reviewed; if data is inconclusive, testing is required to determine if upon exposure to a standard ignition source the material will self-extinguish and not transfer burning debris
SS800-AG-MAN-010/P-9290
Flammability issues

- **Materials:**
  - Acceptable if self-extinguish immediately upon removal from flame
  - All others require review and approval of proposed quantities and locations

- **Alternate procedure for assemblies:**
  - Evaluate flammability of individual components, if heat is produced when energized, location suitability. Submit for review and approval.
Oxygen systems

Similar systems design strategy as NASA’s

- Limit rapid pressurization, velocity, flow impingement, high pressure sections, control of particle generation
- Minimize possibility of leaks
- Follow ASTM Standard Guides for Oxygen Service:
  - G63 - Evaluating non-metals
  - G94 - Evaluating metals
  - G88 - Designing systems for oxygen service
AN EARTH-BASED MODEL OF MICROGRAVITY PULMONARY PHYSIOLOGY

Ronald B. Hirschl, M.D., Joseph L. Bull, Ph.D, and James B. Grotberg, Ph.D., M.D.

There are currently only two practical methods of achieving μG for experimentation: parabolic flight in an aircraft or space flight, both of which have limitations. As a result, there are many important aspects of pulmonary physiology that have not been investigated in μG. We propose to develop an earth-based animal model of μG by using liquid ventilation, which will allow us to fill the lungs with perfluorocarbon, and submersing the animal in water such that the density of the lungs is the same as the surrounding environment. By so doing, we will eliminate the effects of gravity on respiration. We will first validate the model by comparing measures of pulmonary physiology, including cardiac output, central venous pressures, lung volumes, and pulmonary mechanics, to previous space flight and parabolic flight measurements. After validating the model, we will investigate the impact of μG on aspects of lung physiology that have not been previously measured. These will include pulmonary blood flow distribution, ventilation distribution, pulmonary capillary wedge pressure, ventilation-perfusion matching, and pleural pressures and flows. We expect that this earth-based model of μG will enhance our knowledge and understanding of lung physiology in space which will increase in importance as space flights increase in time and distance.
Recent experiments have allowed for the molecular forces and deformations of liquid-liquid and biofluid-soft solid interfaces to be visualized and measured with unprecedented precision in real time. The talk will describe recent measurements and new theoretical treatments of the interactions and deformations of liquid-liquid interfaces [1] such as suspended droplets during collisions, coalescence and detachment, and the implications of the results to predictions of droplet coalescence and biological cell-cell interactions in general. The effects of van der Waals and other short-range molecular and thermal fluctuation forces on droplet coalescence and film instability will be described, as will the role of buoyancy forces and dissolved gases on the hydrophobic interaction between oil droplets and gas bubbles in water [2,3], this interaction being one of the major forces between biological molecules and surfaces in aqueous solutions. Current work is also focusing on the role of surfactants and other amphiphilic molecules at the liquid-liquid interfaces. Preliminary results on the thin film rheology (‘lubricity’ and ‘wear’) of model biological and real cartilage surfaces in various model biofluids and synovial fluid will also be presented, with a discussion of the implications of the results to cartilage, bone and joint degeneration.

Advanced Environmental Monitoring Technologies

Darrell Jan, Ph.D.
Advanced Environmental Monitoring & Control
Program Element Manager
Life Detection Science & Technology Office
NASA/Caltech-Jet Propulsion Laboratory

June 22, 2004
Apollo 12 photograph, taken by lunar module pilot Alan Bean, mission commander Pete Conrad retrieves parts from the Surveyor.
Monitoring & Controlling the environment

- Air
- Water
- Plant chambers
- Food and Food Preparation surfaces
- Gradual buildup of toxic species
- Hazardous events
- Chemical
- Biological

sensors
actuators
Gradual buildup of harmful chemical or microbials

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>DETECTION LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIORITY 1</td>
<td>PPM</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.1</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.01</td>
</tr>
<tr>
<td>Methanol</td>
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</tr>
<tr>
<td>Dichloromethane</td>
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</tr>
<tr>
<td>Perfluoropropane (F218)</td>
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</tr>
<tr>
<td>Acetone</td>
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<tr>
<td>Octamethylcyclotetrasiloxane</td>
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</tr>
<tr>
<td>2-Propanol</td>
<td>3</td>
</tr>
<tr>
<td>Freon 82</td>
<td>5</td>
</tr>
</tbody>
</table>

*microgravity combustion not shown

Hazardous event such as fire or leakage
ILLUSTRATIVE EXAMPLE:

CANARY
Why a canary?

- Continuous air monitor
- Ground-based heritage
- Doesn’t require skilled operator
- Relatively low mass, low power
  - Can consider placing in several locations
- High sensitivity to many toxic gases
- Multifunctional potential:
  - air
  - water
  - food
  - music
- Probably will work in μgravity
- Built in signal processing
- Edible
Why not a canary?

- Requires fuel (food), water, maintenance
- Generates waste products
- Overload requires complete system replacement
- Quantitative capability suspect
- Limited life
- Difficult to interface and network
- Low precision display
  - Could be hard to read in μg
Why not a canary?

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- Generates waste products
- Overload requires complete system replacement
- Quantitative capability suspect
- Limited life
- Difficult to interface and network
- Low precision display
  - Could be hard to read in $\mu$g
Why not a canary?
A canary in water
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Ground-based Commercial technology

- High mass
- High power requirement
- High operator skill
- High capability
- May require gravity

- Lower mass
- Lower power requirement
- Low operator skill
- Low capability
- May require gravity

• Breakthroughs needed to achieve high capability and low mass/power plus autonomy
High Capability & Low Mass/Power + Autonomy = key to future SpaceFlight
Current Practice: in flight

Volatile Organic Analyzer (VOA):
measures about 30 volatile organic species

Major Constituent Analyzer (MCA):
Nitrogen, Oxygen, Carbon Dioxide, Water vapor

ICES 2003-01-2646 Validation of the Volatile Organic Analyzer (VOA) aboard the International Space Station
Thomas Limero, et al

2000-01-2345
International Space Station Carbon Dioxide Removal Assembly Testing
James C. Knox
Current Practice: Post Flight

Grab Sample Bottles: Thorough analysis
By GCMS, over 100 species

ICES 2003-01-2646 Validation of the Volatile Organic Analyzer (VOA) aboard the International Space Station
Thomas Limero, et al

Figure S: Grab Sample Container (GSC)

Formaldehyde Badges

ICES 2003-01-2647 Toxicological Assessment of the International Space Station Atmosphere with Emphasis on Metox Canister Regeneration
John James, et al
Current Practice: Post Flight

Figure 1. Overview of the airflow inside Zarya with opposed panels opened to 90 degrees. This diagram was adapted from Alibaruho et al. (1999) with addition of the flow arrows going from the walls toward the isle through open panels. The goal of the figure is to indicate the potential for disrupted airflow where panels have been opened.
Miniature Mass Spectrometer for Planetary Exploration and Long Duration Human Flight

- 0.5 amu resolution, 1-300 amu range
- Used by astronauts in Shuttle Mission 5A and beyond to detect ammonia and air leaks outside the International Space Station

The QMSA Packaged as the Astronaut’s Trace Gas Analyzer (TGA)

The Quadrupole Mass Spectrometer Array (QMSA)

Smallest flight Mass Spectrometer in the world!
HARDWARE AND DATA ACQUISITION SYSTEM

First Generation Enose: Flight Experiment
Volume: 2000 cm$^3$  Mass: 1.4 kg
Power: 1.5 W ave., 3 W peak
Computer: HP 200LX
Materials:
- container: cast aluminum
- wetted surfaces: glass, PTFE, polypropylene
- seals: silicon rubber

Second Generation ENose
Optimized sensors, faster analysis, improved sensitivity
Volume: 760 cm$^3$  Mass: 0.8 kg
Power: 1.5 W ave., 3 W peak
Computer: Handspring Visor Neo PDA
Materials:
- container: anodized aluminum
- wetted surfaces: alumina, parylene
- seals: Kal-Rez
16S rDNA phylogenetic tree

Red clones are opportunistic pathogen

Liver abscess
hyperurecemia

Cat scratch
disease;
Bone-marrow
infection

Halogen-
reducers

Endocarditis;
hepatic granuloma

SVOZV
(potable
water)

SRVK-hot
(regenerated
water)

Halogen-
reducers

NASA/CP—2004-213205/VOL1
This research concerns flowing granular materials and the development of ways to predict the behavior of such flows and the means to control them. Granular flows are common in industrial processes, mining operations, and in nature. In general, they are poorly understood. The research treats flows in which the particles interact through collisions rather than enduring contacts. Such flows are expected to be important in materials processing activities carried out in space and in mining operations on the surface of the Moon and Mars.

The specific phenomenon of interest in the research is the segregation of the particles in a flow due to differences in their size and/or mass. In many industrial processes a homogeneous aggregate is desired; in these, segregation is undesirable. However, in the mining industry, segregation is exploited in sorting and crushing operations. Because segregation is not well understood, attempts to suppress it or exploit it proceed on an ad hoc basis and are expensive.

In systems that do not involve much agitation of the grains, several mechanisms that involve gravity have been identified as leading to segregation. However, in highly agitated flows there is a mechanism independent of gravity that is available to drive segregation. This is associated with spatial gradients in the energy of the velocity fluctuations of the grains. Collisional interactions between and among different types of grains require that, in general, differences in their concentrations exist to balance differences in particle fluctuation energy.

This segregation mechanism is often masked by gravitational segregation mechanisms on Earth. It is expected to be of equal importance to gravitational segregation in the reduced gravity on Mars and to be the dominant mechanism for segregation on the Moon. It is the only mechanism for segregation in space.

The segregation of colliding particles of different size and mass will be studied on the International Space Station in an axisymmetric shear cell in which the flow is created by the relative motion of bumpy boundaries of a cylindrical annulus. The profile of particle agitation across the cell is controlled by employing boundaries with different bumpiness. The particle segregation is observed using digital video, image analysis, and sophisticated particle tracking algorithms. Two basic systems are to be examined: in one, the spheres are of equal size but differ in mass; in the other, they are of equal mass but differ in size. The observations will be compared to results of simulations and the predictions of theory to establish their respective limits and suggest possible improvements.

Studies of a segregation mechanism that is especially important in reduced gravity should benefit mining and materials-handling activities associated with in-situ resource utilization applications on Mars and the Moon. It should also assist in the interpretation of geologic deposits, particularly in low gravity. It will eventually benefit the design of manufacturing operations and in-space fabrication technologies in zero gravity in support of exploration.
Human Support Technology
Research, Development & Demonstration

Jitendra Joshi
Eugene Trinh
NASA Headquarters
A Journey to Inspire, Innovate, and Discover

- The Human Support Technology research, development, and demonstration program addresses the following areas at TRL 1 through 6:
  - Advanced Power and Propulsion
  - Cryogenic fluid management
  - Closed-loop life support and Habitability
  - Extravehicular activity systems
  - Scientific data collection and analysis
  - Planetary in-situ resource utilization
Human Support Technology Program
Overview

Program Goal

• Our single purpose is to reduce the human support systems development risks to an acceptable level
  – The risks we address are documented in the Bioastronautics Critical Path Roadmap and fall into three categories:
    • Risks to the safety and health of the crew and mission success due to the hazardous environment, autonomy, and isolation
    • Risks to the affordability of the missions by requiring excessive logistical support for the humans in terms of buffers, critical system resources, and non-regenerative supplies
    • Risks to the human support systems in terms of the ‘ilities’ (operability, reliability, maintainability, etc.)
  – Each risk is further characterized by research enabling questions (Bioastronautics Critical Path Roadmap - BCPR)

• Acceptable mitigation through development of products that answer the enabling questions is required for all of the types of risks
### BCPR Risks relevant to HST

#### AHST Risk Rating Criteria for System Performance Risks

<table>
<thead>
<tr>
<th>Rating</th>
</tr>
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<tbody>
<tr>
<td>R</td>
</tr>
<tr>
<td>Y</td>
</tr>
<tr>
<td>G</td>
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<table>
<thead>
<tr>
<th>RISK NUMBER</th>
<th>Theme</th>
<th>Discipline</th>
<th>Risk Category</th>
<th>ISS (1yr)</th>
<th>Moon (30d)</th>
<th>Mars (30m)</th>
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<td>7</td>
<td>HHC</td>
<td>Env Health</td>
<td>Define Acceptable Limits for Trace Contaminants in Air and Water</td>
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<td>BH&amp;P</td>
<td>SHFE</td>
<td>Mismatch between Crew Cognitive Capabilities and Task Demands</td>
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<td>R</td>
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<td>36</td>
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<td>AEMC</td>
<td>Monitor Air Quality</td>
<td>Y</td>
<td>R</td>
<td>R</td>
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<td>AEMC</td>
<td>Monitor External Environment</td>
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<td>R</td>
<td>R</td>
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<td>AEMC</td>
<td>Monitor Water Quality</td>
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<td>R</td>
<td>R</td>
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<td>AHST</td>
<td>AEMC</td>
<td>Monitor Surfaces Food and Soil</td>
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<td>R</td>
<td>R</td>
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<td>AHST</td>
<td>AEMC</td>
<td>Provide Integrated Autonomous Control of Life Support Systems</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<td>41</td>
<td>AHST</td>
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<td>Provide Space Suits and Portable Life Support Systems</td>
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<td>Y</td>
<td>R</td>
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<td>42</td>
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<td>AFT</td>
<td>Maintain Food Quantity and Quality</td>
<td>Y</td>
<td>G</td>
<td>R</td>
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<td>43</td>
<td>AHST</td>
<td>ALS</td>
<td>Maintain Acceptable Atmosphere</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<td>44</td>
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<td>ALS</td>
<td>Maintain Thermal Balance in Habitable Areas</td>
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<td>Y</td>
<td>R</td>
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<td>45</td>
<td>AHST</td>
<td>ALS</td>
<td>Manage Waste</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
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<td>ALS</td>
<td>Provide and Maintain Bioregenerative Life Support Systems</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<td>AHST</td>
<td>ALS</td>
<td>Provide and Recover Potable Water</td>
<td>G</td>
<td>Y</td>
<td>R</td>
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<tr>
<td>48</td>
<td>AHST</td>
<td>AHST</td>
<td>Inadequate Mission Resources for the Human System</td>
<td>Y</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>49</td>
<td>AHST</td>
<td>SHFE</td>
<td>Mismatch between Crew Physical Capabilities and Task Demands</td>
<td>G</td>
<td>Y</td>
<td>R</td>
</tr>
<tr>
<td>50</td>
<td>AHST</td>
<td>SHFE</td>
<td>Mis-assignment of Responsibilities within Multi-agent Systems</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
</tr>
</tbody>
</table>
Human Support Technology Program
Research and Development Content

ADVANCED ENVIRONMENTAL MONITORING & CONTROL
EXTRA-VEHICULAR ACTIVITIES TECHNOLOGY
ADVANCED LIFE SUPPORT
ADVANCED INTEGRATION MATRIX
SPACE HUMAN FACTORS

CONTINGENCY RESPONSE TECHNOLOGIES
- FIRE PREVENTION, DETECTION, AND SUPPRESSION
- IN-SITU FABRICATION AND REPAIR

In Situ RESOURCE UTILIZATION for HUMAN SUPPORT
LOW-GRAVITY and EXPLORATION RESEARCH
- ADVANCED MATERIALS RESEARCH
- QUANTUM TECHNOLOGIES for EXPLORATION
- MULTIPHASE FLOW TECHNOLOGIES
Advanced Life Support

- Duplicate the functions of the Earth in terms of human life support
- Without the benefit of the Earth’s large buffers — oceans, atmosphere, and land masses

- Question is one of how small can the requisite buffers be and yet maintain extremely high reliability over long periods of time in a hostile environment
- Space-based systems must be small, therefore must exercise high degree of control
- Long-duration missions dictate regenerative systems — minimize re-supply
## Parameters for Human Life Support Across Mission Scenarios

<table>
<thead>
<tr>
<th>Duration (Human Tended)</th>
<th>System A: Short-duration, micro-g</th>
<th>System B: Long-duration, micro-g</th>
<th>System C: Long-duration, planetary surface, partial-g</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 – 14 days (Roundtrip)</td>
<td>LP – Low Power</td>
<td>HP – High Power</td>
<td>System A: Short-duration, micro-g</td>
</tr>
<tr>
<td>1 – 5 days</td>
<td>BR – Body Mounted Radiator</td>
<td>DR – Deployable Radiator</td>
<td>System B: Long-duration, micro-g</td>
</tr>
<tr>
<td>1 – 18 months</td>
<td>Closed</td>
<td>Closed</td>
<td>System C: Long-duration, planetary surface, partial-g</td>
</tr>
<tr>
<td>12 – 24 months (Roundtrip)</td>
<td>Closed</td>
<td>Open</td>
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</tr>
<tr>
<td>17 – 20 months</td>
<td>Closed</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>1 – 7 days</td>
<td>Closed</td>
<td>Open</td>
<td></td>
</tr>
</tbody>
</table>
Exploration Timeline


First Uncrewed CEV Flight 1st Crewed CEV Flight 1st Human Mission to Moon

Lunar landing outpost

6 year prime contractor lead-time

Lunar Outpost Tech. Test System B&C

CEV ECLSS Tech Test System A

Lunar Outpost Bioregenerative Test System C

Last year for lunar landing

6 year prime contractor lead-time
Life Support Requirements
Mass Breakdown
(Per Person-Day)

<table>
<thead>
<tr>
<th>DAILY INPUTS - NOMINAL</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.84</td>
</tr>
<tr>
<td>Food Solids</td>
<td>0.62</td>
</tr>
<tr>
<td>Water in Food</td>
<td>1.15</td>
</tr>
<tr>
<td>Food Prep Water</td>
<td>0.79</td>
</tr>
<tr>
<td>Drink</td>
<td>1.62</td>
</tr>
<tr>
<td>Hand/Face Wash Water</td>
<td>1.82</td>
</tr>
<tr>
<td>Shower Water</td>
<td>5.45</td>
</tr>
<tr>
<td>Clothes Wash Water</td>
<td>12.50</td>
</tr>
<tr>
<td>Dish Wash Water</td>
<td>5.45</td>
</tr>
<tr>
<td>Flush Water</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>30.74</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DAILY OUTPUTS - NOMINAL</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>1.00</td>
</tr>
<tr>
<td>Respiration and Perspiration Water</td>
<td>2.28</td>
</tr>
<tr>
<td>Urine</td>
<td>1.50</td>
</tr>
<tr>
<td>Feces Water</td>
<td>0.09</td>
</tr>
<tr>
<td>Sweat Solids</td>
<td>0.02</td>
</tr>
<tr>
<td>Urine Solids</td>
<td>0.06</td>
</tr>
<tr>
<td>Feces Solids</td>
<td>0.03</td>
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<tr>
<td>Hygiene Water</td>
<td>6.68</td>
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<tr>
<td>Clothes Wash Water</td>
<td>11.90</td>
</tr>
<tr>
<td>Clothes Wash Latent Water</td>
<td>0.60</td>
</tr>
<tr>
<td>Other Latent Water</td>
<td>0.65</td>
</tr>
<tr>
<td>Dish Wash Water</td>
<td>5.43</td>
</tr>
<tr>
<td>Flush Water</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>30.74</strong></td>
</tr>
</tbody>
</table>

5.02 - 30.74 kg per person-day

11.3 Metric Tons Per Person-Year
Advanced Life Support

Commander Lousma replaces ARS LiOH canisters on middeck
S82-28921 03/31/82

Mission Pilot Ken Bowersox repairing the Regenerative Carbon Dioxide Removal System wiring.
07/09/92 STS050-20-012

Mass Savings Using a Regenerative Physicochemical Subsystem:
Shuttle Regenerable Carbon Dioxide Recovery System (RCRS)

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass Requirement (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiOH (Conventional CO2 Removal)</td>
<td>635 kg</td>
</tr>
<tr>
<td>RCRS (Regenerable CO2 Recovery System)</td>
<td>226 kg</td>
</tr>
</tbody>
</table>

0-300 kg

Length of Mission (days)
Drivers for Water Purification Technologies:

Closure
• Recovery projected to be 80 % of the recycled water. Water recovery from brine essential.

Power
• Current baseline is power consuming.

Expendables
• ISS system will require ~ 400 kg filters/year

Variable Gravity Compatibility
• Fluids management issues pertinent to system performance in variable gravity
Goals and Objectives

• Intelligent Monitoring and Control of Life Support Systems through focused system analysis, simulation and transport modeling

• TRL 6 Sensor Technologies for human health and process control:
  – Internal (I), for micro and/or reduced gravity environments:
    • Sample Acquisition and Handling optimized for multiphase (i.e., gas, liquid, solid) behavior
    • Monitoring Air, Water, Surface, Food and Soil Quality
    • Monitoring Air, Water, Surface, Food and Soil Microbial Safety
  – External (E) EVA and/or on Planetary Surfaces environment hazards monitoring (e.g., reactive chemicals, erosive dust)
  – I/E Hardware/Software Diagnostic Signatures (leakage, acoustic signals) for Replacement or Repair
  – I/E Particulates and Leak detection

• Tools for establishing Exploration Chemical/Microbial requirements
  – Contamination acceptability limits and monitoring requirements

• Miniaturization to reduce mission resource requirements
  – Maintain high capabilities and sensitivities, while simplifying for robust design
Advanced Extravehicular Activity

- EVA is required for all phases/spirals of the Vision, both in-space and planetary
- Supporting the human outside the protective environment of the vehicle or habitat requires an integrated EVA System
- A new EVA suit/system will be required to support this new initiative
  - The current EVA suit is over 25 years old and is facing significant obsolescence issues
  - The current EVA suit is not compatible with the planetary environments of either the Moon or Mars and does not support the logistical requirements of long term missions
- Development of a new EVA suit/system requires technology advancements similar to those required in the development of a new space vehicle
The TΦFFy Project will conduct a robust research program to address microgravity fluid physics issues associated with Flow Boiling, Condensation, Phase Separation, and System Stability of the liquid metal-based Rankine Power Conversion Systems. The project will include concept development and normal gravity testing, reduced gravity aircraft flight campaigns and flight experiment definition and development.
In-Situ Resource Utilization 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 (ISRU)

Design Drivers are
- Reduced mass and power
- Increased safety and reliability

HST-Cleveland 22 June 2004 ET/RC
Fire Prevention, Detection, and Suppression

- Prevention is the first line of defense against fires in any vehicle design
  - Crew Exploration Vehicle, Habitat, EVA systems
- Acceptance criteria for material flammability in reduced gravity is generally unknown
  - Current methods are *thought* to be conservative but …
  - Margin of safety is unknown and varies with gravity level
  - Over-design based on presumed material flammability increases system mass
- Material flammability risks must be considered in the selection of atmospheres for exploration vehicles and habitats
- False positive (nuisance) alarms on ISS require crew action and reduce confidence in fire detection and suppression (FDS) system
- Spacecraft fire suppression and response based on terrestrial experience and techniques
  - Limited incorporation of fire characteristics in reduced gravity
- Suppressant effectiveness for reduced gravity fire scenarios hasn’t been quantified

- Material flammability assessment requirements are written into vehicle specifications
- Performance of advanced detection and suppression systems is insufficient for down-select/design using relevant low-and partial-gravity data
In Situ Freeform Fabrication Technologies

Fused Deposition Modeling

ABS
PC
PPSF
Al2O3
Si3N4

(MSFC)

Electron Beam Freeform Fab

Aluminum
Titanium
Alloys

Ti-6Al-4V

(LaRC/JSC)

In Situ SFF Deliverables

<table>
<thead>
<tr>
<th>Project Plan Summary</th>
<th>Collaborators</th>
<th>FY '05</th>
<th>FY '06</th>
<th>FY '07</th>
<th>FY '08</th>
<th>FY '09</th>
<th>FY '10</th>
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<tbody>
<tr>
<td>Fabrication Technologies</td>
<td>GRC, Purdue Univ, Col School of Science</td>
<td>▼</td>
<td>△</td>
<td>△</td>
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<tr>
<td>A. Combustion Synthesis Parts and Tools for</td>
<td>Optimize Design</td>
<td>TRL 4</td>
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<td>B. Electron beam Freeform Fabrication</td>
<td>Ceramic Glass</td>
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</table>

Self-Propagating High-Temp Synthesis

Refractory carbides, borides, silicides, inter-metallics, composites, FG mat'ls

Initial Mixture

Propagating Wave

Product

(GRC)

HST-Cleveland 22 June 2004 ET/RC
How will we conduct our Business?

- Low TRL work through competitive NRAs
  - Long lead time items
- Rapid Technology Development Teams
  - Multi-disciplinary teams with clear objectives and deliverables
  - Mature technology to TRL 6
- Directed Research
  - Focused problems

There will be a healthy balance between intramural and extramural work.
Milestone Plan

<table>
<thead>
<tr>
<th>Planned</th>
<th>S</th>
<th>D</th>
<th>K</th>
<th>C</th>
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Exploration EVA System

Lara Kearney
EVA Office
Johnson Space Center
June 22, 2004
In January 2004, the President announced a new Vision for Space Exploration. NASA’s Office of Exploration Systems has identified Extravehicular Activity (EVA) as a critical capability for supporting the Vision for Space Exploration. EVA is required for all phases of the Vision, both in-space and planetary. Supporting the human outside the protective environment of the vehicle or habitat and allowing him/her to perform efficient and effective work requires an integrated EVA “System of systems”.

The EVA System includes EVA suits, airlocks, tools and mobility aids, and human rovers. At the core of the EVA System is the highly technical EVA suit, which is comprised mainly of a life support system and a pressure/environmental protection garment. The EVA suit, in essence, is a miniature spacecraft, which combines together many different subsystems such as life support, power, communications, avionics, robotics, pressure systems and thermal systems, into a single autonomous unit. Development of a new EVA suit requires technology advancements similar to those required in the development of a new space vehicle. A majority of the technologies necessary to develop advanced EVA systems are currently at a low Technology Readiness Level of 1-3. This is particularly true for the long-pole technologies of the life support system.
Existing NASA EVA architecture is over 25 years old (1977) and has evolved from Apollo, Skylab and Shuttle technology and operations.

