NASA/CP—2004-213205/VOL1

Strategic Research to Enable NASA's Exploration Missions Conference and Workshop

Presentations

August 2004

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Strategic Research to Enable NASA's Exploration Missions Conference and Workshop

Presentations

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the National Center for Microgravity Research on Fluids and Combustion
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Space Administration

Glenn Research Center

August 2004

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Strategic Research to Enable NASA's Exploration Missions Conference Program

NANOMOLECULAR BIOSENSORS AND THERAPEUTICS

James R. Baker, Jr. MD
Center for Biologic Nanotechnology
University of Michigan
Ann Arbor, MI

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

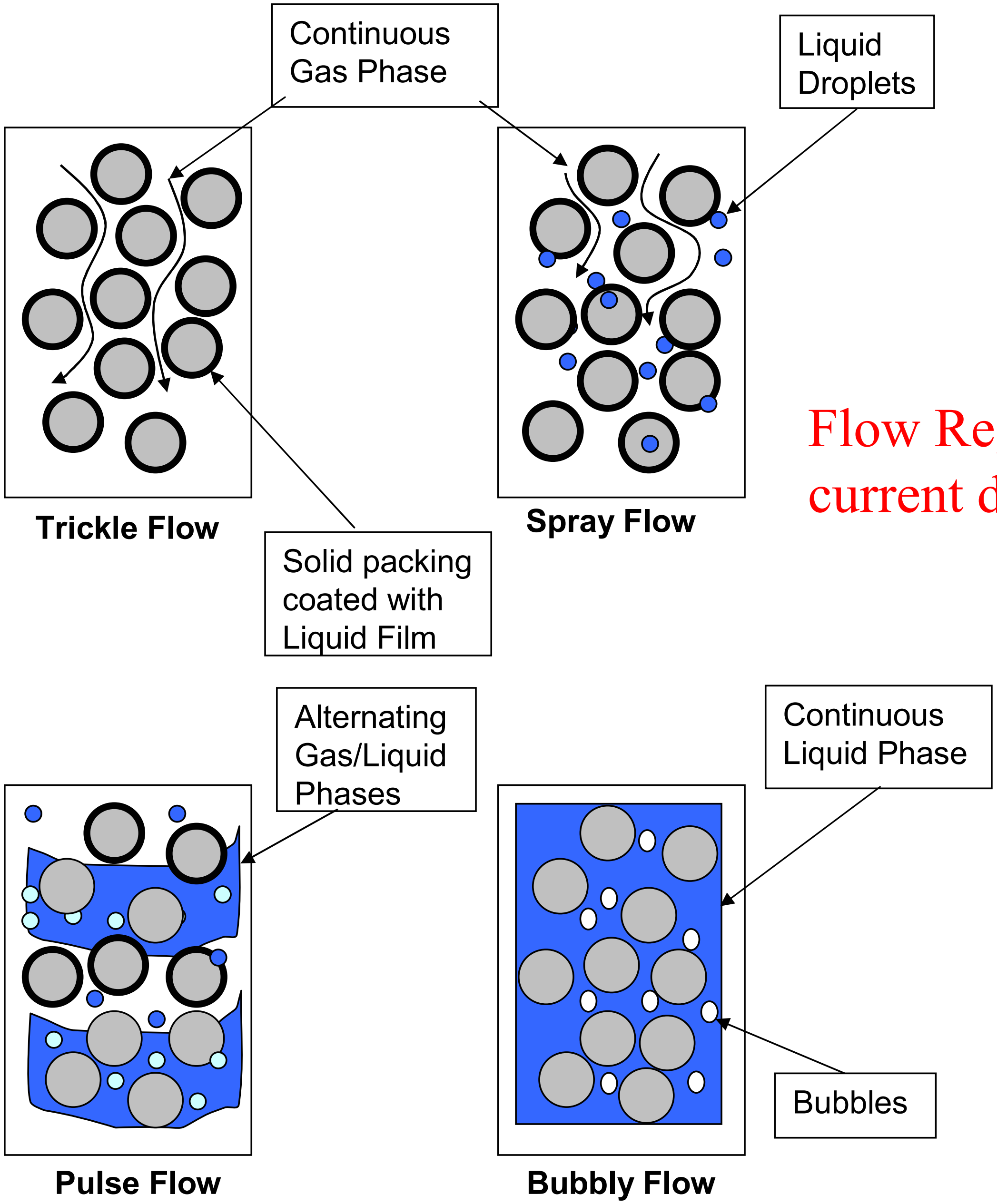
Vemuri Balakotaiah, University of Houston
Brian J. Motil, NASA Glenn Research Center
Mark J. McCready, Notre Dame University
Yasuhiro Kamotani, Case Western Reserve University

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 (CO_2 absorption) Severely Limiting

    [Workshop on Critical Issues in Microgravity Fluids, Transport and Reaction Processes, NASA-TM-212940-2004]
- *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



Continuous Gas Phase

Liquid Droplets

Trickle Flow

Spray Flow

Solid packing coated with Liquid Film

Alternating Gas/Liquid Phases

Continuous Liquid Phase

Bubbles

Pulse Flow

Bubbly Flow

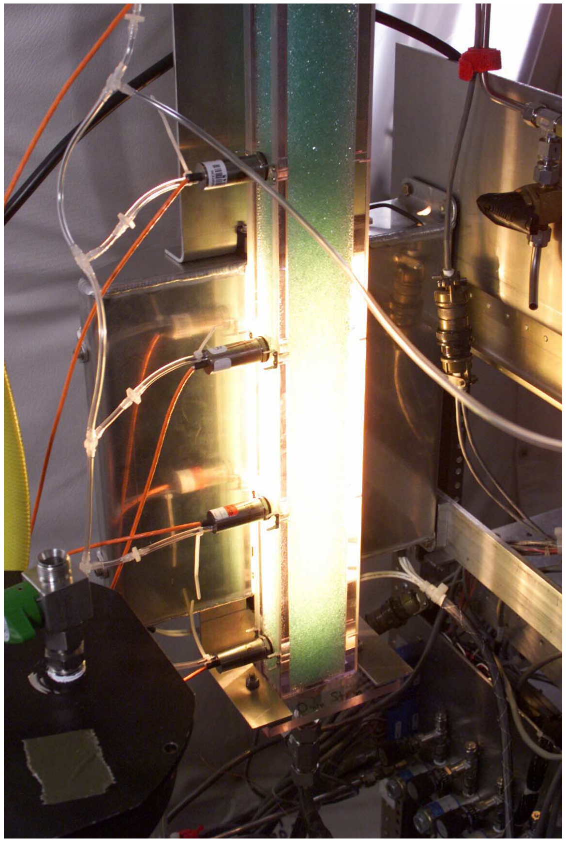
Similarities and Differences Between 1-g and 0-g Cocurrent Downflow Through Packed Beds

- 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

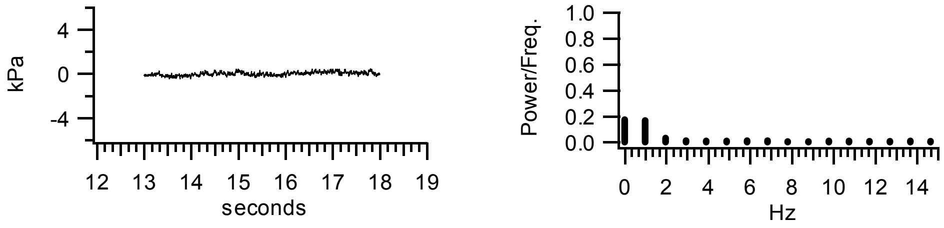
- 12 flights - over 300 test conditions flown on NASA KC-135 aircraft (20 sec/run)
- Rectangular cross section

  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)
- $0.03 < G < 0.8$ kg/(s m^2)
- $3 < L < 50$ kg/(s m^2)
- $0.18 < Re_{LS} < 100$
- $8.5 < Re_{GS} < 175$
- $4 \times 10^{-4} < We_{LS} < 0.2$
- $900 < Su_L < 365{,}000$

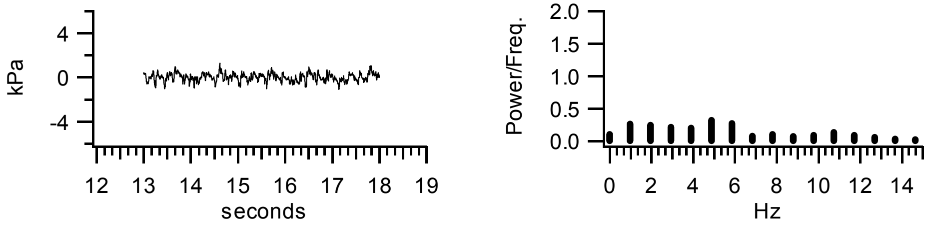


$$Re_{LS} = \frac{\rho_L U_{LS} d_p}{\mu_L} \qquad We_{LS} = \frac{\rho_L U_{LS}^2 d_p}{\sigma} \qquad Su = \frac{d_p \rho_L \sigma}{\mu_L^2} = \frac{Re_{LS}^2}{We_{LS}} \qquad Re_{GS} = \frac{\rho_G U_{GS} d_p}{\mu_G}$$

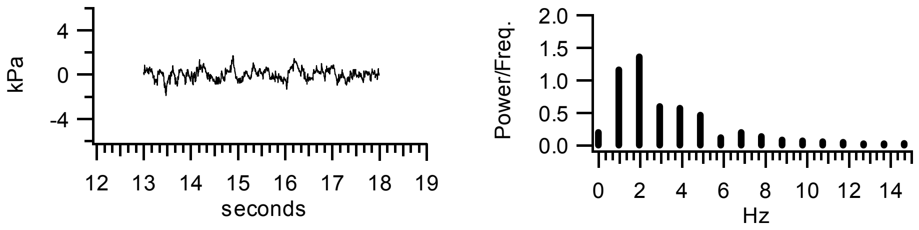
Identification of Flow Regime Transitions



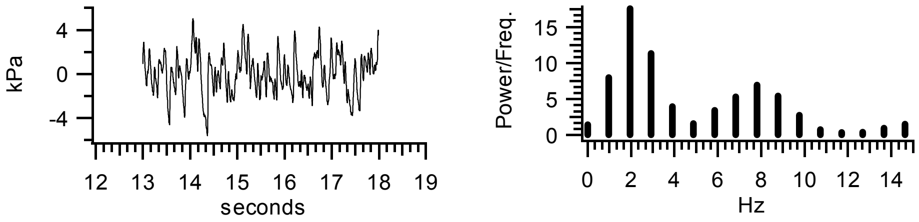
Bubble flow



Bubble flow “near” transition



Pulse flow “near” transition



Pulse flow

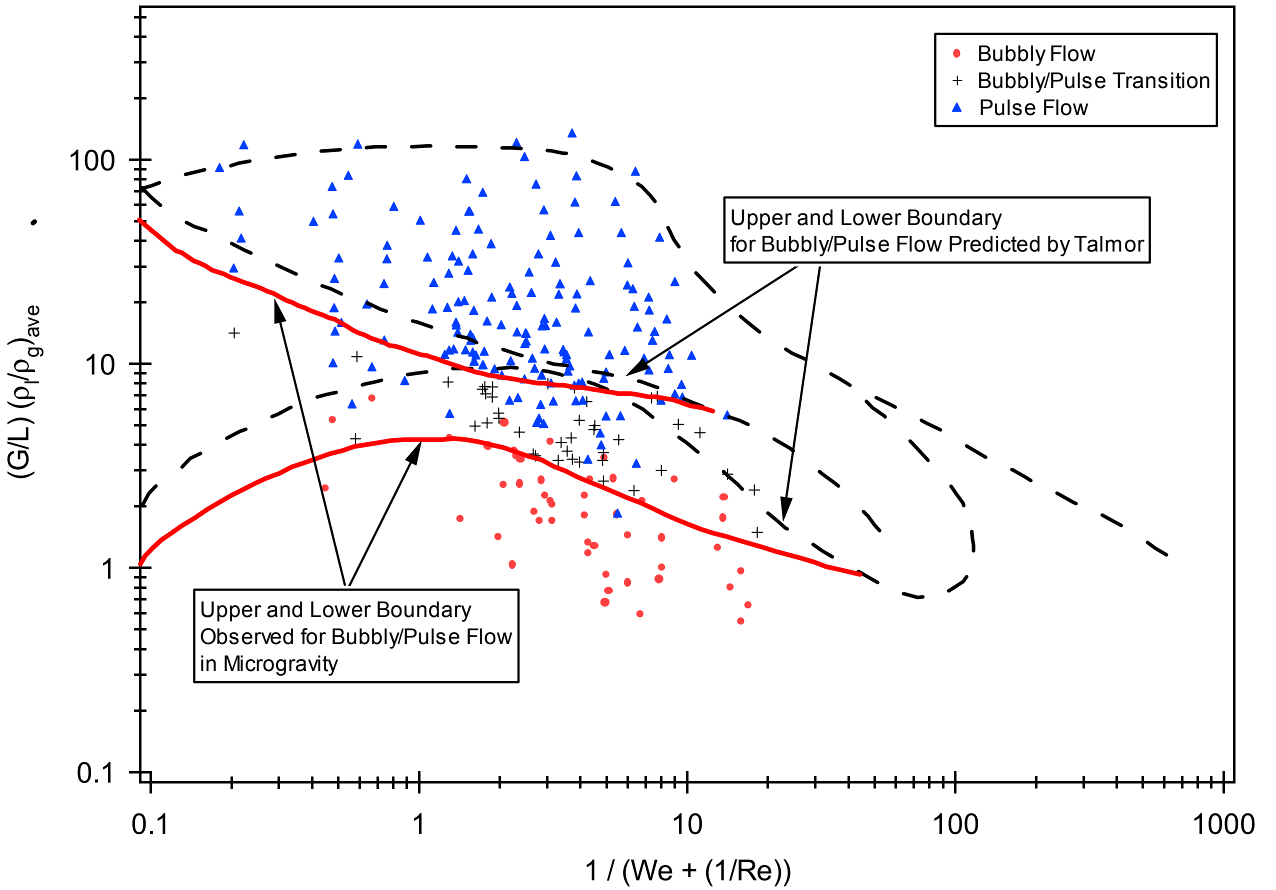
Microgravity Experimental Results Compared to Talmor Map

$$X = \frac{\textit{inertia} + \textit{gravity}}{\textbf{interface} + \textit{viscous}} = \frac{1 + \frac{1}{Fr}}{\frac{1}{We} + \frac{1}{\mathrm{Re}}}$$

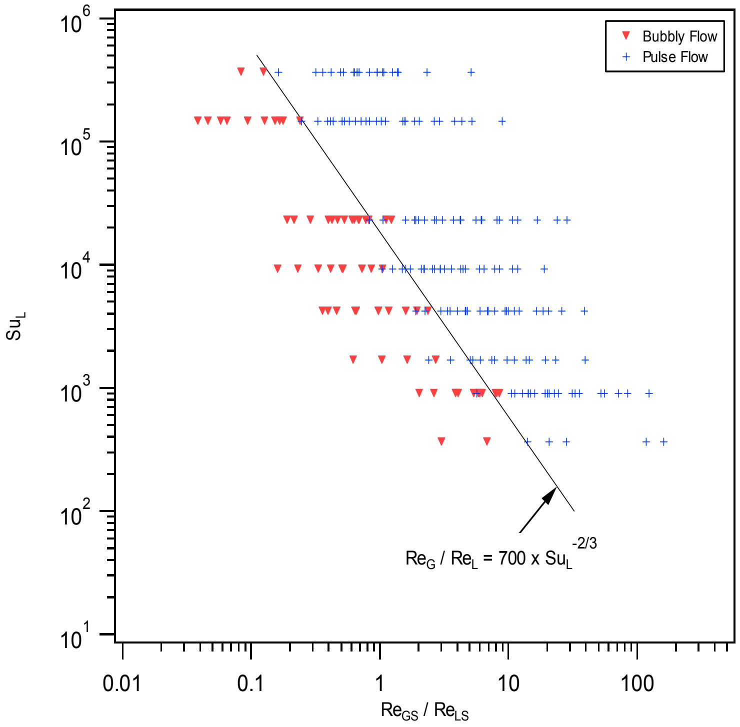
$$We = \frac{D^*(L+G)v_{LG}}{\sigma} \qquad \mathrm{Re} = \frac{D^*(L+G)}{\mu_{LG}} \qquad \mathrm{Fr} = \frac{[(L+G)v_{LG}]^2}{\mathrm{g}D^*}$$

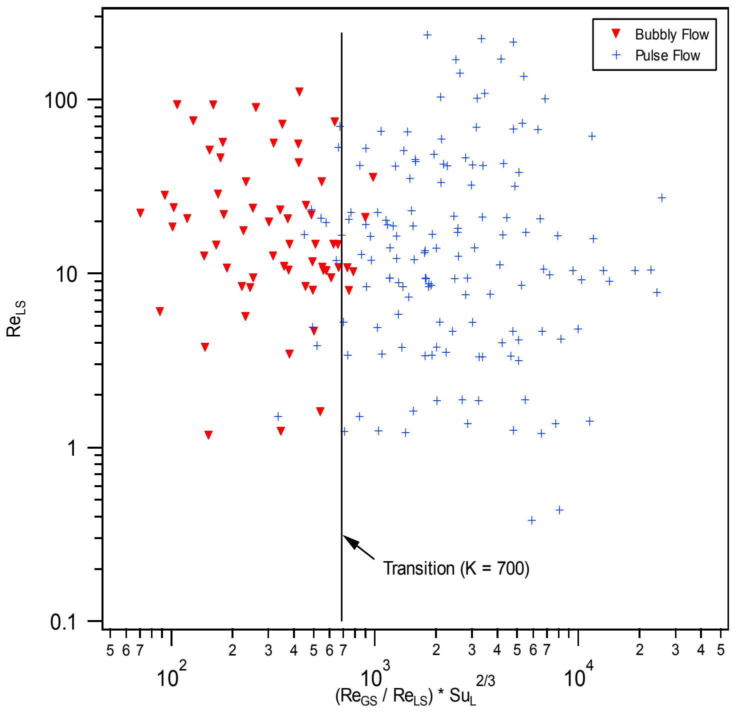
$$v_{LG} = \frac{v_L(L/G) + v_G}{1 + (L/G)}$$

Packed Bed in Microgravity



Flow Regime Transition in Microgravity

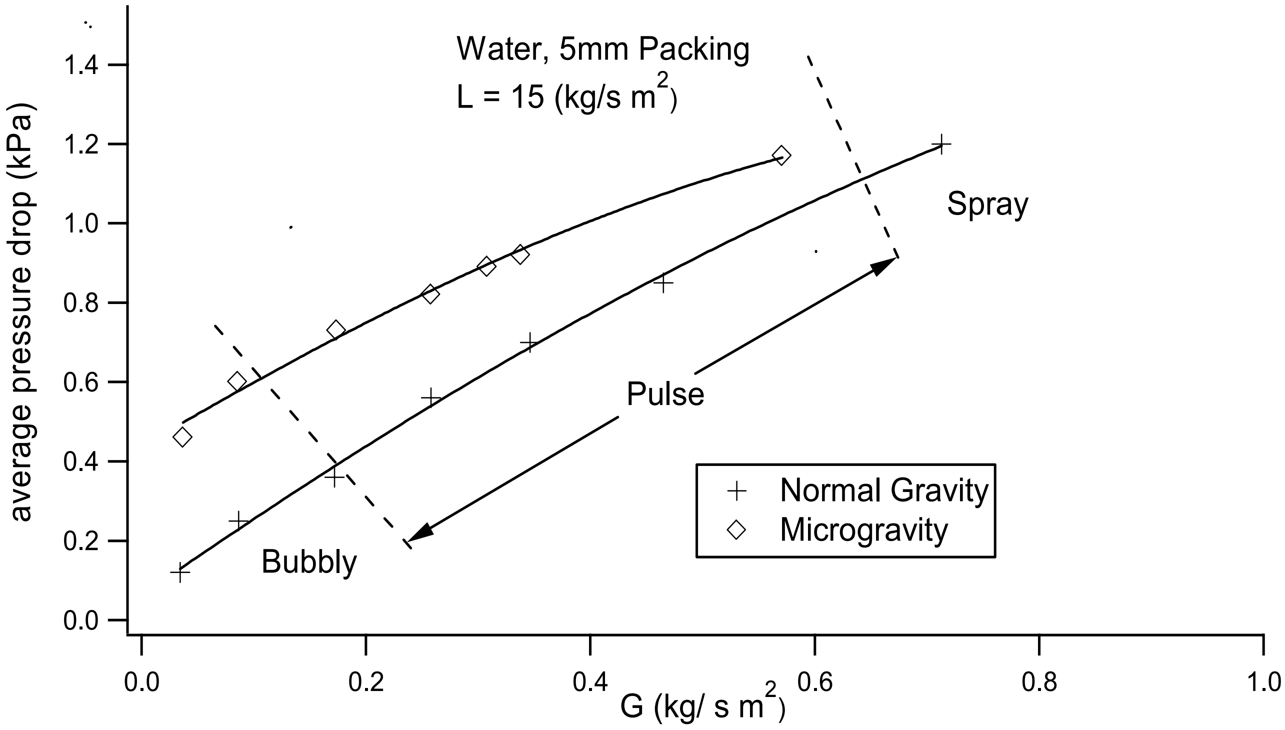




- Bubble-Pulse transition is a function of gas and liquid Reynolds numbers and the liquid Suratman number, where:

$$Su_L = \frac{Re_{LS}}{Ca_{LS}} = \frac{Re_{LS}^2}{We_{LS}} = \frac{d_P \rho_L \sigma}{\mu_L^2}$$

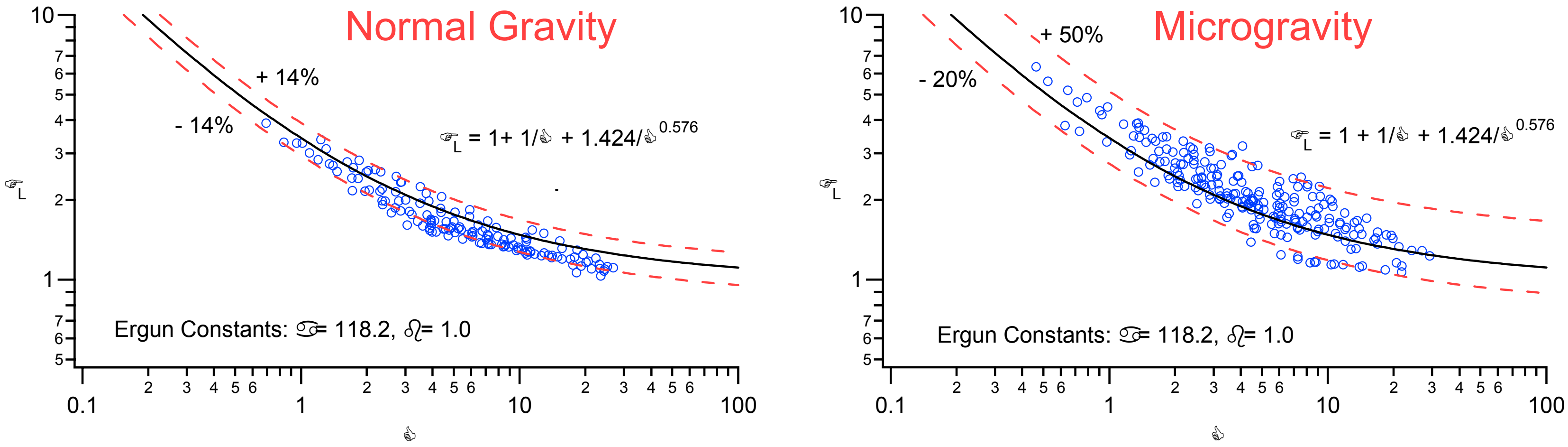
Pressure Drop



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:

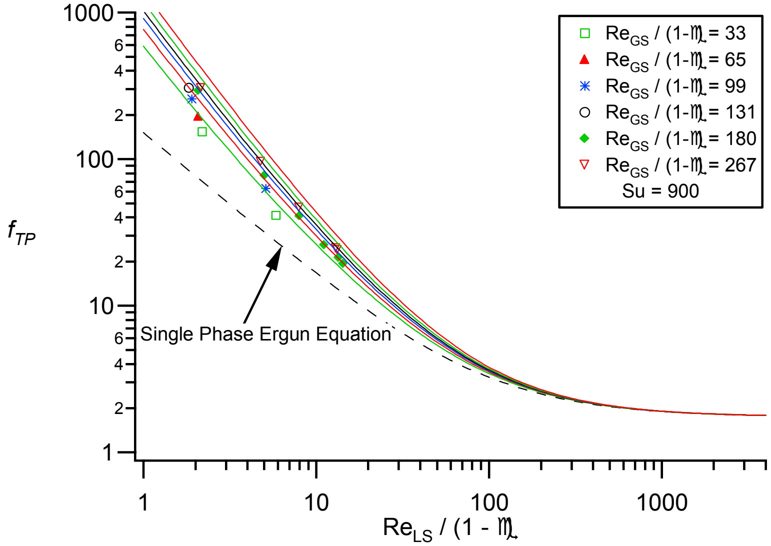
$$\frac{-\Delta P}{Z}\frac{d_P}{\rho_L U_{LS}^2} = \mathrm{f}\left[\frac{Su_L}{Re_{LS}^2}, \frac{1}{Re_{LS}}, Re_{GS}, \varepsilon\right]$$

- 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.