All current EVA systems use large amounts of crew time and vehicle resources; require costly regular ground based maintenance, resupply, and monitoring; and are only compatible with low earth orbit, zero-gravity activities.
## Summary of Existing Architecture Challenges

### Environment
- Suit mass, mobility, visibility and comfort are not compatible with partial gravity planetary environments; Inertial control and useful work/reach area in zero gravity is hampered
- Suit protection from dust intrusion is inadequate
- Available thermal insulation materials either only work in vacuum conditions or are thick and impede suit mobility and glove dexterity; Even with active heating, touch temperatures are limited to short durations and narrow ranges (-120 to +150°F)
- Radiation definition, monitoring and protection are inadequate beyond earth’s ionosphere
- Sensitive environments and science devices can be contaminated by suit by-products

### Productivity
- EVA information processing is limited to simple radio voice and suit/medical telemetry and is based on old technology that is not in-flight reprogrammable; No hands free display exists
- Medical monitoring and treatment of EVA crew is minimal
- Robotic EVA aids in use are primarily large arms with limited mobility and dexterity; Human rovers and mobile dexterous robots need additional attention; Most robotic aids are too reliant upon unique visual and handling aids
- Tools are limited to manual force/torque reaction and zero-gravity transport/restraint; There is limited environmental and mechanical analysis; No drills; Few true repairs; Delicate materials not easily handled

### Logistics
- EVA overhead penalties are high in terms of mass, volume and time; 2600 lbs and 90 ft³ for suits, tools, carriers and consumables on STS-103 for HST; < 20 percent effective crew time
- Suit consumables are expended and require frequent replenishment or considerable time/power to recharge; No in-situ resource utilization is possible
- No suit maintenance capability beyond limited resizing, ORU replacement and consumables replacement
- Airlock designs expend gas/power and are not compatible with dust containment

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Lara Keamey  
June 22, 2004
The Exploration EVA System should use revolutionary new technology, common components, human-robotic cooperation and a flexible architecture to support multi-destination operation with minimal system reconfiguration

Features

- Lightweight, highly mobile suits and dexterous gloves to increase crew productivity, enable long-duration missions and high EVA use rates, mitigate crewmember injury and fit a wide range of crewmember sizes
- Maintainable life support system architecture that is easily reconfigurable to enable multiple destinations
- Integrated human-robotic work capability to increase safety, efficiency, & productivity
- State of the art communications and computing capability for multi-media crew-ground interaction (e.g., integrated communications, high tech information systems, and heads-up displays)
- Operating pressure regimes which decrease EVA overhead by drastically reducing or even eliminating pre-breathe protocols
- Advanced thermal control to increase crew comfort, decrease consumables, and enable multiple destinations (e.g., aerogel insulation, active cooling and heating)
- Common hardware with other vehicle systems to increase vehicle safety & decrease mission mass through common sparing (e.g., power, communication, instrumentation, life support, thermal control)
The Exploration EVA System should follow a spiral development, in parallel with the CEV spirals.
EVA Core and Spiral I/2014 Technology

System Architecture
- Flexible, lightweight, maintainable PLSS
- Lightweight structures
- Integral suit/PLSS interface
- Rapid recharge and checkout

Thermal Control
- Radiators
- Micro refrigeration/heating system
- Auto cooling control
- Phase change materials
- Thermal insulating materials
- Conduction cooling garment

Power
- Batteries
- Fuel Cells

CO₂ Removal
- Cyclic absorption/regeneration
- Venting membranes

Spiral II/Lunar Technology

Environmental Protection
- Dust containment and removal
- Radiation protection

Field Recharge & In-the-Field Servicing
- O₂ connectors
- Field serviceable packs
- In-situ Resource Utilization

Interfaces
- Human-robotic work aids
- Airlock/vehicle
- Crew Escape Systems
- Bio-medical Sensors

Suits
- Lightweight materials
- Mobility systems
- Gloves/Boots
- VIsors
- Zero pre-breathe

Manufacturing Technology
- Lightweight materials
- Custom glove sizing

Electronics and Information
- Heads-up display
- Integrated high capacity communication
- Smart systems monitoring, control, caution, & warning
- High reliability fans, pumps, actuators, sensors

Spiral III/Mars Technology

CO₂ Removal
- Laser CO₂ Decomposition
- Cryogenic CO₂ Removal

Environmental Protection
- Radiation protection
- Dust containment and removal

Field Recharge & In-the-Field Servicing
- O₂ connectors
- Field serviceable packs
- In-situ Resource Utilization

Interfaces
- Human-robotic work aids
- Manned rovers
- Airlock/habitat
- Bio-medical Sensors

Airlock
- Lightweight structures
- Reduced consumables

Spiral N / Exploratory 0-G Technology

Environmental Protection
- Radiation protection

Thermal
- Venting hydride cooler
- Venting cryogenic cooler

Interfaces
- Human-robotic work aids
Boiling is a complex phenomenon where hydrodynamics, heat transfer, mass transfer, and interfacial phenomena are tightly interwoven. An understanding of boiling and critical heat flux in microgravity environments is of importance to space based hardware and processes such as heat exchange, cryogenic fuel storage and transportation, electronic cooling, and material processing due to the large amounts of heat that can be removed with relatively little increase in temperature. Although research in this area has been performed in the past four decades, the mechanisms by which heat is removed from surfaces in microgravity are still unclear. Recently, time and space resolved heat transfer data were obtained in both earth and low gravity environments using an array of microheaters varying in size between 100 microns to 700 microns. These heaters were operated in both constant temperature as well as constant heat flux mode.

Heat transfer under nucleating bubbles in earth gravity were directly measured using a microheater array with 100 μm resolution operated in constant temperature mode with low and high subcooled bulk liquid along with images from below and from the side. The individual bubble departure diameter and energy transfer were larger with low subcooling but the departure frequency increased at high subcooling, resulting in higher overall heat transfer. The bubble growth for both subcoolings was primarily due to energy transfer from the superheated liquid layer–relatively little was due to wall heat transfer during the bubble growth process. Oscillating bubbles and sliding bubbles were also observed in highly subcooled boiling. Transient conduction and/or microconvection was the dominant heat transfer mechanism in the above cases. A transient conduction model was developed and compared with the experimental data with good agreement.

Data was also obtained with the heater array operated in a constant heat flux mode and measuring the temperature distribution across the array during boiling. The instantaneous heat transfer into the substrate was numerically determined and subtracted from the supplied heat to obtain the wall to liquid heat flux. This data was then correlated with high speed (>1000Hz) visual recordings of the bubble growth and departure from the heater surface acquired through the bottom of the heater. The data indicated that microlayer evaporation and contact line heat transfer were not major heat transfer mechanisms for bubble growth, similar to the conclusions for constant wall temperature. The dominant heat transfer mechanism appeared to be transient conduction into the liquid as the liquid rewetted the wall during the bubble departure process.

Pool boiling heat transfer measurements from heaters of varying aspect ratio were obtained in low-g (0.01 g ±0.025 g) and high-g (1.7 g ±0.5 g) using the KC-135 aircraft. The heater aspect
ratio was varied by selectively powering arrays of heaters (2x2, 2x4, 2x6, 2x8, and 2x10) in a 10x10 heater array containing individual heaters 700x700 µm² in size. The liquid was degassed to an air concentration below 3 ppm by repeatedly pulling a vacuum on the vapor/gas above the liquid before measurements were made. The heat fluxes were generally observed to decrease as the heater aspect ratio increased. As the wall superheat increased, Marangoni convection appeared to increase and cause the large bubbles that formed on the heater to shrink, allowing liquid to rewet the surface, increasing the heat transfer. Why Marangoni convection was observed in what is essentially a fully degassed fluid is unclear, but may be due to contaminants or isomers within the fluid.
Boiling Heat Transfer Mechanisms in Earth and Low Gravity: Boundary Condition and Heater Aspect Ratio Effects

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University of Maryland
College Park, MD 20742

This work was sponsored by NASA HQ Office of Biological and Physical Sciences
Acknowledgements

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  John Benton
  Fatih Demiray
  Nagaraja Yaddanapuddi

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  John McQuillen (Grant monitor)
  Jerry Meyers (Constant heat flux results)
  Sam Hussey (Constant heat flux results)
  Glenda Yee (Constant heat flux results)
  John Yaniec
Overview

- Introduction
- Earth gravity boiling mechanisms
  - Constant wall temperature
  - Constant wall heat flux
- Low gravity boiling mechanisms
  - Heater size effects
  - Heater aspect ratio effects
Introduction
Relevance to NASA’s Mission

- Provide fundamental understanding of gravity effects on boiling heat transfer mechanisms at various gravity levels so equipment and transfer processes can be designed efficiently.
Model of Boiling: Mikic and Rosenhow (1969)

- Heat transfer occurs primarily through conduction into liquid after bubble departs surface
Model of Boiling: Microlayer Evaporation Model (Cooper and Lloyd–1969)

- Heat transfer occurs primarily through evaporation of a thin film “microlayer” underneath bubble
Model of Boiling: Contact Line Evaporation
(Wayner, Stephan)

- Heat transfer occurs primarily through conduction/evaporation of a thin meniscus at the three phase contact line
Photograph of Heater Array

1–7mm
Feedback control circuit regulates heater temperature
Frequency response up to 15 kHz.
• Heater resistance changes linearly with temperature
• R1 is chosen for each heater such that the heat flux is constant for all heaters in the array
• Heat flux does not change appreciably with changes in Rh
Test Chamber

Pressure regulator
Compressed air
Stainless steel bellows
Viewports
Stirrer
Light
Window
FC-72
Microscale heater array
Filter
Fill port/vacuum
CCD camera

Not to scale
Experimental Results
(Earth Gravity)
Test Conditions for Constant Temperature Tests

- Fluid: FC-72
- Pressure=1 atm ($T_{\text{sat}}=56.7$ °C)
- Wall temperature=76 °C
- Bulk temperature=52 °C, 41 °C
Heat Transfer Variation During Single Bubble Event

- $T_{\text{bulk}} = 52 \, ^\circ\text{C}$
Change in heat transfer profile observed for low subcooling case—may be linked to changes in baseline heat transfer.
• $T_{\text{bulk}}=41 \, ^\circ\text{C}$
• Bubble oscillates in size due to changing balance between evaporation and condensation
Oscillating Bubble Heat Transfer

Graph showing heat transfer (mW) over time (ms) with data points for outer diameter and inner diameter in microns.
Contact Line Heat Transfer Under Sliding Bubble

- $T_{\text{bulk}} = 41 \, ^\circ\text{C}$
- Bubble velocity $\approx 2.2 \, \text{cm/s}$
Contact Line Sliding Bubble Heat Transfer

- Higher heat transfer observed for advancing contact angle.
Transient Conduction Rewetting Model

\[ \dot{q}' = \frac{k(T_w - T_i)}{\sqrt{\pi \alpha_i t}} \implies \dot{q}(t) = \frac{2k(T_w - T_i)}{\sqrt{\pi \alpha_i}} w v \sqrt{t} \]

- Model given in Demiray and Kim, IJHMT (2004)
- Heater heat transfer proportional to wetting velocity \( v \)
Measured vs. Predicted Heat Transfer

- Good agreement in location and magnitude of peaks in heat transfer.
- Good agreement in shapes of curves.
Test Conditions for Constant Heat Flux Tests

- Fluid: FC-72
- Pressure = 1 atm \( (T_{\text{sat}} = 56.7 \, ^\circ\text{C}) \)
- Bulk temperature = 52.3 °C
- Applied voltage: 6.2 V to 8.3 V
- Average wall temperature: 90 °C to 110 °C

(Single bubbles, coalescing bubbles)
• Initial high voltage (8.7 V–10 V) applies for 3.5 s to initiate nucleation.
• Test voltages between 6.2 V and 8.3 V for 14.2 seconds.
Temperature Measurements

- Data from each heater acquired at 1130 Hz
Temperature Distribution Movie (6.8 V case)

- Video acquired at 1130 Hz.
- Each heater is colored according to heater temperature.

Case: pcb5 6p8v pp
Time Resolved Temperature Distribution During Bubble Nucleation and Departure (6.8 V case)

- Images presented every other frame (565 Hz)
Average Heater Temperature Variation (Single Bubbles)

- Maximum temperature occurs when dry spot size is maximum (M).
- Minimum temperature occurs at bubble departure (D).
Time Resolved Temperature Distribution During Bubble Coalescence and Departure (7.1 V case)

• Images presented every other frame (565 Hz)
 Bubble coalescence results in a small drop in wall temperature.
Determination of Wall-to-Liquid Heat Transfer

- Compute temperature distribution within substrate at each time step after imposing heater temperature distribution on surface.
- Line-by-line TDMA with Gauss-Seidel iteration applied in all three directions
- Heat transfer into substrate was computed at each time step, then subtracted from supplied power to obtain heat transfer into liquid.
Heat Flux Distribution Movie (6.8 V case)

• Video acquired at 1130 Hz.
• Each heater is colored according to heater heat flux.
Time Resolved Heat Flux Distribution During Bubble Nucleation and Departure (6.8 V case)

- Images presented every other frame (565 Hz)
Average Heat Flux Variation (6.8 V case)

- Minimum heat flux occurs when dry spot size is maximum (M).
- Maximum heat flux occurs at bubble departure (D).
Average Heat Flux Variation (7.1 V case) (Bubble Coalescence)

M: Maximum dry spot
C: Coalescence event
D: Bubble departure

Heat Flux (W/cm²)

Frame No.
Experimental Results
(Low Gravity)
Test Conditions for Low-G Results

- Fluid: FC-72
- Pressure=1 atm ($T_{\text{sat}}=56.7$ °C)
- 7 mm heater array
- Bulk temperatures: 28 °C – 52 °C
Low-Gravity Boiling Measurements ($T_{\text{bulk}} = 28^\circ\text{C}$)

- At low wall superheats, surface characteristics affecting nucleation site density appear to dominate the boiling curve behavior.
- Boiling is dominated by thermocapillary convection at higher wall superheats.
- Larger heaters (> 49 mm²) may not dryout completely at higher superheats.

![Diagram showing heat flux and superheat relationship](image)
Aspect Ratio Boiling Observations (7 mm array)

- Strong influence of thermocapillary convection
- Surface tension wants to maintain a spherical bubble shape and can cause an increase in wetted area (compared to square heaters)

\[ \Delta T_{\text{sat}} = 35^\circ \text{C}, \Delta T_{\text{sub}} = 29^\circ \text{C} \]

1.4 x 2.8 mm\(^2\), (2x4) 1.4 x 4.2 mm\(^2\), (2x6) 1.4 x 5.6 mm\(^2\), (2x8)
For a given wall superheat, the heat flux decreases with increasing aspect ratio.

Increasing two dimensionality of the thermocapillary flow field around the heater (increasing aspect ratio).

Mechanisms that increase wetted area fraction:
- Thermocapillary effects
- Surface tension
Thermocapillary flow results from surface tension gradients along an interface which can form due to:

- temperature gradients
- material composition
- electrical potential
**FC-72 Characterization**

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• Mass spectrometry analysis was performed by Dr. Thomas Hartman at Rutgers University
BXF/MABE Flight Experiment
EXTRACORPOREAL SHOCK WAVE THERAPY AS A COUNTERMEASURE FOR BONE LOSS ON EARTH AND IN SPACE

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INTRODUCTION
The purpose of this study is to apply extracorporeal shock waves in an ex vivo rat model with the intent to mimic naturally occurring microdamage that stimulates bone tissue to rebuild. Whereas a continued lack of physiological activity will result in disuse osteopenia, our working hypothesis is that prophylactic application of extracorporeal shock waves will cause microdamage in bone that will stimulate the remodeling, repair and renewal cascade.

METHODS
Extracorporeal shock waves were applied to the anterior surface of the femoral middiaphysis of the prone rat, using the Lithotriptor Modulith® SLX. Waves were applied toward the periosteal surface of the bone in the planar direction. One of six different regimes was applied; wave number and peak pressures were varied, e.g. 500, 1000 and 1500 waves at 43, 76 or 100 MPa. Tissues were explanted and fixed in ethanol prior to bulk staining with calcein blue and embedding in polymethylmethacrylate. Using commercially available image analysis software (OpenLab), the number and mean length of microcracks, observed under an epifluorescent microscope, was compared between the treated side and the contralateral control.

RESULTS
In six of nine experimental groups, more cracks were visible in femoral cross sections from the treated side. These differences were highly significant in the experimental group exposed to 1500 shocks, at all peak pressures, in the lower two peak pressure regimes in the group exposed to 1000 shocks and in the highest peak pressure regime in the group exposed to 500 shocks. Furthermore, the mean microcrack length was comparable to that occurring in response to mechanical loading in physiological and fatigue studies.

DISCUSSION/CONCLUSION
This study proves the feasibility of using exogeneously produced microdamage in bone to mimic that occurring in vivo due to physiological loading and is a first step toward development of a prophylaxis for osteopenia. Currently we are applying the same protocols in an in vivo model to determine whether the presence of exogeneously produced microdamage triggers the remodeling cascade associated with maintenance of healthy bone tissue.
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One of the greatest uncertainties affecting the design of multiphase flow technologies for space exploration is the spatial distribution of phases that will arise in microgravity or reduced gravity. On Earth, buoyancy-driven motion predominates whereas the shearing of the bubble suspension controls its behavior in microgravity. We are conducting a series of ground-based experiments and a flight experiment spanning the full range of ratios of buoyancy to shear. These include: (1) bubbles rising in a quiescent liquid in a vertical channel; (2) weak shear flow induced by slightly inclining the channel; (3) moderate shear flow in a terrestrial vertical pipe flow; and (4) shearing of a bubble suspension in a cylindrical Couette cell in microgravity. We consider nearly monodisperse suspensions of 1 to 1.8 mm diameter bubbles in aqueous electrolyte solutions. The liquid velocity disturbance produced by bubbles in this size range can often be described using an inviscid analysis. Electrolytic solutions lead to hydrophilic repulsion forces that stabilize the bubble suspension without causing Marangoni stresses. We will discuss the mechanisms that control the flow behavior and phase distribution in the ground-based experiments and speculate on the factors that may influence the suspension flow and bubble volume fraction distribution in the flight experiment.
MOBI: Microgravity Observations of Bubble Interactions

Some Thoughts on the Differences between Bubbly Flow at 1g and 0g

Donald Koch
Cornell University

Ashok Sangani
Syracuse University
Increasing Ratio of Shear to Buoyancy
Monodisperse (Potential-Flow) Bubble Suspension $d \approx 1.4 \text{ mm}$

Electrolytes induce hydrophobic bubble-bubble repulsion to prevent coalescence without Marangoni stresses

Dual impedance probe: Bubble velocity and volume fraction profiles
Hot film probe: Liquid velocity
Video: Bubble size and aspect ratio
0.8 M MgSO\textsubscript{4} Increases Viscosity by About 60%

However, Potential Flow Theory Still Provides Accurate Predictions of Drag Coefficient and Aspect Ratio
Averaged equations for bubble suspension

- Bubble phase:
  \[ \frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x_j} (\phi w_j) = 0 \]

  \[ n \frac{dI_i}{dt} = - \frac{\partial P_{ij}}{\partial x_j} + nF_i^b \]

  \[ n \frac{dT}{dt} = - \frac{\partial Q_j}{\partial x_j} + S \]

- Entire mixture:
  \[ \frac{\partial u_j}{\partial x_j} = 0 \]

  \[ \frac{\partial}{\partial t} (1 - \phi) u_i^L + \frac{\partial}{\partial x_j} (1 - \phi) u_i^L u_j^L = - \frac{1}{\rho} \frac{\partial \sum ij}{\partial x_j} + (1 - \phi) g_i \]
Disperse-phase pressure

Negative pressure due to hydrodynamic interactions leads to instabilities on Earth that are absent in microgravity.
Detection of Instabilities: 
Vertical Channel Studies

Liquid Velocity Variance  
Much Larger than Expected  
For Homogeneously 
Distributed Potential-Flow Bubbles

Visual Evidence of Structure:  
Some Horizontal Clustering
Instability in Vertical and Inclined Channel

Frequency Spectrum of Liquid Velocity Shows Most of the Energy is at Frequencies Larger than $U/a$

An Instability That is More Apparent to the Naked Eye Arises at Higher Volume Fractions and Inclination Angles
Inclined Channel:
Bubble volume fraction variation drives suspension flow
Viscosity associated with the instability-induced Reynolds stress is 100 times larger than fluid viscosity and 30 times larger than viscosity predicted for a homogeneous suspension.

\[ \nabla \cdot [\mu_{eff} \nabla U] = -\rho g \phi + \nabla p_f \]
Instability induced bubble pressure or diffusivity is also very large

\[
 n(F_B + F_L + F_D) = \nabla P \rightarrow \nabla \cdot [(U_B + U_L)\phi] - \nabla \cdot [D\nabla \phi] = 0
\]

\[
 D = \frac{1}{36\mu_f dR_d} \frac{\partial P}{\partial \phi}
\]
Apparent bubble viscosity and pressure observed in ground-based experiments in an inclined channel are greatly enhanced by an instability.

The instability results from the negative pressure due to hydrodynamic interactions which would be absent at 0g.
Volume fraction profile in a vertical pipe flow
Deficit of bubbles near pipe wall due to repeated bubble bouncing from wall which would be absent At 0g

FIG. 12. Sequence of photographs illustrating one cycle of the bubble bouncing motion. The bubble radius is 0.7 mm and the inclination angle is 83°.
Couette Flow of Bubble Suspension at 0g

\[ U \approx u_L \]
Gravity-induced instability absent
Repeated bouncing from wall absent
Potential flow approximation more accurate in high Re microgravity shear flow than on Earth

\[ \text{Re} = \frac{\rho \Gamma a^2}{\mu_f} \]
Volume fraction Profile by FEM

\[ S_t = 0.7 \]
\[ \gamma = 1 \]
\[ a/R_m = 0.0078 \]
\[ Re = 40 \]
Minimum and maximum volume fractions

$S_t = 0.7$
$\gamma = 1$
$a/R_m = 0.0078$
$L/a = 15$

Reynolds Number

Minimum and maximum volume fractions $\phi_{inner}$ and $\phi_{outer}$ with average volume fractions $\phi_{av} = 0.1$ and $\phi_{av} = 0.2$.
Lattice-Boltzmann simulations for bubble suspension at finite Re

Bubbles modeled as non-deformable spheres with no tangential stress boundary conditions (specular reflection of lattice gas)
Simulation Parameters:

\[ \frac{R}{L} = 5 \]
\[ \frac{L}{d} = 7.67 \]
\[ \text{Re} = 0.117 \]
Conclusions

A buoyancy-driven instability (not readily apparent to the naked eye) greatly enhances the apparent bubble-phase viscosity and pressure in an inclined channel flow.

Buoyancy driven bubble-wall interactions create a deficit of bubbles near the wall in vertical pipe flow.

These effects should be absent in 0g.

We predict that the bubble volume fraction distribution in microgravity Couette flow will result from a competition between bubble-phase pressure and centrifugal forces.
Acknowledgements

Ying Tsang
Xiaolong Yin
Roberto Zenit

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Humpback whale courtesy of Alaska Dept of Fish and Wildlife
MICROFLUIDIC AND DIELECTRIC PROCESSING OF DNA

Ronald G. Larson, Lin Fang, Lei Li, Vijay Namasivayam, and Mark A. Burns

Department of Chemical Engineering, University of Michigan, Ann Arbor, MI 48109-2136, U.S.A.

ABSTRACT

The manipulation of DNA polymers for genomics, health monitoring, and other applications can be in principle be carried out in microfluidic devices. Using single-molecule experiments and Brownian dynamics simulations we have considered isolated DNA molecules near adsorbing and non-adsorbing walls in the presence of a simple shearing flow and in an evaporating droplet. We have also used electric fields to stretch DNA molecules and adhere them to surfaces, where we might eventually study their interactions with proteins, including proteins that repair or protect DNA from radiation or other damage.

As a test problem, we have chosen the flow in a drying water droplet resting on a substrate. Because of the pinned contact line, the droplet does not shrink its radius until the very last stages of drying, but instead shrinks its height. As a result, fluid that evaporates from the edge of the droplet must be replaced by fluid flowing to the edge from the droplet center [1]; see Fig. 1.

![Figure 1. The flow in a drying droplet with pinned contact line.](image)

This flow convects solute towards the droplet edge, where it deposits it in a ring [1], or “water spot,” frequently seen on dishware that has been left to dry. The “coffee ring” effect can be used to advantage in genomics applications. Schwartz and coworkers have shown that the flow in a drying droplet can be used to stretch out and deposit DNA molecules onto a glass surface treated with 3-aminopropyltriethoxysilane (APTES) to make them strongly bind DNA molecules, which can then be subjected to a restriction enzyme digestion, and the length and relative positions of the fragments measured by simple fluorescence optical microscopy, using DNA stained by intercalating dyes.

We also studied a second flow, the torsional shearing flow produced by motor-driven rotation of a glass disc rotating about its axis above a parallel cover slip. In this simple shearing flow, Brownian dynamics simulations in the absence of hydrodynamic interactions predict that the molecules will become highly stretched as they become adsorbed irreversibly onto a surface [2]. Surprisingly, the observed stretch was much weaker than predicted, even weaker than that
observed in the droplet-drying flow. This reduced stretch was observed not only for DNA chains adsorbed to the surface, but also for chains in the fluid at distances from the surface less than around 1/3 the contour length $L$ of the DNA molecules, which was around $L = 21$ microns for lambda-phage DNA and $L = 67$ microns for T2 DNA [3].

To investigate further the weak stretch of DNA molecules near surfaces in simple shearing flows, we chose another simple shearing flow, namely the pressure-driven channel flow. In this flow, as in torsional shearing flow, we found very weak stretch near the surface, and, moreover, found that the concentration of DNA molecules near the surface was depleted relative to that in the bulk, qualitatively in agreement with recent Brownian dynamics simulations of Jendrejack et al. [4], who included hydrodynamic interactions in their simulations. The hydrodynamic interactions therefore appear to induce migration of stretched DNA molecules from the surface. In this flow, as in torsional shearing flow, we found very weak stretch near the surface, and, moreover, found that the concentration of DNA molecules near the surface was depleted relative to that in the bulk, qualitatively in agreement with recent Brownian dynamics simulations of Jendrejack et al., who included hydrodynamic interactions in their simulations. The hydrodynamic interactions therefore appear to induce migration of stretched DNA molecules from the surface.

Given the imperfect stretch obtained in fluid flows, we have been investigating the use of AC electric fields to stretch DNA molecules. Following the work of Washizu et al., we used a microfabricated device to impose a high frequency, high gradient electric field onto stained DNA molecules, which responded by stretching and migrating to the nearest electrode. The stretching is greatly enhanced by the presence of an entangled polymer matrix for reasons that are still poorly understood (5).

REFERENCES

Microfluidic and Dielectric Processing of DNA

Hua Hu, Lei Li, Lin Fang, Ronald Larson
Manish Chopra, Vijay Namasivayam,
Mark Burns
Dept. of Chemical Engineering
University of Michigan

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NASA National Space Biomedical Research Institute (NSBRI)
NSF Nano Interdisciplinary Research Team
DNA Repair Enzymes

- MutS - detects base-pair mismatches
- Photolyase - removes uv-induced thymine dimers
- DNA glycosylase - recognizes damaged bases
- BRCA1 - repair enzyme, mutations in which leads to breast cancer
- RecA - helps repair double-stranded breaks
Figure 3. The repair of double-strand breaks in DNA. Double-strand breaks can result from exposure to ionizing radiation, oxidative damage, and spontaneous cleavage of the sugar-phosphate backbone of the DNA molecule. Their repair can be effected by either rejoining the broken ends (left) or by homologous recombination with a sister DNA molecule (right). Both processes involve different multi-protein complexes.

From Friedberg 2003
Surface Fixation of DNA

- Deposition by droplet drying
- Molecular “combing” - Bensimon, et al.
- Fluidic suction
- Electro-stretching and anchoring
- Surface tethering
Prototype Microfluidic “Device”

Coffee ring phenomenon
(Deegan RD, et al, NATURE 389: (6653) 827-829 OCT 23 1997)

DNA stretching in an evaporating droplet
(Jing JP, et al., P NATL ACAD SCI USA, 1998)

Microarrays for DNA Analysis
(Blossey R. et al, Langmuir 2002, 18, 2952-2954)
DNA Genomics in an Evaporating Droplet

(Schwartz et al.)
Theory: Model

- Mass, momentum and heat balances in three regions:
  1. Vapor
  2. Liquid
  3. Vapor-liquid interface

\[ \Delta c = 0 \]

\[ J = -D \nabla c \]

\[ \nabla \cdot \dot{\mathbf{o}} = 0 \]

\[ \nabla \cdot \mathbf{v} = 0 \]

\[ \Delta T = 0 \]

Flow is axisymmetric
Results: Temperature Field

The temperature distribution on the droplet surface can be approximately fitted by equation: \[ T = k\tilde{r}^2 + c \]

where, \( k \) and \( c \) are two fitting constants
Theory

- Approximate analytical results with Marangoni force from lubrication assumption

\[
\tilde{u}_r = \tilde{u}_r \left( \frac{3 \tilde{z}}{\tilde{h}} - \frac{3 \tilde{z}^2}{2 \tilde{h}^2} \right) - Ma \tilde{h} \frac{h_o}{R} \left( \frac{\tilde{z}}{\tilde{h}} - \frac{3 \tilde{z}^2}{2 \tilde{h}^2} \right)
\]

\[
\tilde{u}_z = \frac{3}{4} \frac{1}{1 - \tilde{t}} \left[ + \lambda(\theta) \left( 1 - \tilde{r}^2 \right)^{\lambda(\theta) - 1} \left( \frac{\tilde{z}^3}{3 \tilde{h}^2} - \frac{\tilde{z}^2}{\tilde{h}} \right) \right] + \frac{3}{2} \frac{1}{1 - \tilde{t}} \left[ 1 - \tilde{r}^2 \right] \left( 1 - \tilde{r}^2 \right)^{\lambda(\theta) - 1} \left( \frac{\tilde{z}^2}{2 \tilde{h}^2} - \frac{\tilde{z}^3}{3 \tilde{h}^3} \right) \tilde{h}(0, \tilde{t}) + Ma \frac{h_o}{R} \left( \frac{\tilde{z}^2}{\tilde{h}} - \frac{\tilde{z}^3}{\tilde{h}} \right) - Ma \tilde{r}^2 \frac{h_o}{R} \left( \frac{\tilde{z}^3}{\tilde{h}^2} \right) \tilde{h}(0, \tilde{t})
\]

\[
Ma = \frac{\beta k t_f}{\mu R}, \quad \lambda(\theta) = \frac{1}{2} - \frac{\theta}{\pi}
\]
Results: Comparison Between FEM and Analytical Results, Ma=1193

Comparison of velocity fields with Marangoni stress, Ma = 1193
Contact angle, θ=40°

\[ \tau_{rz} \big|_{z=h} = \frac{d\sigma}{dr} \]
Deposition from Octane droplet

- Particle deposition patterns w/ Marangoni
Flowfield in Drying Water Droplet: Comparison Between Experiments and Computations

- **Velocity field** (to reduce the effect of Brownian motion, 250-300 droplets are measured)
Modeling

- **Bead-spring model**
- **Solve using Brownian dynamics (BD)**
DNA deposition from an evaporating droplet

exp

sim

fast evap  slow evap
Comparison Between Simulations and Experiments in Drying Droplets

Droplet: simulation and experimental results agree at medium evaporation rate
Molecular Combing

adapted from Bensimon and coworkers
DNA Electro-Stretching
DNA Stretching

Immobilization

Thiol-On -Gold

Thiol labeled 12-mer (Sigma Genosys)

Lambda DNA (Gibco BRL)

Ligation Reaction

DNA Immobilized on Gold Electrode

Pump through channels patterned with gold electrodes
Enzymatic Cleavage of DNA
Interaction of Dnase I (red) with lambda DNA (green)
Radiation sensor for space environment (from Thomas Zurbuchen, Umich)
Average space radiation

- Space radiation and its components observed at 1 AU.
- UM operates the instruments that measure particles up to 0.1 MeV/nuc.
Modeling of Space Radiation

- Most energetic particles are accelerated in space by shocks.
- These shocks are generated by fast coronal mass ejections.
- UM has a DOD modeling center to model CMEs, their shocks, and the particles they produce.
SUMMARY

Accurate analytic solutions to the fluid flow in a drying droplet can be obtained with and without Marangoni stress using the lubrication approximation. The experimental flow field in water shows much weaker Marangoni effect than predicted, but in octane the expected strong Marangoni flow is observed. The drying droplet flow, molecular combing, fluidic suction, and electrostretching are all capable of aligning and fixing DNA so that interactions of DNA molecules with proteins can be studied. In the future, we plan to examine DNA repair proteins in vitro and in vivo through collaborations at the University of Michigan.
Thanks!
SOLIDS INTERACTING WITH A GAS IN A MICROGRAVITY APPARATUS

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The long-term human or robotic exploration of the Moon and Mars requires the exploitation of indigenous mineral and/or atmospheric resources. Technologies for In-Situ Resource Utilization (ISRU) must be developed for propellant production, habitat, infrastructure, extraction of water and breathable gas, etc.

Although a few of the required minerals are abundant (silicon, sulfur, iron, magnesium, aluminum), others are mainly present in trace amounts (sodium, potassium, chromium, titanium, He3, etc). Consequently, ISRU requires mining, transporting, processing, and separating massive quantities of solid materials.

On Earth, these activities have been carried out on a large scale for more than a century in the oil, chemical, pharmaceutical, mining, food, and infrastructure industries. However, because the basic principles governing the interactions of solids and gases are poorly understood, the design of reliable solids plants still involves three empirical steps: (1) process conception on the lab scale; (2) exhaustive tests in a pilot unit; and (3) operation of a demonstration plant.

Research in the lab answers basic questions of reactivity, contacting, grinding, particle-size-distribution, etc. The pilot unit then reveals practical challenges in scale-up, control, waste disposal, transport, start-up, safety, long-term reliability, wear, maintenance, filtration, product separation, etc. Finally, the demonstration plant showcases commercial viability of the process.

Technology development for ISRU must strike a different balance between empirical design and rational predictions than industrial activities on Earth. While for example new gas-solid processes can be tested on the KC-135, it is more difficult to realistically mimic conditions of reduced gravity at the pilot scale. Thus, ISRU development must also rely on simulations and theory to understand the cost of scale-up.

In computer simulations, solids are followed as discrete entities. Here, the challenge is to model accurately the interactions with the surrounding gas and the collisions amongst particles.
Theories, on the other hand, derive a set of differential equations, usually treating the gas and solid phases as inter-penetrating continua. Neither method should be used blindly for design.

A weakness of simulations is that they simplify interactions to be tractable. A limitation of theories is that basic constitutive laws, drag relations and boundary conditions are not well established, mainly because practical gas-solid suspensions are dense, agitated, inhomogeneous and unstable. For example, in large facilities, solids form clusters that degrade performance. Thus it is harder to scale-up a process involving solids than it is to do so with a single fluid.

Encouragingly, direct numerical simulations (e.g., lattice-Boltzmann) have begun to inform basic gas-solid interactions. However, they must first be tested against well-controlled experiments before using them in reliable process design.

In this context, our main objective is to produce an experimental benchmark for theories and simulations. To do so, the SiGMA flight hardware uses an axisymmetric shearing cell that is shared with other experiments. Unlike experiments such as fluidized beds where the gas velocity must be large enough to defeat particle weight, microgravity will permit us to control independently particle agitation and gas flow.

So far, we have used theories and simulations to design the experiment; we have tested a prototype on the ground and on the KC-135; and the NASA-Glenn team has made progress designing the SiGMA flight hardware. Developers of realistic simulations and theories await our results.

In the talk, we will illustrate the convenience of a long-lasting microgravity environment for studying flows of granular materials with and without gas interaction. We consider collisional granular flows of nearly elastic spheres featuring a single constituent or binary mixtures in various bounded geometries. We review the equations of the kinetic theory for the conservation of mass, momentum, fluctuation energy and species concentration. We illustrate their solutions for shear flows in rectilinear or axisymmetric rectangular channels with or without a body force. We show that proper boundary conditions yield numerical solutions in good agreement with molecular dynamical simulations and with data from physical experiments carried out in microgravity.
Microgravity Segregation of Energetic Grains (μgSEG)

Solids interacting with a Gas in a Microgravity Apparatus (SiGMA)

Michel Louge and James Jenkins
Granular Flow Module

Collisional flows of solid particles

Planetary missions, solid waste management & separation, in situ resource utilization (ISRU).

Microgravity Segregation of Energetic Grains (μgSEG)

Gullies in the northern wall of a crater at 39.1°S, 166.1°W.
Granular Flow Module

Solids interacting with a Gas in a Microgravity Apparatus (SiGMA)

Agitated solids interacting with a gas

Chemical, oil and energy industries; solid transport & drying, waste management & water recovery, thermal systems, ISRU.
Granular Flow Module

Dense, quasi-static particle assemblies
Solid transport and storage, soil mechanics, ISRU.

Robert Behringer

Force networks
Activities

Solids interacting with a Gas in a Microgravity Apparatus (SiGMA)

Microgravity Segregation of Energetic Grains (μgSEG)

Use extended microgravity to isolate basic interaction phenomena in granular media
Part I

Collisional granular flows

Granular segregation

μgSEG
“Temperature” of a colliding granular material

fluctuation velocity $u_i$

$$T = \frac{1}{3} m \, u_i \, u_i$$

fluctuation kinetic energy of the grains


“granular temperature” $\rightarrow$ viscosity

$$\mu_s \propto \rho_s d \sqrt{T / m f_{\mu}(v)}$$

$\rightarrow$ conductivity

$$k_s \propto \rho_s d \sqrt{T / m f_{k}(v)}$$
Collisional granular segregation

In a fully-developed, steady, rectilinear flow:

\[ 0 = (...) \nabla \ln T + \frac{n_A}{nT} \left( \frac{\partial \mu_A}{\partial n_A} \nabla n_A + \frac{\partial \mu_A}{\partial n_B} \nabla n_B \right) \]

\[ \mu g SEG \]

Dominant segregation mechanism in reduced gravity; granular flows on moons and planets; solid waste management, ISRU.
**Approach**

\[ \mu gSEG \]

- Theory
- Scale-up
- Experiments
- Simulations
Part II

Agitated solids interacting with a gas

SiGMA
Gas-solid suspensions

Predict flow behavior at moderate Stokes numbers, low or moderate Reynolds number, and over the entire range of solid volume fractions.

• ISRU, waste management, solid transport
• thermal systems, water recovery
• chemical engineering industries
• oil industry, solid combustion
• agriculture and food industries
• mining industry
Drag force in the limit \( Re = 0 \)

Random array of static spheres
Predictions from theory, experiment and simulation

total drag force
\[
\frac{3\pi \mu d u_{\text{Interstitial}}}{3\pi \mu d u_{\text{Interstitial}}}
\]

courtesy of Martin van der Hoef
Viscous dissipation experiments

Reduce boundary speeds until the viscous dissipation of fluctuation energy dominates its collisional counterpart.

Test duration requires long-lasting microgravity.
Gas drag on agitated solids

Impose a gas pressure gradient on the agitated, sheared granular material.

SiGMA
Approach

SiGMA Scale-up theory experiments

Lattice-Boltzmann simulations

\( T / \dot{\gamma} R \)

Haitao Xu, Michel Louge

Rolf Verberg, Donald Koch, Chris Pelkie
Benefits

Use extended microgravity platform to

Obtain practical information for multiphase flows.
Inform technologies for human exploration of space
and for Earth-based industries.
Rotating Reverse Osmosis for Wastewater Reuse

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Background: Reverse osmosis (RO) has long been in use as a physical membrane separation technology, and it may be useful for wastewater reuse for long-term space missions. However, concentration polarization decreases the flux of solvent through the membrane and the rejection of contaminants as a result of an increase in the solute concentration near the membrane surface. Urea, sodium chloride, and detergent (Geropon TC-42) are major contaminants in spacecraft wastewater. In addition, numerous organic contaminants such as 2-(2-butoxyethoxy) ethanol, caprolactam, 2-propanol, formaldehyde, and methanol have also been found at low concentrations in condensate collected from the cabin of the spacecraft. As the length of space missions increases and wastewater is reclaimed for use as potable water, it is necessary to remove all of these contaminants.

Objectives: Our previous work established the concept of a low-pressure rotating reverse osmosis membrane system. The rotation of the cylindrical RO filter produces shear and Taylor vortices in the annulus of the device that decrease the concentration polarization and fouling commonly seen with conventional RO filtration techniques. A mathematical model based on the film theory and the solution-diffusion model agrees well with the experimental results obtained using this first generation prototype. However, based on the model, the filtrate flux and contaminant rejection depend strongly on the transmembrane pressure. Therefore, the goal of our current work is to improve the flux of the device by increasing the transmembrane pressure by a factor of 3 to 4. In addition, the rejections for a wider variety of inorganic and organic compounds typically found in space mission wastewater are measured.

Rejection of Target Contaminants by Selected Membranes: Flat sheet samples of commercially available reverse osmosis, low pressure RO (LPRO), and nanofiltration (NF) membranes have been tested using a dead-end stirred-cell to remove conventional wastewater contaminants (sodium chloride, urea, and ammonium carbonate) and organic contaminants found in spacecraft condensate. By combining experimental rejection results for various compounds with a model based on the size and electrostatic exclusion properties of the membranes, the pore sizes of the membranes are estimated to be 0.33 nm for RO, 0.34 nm for LPRO, and 0.44 nm for NF membranes. The rejections for both organic and inorganic compounds for these membranes are shown in Figure 1. The rejections of 2-(2-butoxyethoxy) ethanol (BEE) and caprolactam are approximately 80% for the RO and LPRO membranes, because their molecular weights/molecular radii, 162 Da/0.32 nm for BEE and 113 Da/0.28 nm for caprolactam, are large enough to be rejected due to size exclusion. The rejection of these compounds is also relatively high (over 60 %) for the NF membrane. The rejection of ionic compounds is also high (over 80 %) for all membranes due to electrostatic exclusion effects. The rejection of 2-propanol is lower than that of NaCl even though these compounds have similar molecular weights due to electrostatic exclusion of the ionic compound. Urea, formaldehyde, and methanol rejections are quite low because the molecules are small and uncharged. As a result, they are difficult to reject.
by size exclusion or by electrostatic exclusion. Furthermore, the rejection of urea is substantially lower than 2-propanol even though they have the same molecular weight of 60.1 Da. This is because the molecular radius of urea (0.18 nm) is smaller than that of 2-propanol (0.26 nm).

Figure 1. Rejection of different compounds for RO, LPRO, and NF. Operating conditions: ΔP=800 kPa; stirring speed=400 rpm; feed concentration=1 mM; recovery=60 %. (a) RO (AK), (b) LPRO (ESPA), and (c) NF (ESNA) (▲, urea; ■, ammonium carbonate; ○, sodium chloride; ○, methanol; □, 2-(2-butoxyethoxy) ethanol; Δ, caprolactam; ∇, formaldehyde; ◊, 2-propanol).

Rotating Reverse Osmosis: A second generation rotating reverse osmosis system has been designed and fabricated to function at a much higher transmembrane pressure than the original system. The new device operates at 500 psi (3450 kPa) compared to the first generation prototype that operated at 150 psi (1035 kPa). The second generation prototype and fluid circuit (Figure 2a) have also been designed so that testing can be conducted for much longer time periods: tests lasting 4 weeks or more compared to a maximum of a 6-hour test conducted with the first-generation prototype.

Preliminary three day tests exhibit high flux (Figure 2b) and high rejection (over 70 % for NaCl, 80 % for (NH₄)₂CO₃, 97 % for detergent) for the duration of the experiment while maintaining a high recovery ranging from 75 to 90 %. This recovery is significantly higher than the average of recovery of 25 % for typical spiral wound RO systems, a property that is particular advantageous for maximum water recovery. The second generation device exhibits a flux four times greater than that of the first generation prototype primarily due to the higher operating pressure. These experiments are the first step in the validation of rotating reverse osmosis at high transmembrane pressures over long time periods.

Figure 2. (a) Photograph of second generation rotating reverse osmosis filter and fluid circuit and (b) Flux as a function of time for a 3 day experiment. Operating conditions: LPRO (ESPA); ΔP=500 psi; rotation rate=90 rpm; recovery=75 to 90 %; wastewater composed of NaCl (1,000 mg/L), (NH₄)₂CO₃ (3,429 mg/L), and detergent (2,000 mg/L).

Funded by NASA.
Rotating Reverse Osmosis for Wastewater Reuse

Northwestern University
Mechanical Engineering
Richard M. Lueptow

Contributors:
Sangho Lee
Richard Neal
Cynthia Pederson
Yeomin Yoon

Funded by NASA
Filtration Team

Laboratory for Applied Fluid Dynamics

Water Recycle System

Total 11.45 kg

Solid Waste

Wastewater 9.45 kg

Detergent Organic Carbon Inorganic Salts Microorganisms

Final 11.45 kg

Hygiene Flush Water Wash

Condensate

2.27 kg

2 kg

Urine

Wash

2.27 kg 7.18 kg

Food

Urea Organic Carbon Inorganic Salts Microorganisms

Food

2 kg

NASA/CP—2004-213205/VOL1

558
Total Water Requirement for Several Human Space Missions

<table>
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<tr>
<th>ID</th>
<th>Crew Size</th>
<th>Transit Duration, Days</th>
<th>Surface Stay Duration, Days</th>
<th>Total Number of Duration Days</th>
<th>Water Requirement per Person (kg)</th>
<th>Total Water Requirements (kg)</th>
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<td>106,215</td>
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</table>
Removal of Molecules and Ions by Reverse Osmosis

- Compact
- Easy to control
- Small energy consumption compared to evaporation (and fewer contaminants)
- Independent of gravity
- Concentration polarization and membrane fouling are issues
# Key Contaminants

<table>
<thead>
<tr>
<th>Compound</th>
<th>MW (g/mol)</th>
<th>Radius (nm)</th>
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<tbody>
<tr>
<td>Urea</td>
<td>60.1</td>
<td>0.18</td>
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<tr>
<td>Ammonium carbonate</td>
<td>96.1</td>
<td>Cation: 0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anion: 0.133</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>58.5</td>
<td>Cation: 0.184</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anion: 0.121</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compound</th>
<th>MW (g/mol)</th>
<th>Radius (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-(2-Butoxyethoxy) ethanol</td>
<td>162.2</td>
<td>0.32</td>
</tr>
<tr>
<td>Caprolactam</td>
<td>113.2</td>
<td>0.28</td>
</tr>
<tr>
<td>2-Propanol</td>
<td>60.1</td>
<td>0.26</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>30.0</td>
<td>0.22</td>
</tr>
<tr>
<td>Methanol</td>
<td>32.0</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Urine and Flush:
- Sodium chloride
- Ammonium carbonate

Condensate:
- Methanol
- Formaldehyde
- 2-Propanol
- Caprolactam
- 2-(2-Butoxyethoxy) ethanol
Rejection Test: Organic and Inorganic Contaminants

Molecular weight (Da)

- Sodium chloride
- Ammonium Carbonate
- 2-(2-Butoxyethoxy) Ethanol
- Caprolactam
- 2-Propanol
- Formaldehyde
- Urea
- Methanol

Pressure Regulator
Stirred Cell
Magnetic Stirrer
Graduated Cylinder

LPRO (ESPA); C₀ = 1 mM; ΔP = 800 kPa (116 psi);
stirring speed = 400 rpm; pH = 7; recovery = 60 %
Pore Size Calculation

Solvent Flux

\[ J_v = \frac{r_p^2 \Delta P}{8\mu(\Delta x/A_k)} \]

Solute Conc.

\[ C_p = \frac{C_m K_c \phi}{1 - \exp\left(-\frac{K_c}{K_d} J_v \Delta x \right)(1 - \phi K_c)} \]

Concentration Polarization

\[ \frac{C_{i,m} - C_{i,p}}{C_{i,b} - C_{i,p}} = e^{J_v \frac{k_i}{\Delta}} \]

Steric Factors

\[ K_{i,d} = 1.0 - 2.30\lambda_i + 1.154\lambda_i^2 + 0.224\lambda_i^3 \]

\[ K_{i,c} = 1.0 + 0.054\lambda_i - 0.988\lambda_i^2 + 0.441\lambda_i^3 \]

Key Parameters Measured:
\[ J_i; J_v; C_{i,p}; C_{i,b}; \Delta P \]

Key Parameters Calculated:
\[ C_{i,m}; k_i \]

(Lee and Lueptow, 2001 ES&T)
**Pore Size Calculation**

\[
J_v = \frac{r_p^2 \Delta P}{8 \mu (\Delta x/A_k)}
\]

\[
C_p = \frac{C_m K_c \phi}{1 - \exp\left(-\frac{K_c}{K_d} \frac{J_v \Delta x}{A_k}\right)(1 - \phi K_c)}
\]

\[
\frac{C_{i,m} - C_{i,p}}{C_{i,b} - C_{i,p}} = e^{\frac{J_v}{k_i}}
\]

\[
K_{i,d} = 1.0 - 2.30\lambda_i + 1.154\lambda_i^2 + 0.224\lambda_i^3
\]

\[
K_{i,c} = 1.0 + 0.054\lambda_i - 0.988\lambda_i^2 + 0.441\lambda_i^3
\]

**Key Parameters Measured:**

\(J_i, J_v, C_{i,p}, C_{i,b}, \Delta P\)

**Key Parameters Calculated:**

\(C_{i,m}, k_i\)

*(Lee and Lueptow, 2001 ES&T)*
Membrane Properties Obtained from Experiments and Model Calculation

<table>
<thead>
<tr>
<th>Compound</th>
<th>Molecular Radius (nm)</th>
<th>RO (AK)</th>
<th>LPRO (ESPA)</th>
<th>NF (ESNA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-(2-Butoxyethoxy) Ethanol</td>
<td>0.32</td>
<td>0.333</td>
<td>0.327</td>
<td>0.423</td>
</tr>
<tr>
<td>Caprolactam</td>
<td>0.28</td>
<td>0.324</td>
<td>0.327</td>
<td>0.427</td>
</tr>
<tr>
<td>2-Propanol</td>
<td>0.26</td>
<td>0.334</td>
<td>0.349</td>
<td>0.452</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.22</td>
<td>0.335</td>
<td>0.334</td>
<td>0.440</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.19</td>
<td>0.344</td>
<td>0.336</td>
<td>0.448</td>
</tr>
<tr>
<td>Urea</td>
<td>0.18</td>
<td>0.326</td>
<td>0.343</td>
<td>0.448</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.333</strong></td>
<td><strong>0.336</strong></td>
<td><strong>0.440</strong></td>
<td></td>
</tr>
</tbody>
</table>

Effective Membrane Pore Size \( r_p \) (nm)

From Stirred-Cell Test

Laboratory for Applied Fluid Dynamics
Filtration Team
Dependence of Rejection on Solute Radius

From Stirred-Cell Test
Rotating Reverse Osmosis

Taylor-Couette Flow + Reverse Osmosis

Reduces Concentration Polarization and Fouling

Semi Permeable RO Membrane

Concentrate

Feed

Permeate
Taylor-Couette Flow

\[ Ta = \frac{r_i \Omega d}{v} \]

Laminar Couette flow → Taylor vortices → Wavy vortices
Fouling

Deposition of Particles or Solutes on the Membrane Surface

Axial Flow

No Rotation

Particle Deposition
Fouling

Rotation Decreases Fouling

Rotation

Axial Flow
Geometry for Rotating RO

\[ Q_{\text{conc}}(t) \]

\[ C_{c,i}(t) = C_{b,i}(L, t) \]

\[ Q_{\text{feed}}(t) = Q_{\text{conc}}(t) + J_v(t) A_m \]

\[ C_{f,i} = C_{b,j}(0, t) \]
Mass Transfer Model

\[
\frac{\partial C_{b,i}(x,t)}{\partial t} = -\frac{1}{S_a} \left( Q_{conc}(t) + 2\pi r_i \int_0^L J_v(x,t) dx \right) \frac{\partial C_{b,i}(x,t)}{\partial x} + \frac{2\pi r_i \cdot J_v(x,t)}{S_a} C_{b,i}(x,t) - \frac{2\pi r_i \cdot J_{s,i}(x,t)}{S_a}
\]

- **Unsteady Term**
- **Concentrate Flow**
- **Input Flow**
- **Permeate Flow**

\[
J_v = L_v (\Delta P - P_{loss})
\]

\[
J_{s,i} = J_v C_{p,i} = L_s,i (C_{m,i} - C_{p,i})
\]

\[
\frac{C_{m,i} - C_{p,i}}{C_{b,i} - C_{p,i}} = e^{\frac{J_x}{k_i}}
\]

\[
P_{loss} = \sum_{i}^{n} \Delta P_i + \Delta P_{rot} + \Delta P_{axis} + \rho g x
\]

- Water Transport
- Solute Transport
- Concentration Polarization
- Pressure Drop

Laboratory for Applied Fluid Dynamics
Filtration Team
Modeling Operating Conditions

> 40 L/m²-hr Flux
> 80% Rejection
> 80% Recovery

\( \omega = 100 \text{ rpm} \)
Increasing the Flux

Curves of Constant Flux (L/m²/hr)

To Increase Flux: Increase Pressure

*(Lee and Lueptow, 2001 JMS)*
First vs. Second Generation Design

First:
150 psi and 4 to 6 hr tests

Second:
> 500 psi and 24 hr to 3+ month tests
First vs. Second Generation Design

**First:**
150 psi and 4 to 6 hr tests

**Second:**
> 500 psi and 24 hr to 3+ month tests
First vs. Second Generation Design

**First:**
150 psi and 4 to 6 hr tests

**Second:**
> 500 psi and 24 hr to 3+ month tests
Long Term Testing

Fluid Circuit Diagram

- Reservoir
- Pump
- Motor
- Concentrate Line
- Pressure Regulator
- Filter
- Filtrate Line
- Feed Line
Comparison of Rotating RO with Non-Rotating RO

Flux

\[ J_v(t) \text{ (L/m}^2\text{-hr)} \]

\[ J_v(t)A_m \text{ (mL/min)} \]

ω=90 rpm

ω=0 rpm

Rejection

\[ R_i(t) \]

\[ \Delta P = 1000 \text{ kPa}, \ Q_{conc} = 0 \text{ ml/min} \]
Preliminary Results: 24 Hour Test

LPRO (ESPA); ΔP= 3450 kPa (500 psi); rotation speed=90 rpm; recovery=83 %

Rotating RO
Microgravity Issue: Bubbles

- Blocking inlet or outlet conduits
- Blocking membrane at inflow regions between vortices
Summary

- Characterization of Membranes
  - Rejection depends on pore radius

- Rejection Mechanisms
  - Size exclusion for organic compounds
  - Electrostatic exclusion for ionic species

- Developed a second generation Rotating RO system
  - High flux
  - High rejection
  - High recovery

- Model for Rotating RO based on the solution-diffusion model with the film theory

- Experimental flux and rejection match the model
Rotating Reverse Osmosis for Wastewater Reuse

Northwestern University
Mechanical Engineering
Richard M. Lueptow

Contributors:
Sangho Lee
Richard Neal
Cynthia Pederson
Yeomin Yoon

Funded by NASA
Objectives

- Characterization of RO membranes for key contaminants
- Analysis of rejection for key inorganic and organic compounds by RO membranes
- Theoretical model for rotating RO
- Effectiveness of rotating RO experimentally to verify our theoretical model
**Rejection Test: Urea and Ammonium Carbonate**

**Urea Hydrolysis**

\[ CO(NH_2)_2 + 3H_2O \xrightarrow{\text{Urease}} 2NH_4^+ + HCO_3^- + OH^- \]

**From Stirred-Cell Test**

\[ \Delta P = 800 \text{ kPa (116 psi)} \]; stirring speed=400 rpm; pH=7; recovery=60 \%;
urea=2,000 mg/L, ammonium carbonate=3,429 mg/L
Preliminary Results: 3 Day Test

LPRO (ESPA); ΔP = 3450 kPa (500 psi); rotation speed = 90 rpm; recovery = 75-90%
Gas-Liquid Flows and Phase Separation
by
John McQuillen

Strategic Research to Enable NASA’s Exploration Missions
June 22 - 23, 2004
Cleveland, Ohio
Common Issues for Space System Designers

- Ability to Verify Performance in Normal Gravity prior to Deployment.
- **System Stability**
- Phase Accumulation & Shedding
- **Phase Separation**
- Flow Distribution through Tees & Manifolds
- **Boiling Crisis**
- Heat Transfer Coefficient
- Pressure Drop

* Two Phase Flow Facility
Space-Based Technologies Using Two Phase Flow

Exploration Vision

Technology Development

ADVANCED LIFE SUPPORT SYSTEMS
- Condensing heat exchanger
- Wastewater processing
  - Distillation systems
  - Evaporation systems
- Storage transport systems
- Two-phase tolerant pumps
- Low pressure liquid drainage

THERMAL CONTROL SYSTEMS
- Working fluids for internal/external systems
- Heat pump
- Two-phase tolerant pump
- Thermal bus
- Multiple heat source
  - Multiple temperatures
- Systems
  - EVA, ECLSS, Power

NUCLEAR POWER CONVERSION SYSTEMS
- Two-phase distribution problems in condenser manifold
- Gas bubbles in pump
- Interaction between components
- Liquid droplet carry over into turbine inlet
- Thermal transients affecting fatigue of the boiler

Output
- Design Tools
- Engineering Handbooks
- Models

Applied Research
- Boiling
- Condensation
- Phase Separation
- Two-Phase Stability
### Partial Listing of Where Gas-Liquid Flows are in Life Support Systems

<table>
<thead>
<tr>
<th>Stream Type</th>
<th>Air Revitalization</th>
<th>Water Reclamation</th>
<th>Thermal Management</th>
<th>Solid Waste Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Humidity Condensate</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Urine</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spills</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Dish Washing</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sabatier CO$_2$ Reaction</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Solids Drying</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Food Processing</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Life Support Systems

• Commonality of Source Stream
  – Aqueous-based Working Fluid (Water)
  – Into Waste Water Tank
  – Low Pressure Inlet
  – Gas Phase Present
  – Particulate Matter may be Present

• Differences
  – Dissolved Matter → Fluid Property Effects
  – Batch vs. Continuous Input
  – Flow Rates
  – Void Fraction
Thermal Management Systems

Heat Source Temperature

\( T \approx 50 \, ^\circ C \)

\( T \approx 50 \, ^\circ C \)

\( T \approx 20 \, ^\circ C \)

\( T \approx 2 \, ^\circ C \)

\( T \approx 20 \, ^\circ C \)

\( T \approx 2 \, ^\circ C \)

\( T_{\text{Source}} > T_{\text{Radiator}} \)

\( T_{\text{Source}} < T_{\text{Radiator}} \)

Pumped Loop

Vapor Compression

Source > Radiator

Source < Radiator

NASA/CP—2004-213205/VOL1
Vapor Compression Cycle

Two Phase Issues

- Liquid Droplet Carryover
- Lubricant Management
- Parallel Channel Instability

2Ø Separator

2Ø ΔP & Heat Transfer Coefficient

System Stability

Flight Demo

Microgravity Fluid Physics Branch
Glenn Research Center at Lewis Field
The Effect of Reduced Gravity on Gas-Liquid Flows

Negating the Effect of Buoyancy

- Axisymmetric flows
- Reduced Hydrostatic Pressure
- Spherical Bubbles vs. Ellipsoid
- No Gravity-Induced Shearing:
  - Gas Phase Rising relative to Liquid Falling
- Co-flow of Gas and Liquid Phases.