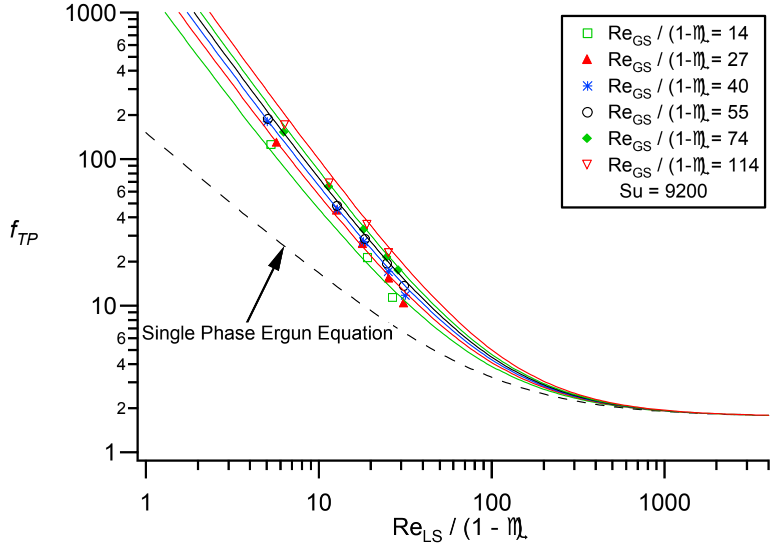
$$f_{\mathrm{TP}} - f_{\mathrm{SP}} = \gamma\left(\frac{Re_{GS}}{1-\varepsilon}\right)^a \left(\frac{1-\varepsilon}{Re_{LS}}\right)^b \left(\frac{(1-\varepsilon)^2 Su_L}{Re_{LS}^2}\right)^c$$

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

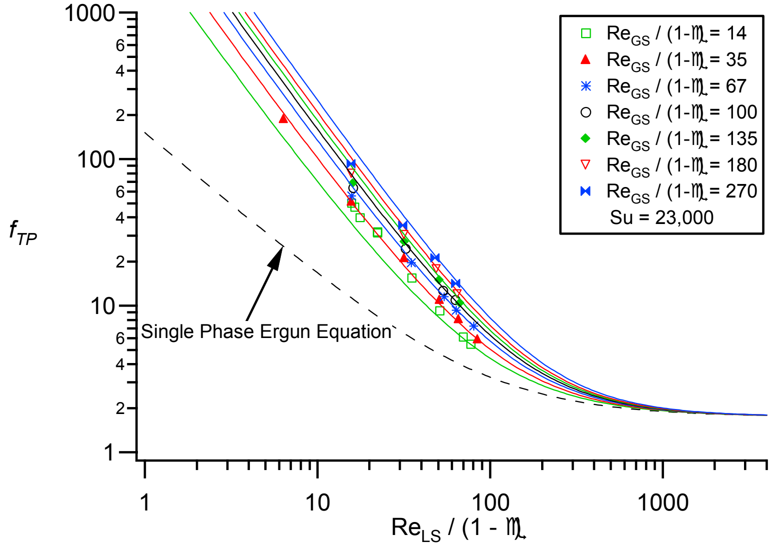
$$f_{\mathrm{TP}} = \frac{-\Delta P}{Z}\frac{d_P}{\rho_L U_{LS}^2}\frac{\varepsilon^3}{1-\varepsilon} = \frac{1-\varepsilon}{Re_{LS}}\left[180 + 0.8\left(\frac{Re_{GS}}{1-\varepsilon}\right)^{\frac{1}{2}}\left(\frac{Su_L(1-\varepsilon)}{Re_{LS}}\right)^{\frac{2}{3}}\right] + 1.8$$



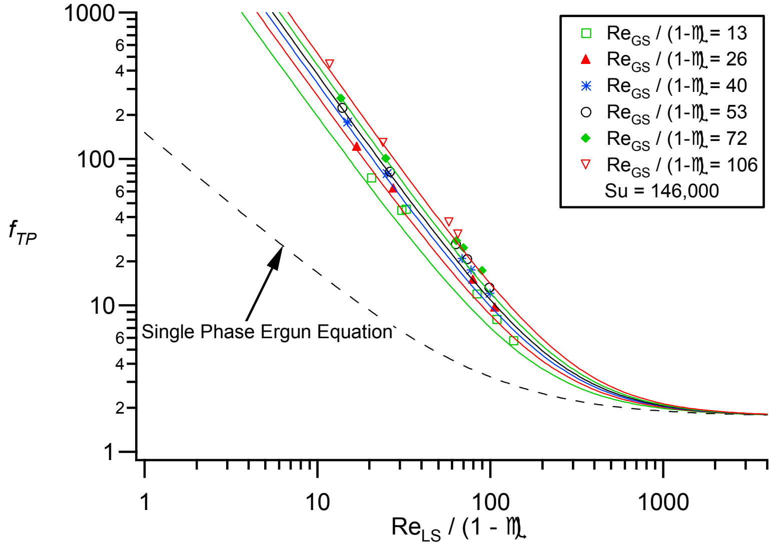
f_{TP}
1000
100
10
1
$Re_{LS} / (1 - \varepsilon)$
1
10
100
1000
$Re_{GS} / (1-\varepsilon) = 33$
$Re_{GS} / (1-\varepsilon) = 65$
$Re_{GS} / (1-\varepsilon) = 99$
$Re_{GS} / (1-\varepsilon) = 131$
$Re_{GS} / (1-\varepsilon) = 180$
$Re_{GS} / (1-\varepsilon) = 267$
Su = 900
Single Phase Ergun Equation



f_{TP}
1000
100
10
1
$Re_{LS} / (1 - \varepsilon)$
1
10
100
1000
$Re_{GS} / (1-\varepsilon) = 14$
$Re_{GS} / (1-\varepsilon) = 27$
$Re_{GS} / (1-\varepsilon) = 40$
$Re_{GS} / (1-\varepsilon) = 55$
$Re_{GS} / (1-\varepsilon) = 74$
$Re_{GS} / (1-\varepsilon) = 114$
Su = 9200
Single Phase Ergun Equation



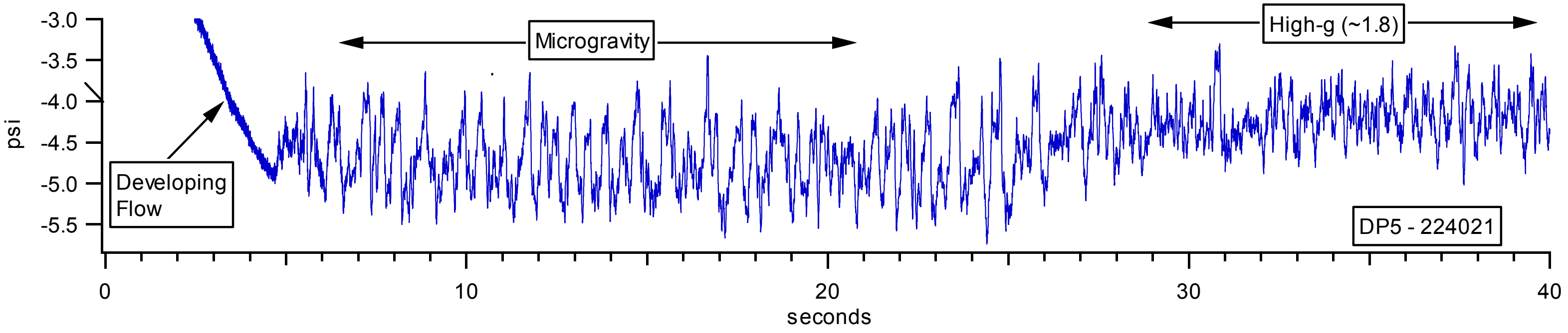
f_{TP}
1000
100
10
1
$Re_{LS} / (1 - \varepsilon)$
1
10
100
1000
$Re_{GS} / (1-\varepsilon) = 14$
$Re_{GS} / (1-\varepsilon) = 35$
$Re_{GS} / (1-\varepsilon) = 67$
$Re_{GS} / (1-\varepsilon) = 100$
$Re_{GS} / (1-\varepsilon) = 135$
$Re_{GS} / (1-\varepsilon) = 180$
$Re_{GS} / (1-\varepsilon) = 270$
Su = 23,000
Single Phase Ergun Equation



f_{TP}
1000
100
10
1
$Re_{LS} / (1 - \varepsilon)$
1
10
100
1000
$Re_{GS} / (1-\varepsilon) = 13$
$Re_{GS} / (1-\varepsilon) = 26$
$Re_{GS} / (1-\varepsilon) = 40$
$Re_{GS} / (1-\varepsilon) = 53$
$Re_{GS} / (1-\varepsilon) = 72$
$Re_{GS} / (1-\varepsilon) = 106$
Su = 146,000
Single Phase Ergun Equation

Pressure Drop & Pulse Characteristics with varying g

- Pulse amplitude decreases with increasing gravity.



	Microgravity (10-18 s)	High Gravity (32-40 s)	Difference
Average Pressure Drop	**4.15 psi**	**4.75 psi**	**.6 psi**
Pulse Amplitude	**2.22 psi**	**1.69 psi**	**.5 psi**

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

B.J. Motil, V. Balakotaiah & Y. Kamotani, “Gas-Liquid Two-Phase Flow Through Packed Beds in Microgravity”, AIChE J.,49,557-565 (2003)

GRAVITY AND GRANULAR MATERIALS

Bob Behringer
Department of Physics
Duke University
Durham, N.C.27708-0305
Phone: 919-660-2550; Fax: 919-660-2525; Email: bob@phy.duke.edu

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

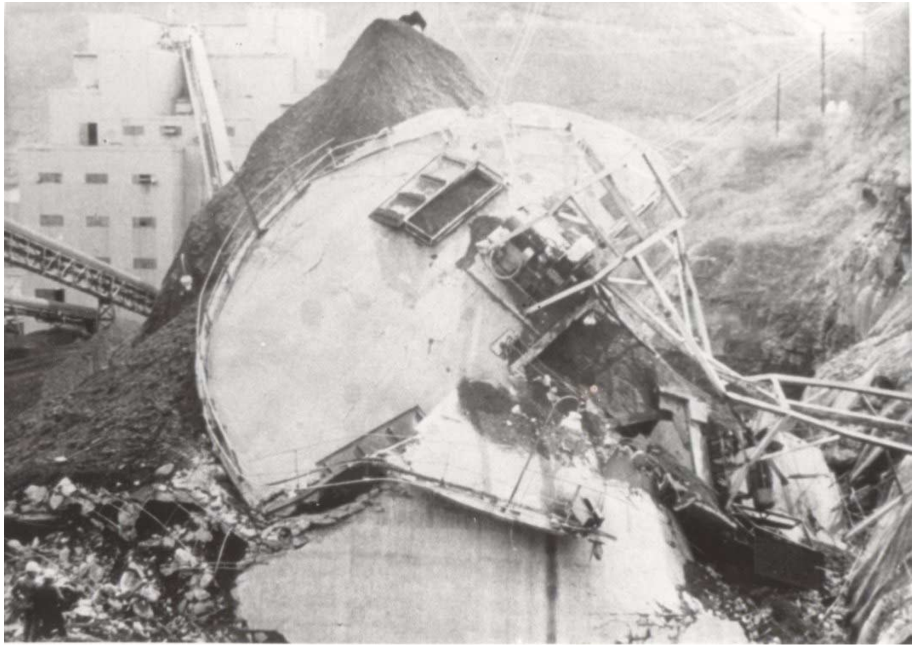
- Practical problems
- Basic properties of granular materials
- 2D shear—insight into role of force chains…
- 3D shear—structural phase transition
- Conclusions

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



The Herald-Sun/**BILL WILLCOX**

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

Scottish news direct from Scotland

Thursday, 29th April 2004

- Sections
- Top Stories
- Latest News
- Scotland
- UK
- International
- Politics
- Sci-Tech
- Health
- Education
- Entertainment
- Gaelic
- Features
- Opinion
- Obituaries
- Article Index
- Hot Topics
- European Union
- Rebuilding Iraq
- Middle East
- Holyrood Parliament
- Reliance security row
- Topics A to Z
- Other Sites

Mars exploration & Beagle 2

Tue 30 Dec 2003

Scientist hope that the Beagle's landing site has not swallowed up the Mars mission's signal.

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 20 minutes after the craft was due to land.

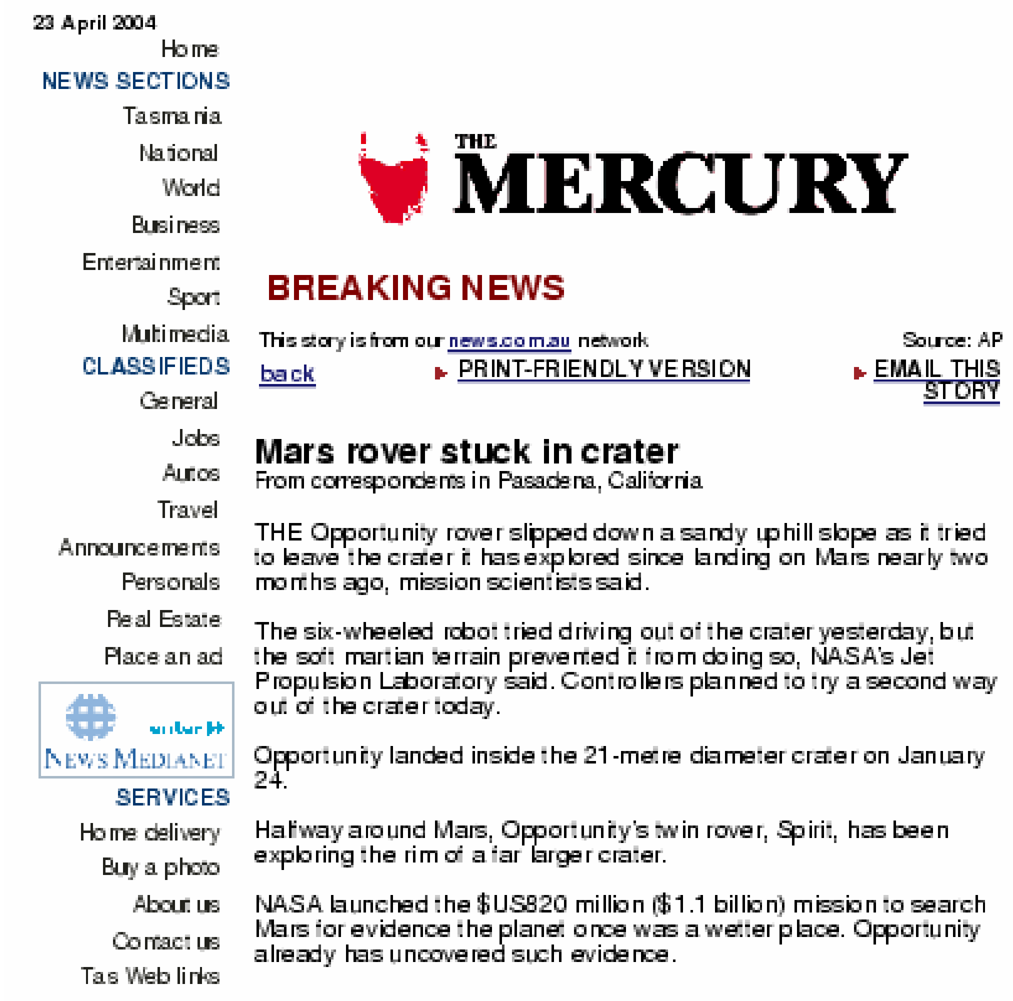
The latest potential setback for the Open University-led team was revealed yesterday, as the fate of the 143lb probe continued to elude astronomers.

However, Lord Sainsbury, the science minister, suggested the government would back a Beagle 3 mission if it failed.

Mars exploration: Page 2

- 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 (15-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 (05-Jan-04)

Rovers in the News



23 April 2004

THE MERCURY

BREAKING NEWS

This story is from our news.com.au network

Source: AP

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

Submitted by GOENKARBOY on 18 January, 2004 - 12:53am.

Title: 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
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:

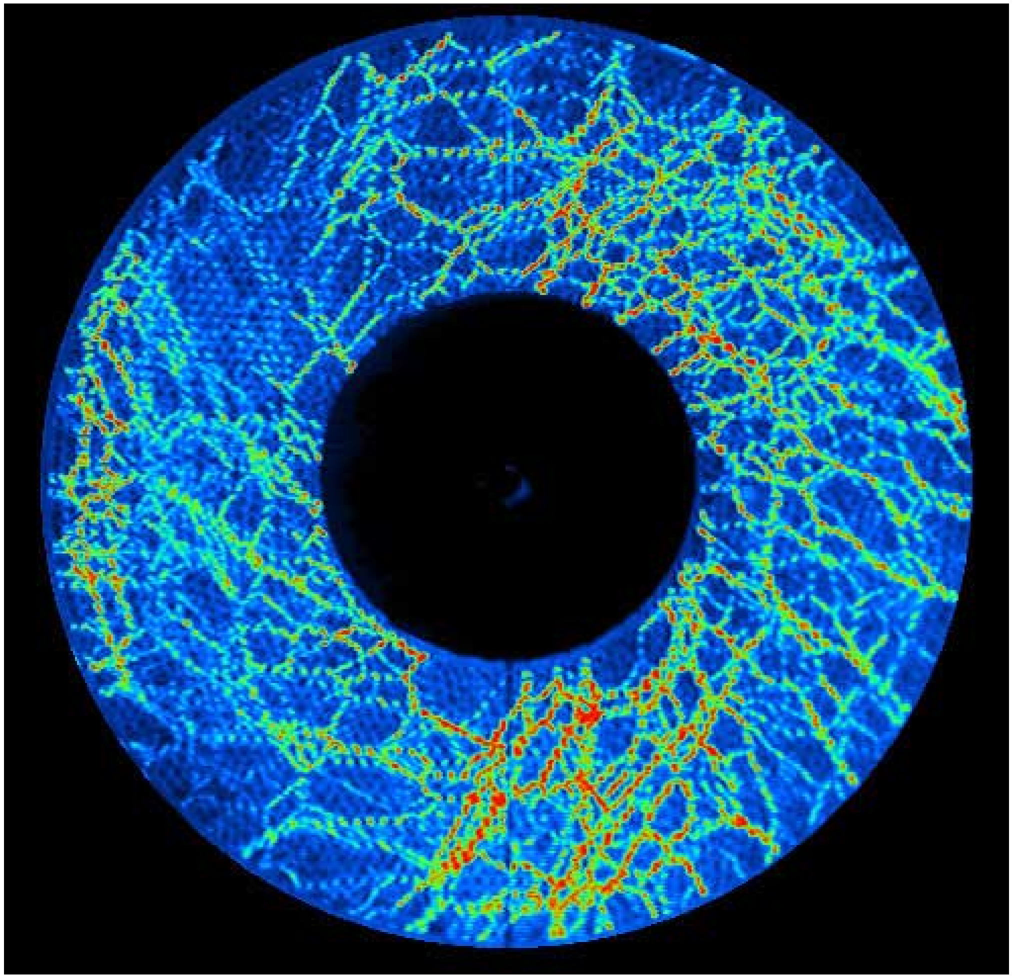
Pasadena -- Ecstatic scientists used the Mars rover's powerful camera Friday to take the first close-up images ever made of the Martian surface and immediately confronted a new mystery over what they saw.

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.