![Radial void fraction distributions](image)

- □ upward
- △ downward
- ○ microgravity
What Do We Know?
Flow Regimes

• 3 (½) Flow Regimes: Bubble, Slug, Annular (Transitional Slug Annular)

• Multiple Models that work well
  – Constant Void Fraction
  – Weber Number Model
  – Suratman Number Criteria
What Do We Know?
Pressure Drop

- Modified Homogenous Equilibrium Model works well
  - Mixture Density
  - Mixture Velocity
  - Liquid Viscosity
Wall Friction Factors $f_L$ in Bubbly Flow:

Reduced Gravity Two Phase Flow:
- $D=6$ mm, $D=10$ mm, $D=19$ mm,
- $D=12.7$ mm, $D=40$ mm

Single-Phase Flow:
- $D=6$ mm, $D=10$ mm, $D=19$ mm

- Blasius
- Poiseuille relationship
Concerns

- Phase Accumulation and Shedding

- Liquid Film Rupture and Dryout
Example: Sabatier Reactor

\[ \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2(\text{H}_2\text{O}) + \text{heat} \]

2Ø Issues
- Separator
- Liquid in Gas Outlet Stream
  - Detection
  - Response
- Influence of Fines
Crew Exploration Vehicle
Thermal Management System

- Capsule-type vehicle
- Functional during Orbital, Re-entry, and Post-Landing Phases
- Closed Loop System – Desire No Flash Evaporators
- Heat Load Estimate
  - Fuel Cells: 7 kW at 50 °C
  - Electronics: 3 kW at 40 °C
  - Cabin: 0.5 kW at 7 °C
- Limit Total Radiator Area < 200 ft²
- Body Mounted Radiator
- Working Fluid
  - Non-Toxic
  - Non-Corrosive
  - Low Freezing Point
Why Separate?

• Critical Process or Component that is intolerant of one Phase
  – Centrifugal pumps with gas bubbles
  – Phase Specific Sensors, i.e., hot wires
  – Biological media negatively impacted by gas

• Better System Performance
  – Condensors Work Better if no liquid present at inlet.
  – Control of Phase Distribution into a manifold
Requirements to Consider

• Available Power
  – Mars Transfer Vehicle has MW but for propulsion
  – CEV has up to 10 kW

• Vibration
  – Wear & tear
  – Noise

• System Life
  – Most will be Life of Mission or Vehicle
  – Some systems may have cleanliness/sterile concerns

• Separator Life

• Flow Rate range
  – ml/min to l/min
Requirements to Consider

- **Acceleration Environments**
  - Pre Launch 1 G
  - Launch – hi-G’s
  - Transit - microgravity
  - De-Orbit – hi-G’s
  - Moon (1/6 G) or Mars (3/8 G)
  - Post Landing 1 G

- **Degree of Separation Desired**

- **Contamination Sensitivity**
  - Separation process negatively impacted by solids or immiscible 2nd liquid phase

- **Tolerance of “Slugging” or “flooding” Events**
  - System capacitance

- **Startup & Shutdown**
# Range of Separator Requirements

<table>
<thead>
<tr>
<th>Stream Type</th>
<th>Near Continuous or Batch</th>
<th>Inlet Void Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Humidity Condensate</td>
<td>Continuous</td>
<td>?</td>
</tr>
<tr>
<td>Urine</td>
<td>Batch</td>
<td>Low</td>
</tr>
<tr>
<td>Dish Washing</td>
<td>Batch</td>
<td>Low-Initially</td>
</tr>
<tr>
<td>Laundry</td>
<td>Batch</td>
<td>Low-Initially</td>
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</tr>
<tr>
<td>Waste Solids Drying</td>
<td>Continuous</td>
<td>High</td>
</tr>
<tr>
<td>Food Processing</td>
<td>Batch</td>
<td>High</td>
</tr>
<tr>
<td>Bioreactor</td>
<td>Continuous</td>
<td>Low</td>
</tr>
</tbody>
</table>
Mechanical Phase Separation

- Centrifuge – Very high G’s
  - Spin outside housing
  - Spin internal float
- Use rotational acceleration to also develop “hydrostatic” pressure rise to pump liquid
  - Rotary Fluid Management Device (Sundstrand)
  - Two Phase Pump (Foster-Miller)
  - MOBI

Click here to play movie
Passive Separation: Membranes

• Use of Hydrophilic Membranes and Surfaces to position liquid interface and withdraw liquid.
• Liquid Acquisition Devices (LAD’s) are used in upper stage propellant tanks to ensure start of rocket motor.
• Gas Phase Breakthrough based on bubble point or LaPlace Eqn using membrane pore size.
• Prone to contamination.
Passive Separation: Inertial

- Phase Separation achieved due to inertial differences in liquid and gas phase inertia

Bubble Flow through Tee

Gas Accumulation in Vena Contracta
Passive Separation: Inertial

- Phase Separation achieved due to inertial differences in liquid and gas phase inertia
Passive Separation: Cyclonic

- Two Phase Flow Injected Tangentially into Cylinder.
- Separation driven by Flow
- Cyclones designed for microgravity will work well in multiple gravity levels
Summary

• Guidance similar to “A design that operates in a single phase is less complex than a design that has two-phase flow ”\(^1\) is not always true considering the amount of effort spent on pressurizing, subcooling and phase separators to ensure single phase operation.

• While there is still much to learn about two-phase flow in reduced gravity, we have a good start.

• Focus now needs to be directed more towards system level problems.

References


- Low Gravity Two Phase Flow Movies
  http://microgravity.grc.nasa.gov/6712/2phase_flow/2phase.html
Organizing Questions for Reduced-Gravity Flammability

Fletcher Miller &
NASA and NCMR Project Scientists
for Combustion Flight Projects
Involving the Flammability of Solids

Strategic Research to Enable NASA’s Exploration Missions
Cleveland, OH June 22-23, 2004
Background

- Currently there are six* combustion flight projects involving flammability of solids at various stages of development
  - Combustion Integrated Rack
  - FEANICS insert

- The objectives of many of these experiments is to perform fundamental research in combustion aboard the International Space Station

- Relevance to spacecraft fire safety was not the only factor in selecting flight projects.
  - Recommendations by outside peer review panels focused on science.

* Plus one international project
• A team consisting of the Microgravity Flight Project Scientists for solid flammability experiments has been reviewing and prioritizing a set of organizing questions for fire prevention (material flammability).

The ability to answer these questions will be the major determinant in the selection of future flight experiments.

In particular the team has been charged with determining:

1. What experiments must be conducted to best answer these questions?

2. Can some of the questions be answered using existing/planned hardware or experimental concepts?
1. Is the NASA STD 6001, Test 1 configuration conservative or non-conservative in assessing material flammability in reduced gravity? * 

- NASA STD 6001, Test 1 is an upward flammability test, considered the most stringent test in normal gravity.
- A material that passes this test would most likely not burn in a quiescent microgravity environment. 
  - More research is needed on practical but “exotic” materials to verify this.
- The degree of conservatism varies with material and cannot be determined from the test data.

* Reduced gravity is taken here to mean either micro or partial gravity, though for today’s session we will focus primarily on microgravity.
Quiescent Microgravity?

- In an emergency, totally quiescent conditions in microgravity cannot be assured.

- Possible sources of air movement:
  - Ventilation system if it cannot be turned off or decay time if it can.
  - Crew movements
  - Use of fire extinguishers
  - Small leaks from the module, or venting
  - Residual g (0.1 mg ~ 1 cm/s)

- The most flammable condition for some materials is at very low velocities, below those for upward spread in normal gravity

- Experiments and models show that in very low speed flows the flame prefers to spread upstream (opposed flow) compared to downstream.

- The question of conservatism of Test 1 therefore may rest on the determination of velocity and flow direction at which to compare.

- In partial gravity, such as lunar or Martian conditions, there will always be buoyant flow.
Calculated Concurrent vs. Opposed Extinction Limits

(Kumar, Shih, & T’ien, Combustion and Flame, 2003)

Thermally thin solid (paper)

Two-dimensional model with radiation

Two entrance lengths considered for opposed flow
2. Is there a normal gravity test that can quantify material flammability in reduced gravity either by itself or in conjunction with NASA-STD-6001, Test 1?

- Attempts to relate Test 1 results to data from other standard tests have met with limited success
- Various methods have been (are being) evaluated
  - limiting oxygen index (maximum oxygen concentration to extinguish a flame)
  - Forced Ignition and Spread Test (FIST)
  - Equivalent Low Stretch Apparatus (ELSA)
- Desirable: Preserve Test 1 data base, though it may need to be expanded to cover other oxygen concentrations.

Conceptual drawing of the apparatus to be tested in the WSTF Controlled Atmosphere Cone Calorimeter.
Forced Ignition and Spread Test (FIST)

Principal Investigator: Prof. Carlos Fernandez-Pello, Univ. of Cal. at Berkeley

Objectives:
- Develop and verify a simplified theory for LIFT-styled ignition and flame spread in 1-g and 0-g
- Determine if 1-g and 0-g behaviors are correlated
- Develop a flammability test method to rank the hazards of materials used on spacecraft using time to ignition, fire spread rate, material properties, critical heat flux
3. How can NASA Standard 6001, Test 1 results be quantified to indicate flammability in reduced gravity? (Can additional, useful data be gathered without changing the test procedure?)

- Test 1 is normally a pass/no-pass test; no determination of passing margins.
- On-going research by Buckley and Torero is quantifying flame stand-off distances from Test 1 to determine an experimental mass-transfer number.
- Comparison of experimental and analytical results allows ranking of flammability.
- Modeling of Test 1 has compared well with experiment for PMMA.

The laminar nature of both flames makes it possible to use a simple formulation to correlate normal and microgravity results.

\[
B = \frac{\text{net heat liberated by combustion}}{\text{heat input to fuel} + \text{heat loss}}
\]
4. How does the flammability, ignitability and Limiting Oxygen Index (LOI) of a material change with gravitational level?

### Some Typical values

<table>
<thead>
<tr>
<th>Material</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane foam</td>
<td>16.5</td>
</tr>
<tr>
<td>PMMA (Perspex)</td>
<td>17.3</td>
</tr>
<tr>
<td>Poly(ethylene)</td>
<td>17.4</td>
</tr>
<tr>
<td>Poly(propylene)</td>
<td>17.4</td>
</tr>
<tr>
<td>Poly(styrene)</td>
<td>17.8</td>
</tr>
<tr>
<td>Plywood</td>
<td>23.0</td>
</tr>
<tr>
<td>Nylon 6.6</td>
<td>24-29</td>
</tr>
<tr>
<td>Nomex</td>
<td>28.5</td>
</tr>
<tr>
<td>PVC (unplasticised)</td>
<td>45-49</td>
</tr>
<tr>
<td>PTFE (Teflon)</td>
<td>95</td>
</tr>
</tbody>
</table>
5. How can the results of small-scale experiments be used to determine the behavior of large-scale fires?
   a. Extend results to conditions and geometries that haven’t been tested
   b. How will flames grow and spread in real situations?
6. How do the flammability and ignitability of materials change in high-$\text{O}_2$ mole fraction, low-pressure, reduced gravity environments?

- Exploration environments may have an enriched oxygen, low pressure atmosphere.
  - Skylab 70% oxygen, 5 psia
  - Apollo 100% oxygen, 5 psia
  - EVA Shuttle/ISS 30% oxygen
- Test 1 is run at atmosphere of use, though data base is smaller at higher oxygen concentrations.
7. How does the propensity for non-flaming/smoldering combustion of materials change in high-O2 mole fraction, low-pressure, reduced gravity environments?

- Smoldering not covered under NASA Std. 6001, Test 1.
- One planned flight experiment: Smoldering, Transition and Flaming (STaF)

PI: Prof. Carlos Fernandez-Pello
Univ. of Cal. at Berkeley
8. What are the other credible ignition sources, other than electrical overheating and electrical short circuits that will exist on exploration vehicles? Do these sources increase or decrease the propensity for ignition in reduced gravity?

- Waste Storage
- Solid Fuel Oxygen Generators
- High pressure oxygen system
- Laser use?
Your Input

Questions:

• Are these the right questions?

• How would you change them?

• Are there other questions that should be considered?

Concepts:

Reiteration of what we need to determine:

1. What experiments must be conducted to best answer these questions?

2. Can some of the questions be answered using existing/planned hardware or experimental concepts?
Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS)

June 23, 2004
Combustion Integrated Rack Overview

- **Fuel/Oxidizer Management Assembly (FOMA)**
- **Combustion Chamber**
- **Optics Bench Slides**
- **Optics Bench**
- **FEANICS Chamber Insert Assembly**
- **Input/Output Processor (IOP)**

- **Environmental Control (ECS)**
  - Air Thermal Control
  - Fire Detection & Suppression
  - Water Thermal Control
  - Gas Interfaces (GN₂, VES, VRS)

- **Rack Closure Door**

- **SAMS RTS**

- **Passive Rack Isolation Subsystem (PARIS)**

- **Science Diagnostics**
  - Color Camera
  - Illumination Package
  - Mid IR Camera
  - Low Light Level (2 Units)
  - High Bit Depth Multi-Spectral
  - High Frame Rate/High Resolution
  OR
  Experiment Specific Diagnostics

- **International Standard Payload Rack (ISPR)**
  - Image Processing and Storage Unit (2) (IPSU)
  - FOMA Control Unit (FCU)
  - PI Avionics Box
  - Electrical Power Control Unit (EPCU)
  - Laptop Computer

- **Electrical Power Control Unit (EPCU)**

- **Experiment Specific Diagnostics**
FEANICS-1 Capabilities

- **15 cm W x 12 cm H x 30 cm L flow tunnel test section**
  - Top surface of fuel flush with tunnel floor
  - 0-25% and 4-96% O\(_2\) sensors at tunnel inlet and outlet
  - 4 LEDs for illumination
  - Gas phase thermocouple for gas inlet and outlet temperature

- **Quiescent or Flow tests with adjustable velocity up to 20 cm/s**

- **Concurrent or Opposed flow testing**

- **Pressures from ~0.5 to ~3.0 atm**

- **Testing:**
  - Flow tests below 27% O\(_2\); We can control O\(_2\) and pressure.
  - Flow tests above 27% O\(_2\); We can control O\(_2\); but no pressure control
  - Quiescent tests: No O\(_2\) or pressure control

- **Ignition by hot wire (one per sample)**

- **Radiant Heater to heat/pyrolyze fuel (peak radiance ~20 kW/m\(^2\))**

- **Carousel Fuel Sizes**
  - Max: 11.5 cm W x 18 cm L x 1.2 cm thick for a 3-sided carousel
  - Min: 3 cm W x 18 cm L x 1.2 cm thick for an 8-sided carousel
FEANICS-1 Insert (w/Radiant Heater)

- Filter Section
- Radiant Heater
- Blower
- O₂ Sensors
- Venturi Inlet
- Flow Direction
- Shutter
- Fuel Sample
- Mounting Rail Guide
- Fuel Carousel
FEANICS-1 Insert with 8-Sided Carousel

- Shutter Motor
- Carousel without containment cover
- Fuel Samples
- Igniter
FEANICS-1 Insert in Combustion Chamber

CUT-AWAY FEANICS TUNNEL W/ INSERT IN CHAMBER
(CHAMBER HIDDEN LOOKING FROM FAN END)
SHOWING OXYGEN ASSEMBLY
(SERIES 2) 3/23/2004
FEANICS-2 Capabilities

- **Similar to FEANICS-1 with the following exceptions**
  - Fuel located in center of tunnel section
  - Split Flow inlet and exit
  - 15 cm W x 12 cm H x 26 cm L flow tunnel test section
  - Ignition by 30 W CO$_2$ laser

- **Fuel Sizes (Max)**
  - 13 cm W x ~ 800 cm L x ~ 0.4 mm thick on a continuous fuel roll.
  - 10 cm W x 16.9 cm L x 1 cm thick in an end loader (7 max).

- **Plan for Fuel Roll** was to use a camera to track flame position and feed fuel into the flame to keep flame position fixed. CIR lost capability to process video real time.
FEANICS-2 Insert with Fuel Rolls

- Venturi Inlet (top and bottom)
- Windows
- Blowers (top and bottom)
- Fuel Supply Roll
- Insert Cover
- Fuel Take-up Roll
- Mounting Rail Guide
### Diagnostics Capabilities

<table>
<thead>
<tr>
<th>Camera System</th>
<th>Pixels Array</th>
<th>Bit Depth (bits)</th>
<th>Frames Per Second</th>
<th>Spectrum (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Light Level-IR</td>
<td>512x512</td>
<td>12</td>
<td>30</td>
<td>400-900</td>
</tr>
<tr>
<td>Low Light Level-UV</td>
<td>512x512</td>
<td>12</td>
<td>30</td>
<td>250-700</td>
</tr>
<tr>
<td>High Bit Multispectral</td>
<td>512x512</td>
<td>12</td>
<td>15</td>
<td>650-950</td>
</tr>
<tr>
<td>Color</td>
<td>640x480</td>
<td>8</td>
<td>30</td>
<td>400-700</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>256x256</td>
<td>12</td>
<td>120</td>
<td>3000-5000</td>
</tr>
</tbody>
</table>
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.
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>
<th></th>
<th>Mission Length</th>
<th>Crew Size</th>
<th>Habitat Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturn/Apollo</td>
<td>&lt; 14 days</td>
<td>3</td>
<td>5 Pisa (pure oxygen)</td>
</tr>
<tr>
<td>Skylab*</td>
<td>28 – 84 days</td>
<td>3</td>
<td>5 Pisa (N2/02, 70%/30%)</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>&lt; 14 days</td>
<td>2 - 7</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
</tr>
<tr>
<td>Spacelab</td>
<td>&lt; 14 days</td>
<td>3 - 4</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
</tr>
<tr>
<td>Mir*</td>
<td>~ 15 years</td>
<td>2 - 6</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
</tr>
<tr>
<td>International Space Station*</td>
<td>15 -20 years Planned</td>
<td>2 - 6</td>
<td>14.7 Pisa (N2/02, 79%, 21%)</td>
</tr>
</tbody>
</table>

*Regenerative life support systems on-board
### Basic ECLSS Functions for Human Support

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• CO2 Removal</td>
<td>• O2 Storage Systems</td>
<td>• Potable H2O Storage</td>
<td>• Smoke Detection</td>
<td>• Cabin Air Temperature Control</td>
<td>• Urine Collection and Pre-treatment</td>
</tr>
<tr>
<td>• CO2 Reduction</td>
<td>• N2 Storage Systems</td>
<td>• Waste H2O Processing</td>
<td>• Fire Detection</td>
<td>• Habitable Volume Air Ventilation</td>
<td>• Fecal Collection &amp; Processing</td>
</tr>
<tr>
<td>• Oxygen Generation</td>
<td>• 02/N2 Atmosphere Pressure Control</td>
<td>• Urine Processing</td>
<td>• Fire Suppression</td>
<td>• Air Filtration</td>
<td></td>
</tr>
<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>• Air Circulation</td>
<td></td>
</tr>
<tr>
<td>• Trace Contaminant Monitoring</td>
<td>• Purge and pressurant supply gases</td>
<td>• Hygiene H2O Supply</td>
<td></td>
<td>• Humidity Control</td>
<td></td>
</tr>
<tr>
<td>• Atmosphere Composition Monitoring</td>
<td>• EVA Support</td>
<td>• Water Quality Monitoring</td>
<td></td>
<td>• Temperature &amp; Humidity Monitoring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• O2/N2 Distribution</td>
<td>• Biocide and Sterilization</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
Variety 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

International Space Station

CEV u-g

Space operations to another planet

CEV u-g

Lunar Outpost

Humans on Another Planet

Partial-g
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

(Complete Atmosphere Revitalization System not shown)

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)

Potable water

OXYGEN GENERATOR ASSEMBLY (OGA)
- Solid Polymer Electrolysis (SPE)
- Power Supply Module (PSM)
- Oxygen
- CO2 REDUCTION SYSTEM (CRS)
  - Sabatier Reactor Sub. (SRS)
  - CO2 Mgmt Sub. (CMS)
- Hydrogen
- Methane
- Carbon Dioxide
- Wastewater

Legend:
- flight experiment subjects
- scars

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649
ISS Node 3
Regenerative ECLSS Racks

** 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)
ECLSS Comparative Technology Testing (1990 – 1992)

(MSFC Building 4755, North End)

**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)

<table>
<thead>
<tr>
<th>Year</th>
<th>Subsystem Selection</th>
<th>Water Recovery Testing</th>
<th>Program Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>Comparative Testing Subsystem Selection</td>
<td>Stage 1A, 2A, &amp; 3A</td>
<td>SSF WP01 PDR 1 two loops (ROH, MFP, TIMES) 2 Strings Dishwasher Laundry</td>
</tr>
<tr>
<td></td>
<td>*ROH = MPH, *TIMES = VCD</td>
<td>Stage B &amp; C</td>
<td>Delete Dishwasher</td>
</tr>
<tr>
<td>1991</td>
<td></td>
<td>Stage 4 &amp; 5</td>
<td>1 loop (WP, VCD) 1 String Laundry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stage 6</td>
<td>1 loop (WP, VCD) 1 String Laundry</td>
</tr>
<tr>
<td>1992</td>
<td></td>
<td>Stage 7</td>
<td>SSF Redesign to ISS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stage 8</td>
<td>SSF Redesign to ISS</td>
</tr>
<tr>
<td>1993</td>
<td></td>
<td>Stage 9</td>
<td>1 loop (WP, VCD) Automated Donor mode</td>
</tr>
<tr>
<td>1994</td>
<td></td>
<td>Stage 10</td>
<td>1 loop (WP, VCD) Automated Recipient mode</td>
</tr>
<tr>
<td>1995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
End-Use Equipment Facility (EEF)
Space Station ECLSS
Water Recovery Testing Area

Vapor Compression Distillation (VCD) Unit

Facility Water Storage

End-Use Equipment Facility (EUF)

Waste Water Storage Tanks

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

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

- Control Room
- Oxygen Generator Assembly/Static Feed Water Electrolyzer
- Carbon Dioxide Removal Assembly
- Major Constituent Analyzer
- Trace Contaminant Control Subassembly
- North Bay of Building 4755
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

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

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

Purification Flow
Product water to Water Processor Assembly

Wastewater Tank

Urine from Node 3

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

Microgravity Sensitivities
L Life
P Performance

VCD Flight Exp’t
Full-scale DA
steady state & transient ops
STS-107
functionality confirmed

KC-135 “flow visualization” testing Feb '02
observed flow patterns & fluid distrib’n

e Distillation Assembly Condensate Control

✓ external heaters added to prevent condensation in stationary bowl
✓ design finalized; release complete 8/02
Urine Processor Assy (UPA) Flight Hardware

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

Product Water Tank
- from Node 3 wastewater bus

Delivery Pump
- to Node 3 potable water bus

Accumulator

Wastewater Tank
- to Node 3 cabin

Filter
- Remove particulates

Particulate Filter
- Remove dissolved contaminants

Multifiltration Beds

Mostly Liquid Separator
- Remove air

O2 from Node 3

Heat Exchanger
to/from Node 3 MTL

Reactors
- Oxidizes organics

Ion Exchange Bed
- Removes reactor by-products

To Node 3 cabin

Reactors
- Oxidizes organics

Ion Exchange Bed
- Removes reactor by-products

Heat Exchanger
to/from Node 3 MTL

Heater
- Heats water to 275F

Preheater
- Heats water to 275F

Regen. HX
- Recovers heat

Gas/Liquid Separator
- Removes oxygen

O2 from Node 3

Microbial Check Valve
- Provides isolation

Reject Line (allows reprocessing)

O2 from Node 3

O2 from Node 3

O2 from Node 3

O2 from Node 3

O2 from Node 3

O2 from Node 3
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
<table>
<thead>
<tr>
<th>Test</th>
<th>Finding</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<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>
</tr>
</tbody>
</table>
International Space Station Oxygen Generator System (OGS) Description

- Core Technology: Solid Polymer Electrolysis (cathode feed)

**Cell Stack**

**Electrolysis Cell Reactions**

\[ 2H_2O \rightarrow 4H^+ + 4e^- + O_2 \]

\[ 4e^- \rightarrow H_2 \]

\[ 4H^+ + 4e^- \rightarrow 2H_2 \]
**Integrated Process**

1. Oxygen & hydrogen produced in 28-cell stack
2. \( \text{O}_2 \) delivered to cabin
3. \( \text{H}_2 \) mixed with excess re-circulated 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
- **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
- **H2 Sensor**
  - General performance demonstrated in bench tests & test bed
  - Transient performance & contamination susceptibility open issues
- **Gas Sensor**
- **Water Absorber**
  - Performance demonstrated in bench tests
  - Capacity validation ongoing in test bed
- **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
- **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**
- L: Life
- P: Performance
OGA Flight Hardware

1. Ion Exchange Bed
   - Removes iodine
   - Feed water from Node 3

2. Nitrogen Purge Manifold

3. Two-phase Fluid Sensors
   - Check for gas bubbles
   - Feed water with air returned to Node 3

4. Ion Exchange Bed
   - Removes iodine
   - Feed water from Node 3

5. Two-phase Fluid Sensors
   - Check for gas bubbles
   - Feed water with air returned to Node 3

6. Absorber
   - Traps liquid water
   - Detect cell stack leaks

7. Hydrogen Sensors
   - Detect cell stack leaks

8. Pump
   - Recirculates water

9. Rotary Separator/Accumulator
   - Separates hydrogen, stores water

10. Cell Stack
    - Produces oxygen

11. Heat Exchanger
    - Rejects waste heat

12. Dome
    - Contains hydrogen leaks

13. Water Absorber

14. Oxygen (O2)

15. Hydrogen (H2)

16. Nitrogen from Node 3

17. Feed water from Node 3

18. To Node 3 vent

19. O2 to cabin

20. Coolant

21. NASA/CP—2004-213205/VOL1
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
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

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

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

Starting Point: TRL 2/3

Technology Flight Experiment Where Necessary

Several Competing Technologies at a Moderate Level of Funding

Goal: TRL 4/5

Functionally-Focused Technology R&D

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

Goal: TRL 6

Systems-Oriented Technology Demos

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

Number of Competing Technologies Being Funded

Total Resources Being Invested in a specific technology

TIME

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

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)

Pilot Program

Round 1 “final” Gateway
Recommendation?

“Spiral N” – Round 1

Year -1 | Year 0 | Year 1 | Year 3
First Gateway
Terminate current?
Add’l Options?
Round 1 Gateway
Recommendation?

Round 2 “final” Gateway
Recommendation?

“Spiral N” – Round 2

Year 2 | Year 3 | Year 4 | Year 6
Second Gateway
Terminate current?
Add’l Options?

“Spiral N” – Round 3
(If any…)

Year 5

NASA/CP—2004-213205/VOL1
Code T/H&RT Strategic Technical Challenges Regarding
“System-of-System” Level Issues.

- **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

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

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

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

**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)

- Potential relationships of Ionic Fluid Technology

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

- 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
We present experimental data on flow pattern transitions, pressure drop and flow characteristics for
cocurrent gas-liquid flow through packed columns in microgravity. The flow pattern transition data
indicates that the pulse flow regime exists over a wider range of gas and liquid flow rates under
microgravity conditions compared to 1-g and the widely used Talmor map in 1-g is not applicable for
predicting the transition boundaries. A new transition criterion between bubble and pulse flow in
microgravity is proposed and tested using the data. Since there is no static head in microgravity, the
pressure drop measured is the true frictional pressure drop. The pressure drop data, which has much
smaller scatter than most reported 1-g data clearly shows that capillary effects can enhance the pressure
drop (especially in the bubble flow regime) as much as 200% compared to that predicted by the single
phase Ergun equation. The pressure drop data are correlated in terms of a two-phase friction factor and its
dependence on the gas and liquid Reynolds numbers and the Suratman number. The influence of gravity
on the pulse amplitude and frequency is also discussed and compared to that under normal gravity
conditions.

Experimental work is planned to determine the gas-liquid and liquid-solid mass transfer coefficients.
Because of enhanced interfacial effects, we expect the gas-liquid transfer coefficients $k_{L}a$ and $k_{G}a$ (where
$a$ is the gas-liquid interfacial area) to be higher in microgravity than in normal gravity at the same flow
conditions. This will be verified by gas absorption experiments, with and without reaction in the liquid
phase, using oxygen, carbon dioxide, water and dilute aqueous amine solutions. The liquid-solid mass
transfer coefficient will also be determined in the bubble as well as the pulse flow regimes using solid
benzoic acid particles in the packing and measuring their rate of dissolution. The mass transfer
coefficients in microgravity will be compared to those in normal gravity cocurrent flow to determine the
mass transfer enhancement and propose new mass transfer correlations for two-phase gas-liquid flows
through packed beds in microgravity.
Fluid Transport

In

Advanced Life Support Systems

Brian J. Motil

NASA Glenn Research Center
Cleveland, Ohio

June 22 & 23, 2004
Primary challenge is to “close the loop” on the physico-chemical components of basic life support while making them extremely reliable:

- Air Revitalization
- Water Reclamation
- Thermal Control
- Solid Waste Management
- Food Processing
- Biomass Production
- Extravehicular Activity (EVA) Support

...with low mass, power and volume.
# Mission Drives Life Support Requirements

<table>
<thead>
<tr>
<th></th>
<th>Lunar Transit Vehicle</th>
<th>Lunar Outpost (LO)</th>
<th>Mars Transit Vehicle</th>
<th>Mars Habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration (Human Tended)</strong></td>
<td>7 – 14 days (Roundtrip)</td>
<td>1 – 18 months</td>
<td>12 – 24 months (Roundtrip)</td>
<td>17 – 20 months</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>0-g</td>
<td>~ 1/6-g</td>
<td>0-g</td>
<td>~ 1/3-g</td>
</tr>
<tr>
<td><strong>Air Revitalization</strong></td>
<td>Open</td>
<td>Closed 75% by mass</td>
<td>Closed &gt;75% by mass</td>
<td>Closed &gt;75% by mass Resupplied by ISRU</td>
</tr>
<tr>
<td><strong>Water Recovery</strong></td>
<td>Collection and Storage</td>
<td>Closed 90% by mass Resupplied by ISRU</td>
<td>Closed &gt;90% by mass</td>
<td>Closed &gt;90% by mass Resupplied by ISRU</td>
</tr>
<tr>
<td><strong>Thermal Systems</strong></td>
<td>Low Power</td>
<td>High Power</td>
<td>High Power</td>
<td>High Power</td>
</tr>
<tr>
<td><strong>Food Systems</strong></td>
<td>Conventional Stored</td>
<td>Conventional Stored with Fresh Food Augmentation</td>
<td>Extended Shelf Life with Fresh Food Augmentation</td>
<td>Extended Shelf Life with Fresh Food Augmentation</td>
</tr>
</tbody>
</table>
Air Revitalization Technologies

• Carbon Dioxide Removal
  – Molecular Sieve.
  – Solid Amine Water Desorption (SAWD)
  – Electrochemical Depolarization Concentrations (EDC)
  – Air Polarized Concentrators (APC)
  – Membrane removal and other Regenerative Technologies

• Carbon Dioxide Reduction
  – Advanced Carbon Formation Reactor System (ACRS)
  – Bosch
  – Sabatier

• Oxygen Generation
  – Electrolysis of water

• Nitrogen Generation

• Trace Contamination Control (TCC)
  – Particulate Fillers
  – Activated Charcoals
  – Chemisorbant beds
  – Catalytic Burners
Water Recovery Technologies

• Urine Recovery
  – Vapor Compression Distillation (VCD)
  – Packed Bed Reactor (PBR)
  – Thermoelectric Integrated Membrane Evaporation System (TIMES)
  – Air Evaporation Systems (AES)
  – Aqueous Phase Catalytic Oxidation Post
  – Supercritical Water Oxidation (SCWO)
  – Vapor Phase Catalytic Ammonia Removal (VPCAR)

• Hygiene Recovery and Potable Processing
  – Reverse Osmosis (PO)
  – Multifiltration (MF)
  – Electrodialysis

• Water Recovery from Condensate
  – Condensation/Separation

Fig. 1. VPCAR process flow diagram.
Solid Waste Management Technologies

- Collection, Segregation, and Storage

- Solid Waste Treatment (stabilization)
  - Super Critical Water Oxidation
  - Wet Oxidation
  - Combustion/incineration
  - Electrochemical incineration

Thermal Control Technologies

- Air Temperature and Humidity Control
  - Condensing heat exchanger/moisture removal
  - Air heat exchanger
Fluid Transport and Reaction Processes

• **Fluid management, transport, and reaction processes are common and critical to many of the ALS subsystems – leading to the following questions...**
  – What are the direct or indirect effects of microgravity on systems that are most critical to the development of ALS?
  – Can closed loop systems (or even components) be developed that are truly gravity independent?
  – If so, how will independence be verified?
  – If not, how will long term verification and testing be conducted?
  – What system level modeling is needed and how do we verify the models?
  – How can the microgravity environment be leveraged to enhance the operation of ALS?
  – Can these systems be operated in a variety of gravity environments?

• **NASA is developing a systematic program of investigation to identify the fluid transport issues relevant to life support.**
  – Program leverages both internal and external experts from Code UG programs.
First step - identify specific critical areas of research with the greatest potential for successful resolution.

- **Fine Particulates** (May 5-7, 2003): Identify problems associated with the control of fine particulates in closed-loop systems.
  - 26 invited participants [http://www.ncmr.org/events/particulate/](http://www.ncmr.org/events/particulate/)

- **Two-Phase Flow, Fluid Stability and Dynamics** (May 15, 2003): Prioritize strategic research thrusts related to multiphase flow of spacecraft power, propulsions and advanced life support systems.
  - 48 invited participants [http://www.ncmr.org/events/multiphase/](http://www.ncmr.org/events/multiphase/)

- **Microgravity Fluids, Transport and Reaction Processes in Advanced Human Support Technology** (August 11-13, 2003): Identify and prioritize fluids, transport and reaction problems associated with AHST and develop strategic collaborative investigations.
  - 52 invited participants
Summary of Workshop Findings

- Recommended increase collaboration by involving microgravity program in early development of AHST through final on-orbit testing.
- NASA should take lead in compiling design guides detailing fundamental mechanisms and predictive tools (models, correlations, etc.) relative to AHST.

**Air Revitalization**
- Determine particulate matter size distribution on ISS (< 10 microns)
- Coordinate effort to understand fire signatures
- Develop packed beds for CO$_2$ removal
- Develop phase separation and liquid degassing techniques for ECLSS.

**Water Recovery**
- Develop 0-g models and correlations for multiphase flow and separation
- Continue technology development for packed bed reactors in 0-g
- Obtain techniques for accurate multiphase metering/sampling
- Develop technology for fixed film (or other types) bioreactors
- Develop technology for phase change/evaporation systems
Summary of Workshop Findings

(Continued)

**Thermal Systems**

- Attain a phenomenological understanding and accumulate pertinent empirical data for two-phase flow systems.
- Develop advanced, efficient, and reliable vapor compression heat pump technologies.
- Develop reliable and low cost dynamic pressure control mechanisms for liquid storage tanks (eliminate venting).

**Solid Waste Management**

- Develop handling and transport of solid waste.
- Models for two- and three-phase flow for very low and very high moisture content.
- Develop monitoring and control systems.
Second step – propose gravity dependent technologies to develop with other NASA Centers.

- Develop predictive/design models and technologies for mitigation of particulate build-up in closed-loop systems (minimize generation, transport, and deposition).
- Develop technologies to monitor and characterize fine particulates.
- Develop models and correlations for bed reactor technology in hypo-gravity.
  - Gas-liquid reactors (fixed or moving)
  - Minimize or eliminate fine particulate generation in fixed PBR (single phase).
- Develop empirical correlations, theoretical models, scaling laws and comprehensive CFD codes for hypo-gravity environment:
  - Two-phase flow in complicated geometries (components, tees, fittings, etc.)
  - Boiling and condensation heat transfer (CHF)
  - Phase distribution and phase transition
- Develop stability criteria for two-phase systems in microgravity.
- Develop advanced phase separation technologies.
- Develop gas-tolerant liquid pump.
Third step - implement recommendations through ground and flight (ISS) based programs.

**ISS FLIGHT**
- Two Phase Flow Facility (ToFFy): Flow Boiling, Condensation, Phase Separation, System Stability
- AHLS-1: Reactor technologies: Fixed and Moving Beds
- AHLS-2: Condensing Heat Exchanger for Space Systems (CHESS)
- AHLS-3: Two-Phase/TBD
- LMM (CVB), BXF (MABE, NPBX), LME, MOBI, CCF

**GROUND BASED**
- Complete existing grants – capitalizing on the “strategic” value.
- Phase in new longer-term ALS R&D through baseline and augmented budgets.
Glenn Research Center’s Role in ALS

- Develop specific components, subsystems, and technologies where the gravitational dependence of fluids, transport and reaction processes are on the critical path to the overall development of ALS systems.

- Provide key design tools, experimentally validated components, trade studies and necessary “trouble shooting” as flight systems are developed.
Flow Boiling Critical heat Flux in Reduced Gravity

Issam Mudawar & Hui Zhang
Boiling and Two-Phase Flow Laboratory
Purdue University

and

Mohammad M. Hasan
NASA Glenn Research Center
Rationale

- Critical heat flux (CHF) is key design parameter for heat-flux-controlled devices
- Ability to predict CHF is of paramount importance to both safety and reliability of two-phase systems
- Vast majority of reduced-gravity boiling studies focused on pool rather than flow boiling
- There are conflicting recommendations concerning viability of pool boiling in microgravity
- Flow boiling is proven method for enhancing CHF relative to pool boiling
- Bulk motion increases CHF by flushing bubbles away from heated wall before they coalesce into insulating vapor blanket, and by constantly replenishing wall with bulk liquid
- Low pumping power favors reducing flow velocity
- Minimum velocity is therefore sought which can adequately increase CHF and suppress detrimental effects of reduced gravity

Focus Area: Thermal Systems and Phase Change Processes

- Future missions for exploration of solar system will require enabling technologies for efficient and reliable energy generation (nuclear, chemical, solar sources), storage (rechargeable batteries, regenerative fuel cells, flywheels, latent heat phase change), and transfer (cabin temperature control, space suit temperature regulation)

- Need for improved energy-to-mass ratios suggests replacing present single-phase operations with two-phase systems. Future design of important thermal subsystems in boilers, condensers, evaporators, heat exchangers, cryogenic fluid storage units, fuel cells, radiators and heat pipes involve complex multiphase fluid flow and transport issues

- Full understanding of multiphase transport phenomena associated with operation of thermal and phase change subsystems in microgravity needed for both design and safe and efficient operation in space
High Priority Recommendations:

- Attainment of phenomenological understanding and accumulation of empirical data for two-phase flow in micro- and macro-geometries, boiling heat transfer, and phase-distribution and phase-transition phenomena in microgravity
- Development of empirical correlations, theoretical models and scaling laws for two-phase flow in complicated geometries, boiling and condensation heat transfer, and phase-distribution and phase-transition phenomena in microgravity
- Development of stability criteria for two-phase heat transfer loops in microgravity
- Development of advanced, efficient, and reliable vapor compression heat pump technology

Challenge

Reduced gravity flow boiling heat transfer and critical heat flux data and models virtually nonexistent!!!
Effects of Orientation on Pool Boiling CHF at One $g_e$

CHF from a horizontal surface

Heat Flux

$g_e$

1$g_e$

CHF = 26 W/cm$^2$

0°

90°

180°

CHF = 5 W/cm$^2$

Saturated PF-5052

Howard & Mudawar (1999)

Phase Change Photo Library (Mudawar, 1984 - 2004)

NASA/CP—2004-213205/VOL1

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Bubble Coalescence Effects

Incipient Flow Boiling

0.35 m/s
0.75 m/s
1.50 m/s

Flow

Pool Boiling

0.50 mm

(50% CHF)

Flow Boiling

< 20% CHF

60% CHF

CHF

Flow

U = 0.5 m/s

12.7 mm

6.4 mm

June 23, 2004
Conference on Strategic Research to Enable NASA’s Space Exploration Missions

Prof. I. Mudawar
One-g_e Flow Boiling CHF Apparatus

Test Module

Rotation Stage

Flow Channel

Heater Block

Heated Wall

Thermocouple Array

Test Module Bottom Plate

Flow

Heater

Boiling Apparatus
Vapor Behavior for Saturated Flow

Downward-facing heater

Upward-facing heater

Upflow

$U = 0.1 \text{ m/s}$

$\theta = 90^\circ$

$g_e$

$U = 1.5 \text{ m/s}$

$\theta = 90^\circ$

$180^\circ$

$270^\circ$

$0^\circ$

Downflow
Variation of CHF with Orientation and Flow Velocity at 1 \( g_e \)
**CHF Regime Map**

- **Wavy Vapor Layer Regime**
  - Orientation: $\theta = 90^\circ$
  - Velocity: $U = 1.5 \text{ m/s}$

- **Pool Boiling Regime**
  - Orientation: $\theta = 0^\circ$
  - Velocity: $U = 0.1 \text{ m/s}$

- **Vapor Counterflow Regime**
  - Orientation: $\theta = 225^\circ$
  - Velocity: $U = 0.1 \text{ m/s}$

- **Stagnation Regime**
  - Orientation: $\theta = 270^\circ$
  - Velocity: $U = 0.1 \text{ m/s}$

- **Stratification Regime**
  - Orientation: $\theta = 180^\circ$
  - Velocity: $U = 0.1 \text{ m/s}$

- **Separated Concurrent Vapor Flow Regime**
  - Orientation: $\theta = 270^\circ$
  - Velocity: $U = 0.5 \text{ m/s}$
Wavy Vapor Layer Regime

$U = 1.5 \text{ m/s}$

5.0 mm

Flow

$g_e$
Vapor Momentum vs Interfacial Pressure

\[ (P_f - P_g) \]

\[ \sigma \delta \left( \frac{2\pi}{\lambda} \right)^2 \]

\[ \text{Pressure Force} \]

\[ \frac{4\pi\sigma\delta}{b\lambda^2} \sin(b\pi) A_w \]

\[ \rho_g U_g^2 u A_w \]

\[ 2\delta \]

\[ b\lambda \]

\[ \lambda \]
**Interfacial Lift-off Model**

- **Critical Wavelength:**
  \[
  \frac{2\pi}{\lambda_c} = \frac{\rho_f \rho_g (U_g - U_f)^2}{2 \rho \left( \rho_f + \rho_g \right)} + \left[ \frac{\rho_f \rho_g (U_g - U_f)^2}{2 \rho \left( \rho_f + \rho_g \right)} \right]^2 + \left( \frac{\rho_f - \rho_g}{\sigma} \right) g \cos \theta
  \]

- **Interfacial Pressure Difference:**
  \[
  \frac{P_f - P_g}{b \lambda^2} = \frac{4 \pi \sigma b \sin (b \pi)}{\lambda^2}
  \]

- **Interfacial Lift-Off Heat Flux:**
  \[
  q_w = \rho_g \left( c_{p,f} \Delta T_{sub,i} + h_{fg} \right) \left( \frac{P_f - P_g}{P_g} \right)^{1/2}
  \]

- **Heater Energy Balance:**
  \[
  q_m = b \cdot q_w
  \]

- **Critical Heat Flux:**
  \[
  q_m = \rho_g \left( c_{p,f} \Delta T_{sub,i} + h_{fg} \right) \left[ \frac{4 \pi \sigma b \sin (b \pi)}{\rho_g} \right]^{1/2} \left( \frac{\lambda}{\lambda_c} \right)^{1/2}
  \]
Comparison of Measured and Predicted CHF at 1 \ g_e

Wavy Vapor Layer Regime (U = 1.5 m/s)

Pool Boiling Regime
0.1 m/s

Wavy Vapor Layer Regime
0.1 m/s

Stratification Regime
0.1 m/s

Vapor Counter-Flow Regime
0.1 m/s

Stagnation Regime
0.1 m/s

Pool Boiling Regime
0.1 m/s

Comparison of Measured and Predicted CHF at 1 \ g_e

Pool Boiling CHF (Zuber et al., 1961)

Measured CHF U = 1.5 m/s

Lift-off CHF Model (Zhang et al., 2002) U = 1.5 m/s

Flooding (Nejat, 1981)

Measured CHF U = 0.1 m/s

q''_m (W/cm^2)

Orientation, \( \theta \)
**Minimum Velocity Required to Overcome Body Force Effects**

**Negligible Component of Body Force Perpendicular to Wall**

\[
\frac{2\pi \sigma (\rho_f + \rho_g)}{\lambda \rho_f \rho_f (\Delta U)^2} = \frac{1}{2} \left[ 1 + \sqrt{1 + 4 \left( \frac{\rho_f - \rho_g}{\rho_f + \rho_g} \right)^2 \frac{\sigma g}{\rho_f \rho_f (\Delta U)^2}} \right]
\]

\[
\frac{Bo}{We^2} = \frac{\left( \rho_f - \rho_g \right) \left( \rho_f + \rho_g \right)^2 \sigma g}{\rho_f \rho_g U^4} \leq 0.09
\]

\[
Bo = \frac{(\rho_f - \rho_g) g L^2}{\sigma} \quad We = \frac{\rho_f \rho_g U^2 L}{(\rho_f + \rho_g) \sigma}
\]

**Negligible Component of Body Force Parallel to Wall**

\[
U_s \sim \left[ \frac{(\rho_f - \rho_g) g D_h}{\rho_f^{1/2}} \right]^{1/2} \ll U
\]

\[
\frac{1}{Fr} = \frac{(\rho_f - \rho_g) g D_h}{\rho_f U^2} \leq 0.13
\]
Minimum Velocity Required to Overcome Body Force Effects

U > 1.5 m/s to overcome body force effects below 1 g_e

FC-72
P = 1.3 bar

\[ \frac{Bo}{We^2} = 0.09 \]

\[ We_L = 2\pi, L = 0.01 \text{ m} \]

\[ We_L = 2\pi, L = 0.1 \text{ m} \]

\[ \frac{1}{Fr} = 0.13 \]

Mars, Moon, Earth
Reduced Gravity Flow Boiling CHF Apparatus

Flight Rack

Two-Phase Loop

Phase Change Photo Library (Mudawar, 1984 - 2004)

Conference on Strategic Research to Enable NASA’s Space Exploration Missions

Prof. I. Mudawar
KC-135 Microgravity Experiments

NASA Glenn Research Center, April 2004

Flight Trajectory

Altitude (ft)

22000 24000 26000 28000 30000 32000 34000

Maneuver Time (s)

0 20 45 65

1.8g_e  Zero-g_e  1.8g_e

Operators:
Dwayne Kiefer (QSS)
Dr. Charles Niederhaus (NASA)
Dr. Juan Agui (NASA)

Phase Change Photo Library
(Mudawar, 1984 - 2004)
Reduced Gravity Flow Loop

Coolant Reservoir

Accumulator

Heat Exchanger

Flow Boiling Module

Flowmeter

In-Line Heater

Pump

Filter

Turbine

Prof. I. Mudawar

June 23, 2004

Conference on Strategic Research to Enable NASA’s Space Exploration Missions
Flow Boiling Module

188 Ohm Resistive Layer (covered with Glass Passivation)
Solder Layer (96% Tin - 4% Gold Metallization)
Al₂O₃ Substrate
Solder Pads
Thermocouple hole
Oxygen-Free Copper Slab

All dimensions in mm

June 23, 2004
Conference on Strategic Research to Enable NASA’s Space Exploration Missions
Prof. I. Mudawar
Thermal Response of Heater

$T$ (°C)

$q''$ (W/cm²)

$t$ (s)
Parabolic Flight Results

FC-72, \( U = 0.14 \) m/s

1.8\( g_e \)

0.17\( g_e \) (Lunar)

Zero-\( g_e \)

Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)
Parabolic Flight Results

FC-72, $U = 1.40 \text{ m/s}$

1.8$g_e$

0.377$g_e$
(Martian)

Zero-$g_e$

Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)
**Parabolic Flight Results**

- **CHF (W/cm²)**
- **U (m/s)**

**Zero-g**

**One-g**

**FC-72**

$\Delta T_{\text{sub,o}} = 2.6 - 12.3 \, ^{\circ}C$

Phase Change Photo Library (Mudawar, 1984 - 2004)
**Conclusions**

**One-G Flow Orientation Study**

- At high velocities, CHF at all orientations dominated by Wavy Vapor Layer Regime. Vapor layer layer propagates along heated wall permitting liquid contact only in troughs of interfacial waves. CHF occurs when liquid contact regions are lifted from wall due to intense vapor effusion.

- Interfacial Lift-off Model very effective at capturing overall dependence of CHF on orientation in Wavy Vapor Layer Regime.

- Flooding limit better suited to CHF prediction in low velocity downflow orientations.

- Dimensionless criteria developed for minimum flow velocity required to overcome body force effects on flow boiling CHF.
Conclusions

Reduced Gravity Study

- Body force has significant effect on nucleate flow boiling at low flow velocities
- Very low coolant velocities (especially below 0.5 m/s) greatly reduce CHF in microgravity
- Increasing flow velocity reduces CHF sensitivity to body force and can eliminate detrimental effects of microgravity on CHF
- Experimental CHF data corresponding to microgravity, lunar and Martian environments demonstrate existence of minimum velocity above which effects of body force on CHF are suppressed
- Experimental CHF data support predictions of theoretical dimensionless minimum velocity criteria
Conclusions

Practical Implications

- This study provides systematic method for reducing power consumption in reduced gravity systems by adopting minimum velocity required to provide adequate CHF and preclude detrimental effects of reduced gravity

- This study proves it is possible to use existing 1 g_e flow boiling and CHF correlations and models to design reduced gravity systems provided minimum velocity criteria are met
Conference-Workshop on Strategic Research to Enable NASA's Exploration Missions

Cleveland, Ohio
June 22-23, 2004

Masami Nakagawa
NASA IPA-GRC
Colorado School of Mines
Space Exploration & Particulate Control

**Fine Particulate Science and Technology**

*for Space Applications*

(May 5-7, 2003 in Cleveland)

Participants: Academics (US 7, International 2)
- Industrial 2
- National Labs 1
- NASA: HQ 1, JSC 2, USRA 1,
- GRC 5, NCMR3

For workshop presentation materials, report and road map are available at:

[http://www.ncmr.org/events/particulate/](http://www.ncmr.org/events/particulate/)
Space Exploration & Particulate Control

NASA Workshop on Critical Issues in Microgravity Fluids,

Transport and Reaction Processes in

Advanced Human Support Technology (AHST)

Sheraton Cleveland Airport Hotel
11 – 13 August 2003
Cleveland, OH

Http://gltrs.grc.nasa.gov
## Space Exploration & Particulate Control

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<td>Fire detection &amp; suppression Suspended particulates* removal</td>
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<td><strong>Habitats</strong></td>
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<td>Oxygen supply CO₂ removal</td>
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*Particulates: solid, liquid and microbe*
Space Exploration & Particulate Control

Filtration

Microgravity

Deposition

EVA&ISRU

Extraterrestrial Environment
A tired mission commander Eugene Cernan, grimy with lunar soil from three days of exploring the Moon’s Taurus-Littrow valley. On his chest, underneath his longjohns, are two of the sensors that relayed biomedical data to mission control. By Harrison Schmidt. Apollo 17, December 7-19, 1972.
Space Exploration & Particulate Control
Atmospherere Revitalization Functional Category

1. CO$_2$ removal: fines generated in a heated, packed bed
2. Fire detection and suppression
   a. Particulate size distribution background (baseline)
   b. Gaseous and aerosol combustion product signatures
   c. Smoke particle agglomeration
   d. Smoke/particulate matter migration and evolution in complex geometries
3. Airborne particulates
   a. Gas-solid separations
   b. Dust deposition
   c. Multi-scale particles interaction and agglomeration
Space Exploration & Particulate Control

Suspended Particulate Matter

Problem: Lack of background data on spacecraft cabin suspended particulate matter size distribution.

Need: Portable monitoring device

Challenges:
1. Agglomeration and transport—wide size distribution
2. Filtration and health standard
3. Particulate matter signature of various materials---smoke particles
Space Exploration & Particulate Control

Recommended Research Areas: High Priority

1. Monitor particulate and microbial background environment (size, morphology, composition). Establish backgrounds) for given crewed environment.

2. Gaseous and aerosol combustion product signatures.

3. Develop and compile system-specific design guides for mechanisms, behaviors, fundamentals, and physics based upon scaling laws, correlations, previous flight experiments and performance, and theory.
Space Exploration & Particulate Control

Recommended Research Areas: Priority

1. Develop robust packed bed technology, particularly monolithic substrates or other non-particulate bed morphology for catalyst and adsorbent media supports.

2. Sensor and electronic systems miniaturization including distributed system.

3. Investigate alternative degassing techniques (e.g., ultrasonic)
Space Exploration & Particulate Control

Sensors (Smoke Detectors, ---)

0.5μ-1.0μ: 185
1.0-5.0: 190
5.0-10: 56
10-25: 41
25-50: 35
50-100: 0
100-200: 6
200-300: 9
300-500: 1
> 500: 3
Space Exploration & Particulate Control

Filters (HEPA Filters, Catalyst Element Filters,...)

Challenges associated with **Microgravity**
1. No gravitational screening ---> longer residence time
2. A wide size distribution ---> dynamic interactions
3. Agglomeration process ---> effective filter design

Real time monitoring of dynamic interaction of airborne particulates

**DATA**

**Implementation**

**Modeling**
Space Exploration & Particulate Control

Moon Mining

Mars Habitat

ISRU and EVA
Space Exploration & Particulate Control

Issues associated with EVA & ISRU

Dust Mitigation
Handling of Regolith on Moon and Mars.
Segregation/Separation in ore beneficiation

Electrostatically and/or magnetically charged particles

Tribo-charge effects
Space Exploration & Particulate Control

International Conference on Environmental Systems (ICES)

JULY 19-22, 2004
Colorado Springs, CO

Particulate Systems for Spacecraft ECLSS Applications

- Removing Dust from Confined Air Volumes
- Synthesis & Evaluation of Activated Carbon Composite
- Airborne particulate matter under microgravity
- Inhalation
Particulate Systems Research
At
NASA-GRC
Juan H. Agui, Robert Green, Jerry Myers, Allen Wilkinson
Enrique Rame, Nihad Daidizic
CSM, UC Boulder, Case Western,
Univ. of Pittsburgh, SUNY Buffalo, MIT
Heather Angel & Phi Thanh: Summer students

Advanced Life Support
• Monitoring particulates
• Filtering particulates

ISRU
• Soil characterization
• Processing
• Tribocharge effects

EVA
• Dust mitigation
John Glenn Biomedical Engineering Consortium

Conference – Workshop on
Strategic Research to enable NASA’s
Exploration Missions

Marsha Nall
Bioscience and Engineering
Program Manager
June 22, 2004

Glenn Research Center
at Lewis Field
JOHN GLENN BIOMEDICAL ENGINEERING CONSORTIUM

Inter-institutional research and technology development, beginning with ten projects in FY02 that are aimed at applying GRC expertise in fluid physics and sensor development with local biomedical expertise to mitigate the risks of space flight on the health, safety, and performance of astronauts.

It is anticipated that several new technologies will be developed that are applicable to both medical needs in space and on earth.