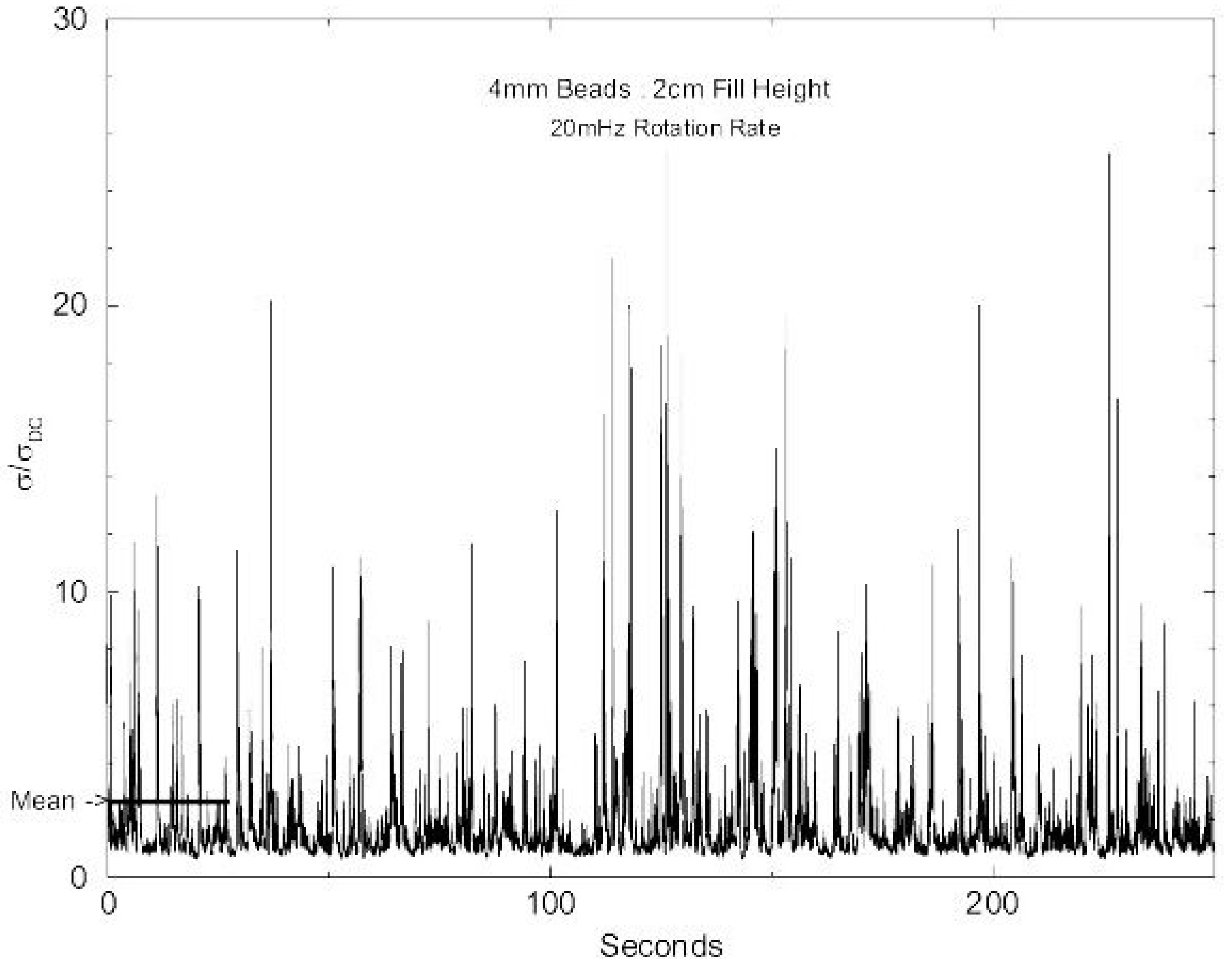
Some Basic Properties of Dense Granular Materials

- 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

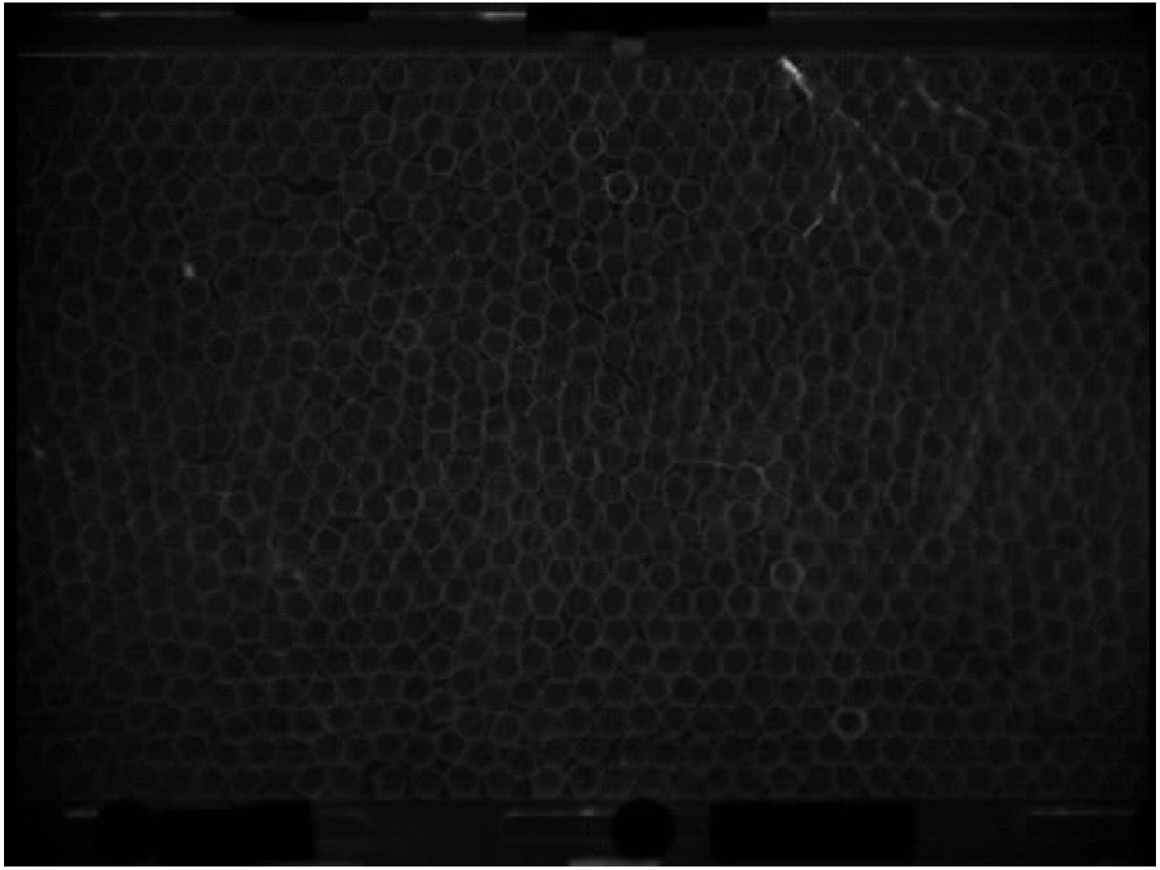
Example of Force Chains—Shear Experiment



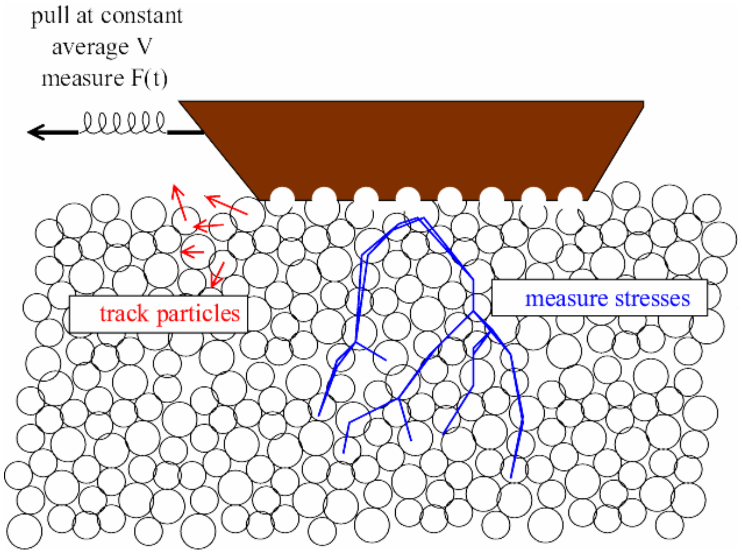
Example of Stress Fluctuations

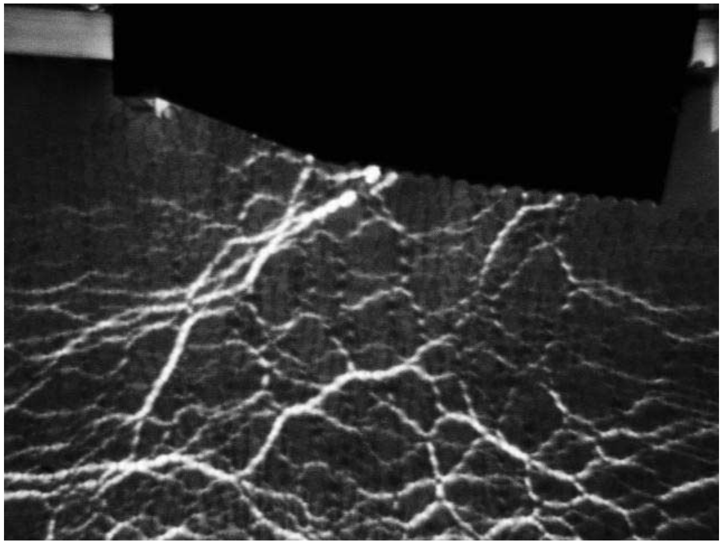


Example of Force Network Evolution

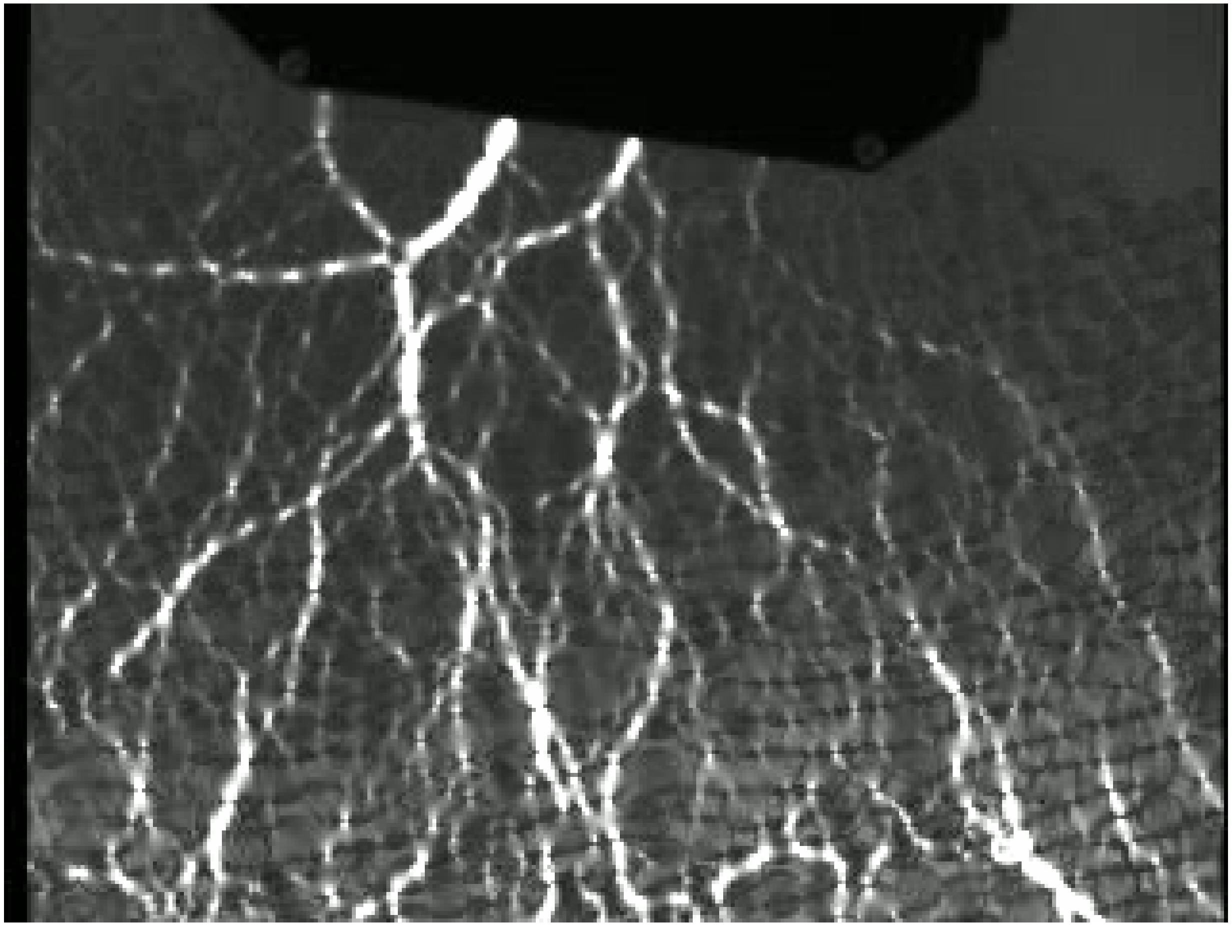


Force chains evolve and break under vehicles



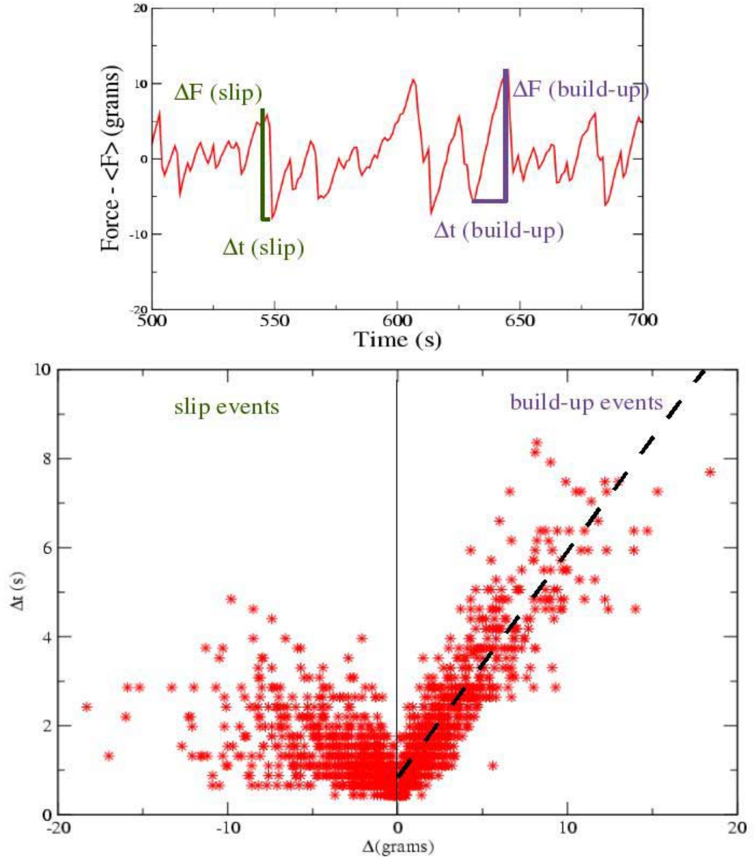


Force chains form and break—making "avalanches"

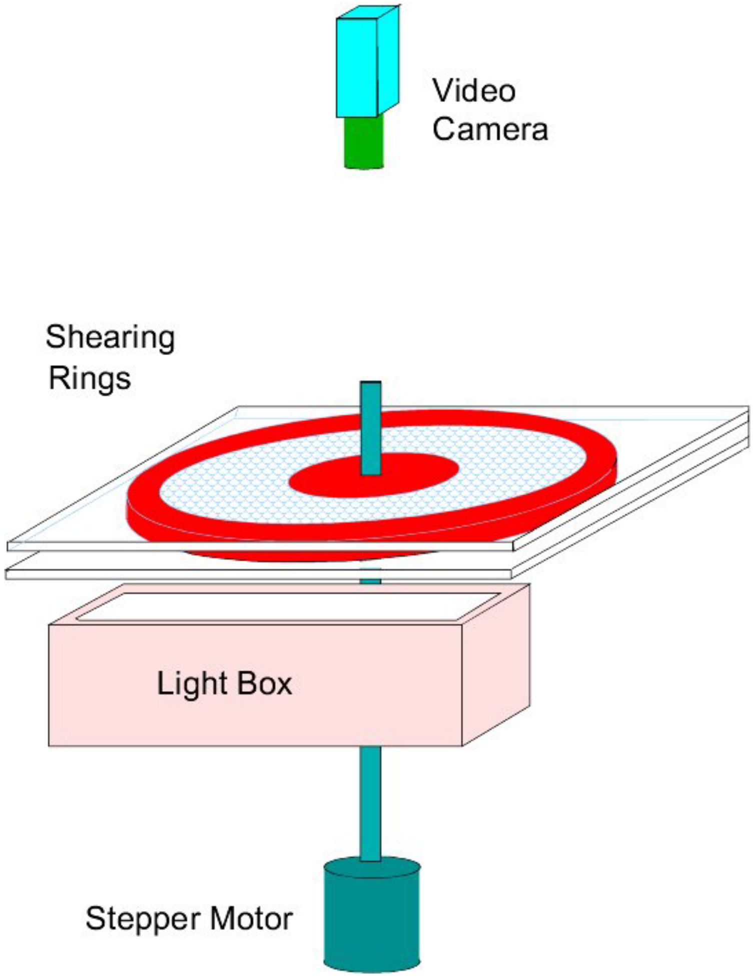


Stress avalanches can predict slip/failure

Stick-Slip Motion

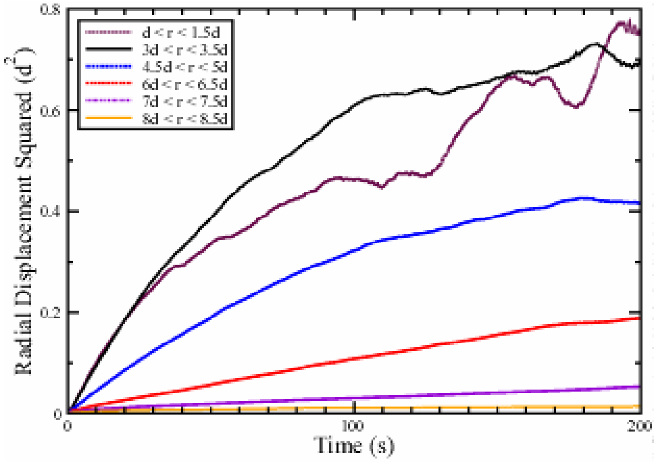


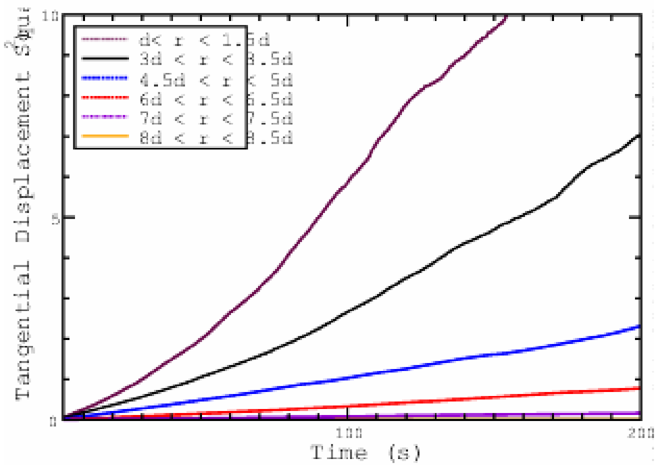
2D Couette Shear Experiments



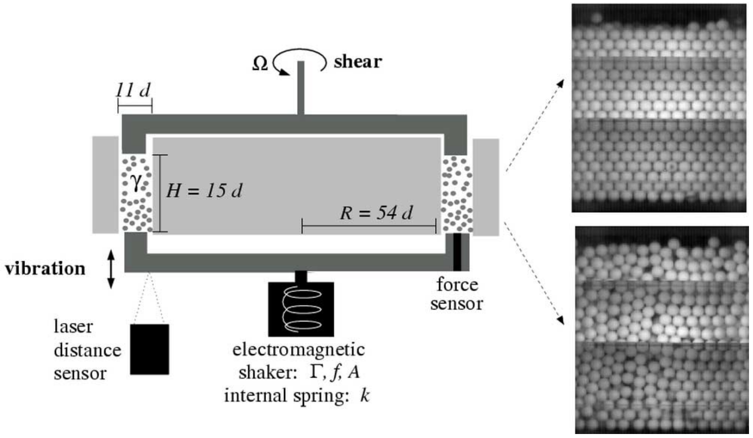
Data for Variance of Particle Positions vs. Time:

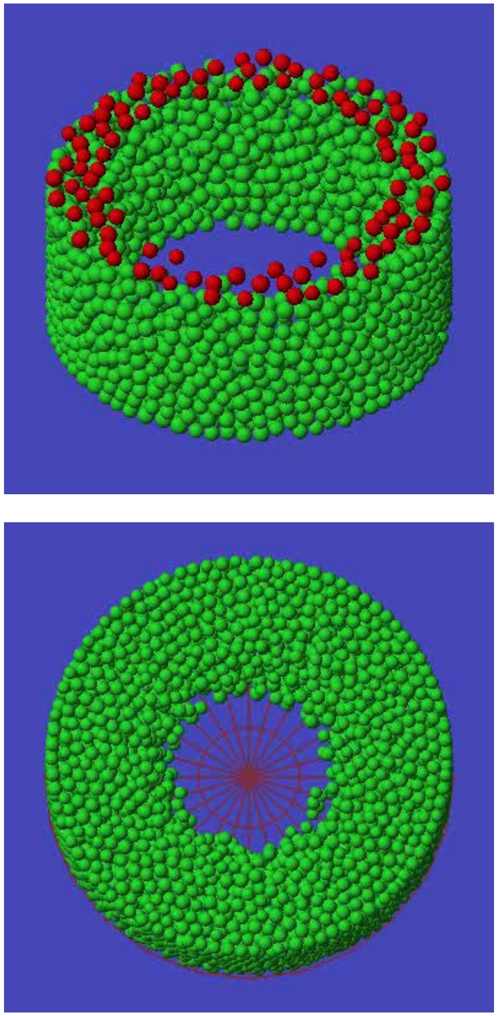
Diffusion is affected by mean velocity and force network