Glenn Research Center at Lewis Field
John Glenn
Biomedical Engineering Consortium

Members:  Case Western Reserve University (CWRU)
          Cleveland Clinic Foundation (CCF)
          University Hospitals of Cleveland (UHC)
          National Center for Microgravity Research (NCMR)
          NASA Glenn Research Center (GRC)

Focus:  Interdisciplinary research leveraging GRC expertise in fluid physics and sensor technology to mitigate critical risks to crew health, safety, and performance identified in the Bioastronautics Critical Path Roadmap

Sponsor:  Office of Biological and Physical Research (OBPR)

Resources:  OBPR Funding - $7.5 M over three years
            Member personnel, facilities, capabilities, leveraging and in-kind contributions

Glenn Research Center
at Lewis Field
## JGBEC Projects

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<th>Project Title</th>
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<td>Confocal And Two-Photon Microscopy For The Assessment Of Countermeasures In</td>
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<tr>
<td>Bone Loss, Hematology, And Immunology</td>
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JGBEC Anticipated Products

Successful conclusion of the projects currently funded by the consortium will result in the following sensor technologies and countermeasures that are compatible with space flight:

- Countermeasure for prevention of bone loss in microgravity
- Prototype portable device to measure human metabolic activity
- Instrument for in-vivo bioluminescent molecular imaging
- Apparatus that will provide several non-invasive optical technologies
- Prototype, wearable sensors’ interface which will wirelessly transmit data
- Revolutionary glucose sensor, self-calibrating requiring no power
- Modified treadmill with incorporated virtual reality capability
- Biochip simulation capability tailored to space applications
- Battery less, potentially implantable unique drug delivery device
- Microscopy capability for assessing countermeasures influence on bone cells

Glenn Research Center at Lewis Field
In Vivo Bioluminescent Molecular Imaging with Application to the Study of Secretory Clusterin, a Potential Biodosimeter During Space Exploration – David Wilson, CWRU

- Introduce luciferase gene from fireflies near a gene of interest in cells
- Luciferase acts as a reporter gene. It expresses luciferase protein whenever the gene of interest is expressed.
- Luciferase protein and its substrate luciferin create light
- Clusterin is secreted by cells in culture and animals following low levels of radiation

**NASA Application:**
Clusterin biodosimeter will measure the biological effect of radiation exposure

**Glenn Research Center** at Lewis Field
Integrating Non-Invasive Technologies to Enable Effective Countermeasures During Prolonged Space Travel – Rafat Ansari, GRC

Experimental Rack On-board the KC-135 for Ocular Blood Flow Experiment

Ocular Blood Flow Monitoring in “0 g” in a test subject (RRA) On-board the KC-135 airplane

- Ocular and nervous system circulatory physiology
- Monitoring of Blood Glucose
- Monitoring of Oxygen
- Brain physiology

NASA Application:
Head-mounted device using non-invasive optical techniques for monitoring astronaut health and for early detection of disease or abnormality

Glenn Research Center at Lewis Field
Microminiature Monitor for Vital Electrolyte and Metabolite Levels in Astronauts – Miklos Gratzl, CWRU

- Painless and easy to insert, wear, and remove
- Free of track infection
- Continuous
- No driving power required
- No calibrations required
- Fully compatible with telemetry
- Simultaneous monitoring of interstitial glucose, pH, and K+
- Self-test and three-day error-free operation or longer

NASA Application:
Microminiature sensor placed under the skin using non-invasive optical techniques for continuous \textit{in vivo} monitoring of astronaut electrolytes and metabolite levels

Glenn Research Center at Lewis Field
Acoustically Induced Microdamage to prevent Bone Loss –
Ulf Knothe, CCF

- Identify the bandwidth and application regime necessary to:
  - enhance fluid flow and mass transport through bone matrix
  - produce low-level, diffuse microdamage similar to that ensuing from normal physiological activity on Earth
- Design an experimental device and to test its efficacy in the hind limb suspension model of the rat

NASA Application:
Through process of ultrasound therapy, which induces bone microdamage and natural rebuilding, develop a countermeasure device to maintain astronaut bone mass for space application.

Glenn Research Center
at Lewis Field
Remote and On-Board Detection, Diagnoses, and Treatment of Serious Cardiac Dysrhythmias (Project “Rescue”) – David York, GRC

- Development of ground based prototype system to test the hypothesis that a system can be provided to detect and diagnose astronaut dysrhythmias both locally on-board a spacecraft and remotely (i.e. from earth) and treated.

- Test the hypothesis that local or remote users of the system can provide commands to, and receive data from the system using only a Web browser.

**NASA Application:**
Non-invasive monitor to detect and diagnose astronaut cardiac dysrhythmias utilizing a wireless communication, low power consumption and high bandwidth data transmission system

**Glenn Research Center at Lewis Field**
Development of a Portable Unit for Metabolic Analysis (PUMA) – Daniel Dietrich, GRC

Design and build a prototype device to measure five key respiratory parameters:
- temperature
- pressure
- volumetric flow rate
- mole fraction of carbon dioxide & oxygen

NASA Application:
Utilize portable device to non-invasively monitor astronaut metabolism during various activities such as exercise to determine overall fitness and effectiveness of exercise programs

Glenn Research Center

at Lewis Field
Controlled-Release Microsystems for Pharmacological Agent Delivery - Shuvo Roy, CCF

- **Ultimate Goal (Long-term)**
  - To develop engineered systems for the delivery of natural and/or synthetic compounds that can counteract adverse effects of microgravity on astronaut health

- **Project Goal (Short-term)**
  - To develop MEMS-based drug delivery systems that will enable space biology/medicine researchers to dispense pharmacological agents locally over a sustained period
  - Miniature, Implantable, controlled-release

**NASA Application:**
Controlled continuous drug delivery system for administering pharmacological agents as countermeasures to adverse effects of microgravity on astronaut health

**Glenn Research Center** at Lewis Field
Rapid Design and Simulation Tools for Space-Based BioChip Devices - Arnon Chait, GRC

- Develop sustained, in-house, biochip design and simulation capabilities to assist/design/optimize space-bound biochips for medical/diagnostics applications.
- Elucidate fundamental space-specific physical phenomena that are common to all biochip devices intended to operate in space.
- Collaborate with and assist program researchers and leading biochip companies with analysis and design of space-capable biochip devices.

NASA Application:
Development of biochip design and simulation capabilities to optimize space-bound biochips for medical/environmental diagnostics applications:

Glenn Research Center at Lewis Field
To design and develop an exercise countermeasure

- Challenge the postural control system
- Exercise balance and locomotor reflexes
- Alleviate adverse adaptations to neurovestibular system

Address multiple physiological systems

- Neurovestibular
- Musculoskeletal
- Cardiovascular

NASA Application:

Provide exercise to address physiological processes of growth and development in muscle, bone, and cardiovascular systems while helping to maintain a sense of physical orientation by stimulating the neurovestibular system

Glenn Research Center

at Lewis Field
Confocal and Two-Photon Microscopy for the Assessment of Countermeasures in Bone Loss and Immunology – Greg Zimmerli, GRC

- Develop fluorescence microscopy techniques to assess, at a cellular level, the effectiveness of countermeasures to effects of long duration space flight
- Fluorescence microscopy techniques:
  - Two-photon
  - Fluorescence Correlation Spectroscopy
  - Fluorescence Resonance Energy Transfer
  - Fluorescence Lifetime Imaging Microscopy
- Quantifying cellular response:
  - Cell proliferation
  - Structure
  - Protein associations

**NASA Application:**

New microscopy techniques will be used to identify and assess potential countermeasures to bone loss in microgravity through investigation of cellular response to other solutions beyond exercise.

**Glenn Research Center**

at Lewis Field
Biomedical Engineering Consortium Projects

- Fluorescent Microscopy of Bone Cell Cultures
- Acoustically Induced Micro-damage to Prevent Bone Loss
- Glucose Levels in PBS:
  - 0 mg/dl
  - 39 mg/dl
  - 95 mg/dl
  - 667 mg/dl
- Microminiature Glucose Sensor
- Nanoporous Membrane
- Micromachined Reservoir
- Pharmacologic Molecule
- Controlled-Release Microsystems for Pharmacological Agent Delivery
- Portable Metabolic Analyzer for Crew
- Bioluminescent imaging for radiation dosimetry
- Detection and Web-based Reporting of Cardiac Dysrhythmia
- Microminiature Glucose Sensor
- Oxygen Sensor
- Virtual Reality Dual-Action Treadmill for Improved Neurovestibular Adaptation
- Rapid Design and Simulation Tools of Space-bound Biochips
- Ophthalmic Tech-Health: For the Benefit of All Human Kind
- Non-invasive Eye Measurements to Reveal the Body’s Health
- Portable Metabolic Analyzer for Crew
- Acoustically Induced Micro-damage to Prevent Bone Loss
JOHN GLENN BIOMEDICAL ENGINEERING CONSORTIUM

http://microgravity.grc.nasa.gov/grcbio/bec.html

Marsha Nall
Marsha.M.Nall@nasa.gov
216 433-5374

Glenn Research Center
at Lewis Field
Strategic Research to Enable NASA's Exploration Missions

Simon Ostrach
Director
National Center for Microgravity Research
Case Western Reserve University
Strategic Research to Enable NASA's Exploration Missions

“What technologies must we create to enable the next explorers to go beyond where we have been?”

“How does the space environment change the behavior of physical and chemical processes and the technologies that rely on them?”

- How can we provide critical data needed for design and engineering purposes?
- How can space exploration advance our knowledge of technologies and processes important on Earth?
Strategic Research to Enable NASA's Exploration Missions

**Physical Science**
- Microgravity Fluids & Transport Dynamics
- Multiphase flow and heat transfer
- Chemically reacting flows
- Microgravity Fluids management
- Combustion

**Power and Propulsion**
- Liquid Management
- Cryogenic Fluids Management and Storage
- Planetary power sources
- In situ resource utilization (ISRU)
- In-space fabrication and repair
- Fire Safety

**Regeneration of air, water, food**
- Waste management/ recycling
- Environmental control and monitoring
- Thermal control
- Sensors, sensor placement & operation

**Bioastronautics**
- Advanced Life Support
- Environmental
- Biosensor Technology
- Food and Crops
- Extra-vehicular activity
- Space Factors Human Engineering
- Radiation
- Crew Health
Research for Design (R4D)

- R4D is a prototype research program where science, technology and engineering teams work closely to identify particular problem areas in mission enabling technology and through practical integration of focused research, design and development rapidly produce solutions that advance the technologies essential for mission success.

- Gaps in knowledge critical to mission enabling technologies identified by mission engineers and designers and the research community

- Research topics and approach, schedule and deliverables defined through close collaboration between science, engineering and design teams

- Approval of research program by mission engineers and designers, i.e., end users.

- Continuous communication between participating science, engineering and design teams-
  - provides feedback essential for keeping research focused, quickly
  - identifies barriers to application of research results and allows for sensible schedule forecasts.
Detection and Prevention of Arrhythmias during Space Flight

Dilip Pillai‡, David Rosenbaum‡, Kathy Liszka†, David York§, Michael Mackin§, Michael Lichter§,

‡MetroHealth Campus, Case Western Reserve University,
†The University of Akron,
§NASA Glenn Research Center.
Introduction

- Effects of prolonged microgravity on the electrical stability of the heart are unknown.
- Documented ventricular arrhythmias in Russian and US space programs.
- Structural remodeling of the heart in microgravity may predispose to arrhythmia.
- Fatal arrhythmias could be the first presentation of underlying cardiac disease.
An Episode of Ventricular Tachycardia during Long-duration Spaceflight

Cardiac atrophy after space-flight

Effect of short and long duration spaceflight on QTc intervals in Healthy Astronauts

Indices of electrical instability in the heart

- Microvolt T wave alternans
- QT restitution curve
- Heart rate variability
- Heart rate recovery after exercise
Natural History Electrical Alternans?

Electrode Enhancement

Reduction of noise through adaptive cancellation of artifact

LL (Center)
LL (Segment)
LL Impedance
Respiration
Noise Reduction
LL Enhanced
T Wave Alternans Measurement

Electrocardiogram

T Wave Spectrum

Arrhythmia-Free Survival

Heart Rate Dependence of T Wave Alternans

QT INTERVAL RESTITUTION

QT INTERVAL

CYCLE LENGTH

slope
POWER SPECTRAL ANALYSIS OF HRV

- LF vagal & symp.
- HF vagal eff with resp.

Graph showing power spectral analysis with peaks at LFmax and HFmax.
HEART RATE RECOVERY AFTER EXERCISE
relative risk of death within 6 years according to heart rate recovery

- decline of HR after exercise is a sign of vagal activation.
- a low recovery value has a negative predictive value of 95

Bicycle ergometer in space station
Study Aims

- Determine if orthogonal lead sets can correct artifactual ECG changes caused by microgravity-induced alterations in cardiac position.
- Determine if markers of susceptibility to SCD (TWA and QT restitution) can be reliably measured during space flight.
- Determine the effects of continuous microgravity on markers of susceptibility to SCD.
Methods: Exercise testing protocol

- Skin preparation
- ECG lead placement
- Activate CH2000 data acquisition system
- Exercise protocol (10 to 15 min)
  - 2.5 min recording during seated rest
  - 5 to 10 min exercise with progressive and gradual elevation of heart rate to 140 bpm
  - 2.5 min seated recovery
Study Protocol

- Sequential testing at baseline, then once monthly.
- Each test comprised of 32 channels of data, approximately 10 - 15 min duration (30 MB).
- Analysis off-line
  - Measure standard ECG intervals
  - Measure TWA as function of heart rate to determine heart-rate threshold for TWA.
  - Measure QT interval restitution during various stages of exercise
  - Calculate QT restitution slope
Anticipated Results

- Microvolt-level TWA and QT interval restitution can be reproducibly measured during space flight.
- Determine effects of continuous exposure to microgravity on TWA and QT interval restitution.
- Determine effects of autonomic dysregulation on these markers.
Conclusions

- Prolonged microgravity alters cardiac stability and may predispose to serious cardiac arrhythmias.

- Effect of microgravity on non-invasive markers of susceptibility to sudden cardiac death can be studied.

- Effective countermeasures and re-adaptive techniques can be deployed for prolonged space exploration.
THANK YOU.
The use of interfacial free energy gradients to control liquid and vapor flows naturally leads to simpler and lighter change-of-phase heat transfer systems because of the absence of mechanical pumps. These “passive” engineering (PE) systems are ideal candidates for the thermal control of spacecraft. The non-isothermal constrained vapor bubble (CVB) is a generic PE system without porous material. A common example is a heat pipe without porous material. The particular CVB system being studied is in the shape of a heat pipe fin.

The dynamic thermophysical principles underlying these heat transfer systems, especially under equivalent microgravity conditions, are not well understood and its uses have not been optimized. Within this project, the CVB is being studied under both earth and microgravity flight conditions to remedy this undesirable situation. The study is multi-faceted: 1) it is a study of a passive heat exchanger; 2) it is a basic engineering study of thermal transport; and 3) it is a basic scientific study of interfacial phenomena, physics and thermodynamics. Although the basic engineering Facets (1) and (2) are emphasized for heat exchanger development, the research is also naturally a basic scientific study in interfacial phenomena, microgravity physics and thermodynamics.

The body force field for fluid flow is a function of the shape dependent pressure field, temperature field, composition field and the equivalent microgravity conditions of the system. We propose that relatively large systems (millimeter compared to micro) with regions of small pressure gradients are needed for both optimum performance (high heat fluxes) and convenient experimental study. Therefore, in this project, relatively large systems with high heat fluxes and small capillary pressure levels set in the condenser are emphasized. However, these large systems are easily distorted by the earth's gravitational field where they are inefficient. “Axisymmetric” systems with small Bond numbers are needed to optimize performance. The term axisymmetric is used herein to mean reflective symmetry with respect to the length axis of the CVB. Due to the sensitivity of systems of this size to gravity and to small temperature and pressure gradients, these thermal control systems need to be studied in the microgravitational environment of intended use.

The use of a transparent quartz cell and related optical techniques increase the understanding of the observed transport processes because the PE system is viewed directly. Based on the augmented Young-Laplace model, the pressure gradient field is obtained using interferometry to measure the liquid thickness profile. The temperature field is obtained using external thermal sensors and the measured vapor pressure in the cell. The Kelvin-Clapeyron model relates the heat flux to the temperature and pressure fields. Using earth-based studies, experimental techniques are being developed with polar and apolar fluids in a quartz cuvette with a square cross-section [inside dimensions of 3x3x40mm]. Under contract with NASA Glenn, Northrop-Grumman is using these results to build a CVB heat exchanger for studies in the Fluids Integrated Rack section of the International Space Station using the Light Microscopy Module. Results obtained under Earth and Space Station conditions will be analyzed and compared.

The macroscopic objectives are to determine the stability, the fluid flow characteristics, the average heat transfer coefficient in the evaporator, and the overall heat conductance of the CVB as a function of the heat flow rate and vapor volume. The microscopic objective is to determine the detail characteristics of
the transport processes in the curved liquid film, which has the shape of an extended meniscus with regions where both the capillary and disjoining pressure are important. The local conditions under which cavitation and instability occur with the formation of a dry region will be determined as a function of heat flux, film thickness and stress.

To date, stable and oscillating regions of evaporation or condensation using pentane, 2-propanol, n-butanol, ethanol, and fluorocarbons have been experimentally studied in the earth’s gravitational field and analyzed. The film thickness profiles were obtained using the Image Analyzing Interferometric (IAI) technique developed in our laboratory with improved analytical procedures. The spreading coefficients, the Hamaker constants, and the contact angles were determined as a function of heat flow rate conditions and related using free energy principles. For example, the pentane/quartz system is a simple completely wetting apolar system during evaporation and condensation. Whereas, the polar 2-propanal/quartz system was found to be partially wetting during low heat flux dropwise condensation. A flat adsorbed film of 2-propanol, approximately 6 nm thick, was found to be unstable during film condensation and convert to dropwise condensation. However, due to flooding, this system can also be completely wetting during condensation at high heat fluxes. Publications reporting on these and other results are available.
CONSTRAINED VAPOR BUBBLE [CVB] HEAT EXCHANGER FOR THERMAL MANAGEMENT

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OUTLINE

1) OVERVIEW OF THE PROGRAM

2) DEVELOPMENT OF THE EXPERIMENTAL TECHNIQUES

3) EXAMPLES OF EXPERIMENTAL RESULTS

4) CONCLUSIONS
RESULTS FROM THE FOLLOWING TWO EXPERIMENTS WILL BE COMPARED:

1) PREPARATORY 1g EXPERIMENTS AT RPI

2) FLIGHT EXPERIMENTS IN 2006 ON THE INTERNATIONAL SPACE STATION, ISS

[ISS FLIGHT HARDWARE & SOFTWARE ARE BEING DEVELOPED BY NORTHROP-GRUMMAN UNDER SEPARATE CONTRACT FROM NASA]
CONSTRAINED VAPOR BUBBLE GENERIC SYSTEM

A PASSIVE ENGINEERING SYSTEM [PES] CONTROLLED BY INTERFACIAL PHENOMENA WHICH REPLIES TO SURFACE TEMPERATURE

\[ T_1 < T_2 \]

\[ P_{v2} > P_{v1} > P_{l} > P_{f2} \]

\[ P_v = P_l + \sigma \kappa + \frac{(-B)}{\delta^n} \]
EXAMPLE SYSTEMS

1) SCHEMATIC OF CVB FIN HEAT EXCHANGER

INSIDE DIMENSIONS OF CURRENT VERTICAL 1g SYSTEM BEING STUDIED AT RPI: 3 X 3 X 40 mm
SCHEMATIC OF FUTURE USE IN LOOP
HEAT PIPE WITH SQUARE CROSS-SECTION
COMPREHENSIVE MULTI-FACETED STUDY

1) THE STUDY AND DEVELOPMENT OF A PASSIVE HEAT EXCHANGER FOR THERMAL CONTROL

2) A BASIC ENGINEERING STUDY OF THERMAL TRANSPORT AND STABILITY

3) A BASIC SCIENTIFIC STUDY OF INTERFACIAL PHENOMENA, PHYSICS AND THERMODYNAMICS
OBJECTIVES

1) THE MACROSCOPIC OBJECTIVES ARE TO DETERMINE THE STABILITY, FLUID FLOW CHARACTERISTICS, AVERAGE HEAT TRANSFER COEFFICIENT AND OVERALL HEAT CONDUCTANCE OF THE CVB HEAT EXCHANGER.

STRATEGIC USE:

DEVELOPMENT OF PASSIVE THERMAL SYSTEMS
2) **THE MICROSCOPIC OBJECTIVE IS TO DETERMINE THE DETAIL CHARACTERISTICS OF THE TRANSPORT PROCESSES IN THE CURVED LIQUID FILM IN WHICH BOTH CAPILLARY AND DISJOINING PRESSURES ARE IMPORTANT.**

**STRATEGIC USE: OPTIMIZE THE TRANSPORT PROCESSES IN THE CONTACT LINE REGION**

3) **DEVELOP THE REQUIRED EXPERIMENTAL TECHNIQUES FOR THE ABOVE.**
BOND NUMBER

BOND NUMBER GIVES THE RELATIVE EFFECT OF SYSTEM SIZE, BODY FORCE, & SURFACE TENSION

\[(\rho_l - \rho_v) g L = \sigma K = 4\sigma / H\]

L = HYDROSTATIC LENGTH ; H = INTERNAL WIDTH

\[
\frac{(\rho_l - \rho_v) g L H}{4\sigma} = BOND \ NUMBER
\]

FOR LARGE L, NEED SMALL H AND/OR SMALL g

THEREFORE, SMALL CHARACTERISTIC LENGTHS, H, ARE NEEDED IN THE EARTH'S GRAVITATIONAL FIELD FOR PASSIVE ENGINEERING SYSTEMS LIKE HEAT PIPES BUT NOT UNDER THE “MICROGRAVITY CONDITIONS” ON THE ISS
MAXIMUM AXIAL HEAT FLOW RATE, $Q_m$, BASED ON VISCOUS LOSSES IN THE CORNER MENISCUS IN REGION III OF THE CVB WITH $g \rightarrow 0$

$$Q_m = \frac{C \sigma h_{fg} H^3}{\nu k_{fl} L} \propto \frac{H^3}{L}$$

$H =$ INTERNAL WIDTH ; $L =$ INTERNAL LENGTH

MAXIMUM AXIAL HEAT FLUX, $q_m''$

$$q_m'' = \frac{Q_m}{H^2} = \frac{C \sigma h_{fg} H}{\nu k_{fl} L} \propto \frac{H}{L}$$

e.g., with $H/L = 3/30$, $q_m'' = 4.79$ W/cm²

THEREFORE, RELATIVELY LARGE SYSTEMS ARE NEEDED FOR MAXIMUM HEAT FLUX

HOWEVER, THE CHARACTERISTICS OF SYSTEMS WITH LOW CAPILLARY PRESSURES ARE UNKNOWN
\[
\frac{dK}{dx} = - \frac{\nu k_{fl} Q}{C_l^3 \sigma h_{fg}} K^4 - \frac{\rho g}{\sigma}
\]

CORNER CURVATURE, \( K \), VERSUS AXIAL POSITION FOR VARIOUS HEAT FLOW RATES BASED ON VISCOSOUS LOSSES IN THE CORNER MENISCUS IN REGION III: “\( \mu \) g” ON ISS VERSUS 1 g

![Graph showing curvature versus axial position for different heat flow rates.](image)

Figure 8. Curvature versus axial position

EXPERIMENTAL TECHNIQUES
THE THICKNESS PROFILE OF A CURVED LIQUID FILM IS OBTAINED USING IMAGE ANALYZING
INTERFEROMETRY, IAI, WHICH RECORDS THE NATURALLY OCCURRING REFLECTIVITY PROFILE

REFLECTIVITY PROFILE GIVES THICKNESS PROFILE WHICH GIVES THE CURVATURE PROFILE, $K(x, y)$, AND THE PRESSURE FIELD, $P(x, y)$

$$P_l = P_v - \sigma K - \left( \frac{-B}{\delta^n} \right)$$

MENISCUS CURVATURE PROFILE
IN CONTACT LINE REGION, K VS y:

\[ \Delta K = \frac{\rho g}{\sigma} \Delta x \]
EFFECT OF HEAT INPUT ON AXIAL CURVATURE PROFILE FOR ETHANOL/QUARTZ SYSTEM

![Graph showing the effect of heat input on axial curvature profile for an ethanol/quartz system. The graph includes modeling results, experimental data with Q = 0.49 W, and isothermal modeling results.]
IMAGE OF DROPWISE CONDENSATION WITH CONDENSATE BEING REMOVED BY THE CORNER MENISCUS: 2-PROPANOL ON QUARTZ
TEMPERATURE DIFFERENCE, $T_{\text{SURFACE}} - T_{\infty}$, VERSUS AXIAL DISTANCE

DRY CELL VERSUS 1g CVB WITH PENTANE FOR THE SAME HEATER TEMPERATURE

OVERLAP REGION SHOWS DRYOUT LENGTH WHICH IS A FUNCTION OF THE BODY FORCE

$T_{\text{heater}} = 424.8$ K
EXPERIMENTAL DATA ON THE FOLLOWING FLUIDS HAVE BEEN OBTAINED:

STEADY STATE AND OSCILLATING:
PENTANE: APOLAR; CVB TO BE USED ON ISS
PENTANE: APOLAR; LOOP CONFIGURATION

STEADY STATE CVB:
ETHANOL: POLAR; TO BE USED ON THE ISS

DROPWISE CONDENSATION:
n-BUTANOL [θ > O; APOLAR]
2-PROPANOL [θ > O; POLAR]
CONCLUSIONS

1. USING 1g PREPARATORY EXPERIMENTS, EXPERIMENTAL TECHNIQUES TO STUDY THE HEAT TRANSFER CHARACTERISTICS OF THE CVB HAVE BEEN DEVELOPED.

2. IMAGE ANALYZING INTERFEROMETRY CAN BE USED TO OBTAIN THE PRESSURE GRADIENT FOR LIQUID FLOW AND STABILITY.

3. THERMOCOUPLES PLUS MODELING CAN BE USED TO OBTAIN THE THERMAL CHARACTERISTICS
4. ALTHOUGH THE HIGH TRANSPARENCY OF QUARTZ FOR VISUAL WAVELENGTHS MAKES IT AN IDEAL MATERIAL FOR VISUAL OBSERVATIONS, THE OPERATION OF A QUARTZ CVB IS SIGNIFICANTLY EFFECTED BY RADIATION LOSSES DUE TO THE LOW TRANSPARENCY FOR WAVELENGTHS ABOVE 2 μm.

5. FLIGHT HARDWARE AND SOFTWARE ARE BEING DEVELOPED BY NORTHROP-GRUMMAN UNDER SEPARATE CONTRACT FROM NASA FOR FLIGHT EXPERIMENTS IN 2006 ON THE INTERNATIONAL SPACE STATION, ISS.
HOWEVER, THE TRANSMISSIVITY OF FUSED SILICA IS NOT A SIMPLE FUNCTION OF ELECTROMAGNETIC WAVELENGTH

IN THE ABSENCE OF NATURAL CONVECTION, THE OPERATION OF A QUARTZ CVB WILL BE SIGNIFICANTLY EFFECTED BY RADIATION LOSSES.
A SCHEMATIC DRAWING OF THE FOUR REGIONS OF CVB

IN 1g REGION III IS SMALL
IN µg REGION III CAN BE LARGE
Fire Prevention, Detection, and Suppression

Gary A. Ruff
NASA John H. Glenn Research Center

Workshop on
Strategic Research to Enable NASA’s Exploration Missions

June 22 - 23, 2004
Marriott Downtown at Key Center
Cleveland, Ohio USA
In mid-1999, the Space and Life Sciences Directorate at Johnson Space Center was challenged to develop a new paradigm for NASA human life sciences

- Space Medicine
- Space Biomedical Research and Countermeasures
- Advanced Human Support Technology

A new thrust - **Bioastronautics** - was formulated with a budget augmentation request

**Objective:**

- Expanded extramural community participation through the National Space Biomedical Research Institute
- Initiated the detailed planning and implementation of Bioastronautics
  - An Integrated Approach to Ensure Healthy and Safe Human Space Travel
  - Assist in the Solution of Earth-based Problems
Bioastronautics Initiative

• **Builds upon previous and ongoing work**
  – A significant amount of fundamental knowledge has been created through ground and flight research
  – Apply this knowledge base to applications and solutions which will provide *safer human operations in space*

• **Utilizes new research resources**
  – ISS/STS research opportunities
  – Ground analogs

• **Leverages new and unique capabilities**
  – Scientific community to focus on NASA issues
  – Transfer knowledge to Earth based problems
  – Cooperate with other Federal Agencies
  – Develop new technologies
    • smart medical systems
    • biologically-inspired technologies
    • fire protection
• **Substantially improve spacecraft fire safety**
  – $1M per year for four years (initial funding level)
  – Grant-based through NRAs and directed research

• **Fire safety practices and procedures**
  – ISS and Shuttle operations
  – Prolonged human-crew missions in Earth orbit and beyond
  – Lunar and/or Martian habitats
    • In-situ resource utilization
    • Propellant manufacture and storage
Advanced Human Support Technology

Spacecraft Fire Safety Research Roadmap

Flammability of Practical Materials

- Deep seated fires in non-1g environments
- Ignition and combustion of high-P GOx
- Flammability of plastic and composites in hypo-g
  • Improved test methods to rank materials

FIRE SIGNATURES AND DETECTION

- Component level sensors
  • Method to characterize fire signatures
- Fire extinguishants
  • Flame growth and stability models in practical configurations
- Extinguishment in non-1g
  • Trade-off of flame-suppression techniques

FIRE SUPPRESSION AND RESPONSE

- Integrated sensors
  • Fire and pre-fire signatures of practical materials
- Dispersion techniques
  • Flame suppression methods in high O2
- Extinguishment in non-1g
  • Trade-off of flame-suppression techniques
- Limited oxygen and flow for flame propagation
- Practical material flammability for in-situ propellant manufacture
- Complete data base for fire signatures and demonstration of new detection systems
- Experimentally (microgravity and partial-g) validated fire suppressant performance, analysis & models
- Flammability measurements and correlation from μg to 1g; new validated test methods for material rankings

2001-2004

2004-2007

2007-2010
Microgravity Combustion Science Program

- 99 NRA – Bioastronautics
  - Test methods for material flammability (2 GRD)
  - Smoldering/fire initiation (FLT)
  - Fire suppression (2 GRD)
  - Fire signatures and detection (FLT)

- 01 NRA
  - Fire signatures in reduced gravity (GRD)
  - Fire suppression (4 GRD)

- 02 NRA – Human Research Initiative
  - Fire suppression (2 GRD)
  - Fire detection (1 GRD)
  - Large-scale modeling (2 GRD)


Microgravity Science Glovebox (MSG) in the Destiny laboratory on the ISS (Astronaut: Peggy A. Whitson)

Launch: October 2006 on ULF-2
Spacecraft Fire Safety Research Roadmap

2001-2004

- Flammability of practical materials
  - Flammability of plastic and composites in hypo-g
  - Improved test methods to rank materials

- Deep seated fires in non-1g environments
- Ignition and combustion of high-P GOx

2004-2007

- Limiting oxygen and flow for flame propagation
- Practical material flammability for in-situ propellant manufacture

- Component level sensors
- Method to characterize fire signatures
- Integrated sensors
- Fire and pre-fire signatures of practical materials
- Dispersion techniques
- Flame suppression methods in high O2

2007-2010

- Flammability measurements and correlation from μg to 1g; new validated test methods for material rankings

- Complete data base for fire signatures and demonstration of new detection systems

- Experimentally (microgravity and partial-g) validated fire suppressant performance, analysis & models

Advanced Human Support Technology

FLAMMABILITY OF PRACTICAL MATERIALS

FIRE SIGNATURES AND DETECTION

FIRE SUPPRESSION AND RESPONSE
“This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart.” – President Bush
Vision for Space Exploration

• Pursue Compelling Questions
  – Exploration of the solar system will be guided by compelling questions of scientific and societal importance.
  – Consistent with the NASA Vision and Mission, NASA exploration programs will seek profound answers to questions of our origins, whether life exists beyond Earth, and how we could live on other worlds.

• For Sustainable Exploration
  – NASA will pursue breakthrough technologies, investigate planetary resources, and *align ongoing programs to develop sustainable, affordable, and flexible solar system exploration strategies.*
  – The vision is not about one-time events and, thus, costs will be reduced to maintain the affordability of the vision

• Starting Now
  – *NASA will pursue this vision as our highest priority*
  – Consistent with the FY 2005 Budget, NASA will immediately begin to realign programs and organization, demonstrate new technical capabilities, and undertake new robotic precursor missions to the Moon and Mars before the end of the decade.
Fire Prevention, Detection, and Suppression

- Office of Biological and Physical Research addressed how to develop products for The Vision for Space Exploration
- Fire Prevention, Detection, and Suppression was designated a sub-element in the Advanced Human Support Technology product line

So What?

- Outcomes are now products to support exploration missions
  - Required for design points in the development of CEV
- Opportunity to expand efforts in each of the areas on the research roadmap
Advanced Human Support Technology

What Do We Do Now?

- Identify needs and issues from “customers”
  - ISS Materials and Processes
  - ISS Environmental Control and Life Support
  - ISS Fire Detection and Suppression

Potential Products

Needs

Questions

- Scientific and technological questions that must be answered to deliver the products
  - assessment of knowns and unknowns
  - incomplete answers increases risk

- How do you answer the questions?
  - experiments (flight and ground)
  - modeling
  - system verifications

Concepts

- What is finally used by the customer
  - contract specification
  - design rules
  - procedures

Products
**What Do We Do Now?**

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  - contract specification
  - design rules
  - procedures
Issues and Needs Identified in 2001 Workshop

Fire Prevention and Material Flammability

1. Flammability at Elevated Oxygen Levels
   - Ignition mechanisms and flammability for pressurized oxygen systems was the highest priority
   - Increased O$_2$ fraction and sub-atmospheric pressure considered for exploration vehicles and habitats

2. Fire Scenarios for ISS/STS
   - Overheating of electrical cables, short circuits, SFOG, pressurized gaseous oxygen systems

3. Testing/Screening Methods
   - Augment existing test methods (flaming and non-flaming)
   - Improved understanding of relationship between 1-g testing and microgravity performance

Issues and Needs Identified in 2001 Workshop

Fire Prevention and Material Flammability

4. Development of New Materials
   • Foams, fabrics, and films
   • Radiation shielding
   • Composites

5. ISRU Processes and Storage
   • “Little activity, probably premature given absence of even long-term plans for manned missions beyond moon (if that)” 7th International Workshop on Microgravity Combustion and Reacting Systems, June 2003, Cleveland, OH

Issues and Need Identified in 2001 Workshop

Smoke and Fire Detection

1. Detection Systems
   - What should we detect for different types of fires?
   - Where do we put the detectors?
   - Does the detector produce frequent nuisance alarms?

2. Crew Response
   - Is detection quick enough to give the crew adequate time to respond?
   - How does the crew know where the fire is?
   - Can the sensor give an indication of the danger level?
   - What capability is required for post-fire sensing?

Issues and Needs Identified in 2001 Workshop

Fire Suppression and Response

1. Specification of the Conditions Prior to the Response
   - Simulation and verification of flow in compartments
   - Characterization of fire events

2. Evaluation of Fire Suppressants
   - Agent transport in low gravity
   - Extinguishing agent performance in low gravity
   - Gaseous and particulate emissions from fires and suppressants

3. Effectiveness of Fire Response Strategies
   - Development of fire-response concepts
     – Obscuration mitigation
   - Agent distribution requirements and behavior
   - Post-fire sampling and characterization

Advanced Human Support Technology

What Do We Do Now?

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  - ISS Environmental Control and Life Support
  - ISS Fire Detection and Suppression

Potential Products

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  - system verifications

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  - procedures

Needs

Products
1. Normal gravity material flammability test
   a. Candidate test(s) identified
   b. Suitable acceptance criteria for reduced gravity flammability
   c. Reduced gravity verification of normal gravity flammability test
   d. Revision/supplement to NASA-STD-6001

2. Material flammability assessment in candidate atmospheres for exploration vehicles
   - 30% O₂ fraction and 0.7 atm
   - Higher oxygen fractions for EVA

3. Design rules to prevent ignition and flame spread of practical materials
   a. Gain understanding with simple materials
   b. Relationship between the materials you can understand and materials that are actually used
4. Verified models of fire precursor transport in low and partial gravity
   a. Development of models for large-scale transport in reduced gravity
   b. Validated CFD simulations of transport of fire precursors and contaminants
   c. Evaluation of the effect of scale on transport and reduced-gravity fires

5. Advanced fire detection system for gaseous and particulate pre-fire and fire signatures
   a. Quantification of pre-fire pyrolysis products in microgravity
   b. Suite of gas and particulate sensors
   c. Reduced gravity evaluation of candidate detector technologies
   d. Reduced gravity verification of advanced fire detection system
   e. Validated database of fire and pre-fire signatures in low and partial gravity
6. Verified design rules for reduced gravity suppressant systems
   a. Quantification of suppressant effectiveness in low and partial gravity
   b. Reduced gravity verification of suppressant system performance

7. Virtual Reality Simulations of fire scenarios
   a. Realistic visual representation of a fire environment
   b. Interactive participation in fire simulation
   c. Fire response module for crew training
What Do We Do Now?

- Identify needs and issues from “customers”
  - ISS Materials and Processes
  - ISS Environmental Control and Life Support
  - ISS Fire Detection and Suppression

- Scientific and technological questions that must be answered to deliver the products
  - assessment of knowns and unknowns
  - incomplete answers increases risk

- How do you answer the questions?
  - experiments (flight and ground)
  - modeling
  - system verifications

- What is finally used by the customer
  - contract specification
  - design rules
  - procedures
Organizing questions were drafted in the areas of
- Fire prevention and material flammability
- Fire suppression and response
- Fire detection

Working groups were formed within the Microgravity Combustion Science Branch (NASA and NCMR)
- Fire prevention and material flammability
  - Facilitator: Dr. Fletcher Miller
- Fire suppression
  - Facilitator: Dr. Fumiaka Takahashi

Purpose of working groups
- Review organizing questions
- Which are addressed by current experiments/hardware?
  - How well are they addressed?
- Develop concepts for experiments that address the questions
What Do We Do Now?

- Identify needs and issues from “customers”
  - ISS Materials and Processes
  - ISS Environmental Control and Life Support
  - ISS Fire Detection and Suppression

Potential Products

- Scientific and technological questions that must be answered to deliver the products
  - assessment of knowns and unknowns
  - incomplete answers increases risk

Needs

Questions

- How do you answer the questions?
  - experiments (flight and ground)
  - modeling
  - system verifications

Concepts

- What is finally used by the customer
  - contract specification
  - design rules
  - procedures
What do you want from us?

Discussion, critique, and ideas

• organizing questions
• products to be delivered
• concepts of potential experiments
• research needs
Summary

• Much has changed since January 2004
• We have the opportunity to impact the Vision for Space Exploration
  – Provide fire safe designs and countermeasures for exploration spacecraft and habitats
• The process we have been following has expanded the research plan developed at previous workshops
  – Increased scope and imposed a schedule
• We can deliver the best products through the collaboration of
  – NASA (Scientists, operations, and flight support personnel)
  – Government labs
  – Academia
  – Industry
Fire Suppression and Response

Strategic Research to Enable NASA’s Exploration Missions
June 22 - 23, 2004
Cleveland, OH

Fire Prevention, Detection, and Suppression
Overview

• Organizing Questions
• Programmatic Background
• Experimental Concepts
• Discussion
Fire Prevention, Detection, and Suppression

Organizing Questions for Research in Fire Suppression and Response
Background

- Limited research to date directed toward extinguishment of existing fires
  - Venting extinguishment testing (Skylab and KC-135)
  - CO₂ extinguishment testing (KC-135)
  - Thin-fuel Flammability limit testing (drop towers and KC-135)

- Testing has been limited to partially developed small fires

- Development of a reliable extinguishment system will require testing of extinguishment of a variety types of fires in a range of geometries, including well established fires
Organizing Questions

1. What is the relative effectiveness of candidate suppressants to extinguish a representative fire in reduced gravity, including high-\(O_2\) mole fraction, low-pressure environments?

2. What are the relative advantages and disadvantages of physically-acting and chemically-acting agents in spacecraft fire suppression?

3. What are the \(O_2\) mole fraction and absolute pressure below which a fire cannot exist?

4. What effect does gas-phase radiation play in the overall fire and post-fire environments?

5. Are the candidate suppressants effective to extinguish fires on practical solid fuels?

6. What is required to suppress non-flaming fires (smoldering and deep-seated fires) in reduced gravity?

7. How can idealized space experiment results be applied to a practical fire scenario?

8. What is the optimal agent deployment strategy for space fire suppression?
1. What is the relative effectiveness of candidate suppressants to extinguish a representative fire in reduced gravity, including high-O\textsubscript{2} mole fraction, low-pressure environments?

- CO\textsubscript{2}, N\textsubscript{2}, He, water mist, microencapsulated water, ...
- What metric do you use for effectiveness when evaluating different suppressants?
- What test configuration (or range of configurations) should be used?
2. What are the relative advantages and disadvantages of physically-acting and chemically-acting agents in spacecraft fire suppression?

- Chemical suppressants may be effective at concentrations below SMAC values
- Are chemical suppressants equally effective in reduced gravity?
- What metric do you use for effectiveness when evaluating different suppressants?
- What test configuration (or range of configurations) should be used?
3. What are the \( \text{O}_2 \) mole fraction and absolute pressure below which a fire cannot exist?

- Provides a lower limit for design of a suppression delivery system
- Presume a physically-acting extinguishing agent
- Value will depend on configuration, fuel, and diluent
  - Testing with \( \mu \text{g} \) droplet combustion has shown the limiting oxygen index (LOI) for droplet combustion to be substantially (~4 mol %) below that for solids or normal gravity droplet testing.
4. What effect does radiative absorption in the gas phase play in the overall fire and post-fire environments?

- Prior work with radiatively participating gases indicate that extinguishing CO$_2$ concentrations in oxidizing environments might result in broader flammability limits due to radiative feedback from the CO$_2$ rich ambient.
- Effect is minimized in normal gravity because of buoyancy.
5. Are the candidate suppressants effective to extinguish fires on practical solid fuels?

- Evaluating agent effectiveness may require a simple geometry
- How is the connection made to a practical solid fuel?
- Is a space flight verification test required?
6. What is required to suppress non-flaming fires (smoldering and deep-seated fires) in reduced gravity?

- NFPA Standard 12 requires a 20-minute holding time with CO₂
- Smoldering combustion is one of the most probable spacecraft fire scenarios (cable overheat, trash and bio-matter storage) yet holding times are unknown
- Deep seated fires (i.e., fires that can re-ignite after suppression of the gas-phase flame) have not been addressed for microgravity conditions
- Competition between heat loss (diffusion) and oxidant diffusion timescales
- Geometry can be either smoldering or dispersed solid (e.g. crib or trash fire)
- Testing will first establish whether re-ignition can occur and then extinguishment criteria will be established
7. How can idealized space experiment results be applied to a practical fire scenario?

- Real fire geometries are complex and involve radiative interaction between burning solids.
- Model development concurrent with small scale extinguishment tests will build framework for large scale tests.
- Model validation with large scale testing will ultimately be required to assure extinguishment effectiveness.
8. What is the optimal agent deployment strategy for space fire suppression?

- Normal gravity buoyant pumping of agent into fire is absent in μg (in both flooding and targeted application of agent)
- Fire brand transport and flammability must be considered in the design of hand-held extinguishers
- Fire brands released by agent deployment will not settle as in 1-g
- Flooding applications must be validated by computational modeling of agent deployment combined with experimental understanding of local extinguishment
- Data from the prior questions should be able to help address this issue
Programmatic Background

- The Combustion Integrated Rack is currently scheduled for launch on ULF-2 in October 2006
- In March, a proposal was made at HQ to move the CIR launch to ULF-1.1 in June 2005
- What experiment can be run that supports the exploration mission?
  - Existing hardware \textcolor{red}{MDCA} or \textcolor{red}{MGFA} inserts
- Two concepts were developed for rapid deployment
- The proposal was not accepted but the concepts remain relevant
Brainstorming

• Fire Suppression
  – Carriers
    • ISS Glovebox
    • CIR new insert
    • FEANICS
  – Experiments
    • GBEX (cup burner)
    • FLEX (MDCA hardware)
    • Porous plate/cylinder
    • Backward Facing Step
    • Real Materials
    • Smoldering Materials

Fire Prevention, Detection, and Suppression
Fire Prevention, Detection, and Suppression

Research Plan for
Fire Signatures and Detection

Strategic Research to Enable NASA’s Exploration Missions

June 22 - 23, 2004
Marriott Downtown at Key Center
Cleveland, Ohio USA
3. Advanced fire detection system for gaseous and particulate pre-fire and fire signatures
   a. Quantification of pre-fire pyrolysis products in microgravity
   b. Suite of gas and particulate sensors
   c. Reduced gravity evaluation of candidate detector technologies
   d. Reduced gravity verification of advanced fire detection system
   e. Validated database of fire and pre-fire signatures in low and partial gravity

4. Verified models of fire precursor transport in low and partial gravity
   a. Development of LES models for large-scale transport in reduced gravity
   b. Validated CFD simulations of transport of fire precursors
   c. Evaluation of the effect of scale on transport and reduced gravity fires
FPDS Organizing Questions

Fire Signatures and Detection

1. What is the background particulate and chemical species loading in a spacecraft and how does it vary with time?

2. What are the appropriate pre-fire and fire signatures for fire detection in low and partial gravity?

3. Is there a normal gravity analog to quantify low and partial gravity fire signatures?

4. What type or suite of sensors minimize the time to alarm and yet eliminate nuisance alarms?

5. Where should fire detectors be placed to minimize the time for a detection system to alarm?

6. How much warning time will the crew get with a particular fire detection system?
Signatures, Sensors, and Simulations

- Quantification of fire and pre-fire signatures

- Development and characterization of sensors
  - Electronic nose
  - MEMS gas sensors
  - Particulate sensors
  - IR absorption spectrometer

- Simulations tools to determine the transport of smoke, fire precursors, and contaminants
  - Where sensors should be located
  - Time to alarm
Quantification of Fire and Pre-Fire Signatures

- Effect of microgravity on size distribution of pre-fire and fire particulates
- Effect of microgravity on combustion products and concentrations
  - Flames are often cooler and less radiant
  - Average size and range of soot particle sizes are greater
  - Combustion-product nature and quantities are altered
Characterization of Smoke from Microgravity Fires for Improved Spacecraft Fire Detection

PI: Urban, NASA-GRC; co-I: Mulholland, Cleary, and Yang, NIST; Yuan, NCMR

- Experiment to be conducted in the Microgravity Science Glovebox
  - quantify the size distribution of liquid smokes from silicon rubber, cotton, Teflon, and DBT
Quantification of Fire and Pre-Fire Signatures

- Background particulate loading

- **Dust and Aerosol measurement Feasibility Test (DAFT)**
- Risk mitigation experiment for Smoke to evaluate the performance of the TSI P-Trak in microgravity
  - Commercially available condensation nuclei counter in microgravity
  - Manifested for Progress Flight 16P (Nov 2004)
DAFT Hardware

P-Trak, Alcohol Wick (w/Container) and Batteries

DustTrak and Batteries

Note: Engineering hardware shown without flight labels and Velcro.
**Additional Benefits of DAFT**

- During DAFT experiment operations, measurements of the ISS cabin atmosphere will be taken with the P-Trak and DustTrak instruments.
  - P-Trak measures particle counts per unit volume.
  - DustTrak measures particle mass concentration per unit volume.
  - Currently lacking air quality measurements aboard the ISS.
  - DAFT will operate in front of EXPRESS Rack 5 but can acquire samples at various locations within ISS as requested by ECLSS personnel.

*DAFT-3 in front of EXPRESS Rack*
Quantification of Fire Signatures for Practical Spacecraft Materials

Dr. Randy Vander Wal, National Center for Microgravity Research

- measure the time history of various fire signatures of typical spacecraft materials in 1-g at varying heating rates, temperatures, convective velocities, and oxygen concentrations,

- conduct tests in the Zero-Gravity Facility at NASA John H. Glenn Research Center to investigate the manner that a microgravity environment alters the fire signature,

- compare 0-g and 1-g time histories and determine if 0-g data exhibits the same dependence on the test parameters as experienced in 1-g
Development and characterization of sensors

- Concurrent development of candidate technologies
  - **Electronic nose**
    - JPL: Advanced Environmental Monitoring and Control
    - KSC: 2002 NRA (HRI)
      
      Advanced Fire Detection Using Machine Olfaction
      B. Linnell, ASRC Aerospace
  
  - **MEMS gas and particulate sensors**
    - GRC: Jointly funded with the Aviation Safety Program
      
      Development of a MEMS Spacecraft Fire Detector
      G. Hunter and P. Greenberg, GRC
  
  - **IR absorption spectrometer**
    - JPL: Space Physics
    - Southwest Sciences, Inc. (SBIR)
Development and characterization of sensors

- **Evaluate prototype detectors as part of the fire signature quantification effort**
  - Requires a secondary measurement capability and procedure
  - Normal-gravity and ground-based micro-g testing as appropriate

- **Evaluate suite of species and particulate sensors**
  - Conceptually similar to testing on the NIST Fire Emulator/Detector Evaluator

- **Reduced gravity verification of advanced fire detection system**
  - Hardware and software
02 NRA (Human Research Initiative)

- Fire Suppression and Safety in Reduced Gravity
  PI: K. Kailasanath, NRL

- Engineering Tool for Fire System Safety Placement
  PI: R. Roby, Combustion Science and Engineering

- Large-Scale Fire Dynamics in Spacecraft in Reduced Gravity
  PI: G. Linteris, NIST
FPDS Organizing Questions

Fire Signatures and Detection

1. What is the background particulate and chemical species loading in a spacecraft and how does it vary with time?

2. What are the appropriate pre-fire and fire signatures for fire detection in low and partial gravity?

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5. Where should fire detectors be placed to minimize the time for a detection system to alarm?

6. How much warning time will the crew get with a particular fire detection system?
Questions

- Are the questions relevant and posed correctly?
- What should be added?
  - **Expand Smoke experiment to other materials**
    - Further examine overheating electrical components and circuit boards
    - Evaluate other fire signatures (radiation, temperature, ...)
    - Are the research and technology development efforts appropriate?
  - **End-to-end MEMS fire detector for evaluation of low-g fire signatures**
    - Incorporate capability into MSG Smoke+ experiment
- Are there technologies and/or research groups that should be included?
DNA Configurations in the Flow Through Arrays with Application to Biosensors

Eric S.G. Shaqfeh, Victor Beck  
Department of Chemical Engineering,  
Stanford University, Stanford CA 94305-5025

Nerayo Teclemeriam, Susan J. Muller  
Department of Chemical Engineering,  
University of California, Berkeley, CA 94720-1462

The miniaturization of lab analysis via microfluidics now allows one to consider designing devices for the manipulation of individual molecules. Manipulation of DNA in microfluidic devices has now received an enormous attention in this context, primarily through sieving and sorting applications. However, new results in flow suggest that reactions in flow including concatenation or hybridization may be many times faster than under equilibrium conditions and thus flow can be used to control the access to the chain for any number of sequence specific linkers. Such an scheme could form the basis for a sensor for DNA damage either for military or space applications. At the heart of this the molecule to a significant fraction of its extensibility, keep it stretched to allow hybridization to linker groups, and then sieve any unlinked species from the mixture for analysis of hybridization downstream. Engineering of such a sensor is most efficiently done if large scale simulation of DNA in flow is used as an engineering tool to narrow the possible designs. A suggested device design is shown below.

Figure 1. Schematic for single molecule sequencing microdevice.
Stretching and sieving of DNA in the microdevice above involves understanding DNA configurations in the flow through post arrays of various concentrations, arrangements, and sizes. We review the large scale numerical simulation of DNA in flow through post arrays with a focus on the applications associated with the development of this biosensor including answering the following questions:

1) How does pressure driven flow differ from electrophoresis through an array?
2) Are there optimal arrangements and optimal post sizes for each in order to achieve stretch and separation?

We then demonstrate how such simulation can guide design of such a device and make preliminary comparison to experiments regarding the configuration distributions in the flow though fabricated post arrays.
Space Experiment Concepts: Cup-Burner Flame Extinguishment

Fumiaki Takahashi
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Supported by NASA OBPR
Acknowledgment

In-House

GBEX-Gaseous Burner Extinguishment Experiment

GRC
Roger Forsgren (PM)
Scott Numbers
Dennis Stocker

NCMR
Peter Sunderland

ZIN
Gregory Funk
Dale Robinson
David Althausen
Mike Jamison
Rita Cognition

Akima
David Bennett

NRA-99

Physical and Chemical Aspects of Fire Suppression in Extraterrestrial Environments

NIST
Gregory Linteris (co-I)

ISSI
Viswanath Katta (co-I)
Background

- NASA’s Fire Safety Approach
  - *Fire prevention plays a key role*
  - fire safety program for manned space flight has been based on controlling the materials flammability and eliminating ignition sources
  - *Space exploration expands platform*
  - longer duration missions to the moon, Mars, or aboard the International Space Station (ISS) increase the likelihood of fire events
  - various gravity levels affect fire behavior
    - ISS: $\mu g$, lunar: $1/6g$, Martian: $1/3g$
Objectives

◆ Space Fire Suppression Processes & Technology

- Be prepared for space fire suppression!
  ⇒ need better understanding of physical and chemical suppression processes in reduced gravity environments simulating various missions

- Develop space fire suppression technology
  ⇒ the results must provide useful data leading to technology development of fire suppression systems in various platforms
Organizing Questions  Fire Suppression

- **Fire-Extinguishing Agent Effectiveness in Space Environments**
  1. What is the relative effectiveness of candidate suppressants to extinguish a representative fire in reduced gravity, including high-O$_2$ mole fraction, low-pressure environments?
  2. What are the relative advantages and disadvantages of physically acting and chemically acting agents in space fire suppression?
  3. What are the O$_2$ mole fraction and absolute pressure below which a fire cannot exist?
  4. What effect does gas-phase radiation play in the overall fire and post-fire environments?
  5. Are the candidate suppressants effective to extinguish fires on practical solid fuels?