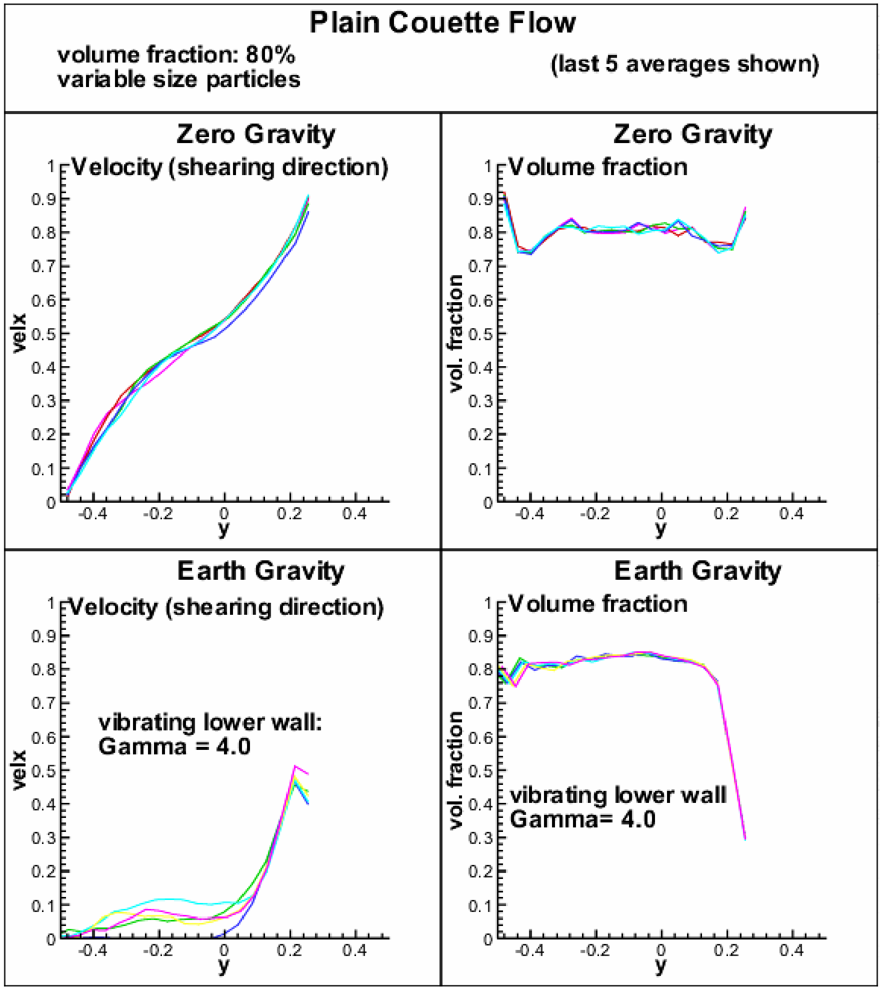


3D Shear + Vibration: Experiments and Simulations

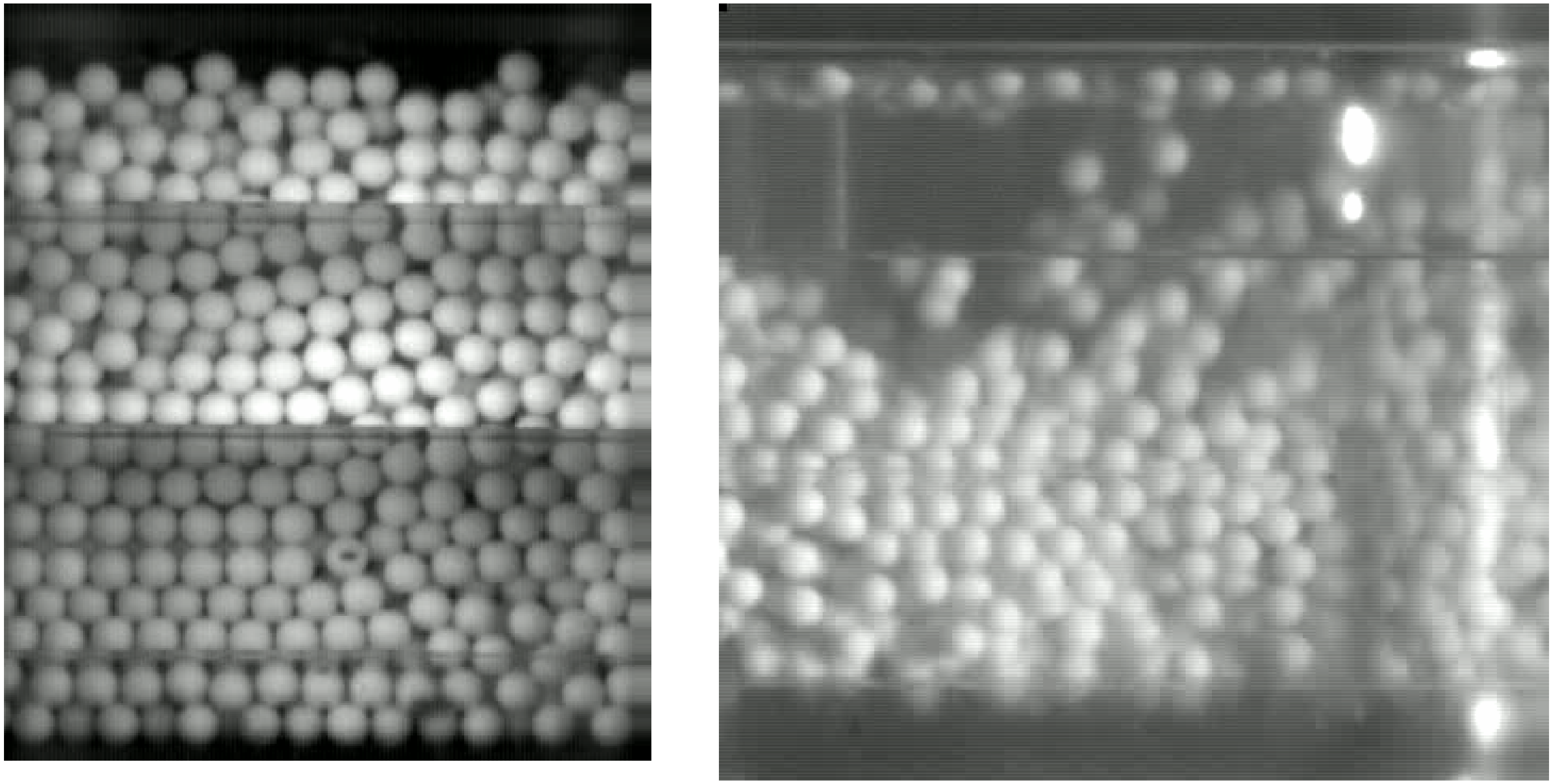




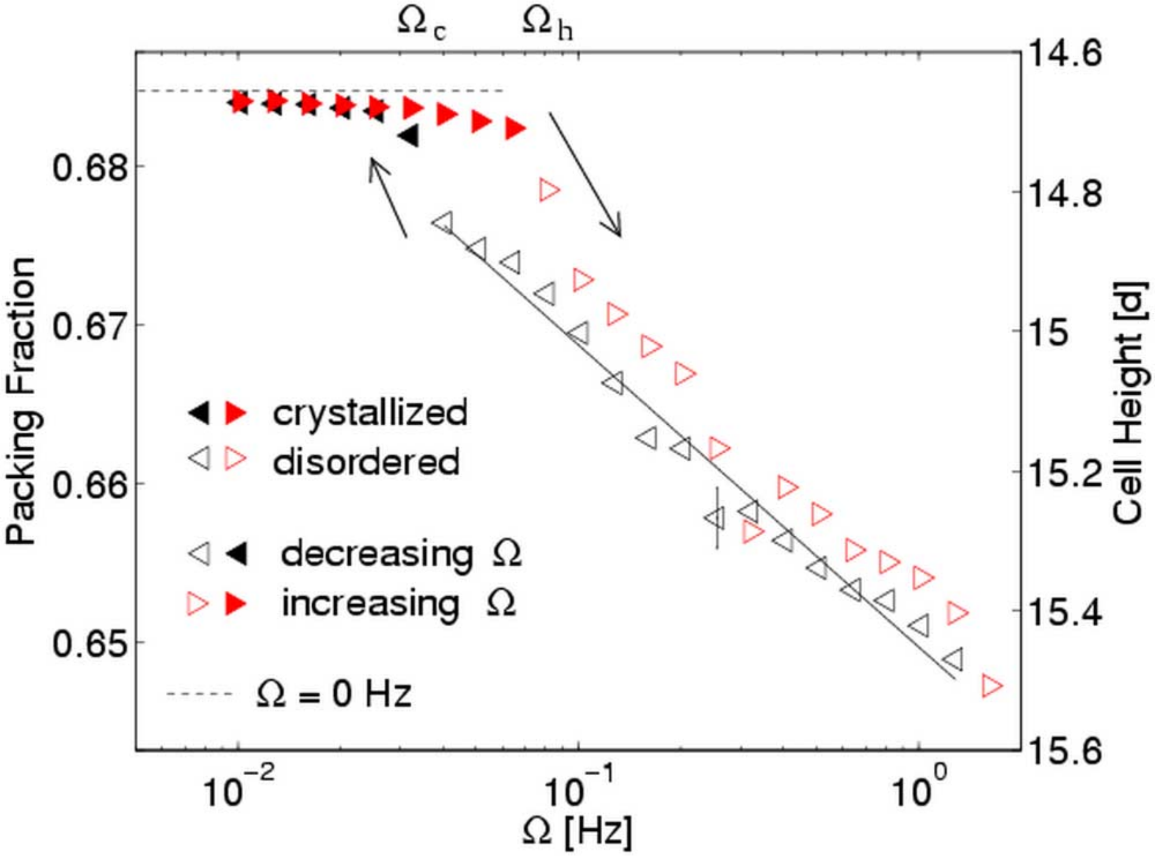
Computations show need for zero g



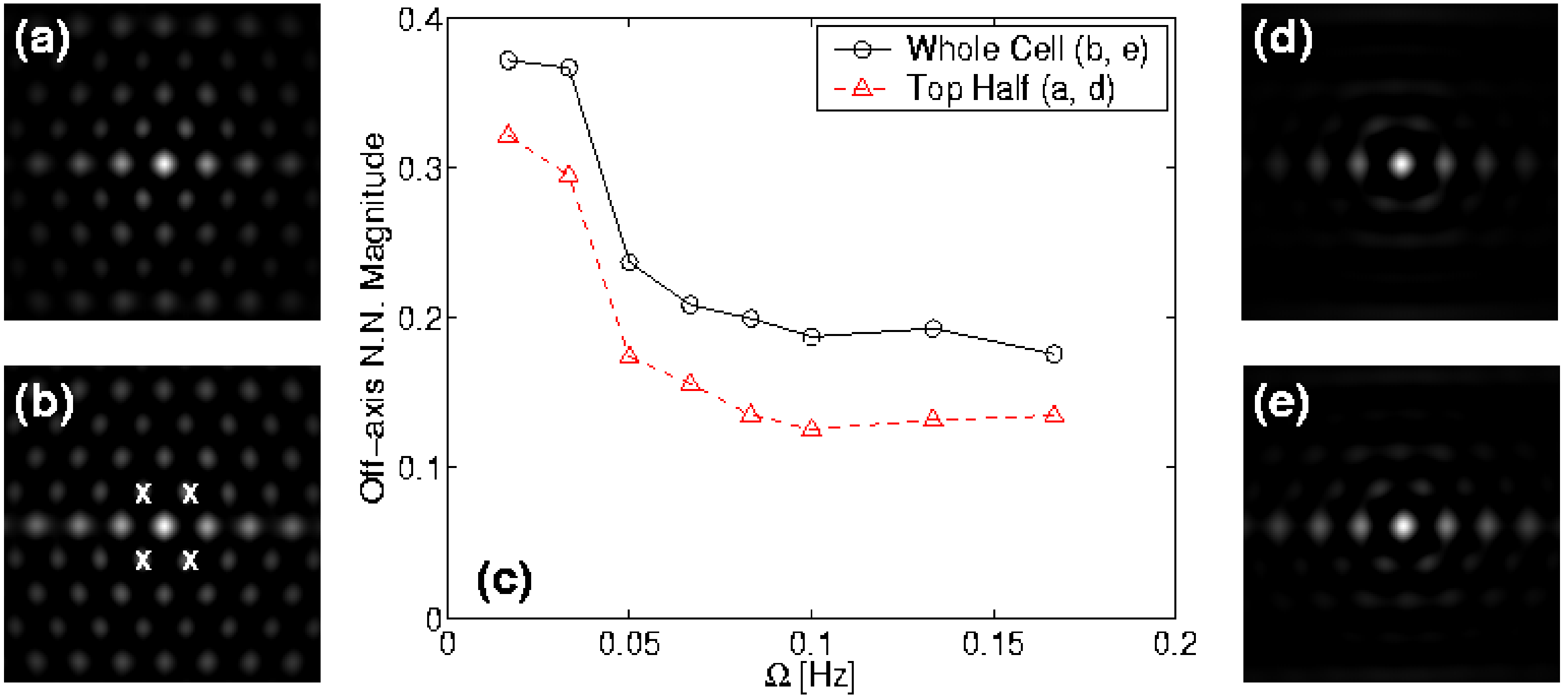
Clips from Experiments



Freezing by Heating—Competition between shearing and vibration ($\Gamma = 2.0$)



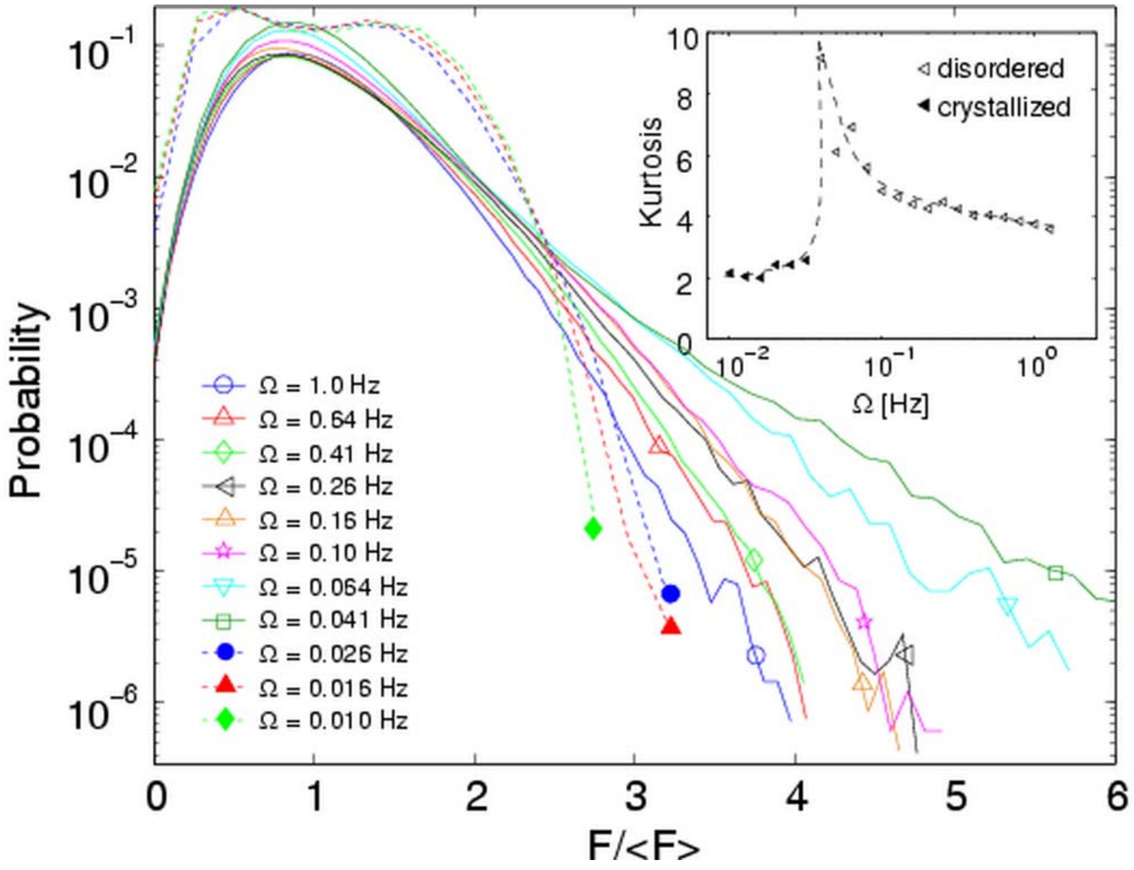
Spatial Autocorrelations show disorder with shear (a, b, d, e) and more quantitatively, c.



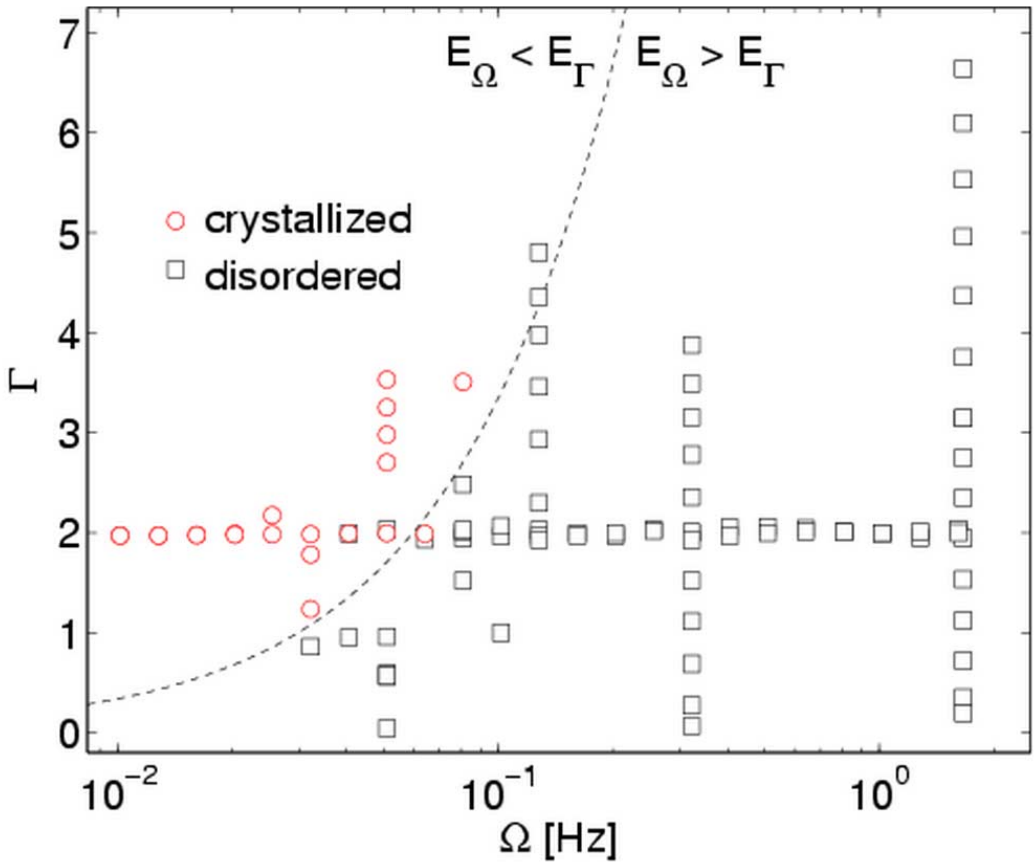
Ω = 0.0167 Hz

Ω = 0.167 Hz

Force Probability Distributions: Singular behavior in the Kurtosis



Phase Diagram in Shear Rate (Ω) and Shaking Amplitude (Γ)



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

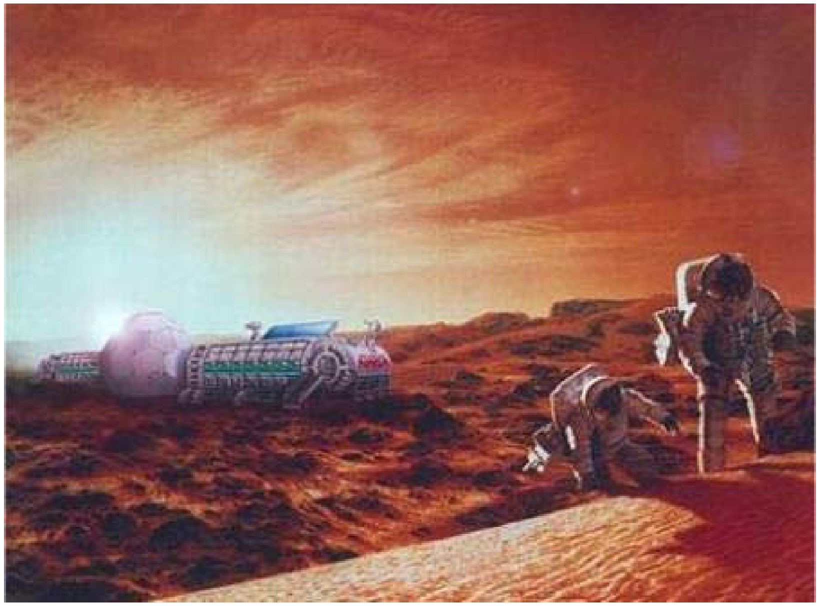
MEDICAL LAB ON A CHIP

Mark A. Burns,*† Brian N. Johnson,* Rohit Pal,* Ming Yang,* Rongsheng Lin,*
Nimisha Srivastava,* S. Zafar Razzacki,* Kenneth J. Chomistek,* Dylan Heldsinger,*
Moon-Bin Yim,* Victor Ugaz,* Madhavi Krishnan,* Vijay Namasivayam,*
Oveta Fuller,‡ Ronald G. Larson,* and David T. Burke¥

*Department of Chemical Engineering
†Department of Biomedical Engineering
‡Department of Microbiology and Immunology
¥Department of Human Genetics
University of Michigan
Ann Arbor, MI 48109-2136

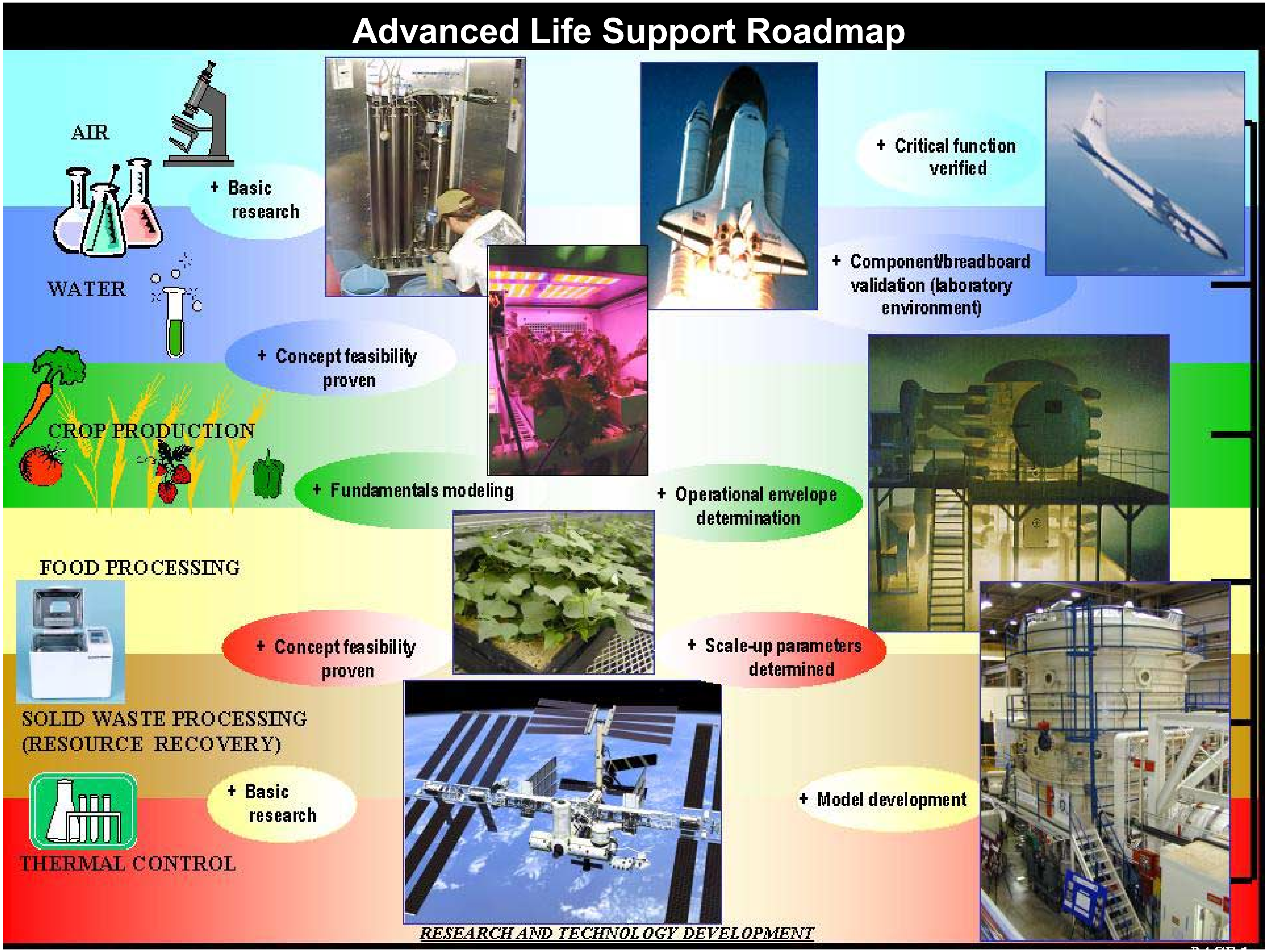
The low per-unit cost of microfabricated devices along with the ability to integrate multiple components on a single device allows for the construction of a variety of complex chemical analysis system. These complex systems can be only a squared centimeter or less in size but can perform functions normally 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 saliva, blood, and other medially 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 Roadmap



AIR

WATER

CROP PRODUCTION

FOOD PROCESSING

SOLID WASTE PROCESSING
(RESOURCE RECOVERY)

THERMAL CONTROL

- + Basic research
- + Concept feasibility proven
- + Fundamentals modeling
- + Concept feasibility proven
- + Basic research
- + Critical function verified
- + Component/breadboard validation (laboratory environment)
- + Operational envelope determination
- + Scale-up parameters determined
- + Model development

RESEARCH AND TECHNOLOGY DEVELOPMENT

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

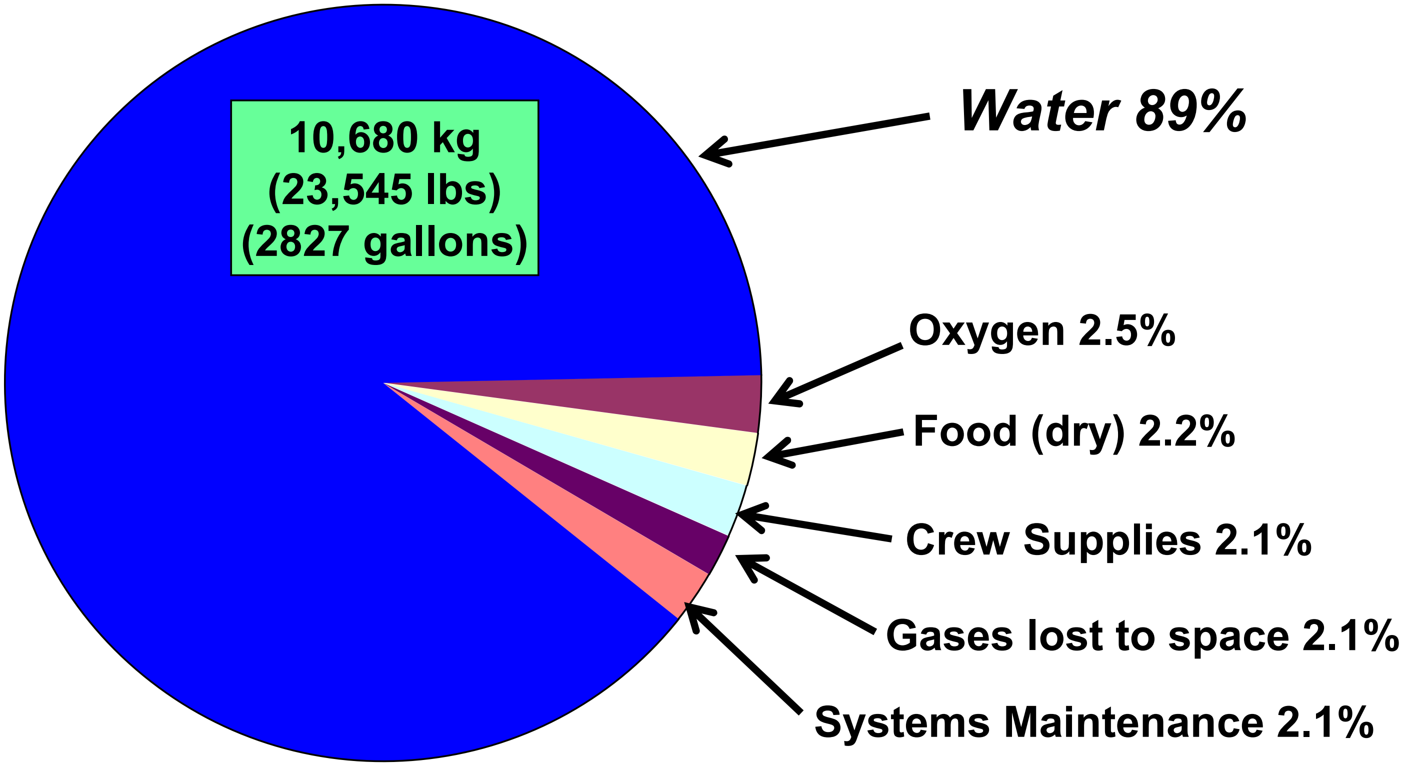
Human Life Support System Requirements

Consumables	Kilograms per person per day	
Gases		**0.8**
Oxygen	0.84	
Water		**23.4**
Drinking	1.62	
Water content of food	1.15	
Food preparation water	0.79	
Shower and hand wash	6.82	
Clothes wash	12.50	
Urine flush	0.50	
Solids		**0.6**
Food	0.62	
TOTAL		**24.8**

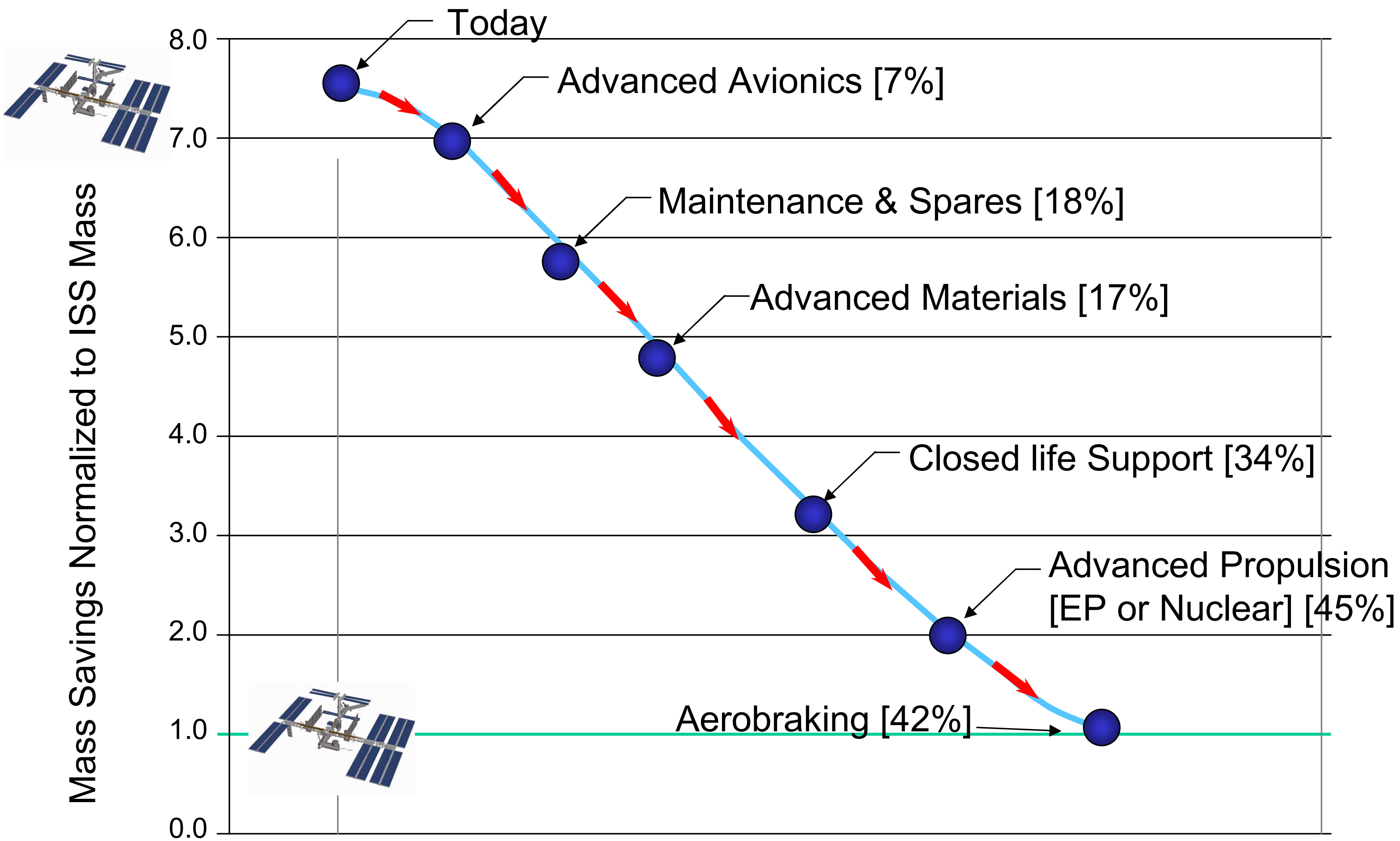
Wastes	Kilograms per person per day	
Gases		**1.0**
Carbon Dioxide	1.00	
Water		**23.7**
Urine	1.50	
Perspiration/respiration	2.28	
Fecal water	0.09	
Shower and hand wash	6.51	
Clothes wash	11.90	
Urine flush	0.50	
Humidity condensate	0.95	
Solids		**0.2**
Urine	0.06	
Feces	0.03	
Perspiration	0.02	
Shower & hand wash	0.01	
Clothes wash	0.08	
TOTAL		**24.9**

Human Life Support System Requirements

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



Mass Cost of Human Mars Mission Using Today's Technologies



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

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

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 administrates 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

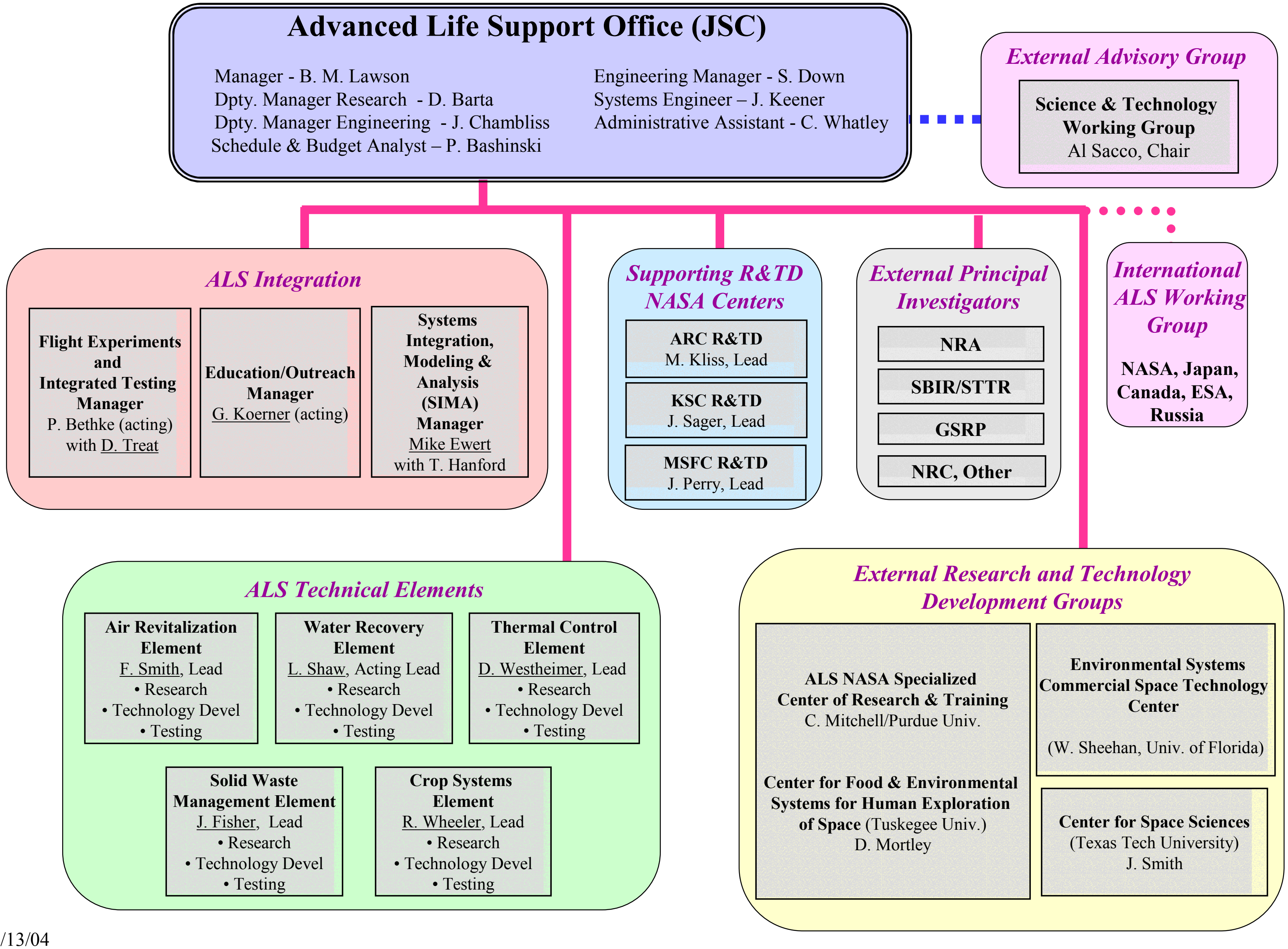
– Funding for tasks is implemented through the most appropriate method.

– 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 Program Element Organization



Advanced Life Support Office (JSC)

Manager - B. M. Lawson
Dpty. Manager Research - D. Barta
Dpty. Manager Engineering - J. Chambliss
Schedule & Budget Analyst – P. Bashinski

Engineering Manager - S. Down
Systems Engineer – J. Keener
Administrative Assistant - C. Whatley

External Advisory Group

Science & Technology Working Group
Al Sacco, Chair

ALS Integration

Flight Experiments and Integrated Testing Manager
P. Bethke (acting)
with D. Treat

Education/Outreach Manager
G. Koerner (acting)

Systems Integration, Modeling & Analysis (SIMA) Manager
Mike Ewert
with T. Hanford

Supporting R&TD NASA Centers

ARC R&TD
M. Kliss, Lead

KSC R&TD
J. Sager, Lead

MSFC R&TD
J. Perry, Lead

External Principal Investigators

NRA

SBIR/STTR

GSRP

NRC, Other

International ALS Working Group

NASA, Japan, Canada, ESA, Russia

ALS Technical Elements

Air Revitalization Element
F. Smith, Lead
- Research
- Technology Devel
- Testing

Water Recovery Element
L. Shaw, Acting Lead
- Research
- Technology Devel
- Testing

Thermal Control Element
D. Westheimer, Lead
- Research
- Technology Devel
- Testing

Solid Waste Management Element
J. Fisher, Lead
- Research
- Technology Devel
- Testing

Crop Systems Element
R. Wheeler, Lead
- Research
- Technology Devel
- Testing

External Research and Technology Development Groups

ALS NASA Specialized Center of Research & Training
C. Mitchell/Purdue Univ.

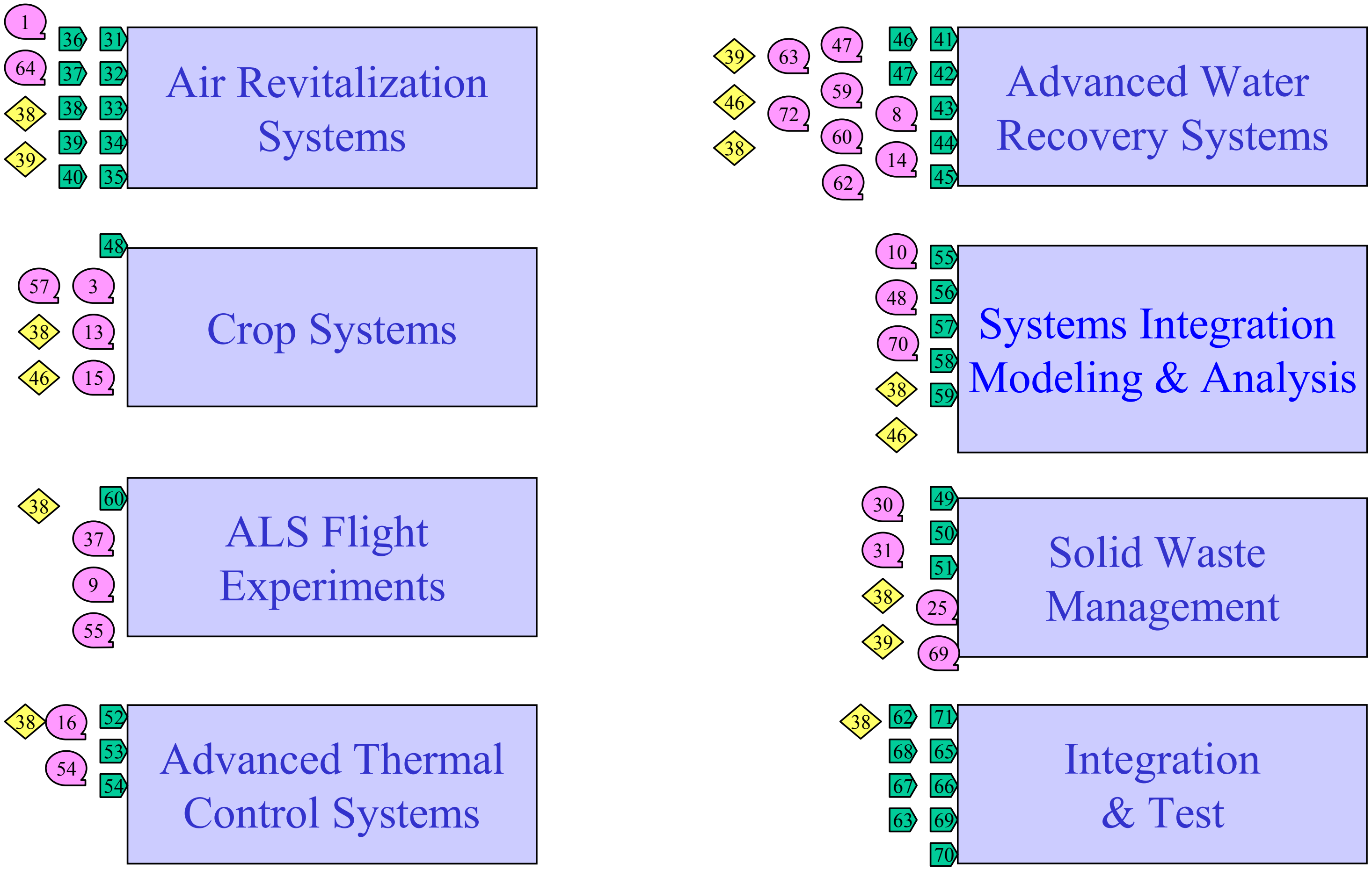
Center for Food & Environmental Systems for Human Exploration of Space (Tuskegee Univ.)
D. Mortley

Environmental Systems Commercial Space Technology Center
(W. Sheehan, Univ. of Florida)

Center for Space Sciences
(Texas Tech University)
J. Smith

4/13/04

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

TDP (39) 🟩

NRA (26) ●

◇

Research Center	Manpower	
	Civil Service	Contractor
JSC (38)	9	19
ARC (39)	5	5
KSC (46)	4	xx

Augmentation Major Products

Air

- Gas Supply (2)
- CO_2 Removal (3)
- Advanced CO_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

	Phase I	Phase II	Phase IIA	Phase III
Duration	15-days	30-days	60-days	91-days
Dates	Completed August '95	Completed July '96	Completed March '97	Completed December '97
Crew Size	1	4	4	4
Technologies	Air revitalization using crops with P/C	Regenerative P/C technologies	ISS life support technologies	Integration of physicochemical & biological technologies
Regeneration	Air	Air & water	Air & water	Air, water, solid waste, food

Lunar Mars Life Support Test Project

Phases III: 91-day, 4-Person Tests

Biological Water Recovery System

Carbon Dioxide Removal System

Carbon Dioxide Reduction System

Oxygen Generation System

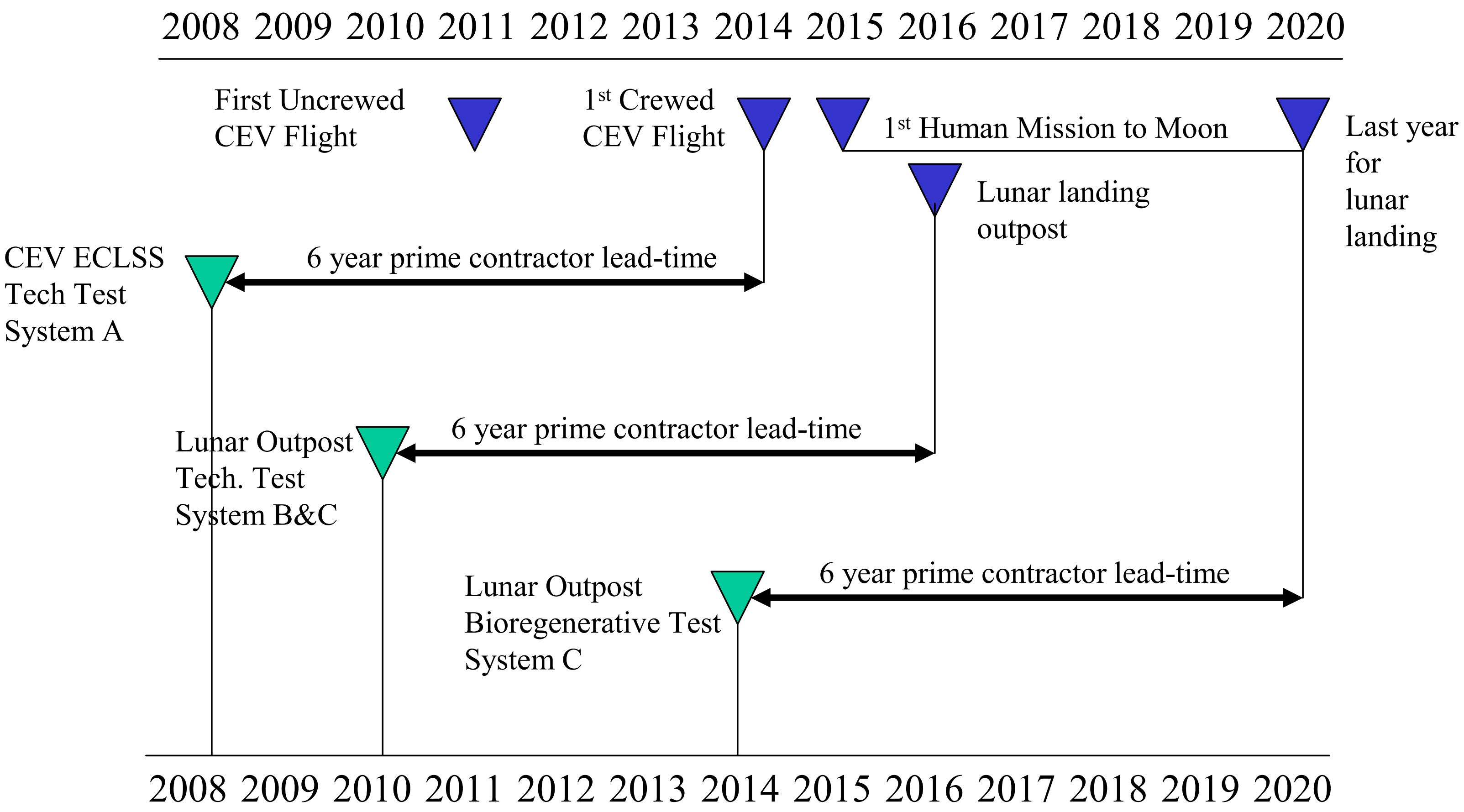
Control Room

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

VPGC Wheat Harvest

Solid Waste Incinerator

ALS Integrated Test Plans Support the Exploration Timeline



2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

First Uncrewed CEV Flight

1st Crewed CEV Flight

1st Human Mission to Moon

Last year for lunar landing

Lunar landing outpost

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

2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

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.