- **Space Fire Suppression Technology Development**
  7. How can idealized space experiment results be applied to a practical fire scenario?
  8. What is the optimal agent deployment strategy for space fire suppression?
Agent Effectiveness

◆ Cup-Burner Method: dynamic co-flow diffusion flame
  ● Standard Test
    ⇒ the most widely used test specified in national and international standards (NFPA 2001, AS 4214, ISO 14502)
    ⇒ measure the minimum extinguishing concentration (MEC) which renders the “inhibited” air incapable of supporting diffusion flame combustion
    ⇒ the minimum design concentration of a gaseous agent for a fire protection system is determined by adding at least 30% to the cup-burner MEC value by manufacturer
    ⇒ the third party approval (e.g., UL, Factory Mutual) of a fire extinguishing system requires large-scale pan fire tests in relation to the cup-burner MEC values
MEC Minimum Extinguishing Concentration

Hamins et al. (1994)

Gaseous hydrocarbon
Liquid hydrocarbons
Jet fuels
Lubricants

Volume Percent of Agent in Oxidizer

Propane
Heptane
JP-5
JP-8
5606
83282

Halon
FM-200
HCFC-227
HFC-236
HCFC-124
HFC-125
HFC-134a
FC-116
HCFC-22
HFC-32/125
N2

Hamins et al. (1994)
Laboratory Flame vs. Real Fire

◆ Cup- Burner Flame Behavior:
  ● Relatively system independent:
    ⇒ the MEC is nearly independent of the fuel cup size, chimney size, fuel velocity, and oxidizer velocity
    ⇒ the cup-burner MEC values are nearly equal to those for low strain rate counterflow diffusion flames
  ● Scale model of a real fire:
    ⇒ flame segments subjected to various strain rates, including stabilized/spreading edge diffusion flames
    ⇒ flame flickering and separation in 1g, affecting the air and agent entrainment into fire zone
    ⇒ extinguishment occurs via dynamic blow-off process rather than global extinction typical of counterflow diffusion flames

Click here to play movie

Cup Burner

Pool Fire

http://www.me.uwaterloo.ca/~ew eckman/fire/firehome.htm
GBEX Gaseous Burner Extinguishment EXperiment

CUP BURNER
CHIMNEY
IGNITER
FLAME DETECTOR
OXIDIZER+AGENT INLET
FUEL INLET

NASA/CP—2004-213205/VOL1 888
GBEX in CIR

OXIDIZER + AGENT INLET
ULTRASONIC ATOMIZER
COMBUSTION INTEGRATED RACK
CUP BURNER
CHIMNEY
FUEL INLET
IGNITER
**GBEX**  Gaseous Burner Extinguishment EXperiment

- **Dimensions:**  5/8 Scale
  - *Burner:* 17 mm ID
  - *Chimney:* 51 mm ID × 350 mm length

- **Test Matrix:**
  - *Fuel:* CH$_4$
  - *Oxidizer:* O$_2$-N$_2$ mixture
    - Oxygen mole fraction: 0.21, 0.3
    - Velocity: 1 – 12 cm/s
  - *Agent:* CO$_2$, N$_2$, He, Water Mist, Inert Gas/Water Mist
  - *Gravity:* μg
  - *Pressure:* 1 atm, 0.7 atm
MSG Microgravity Science Glovebox

Adapter Plate

Power Box

Video Tilter Box

Nikon D100 Camera

Chamber

Video Camera w/ Turning Mirror

Controller Assembly (outside MSG)
Microgravity Science Glovebox

- **Dimensions:**
  
  - **Burner:** 12 mm ID
  - **Chimney:** 79 mm square × 187 mm length

- **Test Matrix:**
  
  - **Fuel:** CH$_4$
  - **Oxidizer:** Air
  - **Agent:** N$_2$
  - **Gravity:** μg
  - **Pressure:** 1 atm
  - **Velocity:** 1 – 50 cm/s
FSEE Fire Suppression in Extraterrestrial Environments

Drop/KC-135 Rig

- CHIMNEY
- CUP BURNER
- CHAMBER
- COMPUTER & I/O BOX
- BATTERIES
- PIV-MZI OPTICS
- FLOW MODULES
**FSEE**  Fire Suppression in Extraterrestrial Environments

**Dimensions:** Full Scale

*Burner:* 28 mm ID  
*Chimney:* 85 mm ID × 533 mm length

**Test Matrix:**

*Fuel:* Gas: CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>  
Liquid: n-C<sub>7</sub>H<sub>16</sub>, CH<sub>3</sub>OH  
Solid: trioxane (3[CH₂O]), PMMA

*Oxidizer:* O<sub>2</sub>-N<sub>2</sub> mixture  
Oxygen mole fraction: 0.21 – 0.3  
Velocity: 3 – 20 cm/s

*Agent:* CO<sub>2</sub>, N<sub>2</sub>, He, Ar  
CF<sub>3</sub>H(HFC-23), C<sub>3</sub>F<sub>7</sub>H (HFC-227ea), CF<sub>3</sub>Br (Halon 1301)  
Water Mist, Inert/Water Mist, Microencapsulated Water

*Gravity:* μg, lunar (1/6 g), Martian (1/3 g), 1g

*Pressure:* 0.7 – 1 atm
Dynamic Flame Extinguishment

**Experiment (1g)**

Methane Air + 15.9% CO₂

\[ U_{CH₄} = 0.92 \text{ cm/s} \]
\[ U_{ox} = 6.7 \text{ cm/s} \]

**Direct Numerical Simulation (0g)**

Methane Air + 30.7% He

\[ U_{CH₄} = 0.92 \text{ cm/s} \]
\[ U_{ox} = 10.7 \text{ cm/s} \]

- Full chemistry (GRI Mech 1.2)
- Radiative loss
- Mixture rules

Extinguishment Limits

Answering to Organizing Questions

- **Cup-burner flame extinguishment experiment can:**
  
  1. measure the relative effectiveness (MEC) of candidate suppressants in low-\(g\), including high-O\(_2\), low-P environments
  2. determine the \(X_{O_2}\) (LOI) below which a fire cannot exist
  3. examine the effect of radiation in fire and post-fire environments
  4. reveal advantages/disadvantages of physical/chemical agents
  5. measure the agent effectiveness for practical solid fuels
  
  7. provide an idealized space experiment applicable to a practical fire scenario
  
  8. produce useful data in relation to agent deployment strategy
Conclusions

- **Space Fire Suppression Processes & Technology**

  → Space experiment concepts of **cup-burner flame extinguishment** have been conceived to address to the key issues (i.e., organizing questions) in space fire suppression

  → **Cup-burner flame extinguishment experiment** can reveal **physical and chemical suppression processes** and provide **agent effectiveness data** useful for technology development of **space fire suppression systems** in various reduced-gravity platforms
MICROMINIATURE MONITOR FOR VITAL ELECTROLYTE AND METABOLITE LEVELS OF ASTRONAUTS

Koji Tohda and Miklos Gratzl

Ions, such as proton (pH) and potassium, play a crucial role in body fluids to maintain proper basic functioning of cells and tissues. Metabolites, such as glucose, control the energy available to the entire human body in normal as well as stress situations, and before, during, and after meals. These molecules diffuse easily between blood in the capillaries and the interstitial fluid residing between cells and tissues. We have developed an approach to monitoring of critical ions (called electrolytes) and glucose in the interstitial fluid under the human skin. Proton and potassium levels sensed using optode technology that translates the respective ionic concentrations into variable colors of corresponding ionophore/dye/polymeric liquid membranes. Glucose is monitored indirectly, by coupling through immobilized glucose oxidase with local pH that is then detected using a similar color scheme. The monitor consists of a tiny plastic bar, 100-200 µm wide and 1-2 mm long, placed just under the skin, with color changing spots for each analyte as well as blanks. The colors are read and translated into concentration values by a CCD camera. Direct optical coupling between the in vivo sensing bar and the ex vivo detector device requires no power, and thus eliminates the need for wires or optical fibers crossing the skin. The microminiature bar penetrates the skin easily and painlessly, so that astronauts could insert it themselves. The approach is fully compatible with telemetry in space, and thus, in vivo clinical data will be available real time in the Earth based command center once the device is fully developed. The information provided can be used for collecting hitherto unavailable vital data on clinical effects of space travel. Managing clinical emergencies in space with the sensor already in place should also become much more efficient than without a continuous monitor, as is currently the case. Civilian applications may include better glucose control of patients with moderate to severe diabetes: a growing health problem in the US and worldwide.
Combustion and Reacting Systems for Exploration

Workshop on

Strategic Research to Enable NASA’s Exploration Missions

June 22 - 23, 2004
Marriott Downtown at Key Center
Cleveland, Ohio USA
The President has redirected NASA’s mission to be exploration-based instead of our traditional science / earth application
The President’s Vision

1. Return the Shuttle to safe flight as soon as practical, based on CAIB recommendations
2. Use Shuttle to complete ISS assembly
3. Retire the Shuttle after assembly complete (2010 target)
4. **Focus ISS research to support exploration goals; understanding space environment and countermeasures**
5. Meet foreign commitments
6. Undertake lunar exploration to support sustained human and robotic exploration of Mars and beyond
7. Series of robotic missions to Moon by 2008 to prepare for human exploration
8. Expedition to lunar surface as early as 2015 but no later than 2020
9. **Use lunar activities to further science, and test approaches (including lunar resources) for exploration to Mars & beyond**
10. Conduct robotic exploration of Mars to prepare for future expedition
11. Conduct robotic exploration across solar system to search for life, understand history of universe, search for resources
12. Conduct advanced telescope searches for habitable environments around other stars
13. **Demonstrate power, propulsion, life support capabilities for long duration, more distant human and robotic missions**
14. Conduct human expeditions to Mars after acquiring adequate knowledge and capability demonstrations
15. Develop a new Crew Exploration Vehicle; flight test before end of decade; human exploration capability by 2014
16. Separate cargo from crew as soon as practical to support ISS; acquire crew transport to ISS after Shuttle retirement
17. Pursue international participation
18. Pursue commercial opportunity for transportation and other services
Combustion and Reacting Systems in Reduced Gravity

Where does combustion fit in?
--in a variety of reacting systems

1. Spacecraft Fire Prevention, Detection, and Suppression
2. Advanced Life Support
   Air/water revitalization (Sabatier, Bosch), Waste management (Incineration)
3. In Situ Resource Utilization (ISRU)
   Fuel / consumables from regolith / atmosphere
4. Extra vehicular Activity
   Air revitalization, Power systems (MEMS scale combustors)
5. In-situ Fabrication and Repair
   SHS

Of these we have the lead responsibility in Fire Safety
Funding

How will funding work?
Funding

How will funding work?

I wish I knew

Anticipate a mixture of curiosity driven research (old NRA model) and directed research to meet roadmap goals

NRA research will focus on research supporting exploration

Directed research will be product driven and aligned with roadmaps and schedules – expect a mixture in intramural and extramural research, funding process will likely involve multiple mechanisms
Fire Safety Research Plan Development

We have long argued relevance to SFPDS

We have now been told to deliver a product (fish or cut bait)

We are constrained by the availability of upmass and test facilities, we need to be resourceful in our approach

Experiments must be carefully developed to make efficient use of flight opportunities and meet schedule milestones

To be efficient, we need to start with a clean plate but we don’t want to throw out good, relevant, work unnecessarily

At this point decisions have not been made, no one is “in” or “out”

Such decisions will be made based upon an integrated plan
Project Constellation (Crew Exploration Vehicle)

Systems Engineering

Nation/NASA Vision

Requirements

Level 0, 1...

Critical Milestones

System Integration

Demonstration

Non-advocacy Reviews

Independent Cost Reviews

Spiral 1

Crewed Flight

Spiral 2

Moon (2015-2020)

Spiral Nth

Mars (2020+)

- CEV Demo
- 1st Launch Lunar Robotic Orbiter
- 1st Uncrewed CEV Fit
- 1st Crewed CEV Fit
- 1st Human Moon Mission

04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20
Major Milestones

- 2008: Initial flight test of CEV
- 2008: Launch first lunar robotic orbiter
- 2009-2010: Robotic mission to lunar surface
- 2011 First Unmanned CEV flight
- 2014: First crewed CEV flight
- 2012-2015: Jupiter Icy Moon Orbiter (JIMO)/Prometheus
- 2015-2020: First human mission to the Moon
### GRC/BPRPO ISS Utilization Traffic Model

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### Facilities

- AMS
- CAM

### Combustion Integrated Rack Payloads

- CIR - FEANICS - A
- CIR - FEANICS - B

### Fluids Integrated Rack Payloads

- MOB
- AHLS-1
- AHLS-2
- MOB

### ExPRESS Rack or Stand-Alone Payloads

- FOAM

### Microgravity Science Glovebox Payloads

- CCF-1
- CCF-2
- CCF-3

### Non-GRC Payloads

- CCA-1
- CCA-2

### Acceleration Measurement Payloads

- SE-SAMS F06
- SE-SAMS F04
- SE-SAMS F02
- TSH-FIR
- TSH-SAMS Spac
- SE-SAMS F03
- SE-SAMS F05
- SE-SAMS F07
- SE-SAMS F06
- SE-SAMS F04
- TSH-SAMS Spac

### Notes:

- HRF - Human Research Facility
- MELS - Minus Eights Laboratory Freezer
- EMCS - European Modular Calibrator System
- WORS - Waste Observation Rack Facility
- SpaceDURUM - Space Dynamically Responding Ultrasonic Matrix System
- HRB - Holding Habitat Rack
- MAERS - Muons Atoms Research and Exercise System
- LSMM - Light Microscopy Module
- GFM - Granular Flow Module
- CCA - Commercial CIR Apparatus
- AMS - Alpha Magnetic Spectrometer
- CAM - Centrifuge Accommodations Module

### Acronyms:

- CIR - Combustion Integrated Rack
- FIR - Fluids Integrated Rack
- MSG - Microgravity Science Glovebox
- ER - ExPRESS Rack
- MSRR – Materials Science Research Rack
- FSL – Fluids Science Laboratory
- FEANICS - Flow Enclosure Accommodating Novel Investigations in Combustion of Solids
- BXF – Boiling Experiment Facility
- LMM - Light Microscopy Module
- GFM – Granular Flow Module
- CCA – Commercial CIR Apparatus

### Legend:

- CIR
- FIR
- MSG-GI
- MSG-PF
- ER
- MSRR
- FSL
- Stand-Alone
- MPLM Flight
- Progress Flight
- Soyuz Flight
- ATV Flight

### Advanced Life Support Systems
- Advanced Environmental Monitoring & Control
- Advanced Extra Vehicular Activity
- Low Gravity & Exploration Research
- In-Situ Resource Utilization
- Fundamental Science

### Advanced Life Support Systems

- Advanced Environmental Monitoring & Control
- Advanced Extra Vehicular Activity
- Low Gravity & Exploration Research
- In-Situ Resource Utilization
- Fundamental Science

### Advanced Environmental Monitoring & Control

- Advanced Extra Vehicular Activity
- Low Gravity & Exploration Research
- In-Situ Resource Utilization
- Fundamental Science

### Advanced Extra Vehicular Activity

- Low Gravity & Exploration Research
- In-Situ Resource Utilization
- Fundamental Science

### Low Gravity & Exploration Research

- In-Situ Resource Utilization
- Fundamental Science

### In-Situ Resource Utilization

- Fundamental Science

### Fundamental Science

- N/A
Fire Safety Research Plan Development

We are building a new-comprehensive plan for SFPDS and need to vet it with the community.

At this point we have draft end products and associated questions / objectives.

Approach will be a combination of ground-based testing, modeling and flight validation, we expect integrated teams to address the issues.

We need your input on the validity and completeness of the questions and the associated approaches to address them.
Fire Detection Organizing Questions

Workshop on

Strategic Research to Enable NASA’s Exploration Missions

June 22 - 23, 2004
Marriott Downtown at Key Center
Cleveland, Ohio USA
Fire Detection
Sub-Element Products

1. Verified models of fire precursor transport in low and partial gravity
   a. Development of models for large-scale transport in reduced gravity
   b. Validated CFD simulations of transport of fire precursors
   c. Evaluation of the effect of scale on transport and reduced-gravity fires

2. Advanced fire detection system for gaseous and particulate pre-fire and fire signatures
   a. Quantification of pre-fire pyrolysis products in microgravity
   b. Suite of gas and particulate sensors
   c. Reduced gravity evaluation of candidate detector technologies
   d. Reduced gravity verification of advanced fire detection system
   e. Validated database of fire and pre-fire signatures in low and partial gravity
Fire Signatures and Detection

1. What is the background particulate and chemical species loading in a spacecraft and how does it vary with time?
   Impact of absence of gravitational settling, long term off-gassing, ECLSS performance.

2. What are the appropriate pre-fire and fire signatures for fire detection in low and partial gravity?
   Smoke particulate, gaseous species, light emission

3. Is there a normal gravity analog to quantify low and partial gravity fire signatures?
FPDS Organizing Questions

Fire Signatures and Detection -continued

4. What type or suite of sensors minimize the time to alarm and yet eliminate nuisance alarms?
   Tradeoff between mass, reliability and false alarms

5. Where should fire detectors be placed to minimize the time for a detection system to alarm?
   No buoyant convection, tortuous flow paths

6. How much warning time will the crew get with a particular fire detection system?
   Consider convection time in module, fire growth rate
In Vivo Bioluminescent Imaging of Gene Expression, including Radiation Induced Gene Expression

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Acknowledgements

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- DOE funding, PI: Boothman
**Imaging of Gene Expression**

- Introduce reporter gene under control of the promoter of a gene of interest
  - Transfect cultured cells and implant
  - Target cells with *in vivo* gene delivery
  - Create transgenic animals
- When protein is expressed by the gene of interest, the reporter protein is simultaneously expressed
- Reporter protein makes probe molecules visible to optical, radionuclide, or MR imaging devices
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Bioluminescent Imaging

Start with gene originating from fireflies.
Bioluminescent Imaging of Gene Expression

- Introduce luciferase reporter gene from fireflies under control of the promoter of a gene of interest
- Probe molecule, luciferin, is injected into animal and freely enters cells.
- When it is expressed, the luciferase enzyme acts on probe molecule, luciferin, to create light.

Luciferase

\[
\text{ATP} + \text{D-luciferin} + \text{O}_2 \rightarrow \text{oxy} + \text{AMP} + \text{PPi} + \text{CO}_2 + \text{light}
\]
Bioluminescent Imaging of Gene Expression

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Bioluminescence Imager

- Liquid nitrogen cooled camera
- Light tight box
- Collects ≈ 90% of light photons
- Image for 1 m – 6 m
Light Propagation

- Light diffusion model
- Assumptions
  - Point Source
  - Semi-infinite homogeneous medium
Surface Radiance Profile

Bacterial Clearance (Liver)

Assumptions
- $\lambda = 630$ nm
- depth = 5 mm
- $\mu_a = 0.25$ cm$^{-1}$
- $\mu_s = 15$ cm$^{-1}$

Light is spread and attenuated as it propagates through tissue.
What are these extra spots?

*Cosmic ray artifacts!*
Cosmic Ray Artifacts in BLI
MDMC Algorithm for Cosmic Ray Correction

• Detection of cosmic rays using mathematical morphology
  – Use multiple SE’s to capture the variation in shapes of cosmic ray artifacts

• Region grow to obtain surrounding artifactual pixels

• Fit nearby background pixels to 2nd order polynomial

• Replace cosmic artifact with intensities estimated from the 2nd order polynomial
Algorithm Evaluation

• Created synthetic image segments by “pasting” artifacts into artifact-free signal and background areas

• New algorithm substantially outperformed 5 other algorithms and reduced cosmic ray artifact energy by > 99%
Before

After
Application of Bioluminescent Imaging to Clusterin Gene Expression
Secretory Clusterin (sCLU)

- Up-regulated when a cell is stressed by cyto-toxic agent such as chemotherapy drug or PDT or by radiation – potential radiation biodosimeter
- CLU expression is an early marker of cancer
- Cyto-protective protein that acts to keep cancer cells alive
- p53 negatively regulates sCLU levels. Loss of p53 function results in elevated sCLU levels. (Criswell et al., Cancer Biol. & Ther., 2003).
  - Since 50% of cancer cells have lost p53, these cells over-express sCLU which acts to protect the cancer cells against radiation and chemo therapies.
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Cyto-protection and sCLU

- Reduces radiation lethality
- Reduces lethality from chemotherapy agents
  - Adriamycin
  - Cisplatin
  - VP16
  - Topotecan
- Reduces lethality from PDT
Radiation in Space

- Risks 38, 39, 40, 41, and 42 in *critical path roadmap*
- Highest priority ratings (many 1’s)
- Research aims:
  - radiation biodosimeter
  - radiation counter-measures
### Questions Addressed

#### 7.10 Radiation Effects

<table>
<thead>
<tr>
<th>Risk</th>
<th>CQ No.</th>
<th>Critical Question</th>
<th>CQ Priority</th>
<th>Critical Question &amp; Risk Mitigation/CM Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogenesis Caused by Radiation (Risk No. 38)</td>
<td>10.09</td>
<td>What are the cancer risks in humans from spaceflight?</td>
<td>1</td>
<td>Risk Assessment</td>
</tr>
<tr>
<td></td>
<td>10.11</td>
<td>What is the acceptable accuracy for risks of acute and late effects in humans from photons to adequately extrapolate to space?</td>
<td>1</td>
<td>Risk Assessment</td>
</tr>
<tr>
<td></td>
<td>10.05</td>
<td>Are there unique biological effects associated with HZE’s?</td>
<td>1</td>
<td>Mechanisms</td>
</tr>
<tr>
<td></td>
<td>10.07</td>
<td>How can animal and cell experiments be done and data best be used to extrapolate to the human risk from space radiation?</td>
<td>1</td>
<td>Mechanisms</td>
</tr>
<tr>
<td></td>
<td>10.10</td>
<td>What are the risks from SPE’s and what is their impact on operations, EVAs and surface exploration?</td>
<td>1</td>
<td>Risk Assessment</td>
</tr>
<tr>
<td></td>
<td>10.08</td>
<td>How do the thickness, design, and material composition of space vehicles affect the internal radiation environment and biological assessment?</td>
<td>1</td>
<td>Countermeasures</td>
</tr>
<tr>
<td></td>
<td>10.06</td>
<td>Do we have strategies for calculating risks that are adequate if expected data are provided and what are uncertainties?</td>
<td>2</td>
<td>Countermeasures</td>
</tr>
<tr>
<td></td>
<td>10.04</td>
<td>Are there differences in response to particles with similar LET, but with different atomic numbers and energies?</td>
<td>2</td>
<td>Mechanisms</td>
</tr>
<tr>
<td></td>
<td>10.12</td>
<td>What are the effects of age, gender, and inter-individual diversity?</td>
<td>2</td>
<td>Mechanisms</td>
</tr>
<tr>
<td></td>
<td>10.01</td>
<td>Are the biological effects for protons above 10 MeV sufficiently similar to photons that photon data can be used for their consequences?</td>
<td>3</td>
<td>Mechanisms</td>
</tr>
<tr>
<td></td>
<td>10.03</td>
<td>Are there chemopreventive or biological agents which would mitigate acute or late effects?</td>
<td>3</td>
<td>Countermeasures</td>
</tr>
</tbody>
</table>
IR Dose Response

- Created well plates containing cells with luciferase under control of the CLU promoter
- Radiated cells with low energy radiation
- Induction of sCLU at exposures of 0.1 cGy
- Increasing dose response indicating the possibility of a biodosimeter
**Temporal Response of CLU**

- Response of radiated cells depends upon exposure and time
- Strong response at 3-4 days post exposure
Effect of p53 Gene on CLU

- With loss of p53, increased basal and IR induced CLU activity
- Significant CLU induction by IR at 0.5 Gy

With loss of p53, increased basal and IR induced CLU activity

Significant CLU induction by IR at 0.5 Gy
Clusterin BLI Mouse

- Transgenic mouse with luciferase gene under control of clusterin promoter
- Imaged 3 days after exposure showing response of clusterin to radiation
- Skin on tail and paws glows because of sepsis
- *In vivo* imaging of transgenic mouse particularly intriguing for studies of the radiation bystander effect and radiation countermeasures
Future Work & Relevancy to Space

- Measure *in vivo* dose response in the sCLU-BLI mouse
  - Temporal response
  - Dose response
- Determine signaling pathways and modifiers; e.g., effect of testosterone
- Measure dose response to high LET radiation at Brookhaven National Laboratory and compare to low LET experiments
- Develop sCLU-BLI mouse as an *in vivo* read-out of cancer
  - create mice without P53 gene in order to *accelerate* cancer formation following radiation
  - evaluate *in vivo* radiation counter-measures

Towards the creation of a bio-dosimeter for astronauts

Develop radiation counter-measures
Clearance of Bacterial Pneumonia

Mouse 2, 1:3 dilution of bacteria

Doerschuk & Wilson
Fewer Mice in Space

**Conventional Serial Sacrifice**

- 1 day
- 2 days
- 4 days
- 7 days

**Bioluminescent Molecular Imaging**

- 1 day
- 2 days
- 4 days
- 7 days
Summary

• BLI is simple and relatively inexpensive
• Scatter and absorption limits the ability to localize and obtain absolute gene activity
• Can measure relative activities in a single animal over time
• Useful for studying radiation biology, bacterial infection, and many other applications, possibly in space
One of the more-serious side effects of extended space flight is an accelerated bone loss [Bioastronautics Critical Path Roadmap, http://research.hq.nasa.gov/code_u/bcpr/index.cfm]. Rates of bone loss are highest in the weight-bearing bones of the hip and spine regions, and the average rate of bone loss as measured by bone mineral density measurements is around 1.2% per month for persons in a microgravity environment [T. Lang et al., JBMR 2004]. Figure 1 shows that an extrapolation of the microgravity-induced bone loss rates to longer time scales, such as a 2.5 year round-trip to Mars (6 months out at 0 g, 1.5 year stay on Mars at 0.38 g, 6 months back at 0 g), could severely compromise the skeletal system of such a person.

It is well known that bone remodeling responds to mechanical forces. We are developing two-photon microscopy techniques to study bone tissue and bone cell cultures to better understand the fundamental response mechanism in bone remodeling. Osteoblast and osteoclast cell cultures are being studied, and the goal is to use molecular biology techniques in conjunction with Fluorescence Lifetime Imaging Microscopy (FLIM) to study the physiology of in-vitro cell cultures in response to various stimuli, such as fluid flow induced shear stress and mechanical stress. We have constructed a two-photon fluorescence microscope for these studies, and are currently incorporating FLIM detection. Current progress will be reviewed. This work is supported by the NASA John Glenn Biomedical Engineering Consortium.

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Biophotonics and Bone Biology

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² National Center for Microgravity Research
³ Cleveland Clinic Foundation
Goal: Develop advanced fluorescence microscopy techniques to study bone cell physiology

Motivation:

- Cells cultured in microgravity exhibit different gene expression profiles.
- Cytoskeleton in space-based osteoblast cell cultures is less well-developed.
- T-cell lymphocyte (immune cells) activation is suppressed in microgravity

Microgravity has a harmful effect on human physiology

- Bone loss in hips and spine, 1% per month
- Immunodeficiency
- Loss of blood plasma, anemia
- Cardiac dysrhythmia

Like an accelerated osteoporosis

Ref. document: Bioastronautics Critical Path Roadmap
Normal trabecular (spongy bone) structures

Osteoporotic trabecular structures

Bone mineral density (BMD) loss: Effect of aging


Microgravity BMD loss: 1.2% per month (Lang et al., JBMR 2004)

Model a trip to Mars: \[
\frac{d}{dt} BMD = \frac{d}{dt} BMD_{aging} + \frac{d}{dt} BMD_{g-level}
\]

Linear response model:

\[
\frac{d}{dt} BMD_{g-level} = \frac{0.012 \cdot BMD}{mo.} (g^* - 1)
\]

Calculate:

\[
BMD(t) = BMD(t_0) + \int_{t_0}^{t} \frac{d}{dt} BMD \ dt
\]

\[
g^* = \frac{\text{local accel.}}{9.8 \ m/s^2}
\]
Bone loss

Hypothetical effects of aging and modeled trip to Mars

Mars trip: 6 mo. out (0g), 18 mo. stay (0.38g), 6 mo. return (0g)
Bone Remodeling: Balance between osteoclasts and osteoblasts

Use two-photon fluorescence microscopy to study macrophage, osteoclast and osteoblast cells
Background: Two-photon absorption

Single-photon absorption

Fluorescence intensity $\sim I_0$

820 nm fluorescence

535 nm

488 nm

Two-photon absorption

Fluorescence intensity $\sim I_0^2$

820 nm fluorescence

535 nm

Excitation rate (photons/s), $\phi$

1 - photon

$\phi_{1p} \approx 4P_0\eta_1\sigma_{1p}\frac{(NA)^2}{hc\lambda}$

2 - photon, pulsed laser

$\phi_{2p} \approx 8\langle P_0 \rangle^2\frac{\eta_2\sigma_{2p}(NA)^4}{\tau_p f_p (hc\lambda)^2}$

$(\tau_p f_p)^{-1} \approx 10^5$

$\frac{\phi_{2p}}{\phi_{1p}} \approx 5 \cdot 10^{-4} / mW$
Advantages of two-photon excitation:

Fluorescence excitation is limited to the focal volume
- confocal-like performance, but no need for pinhole in detection optics,
- less photobleaching
- improved contrast

Longer wavelength excitation
- reduced Rayleigh scattering \(1/\lambda^4\),
  better depth penetration
- less absorption/damage in tissue;
  biological “optical window”
- larger spectral gap in excitation/emission spectra

Disadvantages of two-photon:

- Large, expensive laser:
  - complete two-photon systems available commercially for $500k-$700k
- Slightly lower resolution due to longer excitation wavelength
Two-photon microscopy layout

M: mirror
S: shutter
f: filter
L: lens
D: dichroic
GM: galvanometer mirrors (2)
PMT: photomultiplier tube

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Biophotonics Lab
Fine tuning the optical alignment:
Scan a fluorescent lake sample (e.g., fluorescein in methanol), align scanhead, scope.

Point-spread-function measurement:
scan 0.093 μm diameter fluorescent microspheres in x,y,z

- x,y FWHM = 0.32 μm
- z-scan FWHM = 0.72 μm
Add micro-incubator for 37 °C, 5% CO₂ control:

CHO cells expressing YFP; Time lapse: 2 minutes/frame

Cells provided by Prof. Gabor Forgacs, U. Missouri and Dr. Rusty Lansford, CalTech

Mouse kidney section: z- scan
Application: Imaging bone tissue

Sample provided by: Melissa Knothe Tate, Cleveland Clinic Foundation

Human femur

Femoral head

Section from femoral head stained with basic fuschin and embedded in PMMA

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Biophotonics Lab
Bone section, 12 µm depth, $\lambda_{ex.}: 810$ nm

435-485 nm
Autofluorescence
Mineralized matrix?

590-640 nm
Basic fuschin stain

640-700 nm
Autofluorescence
Collagen matrix
Confocal (top, 568 nm) versus Two-photon (bottom, 910 nm)

Cortical bone (femur)
Producing osteoclasts in-vitro:

- Macrophage
  - + RANKL
    - Osteoclast precursor
    - Multinucleated osteoclast
  - TRAP+
    - TRAP (no RANKL treatment)
Fluorescence Lifetime Imaging Microscopy (FLIM)
- Presently adding FLIM capability to the microscope

Fura-2 dye (Calcium indicator), MC3T3 cells

Intensity is a function of many variables
(dye and Ca conc., excitation/collection efficiency)

- OK for qualitative imaging
- Quantitative data is possible but difficult

Example FLIM image: Elson et al., Optics and Photonics News, Nov ‘02

Fluorescence lifetime \( \tau = \frac{1}{\Gamma + k} \)  
\( \Gamma \), radiative decay rate  
k, non-radiative decay rate

k=k(pH, Ca++, viscosity, membrane potential)

- Provides quantitative data regarding cell physiology
Summary

• We are applying two-photon fluorescence microscopy techniques to the study of bone tissue and bone cell biology

• Ultimate goal is to understand bone loss in microgravity

• FLIM/FCS/protein expression will be used to study effects of fluid flow, acoustic vibrations, electro-mechanical forces on bone cells

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Strategic Research to Enable NASA's Exploration Missions Conference and Workshop

Presentations

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The primary focus of the conference on Strategic Research to Enable NASA's Exploration Missions is to inform the research community of the changing direction of the NASA Office of Biological and Physical Research programs to support the future exploration missions. The conference includes invited plenary talks, technical paper presentations, poster presentations, and exhibits in the areas of Human Life Support Technology and Human Health. This CP is a compilation of the abstracts, presentations, and posters presented at the conference.