Parameters for Human Life Support Across Mission Scenarios

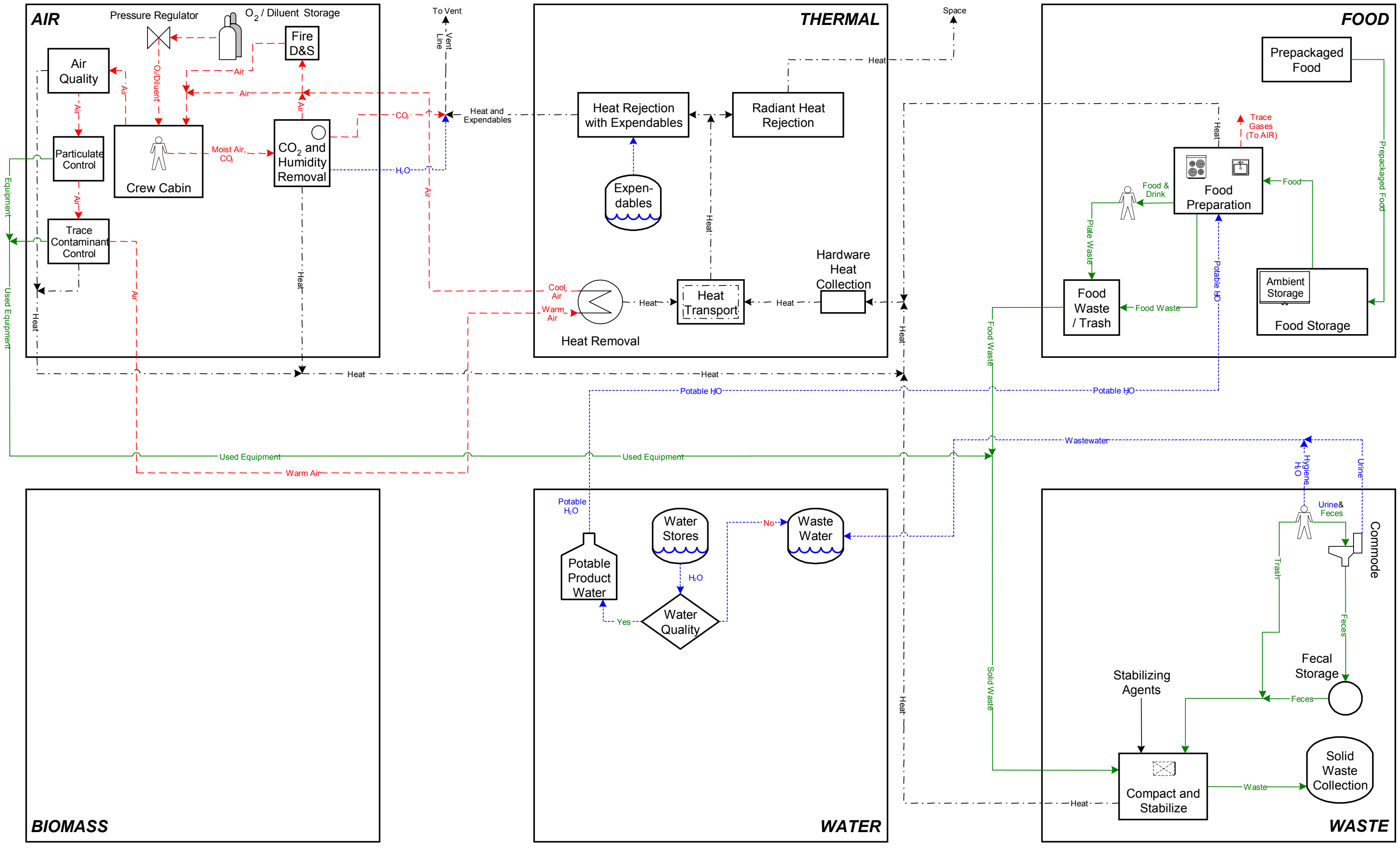
	Lunar Transit Vehicle (LTV)	Lunar Landing Vehicle (LLV)	Lunar Outpost (LO)	Mars Transit Vehicle (MTV)	Mars Landing Vehicle (MLV)	Mars Habitat (MH)	Pressurized Rover (PR)
Duration (Human Tended)	7 – 14 days (Roundtrip)	1 – 5 days	1 – 18 months	12 – 24 months (Roundtrip)	1 – 45 days	17 – 20 months	1 – 7 days
Air Revitalization	Open	Open	Closed	Closed	Open	Closed ISRU	Open
Water Recovery	Collection and Storage	Collection and Storage	Closed ISRU	Closed	Collection and Storage	Closed ISRU	Collection and Storage
Waste Management	Stored	Stored	Volume Reduction Mineralization Stabilization Resource Recovery	Volume Reduction Stabilization De-watering	Volume Reduction Stabilization	Volume Reduction Mineralization Stabilization Resource Recovery	Stored
Food Systems	Conventional Stored	Conventional Stored	Conventional Stored with Fresh Food Augmentation	Extended Shelf Life with Fresh Food Augmentation	Extended Shelf Life	Extended Shelf Life with Fresh Food Augmentation	Extended Shelf Life
Thermal Systems	LP-BR	LP-DR	HP-DR	HP-DR	LP-BR	HP-DR	LP-BR
System Configuration	System A	System A	System C	System B	System A	System C	System A

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

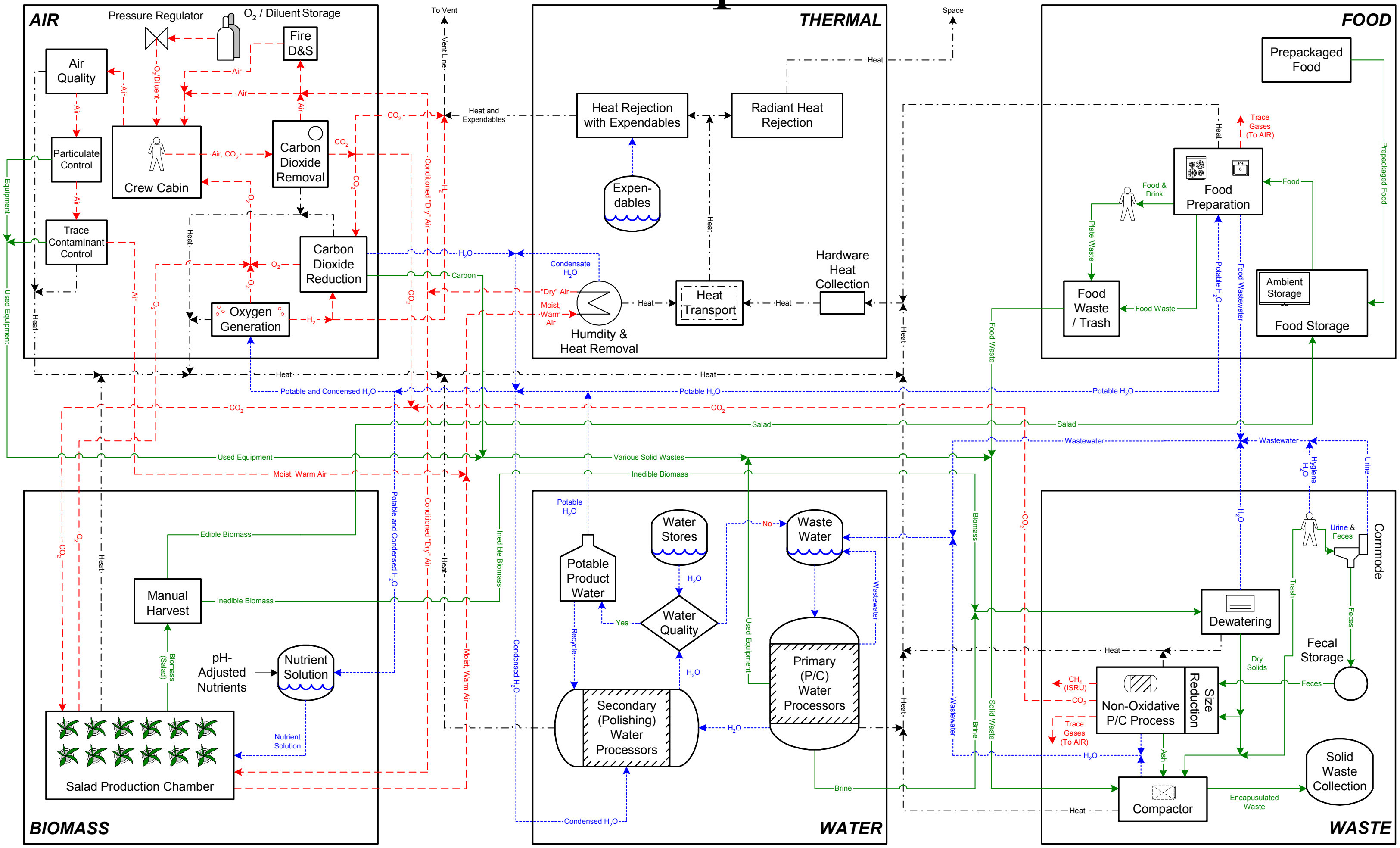
LP – Low Power HP – High Power
BR – Body Mounted Radiator
DR – Deployable Radiator

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

Crew Exploration Vehicle Schematic Group A

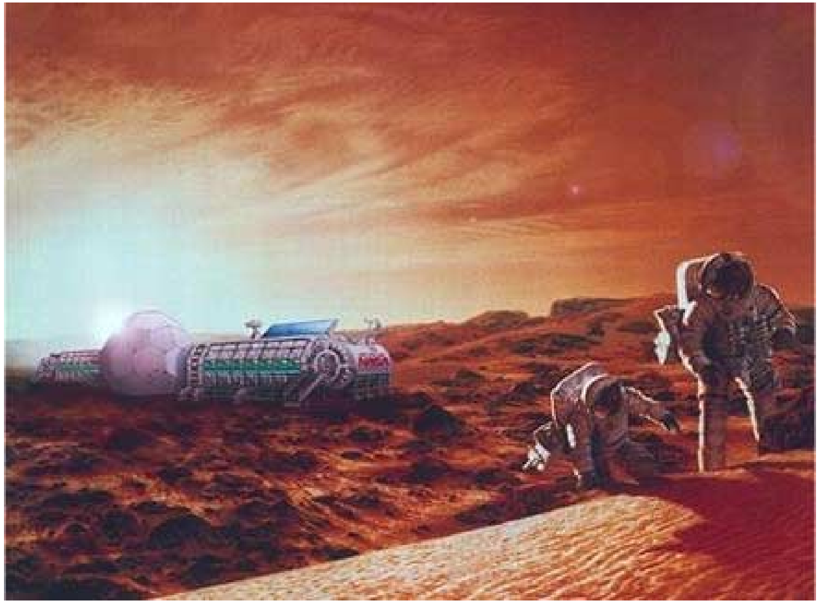


Mars Transit Vehicle Schematic
Group B



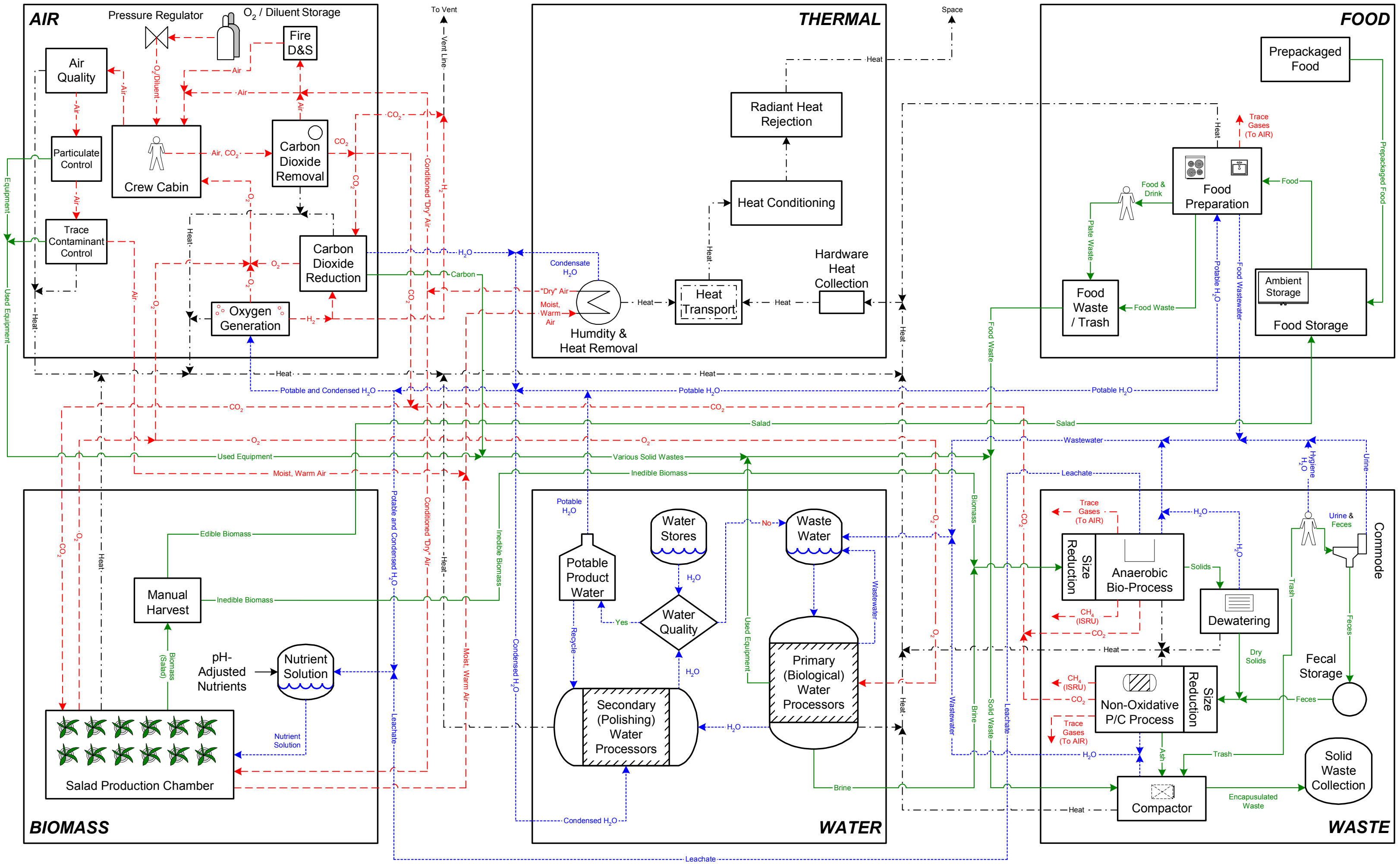
Mars Mission Concepts

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

Surface Habitat Schematic
Group C



ALS Projects Showing Promise for Exploration

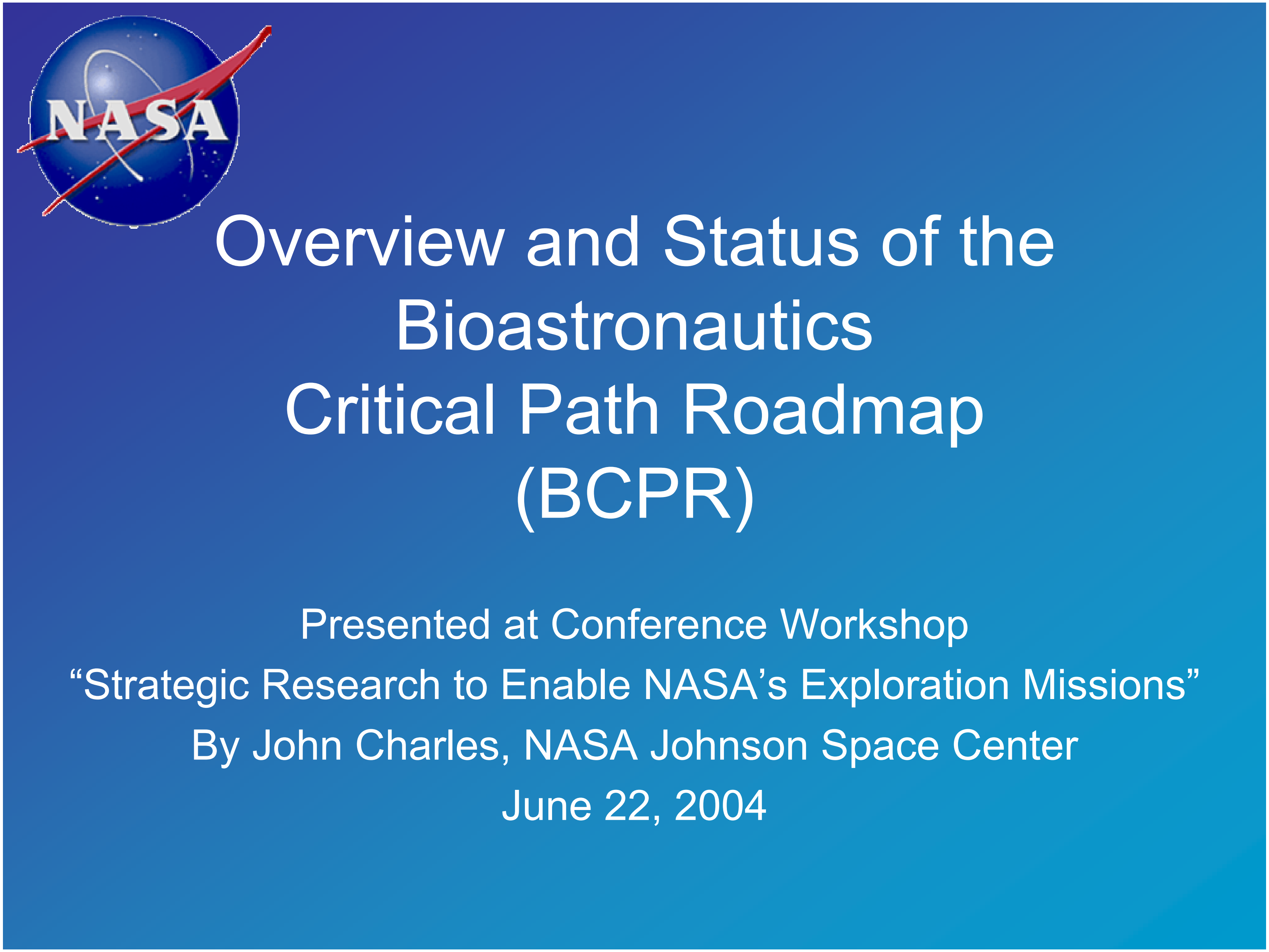
- ALS Proposed Projects show great promise to meet exploration goals
  - Sabatier- CO2 reduction
  - Advanced Trace Contaminant Control
  - Advanced CO2 removal and reduction system
  - Biological Water Processor
  - Rotating Reverse Osmosis
  - Vapor Phase Catalytic Ammonia Removal System
  - Cascade 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.
- ES-CSTC – Environmental Systems Commercial Space Technology Center. University of Florida
- 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

- *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 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

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
- BCPR configuration control by Critical Path Control Panel (CPCP) (2000-2003, 2005ff)
- 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

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

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

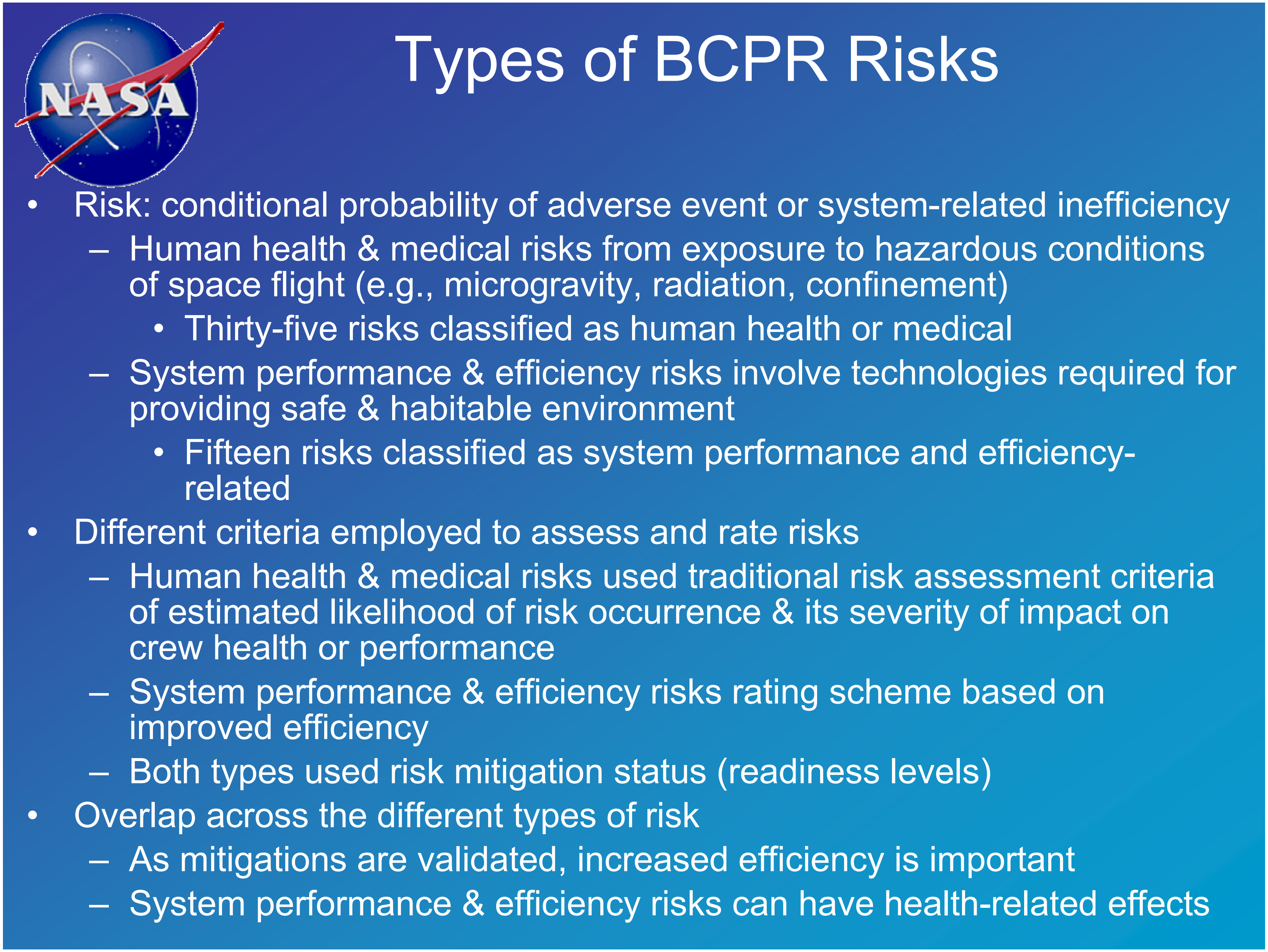
2016: End ISS validation of countermeasures

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

Human Health and Countermeasures Behavioral Health & Performance Radiation Health	Risk Assessment & Acceptability
	Mechanisms and Processes
	Countermeasure Strategies
	Medical Diagnosis & Treatment
Autonomous Medical Care	Prevention (selection and countermeasures)
	Monitoring
	Diagnosis
	Treatment
	Informatics (cross cutting)
Advanced Human Support Technology	Research Requirements/Specifications
	Design Tools
	Technologies
	Operations and Training

Risk Mitigation Status

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

TRL Definition	TRL/CRL Score	CRL Definition	CRL category	
Basic principles observed	1	Phenomenon observed and reported Problem defined	Basic research	
Technology concept and/or application formulated	2	Hypothesis formed, preliminary studies to define parameters. Demonstrate feasibility		
Analytical and experimental critical function/proof-of-concept	3	Validated hypothesis. Understanding of scientific processes underlying problem		Research to prove feasibility
Component and/or breadboard validation in lab	4	Formulation of countermeasures concept based on understanding of phenomenon	Countermeasure development	
Component and/or breadboard in relevant environment	5	Proof of concept testing and initial demonstration of feasibility and efficacy		
System/subsystem model or prototype demonstration in relevant environment	6	Laboratory/clinical testing of potential countermeasure in subjects to demonstrate efficacy of concept		
Subsystem prototype in a space environment	7	Evaluation with human subjects in controlled laboratory simulating operational space flight environment		Countermeasure demonstration
System completed and flight qualified through demonstration	8	Validation with human subjects in actual operational space flight to demonstrate efficacy and operational feasibility		
System flight proven through mission operations	9	Countermeasure fully flight-tested and ready for implementation	Countermeasure operations	

Defining Levels of Accepted Risk

- Tolerance limits (desirable operating bands) for <u>human system</u>
  - 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)

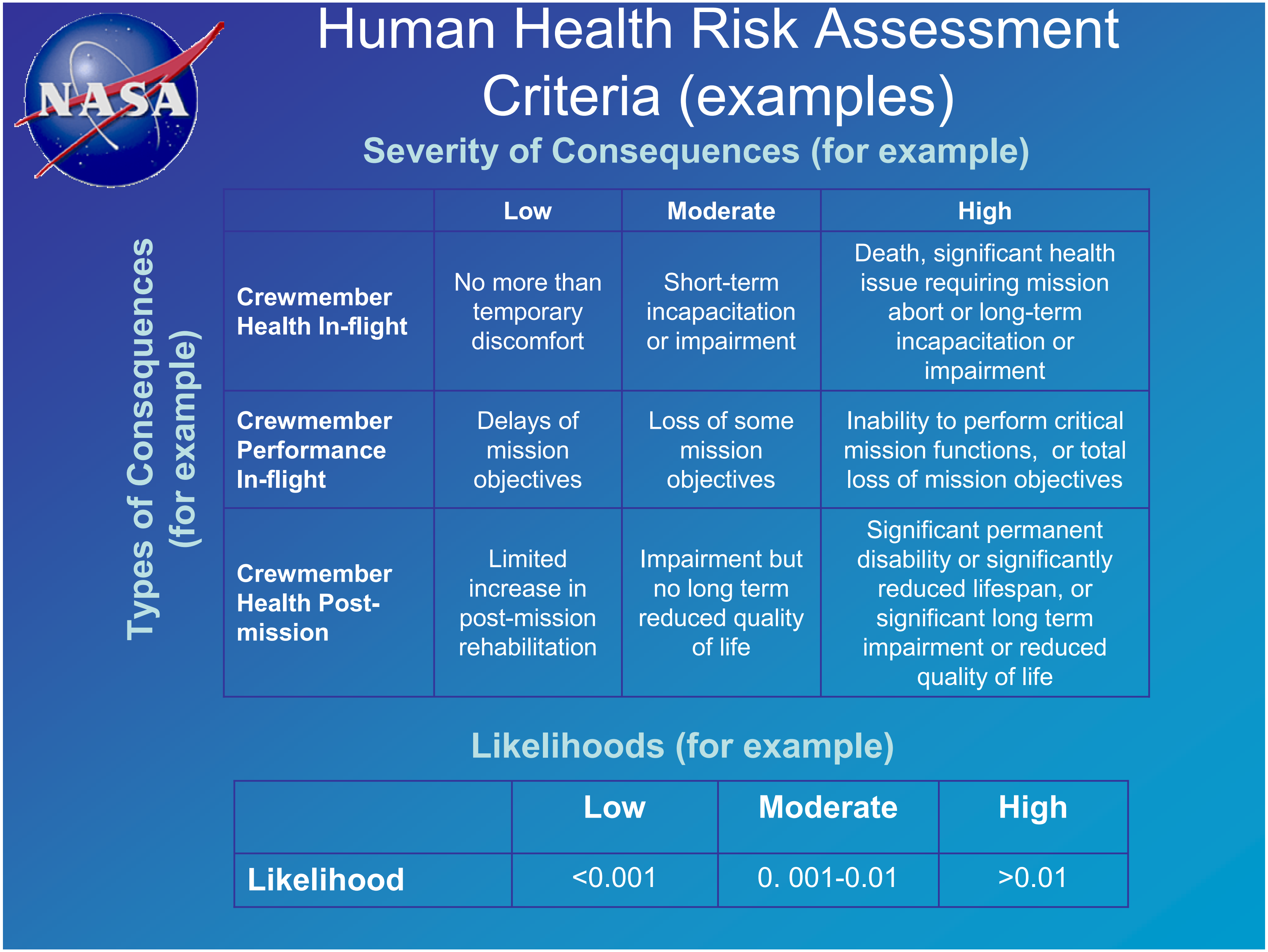
- **Statement of Work**
  - Conduct an independent review of the content and processes currently used for communication, assessment, and implementation of the BCPR with respect to clinical issues and bioastronautics research for the missions contemplated in the President's exploration initiative
    - 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)

Types of Consequences (for example)

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

Likelihoods (for example)

	Low	Moderate	High
Likelihood	<0.001	0. 001-0.01	>0.01

A Recent Risk Rating Exercise

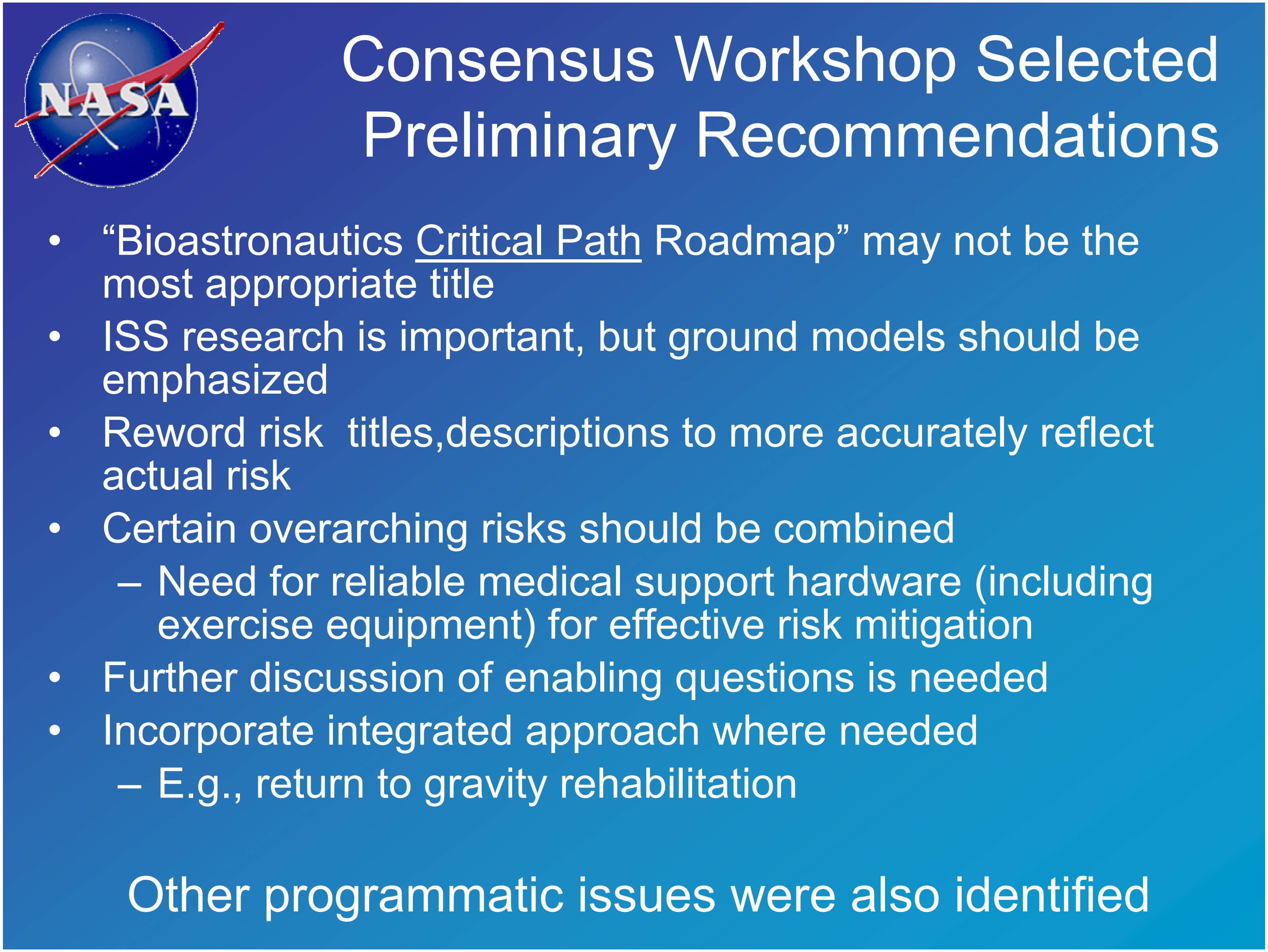
- Consensus workshop participants: representatives of Astronauts, Space Medicine and Researchers
- Participants answered two questions for each BCPR risk :
  - If the US committed to sending humans to Mars today how worried would you be?
    - Scale 0 (not worried) to 10 (very worried)
  - How important 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!)

Office of Biological and Physical Research

Overview

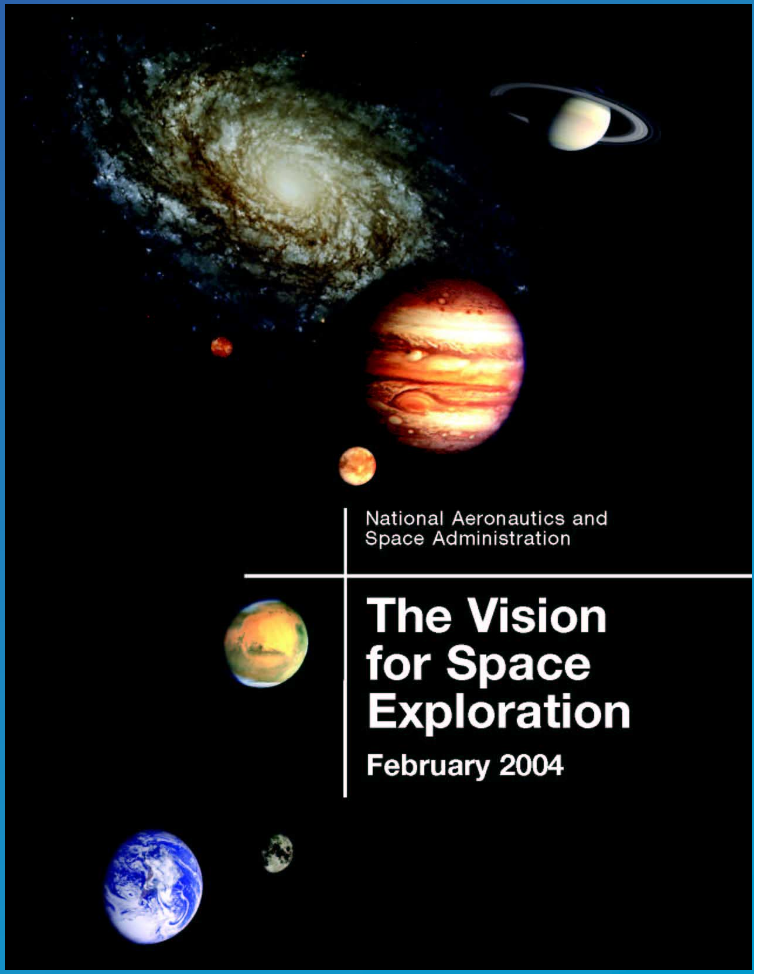
Transitioning to The Vision for Space Exploration

June 2004

Strategic Directives Guiding the Human Support Technology Program

- Vision for Space Exploration (February 2004)
- President’s Commission on Implementation of the United States Space Exploration Policy Report:”*A Journey to Inspire, Innovate,and Discover”*

  (June 2004)

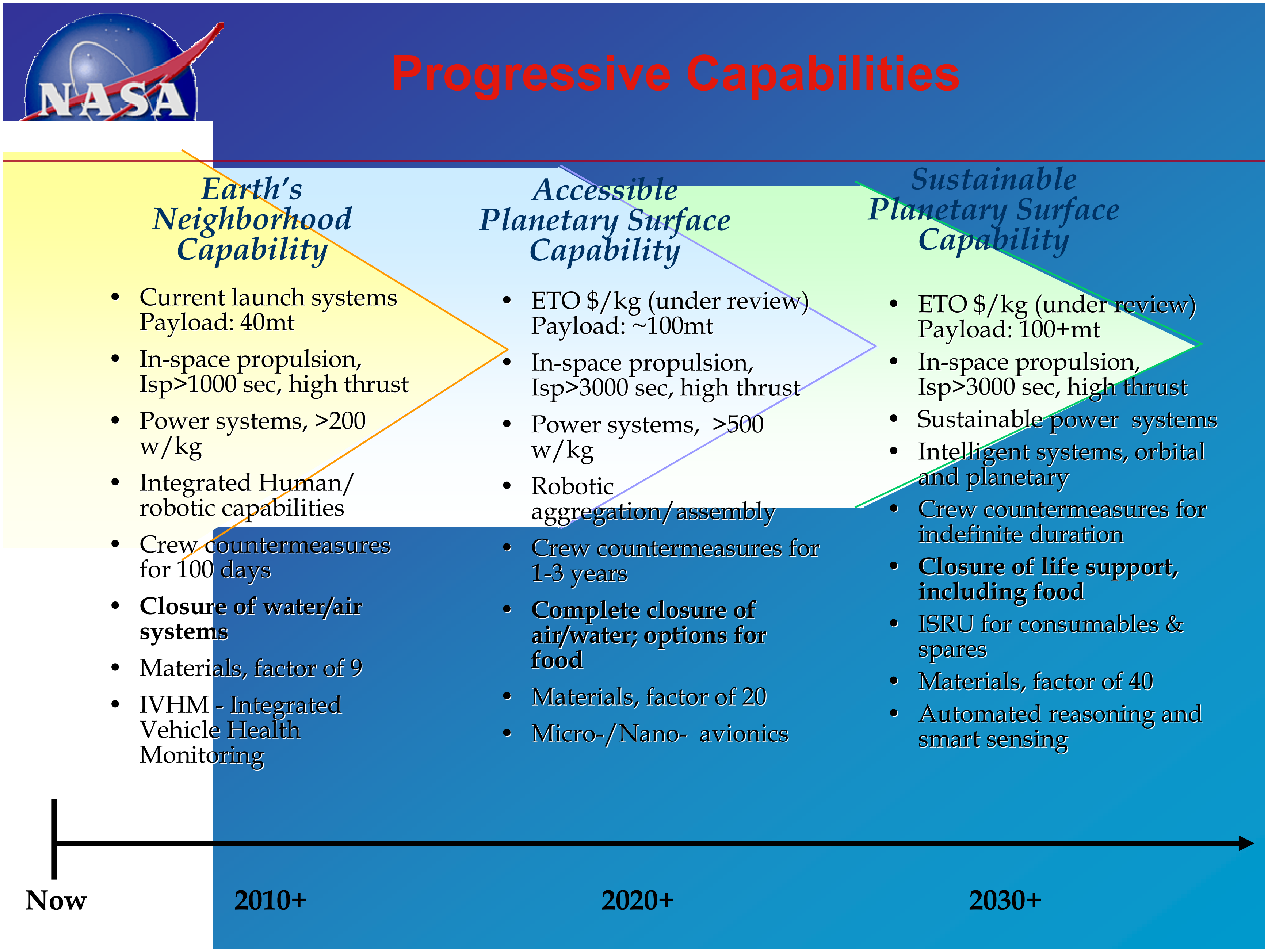


National Aeronautics and
Space Administration

**The 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

A Journey to Inspire, Innovate, and Discover

- 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*

Risk Mitigation Status
Technology Readiness Level (TRL)
and Countermeasures Readiness Level (CRL)

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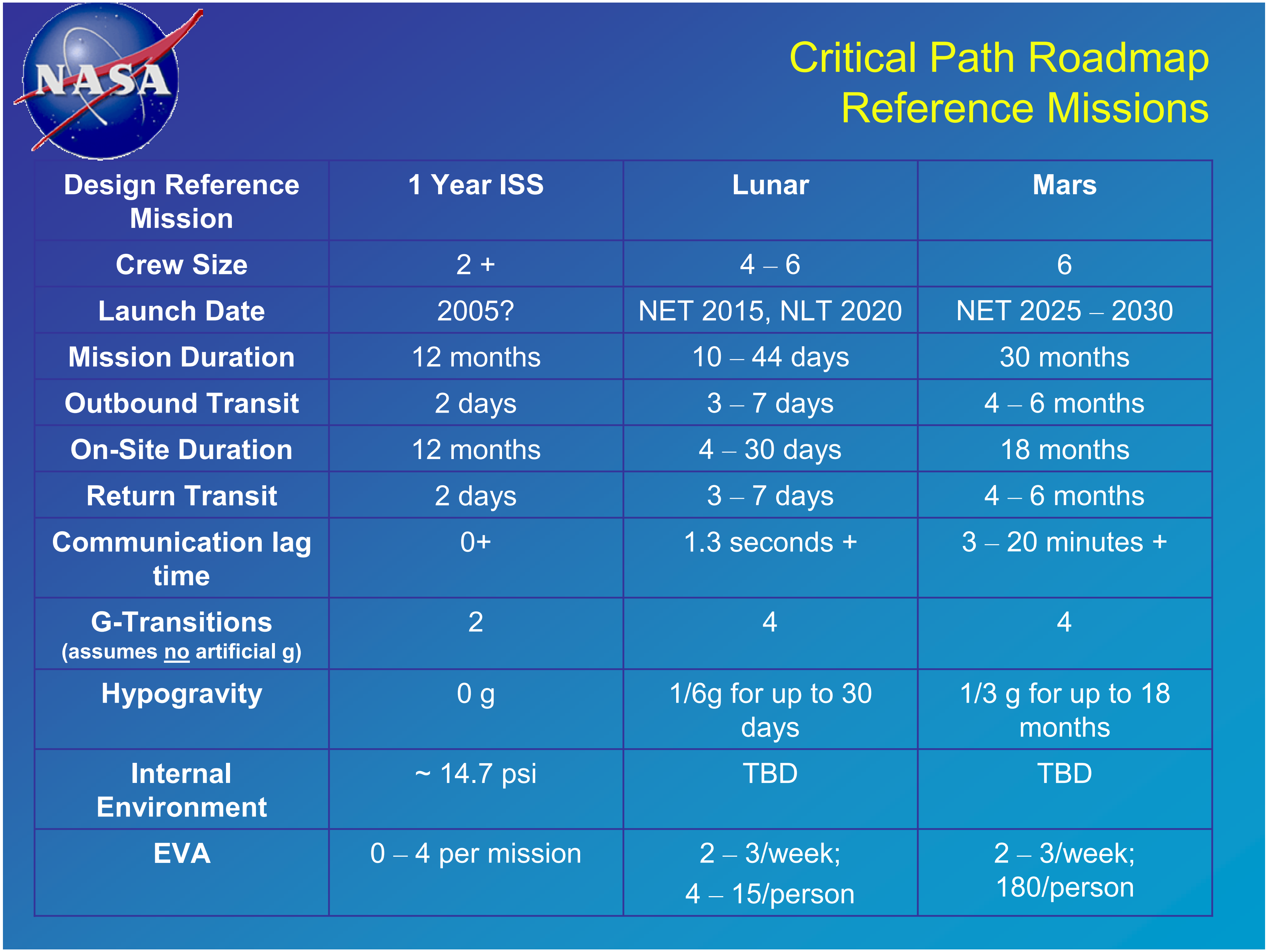
System flight proven through mission operations	9	Countermeasure fully flight-tested and ready for implementation	Countermeasure operations	

Biological And Physical Research Enterprise
Aligning With The Vision For U.S. Space Exploration

- 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



Critical Path Roadmap Reference Missions

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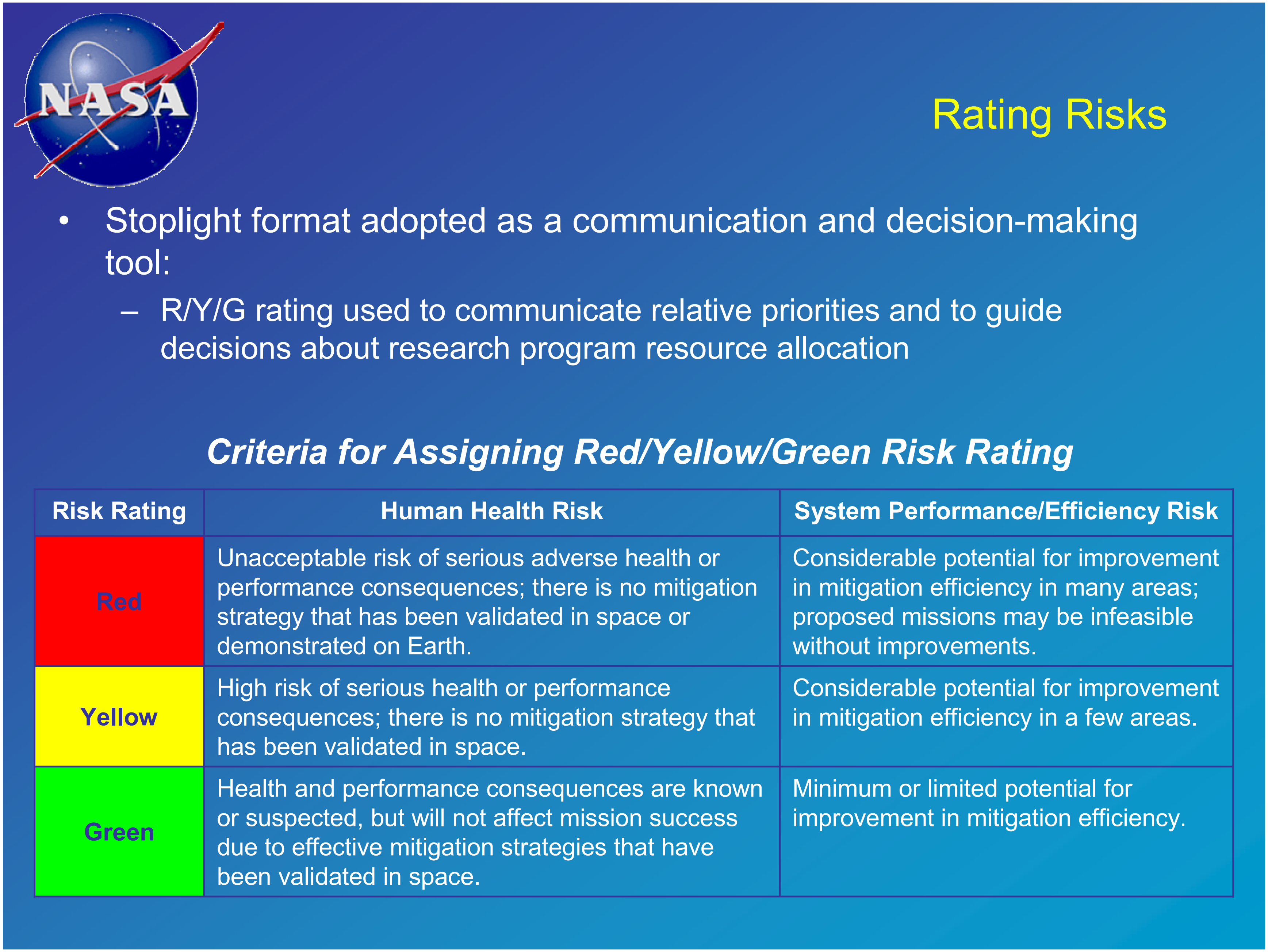
Internal Environment	~ 14.7 psi	TBD	TBD
EVA	0 – 4 per mission	2 – 3/week; 4 – 15/person	2 – 3/week; 180/person

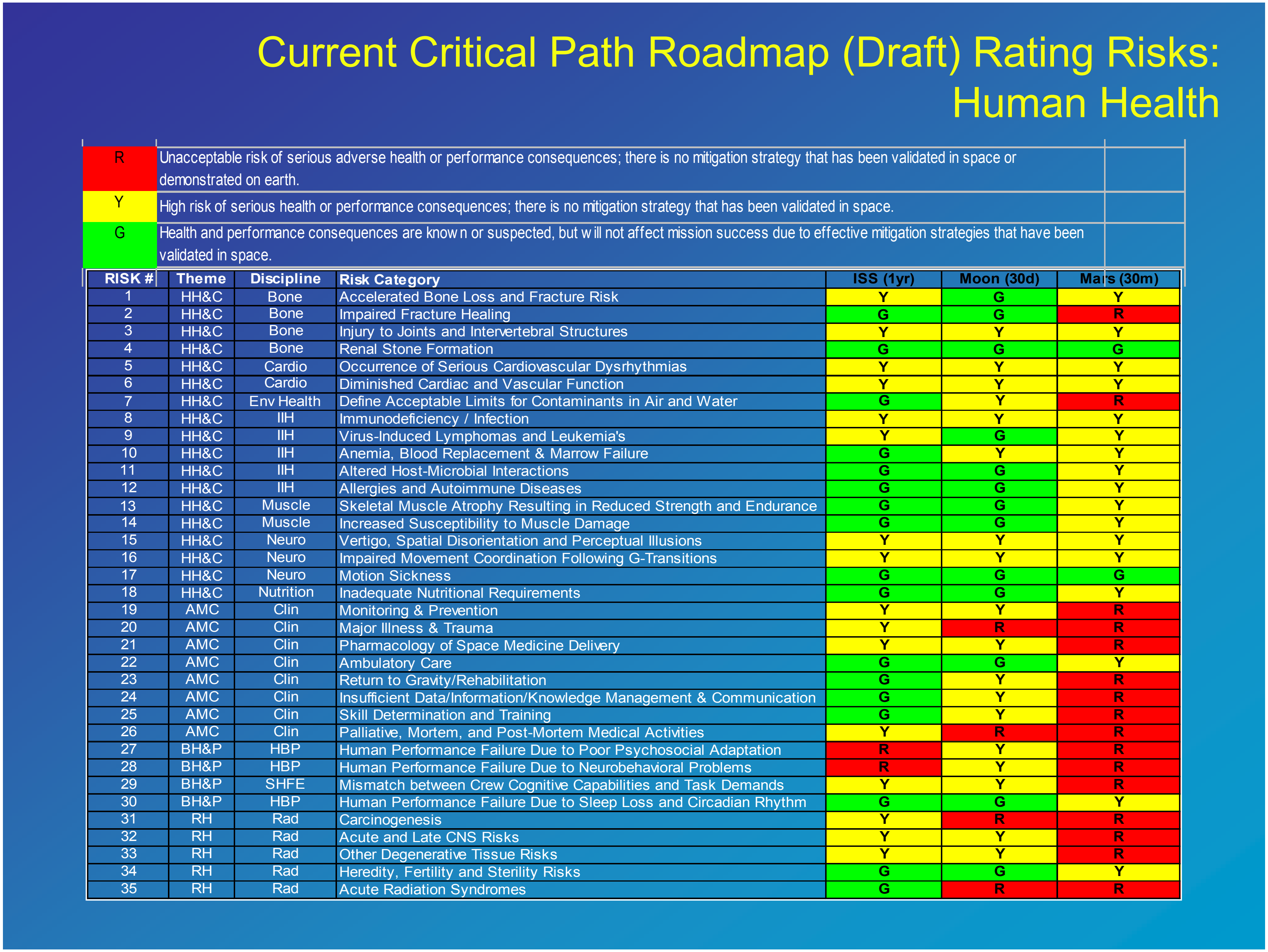


Rating Risks

- 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

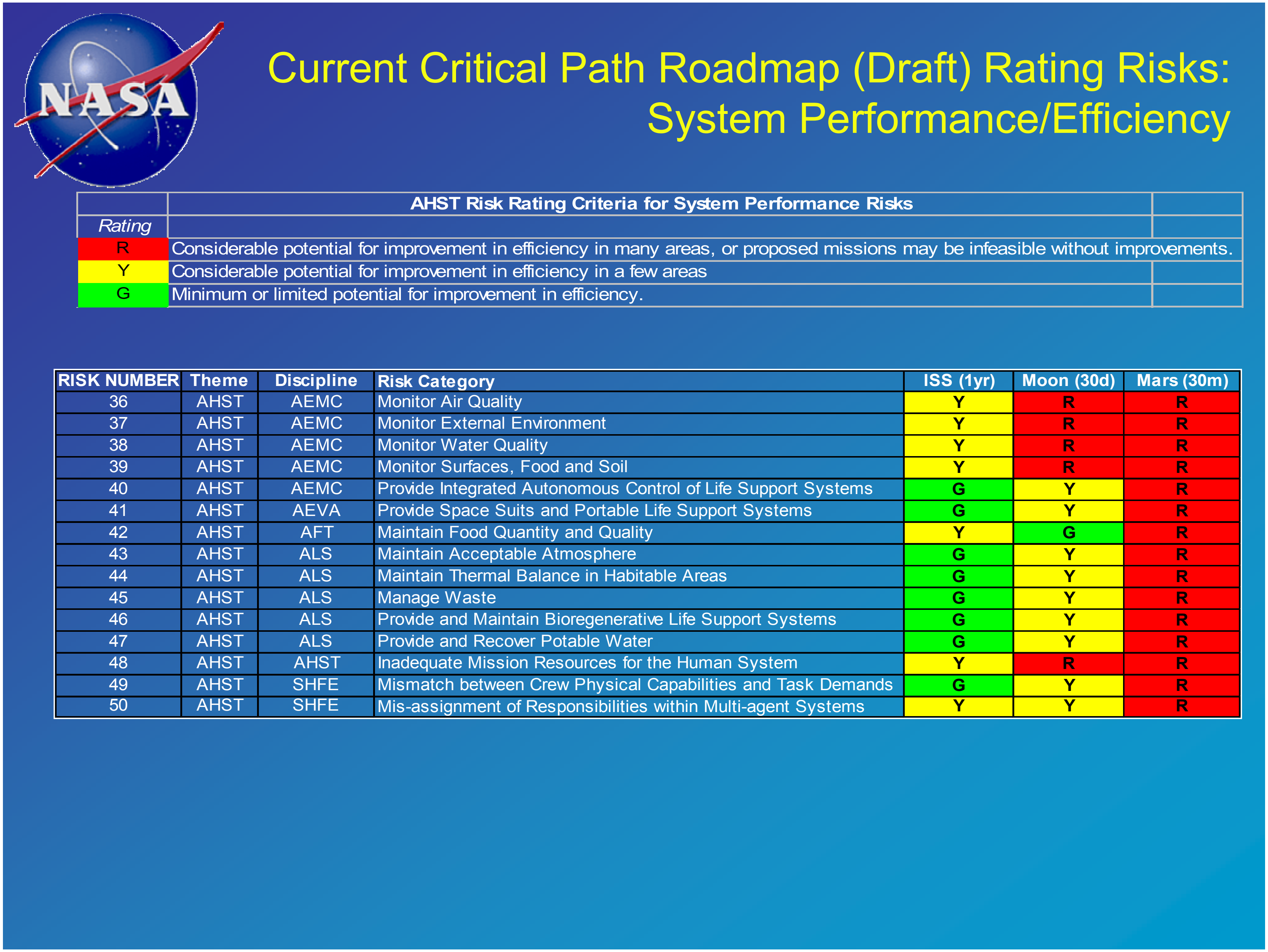
Risk Rating	Human Health Risk	System Performance/Efficiency Risk
Red	Unacceptable risk of serious adverse health or performance consequences; there is no mitigation strategy that has been validated in space or demonstrated on Earth.	Considerable potential for improvement in mitigation efficiency in many areas; proposed missions may be infeasible without improvements.
Yellow	High risk of serious health or performance consequences; there is no mitigation strategy that has been validated in space.	Considerable potential for improvement in mitigation efficiency in a few areas.
Green	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.	Minimum or limited potential for improvement in mitigation efficiency.



Current Critical Path Roadmap (Draft) Rating Risks: Human Health

R	Unacceptable risk of serious adverse health or performance consequences; there is no mitigation strategy that has been validated in space or demonstrated on earth.
Y	High risk of serious health or performance consequences; there is no mitigation strategy that has been validated in space.
G	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.

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



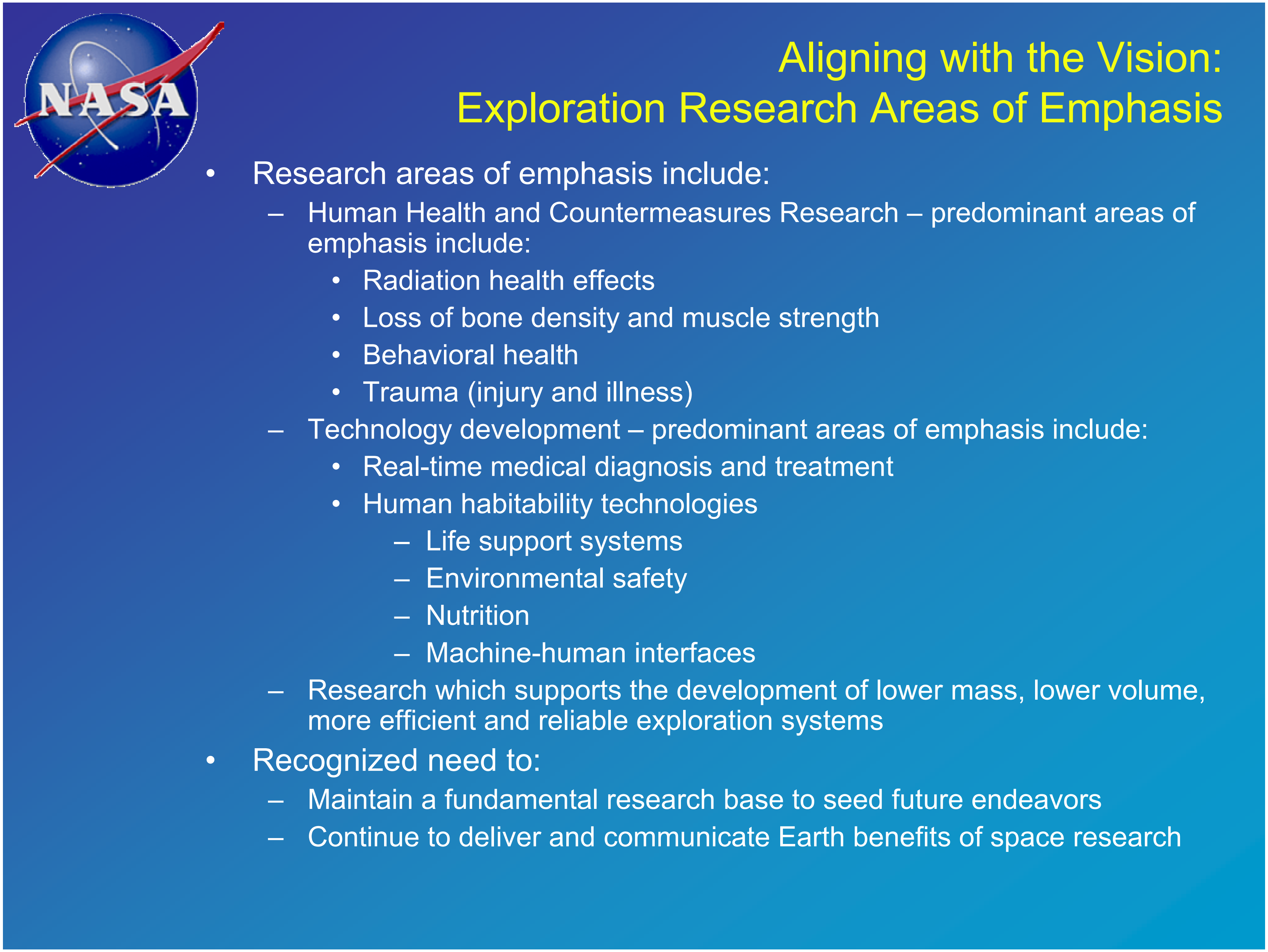
Current Critical Path Roadmap (Draft) Rating Risks: System Performance/Efficiency

	AHST Risk Rating Criteria for System Performance Risks
Rating	
R	Considerable potential for improvement in efficiency in many areas, or proposed missions may be infeasible without improvements.
Y	Considerable potential for improvement in efficiency in a few areas
G	Minimum or limited potential for improvement in efficiency.

RISK NUMBER	Theme	Discipline	Risk Category	ISS (1yr)	Moon (30d)	Mars (30m)
36	AHST	AEMC	Monitor Air Quality	Y	R	R
37	AHST	AEMC	Monitor External Environment	Y	R	R
38	AHST	AEMC	Monitor Water Quality	Y	R	R
39	AHST	AEMC	Monitor Surfaces, Food and Soil	Y	R	R
40	AHST	AEMC	Provide Integrated Autonomous Control of Life Support Systems	G	Y	R
41	AHST	AEVA	Provide Space Suits and Portable Life Support Systems	G	Y	R
42	AHST	AFT	Maintain Food Quantity and Quality	Y	G	R
43	AHST	ALS	Maintain Acceptable Atmosphere	G	Y	R
44	AHST	ALS	Maintain Thermal Balance in Habitable Areas	G	Y	R
45	AHST	ALS	Manage Waste	G	Y	R
46	AHST	ALS	Provide and Maintain Bioregenerative Life Support Systems	G	Y	R
47	AHST	ALS	Provide and Recover Potable Water	G	Y	R
48	AHST	AHST	Inadequate Mission Resources for the Human System	Y	R	R
49	AHST	SHFE	Mismatch between Crew Physical Capabilities and Task Demands	G	Y	R
50	AHST	SHFE	Mis-assignment of Responsibilities within Multi-agent Systems	Y	Y	R

Biological And Physical Research Enterprise Efforts to Align With Vision For U.S. Space Exploration

- 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 on-going 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)

ISS – Human Support Systems Research, Development, and Demonstration

- 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

ISS – Human Support Systems Research, Development, and Demonstration

- 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

Susan E. D'Andrea Ph.D.*, Michael W. Kahelin B.S.
Department of Biomedical Engineering, The Cleveland Clinic Foundation, Cleveland, OH

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

INTRODUCTION

FIGURE 1: Dual Track Treadmill

While the neurovestibular system is capable of adapting to altered environments such as microgravity, the adaptive state achieved in space in 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.

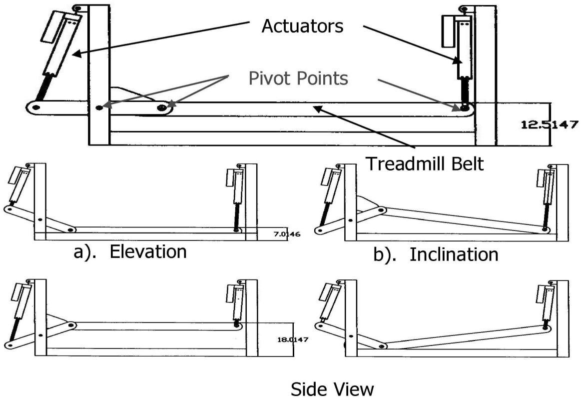


Figure 2: Treadmill Schematic

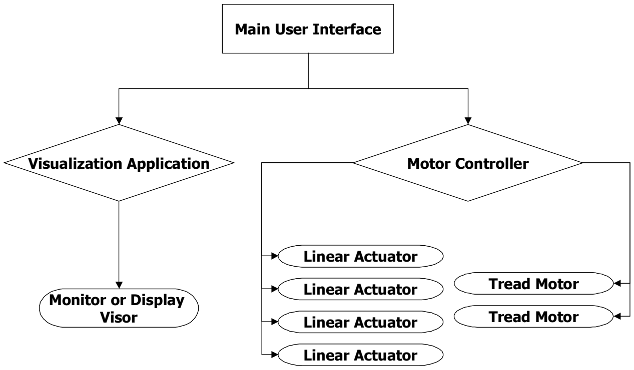


Figure 3: System Overview

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

1. Bloomberg, *et al.*, 1997. Journal of Vestibular Research, Vol. 7, Nos 2/3, pp 161-177.
2. Oman, C.M *et al.*, 1996. Journal of Applied Physiology, Vol. 81, No. 1, pp. 69-81.

ACKNOWLEDGEMENTS

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*Susan E. D'Andrea, Ph.D.
Department of Biomedical Engineering/ND20
The Cleveland Clinic Foundation
9500 Euclid Avenue
Cleveland, OH 44195

Phone: 216.444..5347
Fax: 216.444.9198
Email: dandreas@bme.ri.ccf.org

Conference-Workshop on Strategic Research to Enable
NASA’s Exploration Missions

Cleveland, Ohio, June 22-23, 2004

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

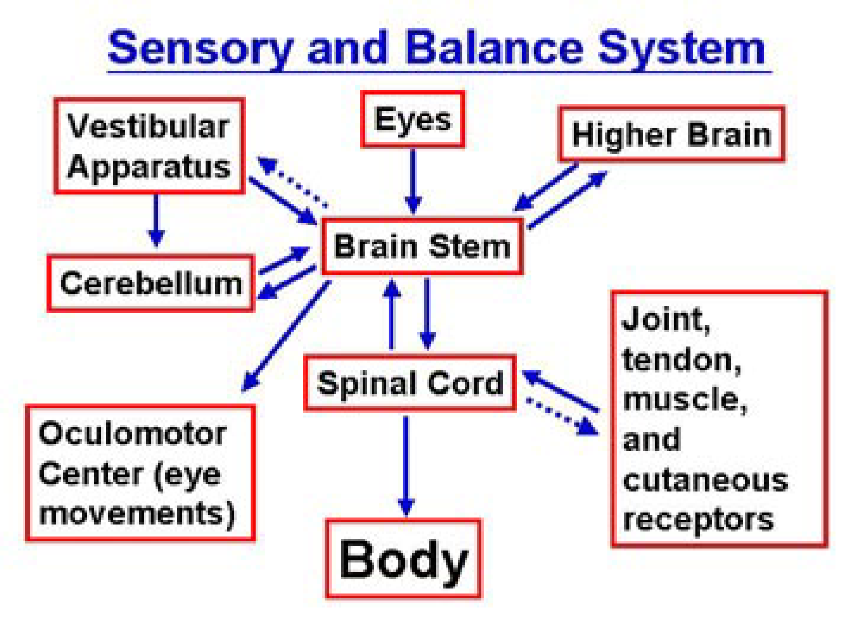
- Space motion sickness, visual reorientation illusions, inversion illusions
- Post flight modifications to posture, balance, locomotion, head-eye coordination

Visual Reorientation Illusions

Inversion Illusions

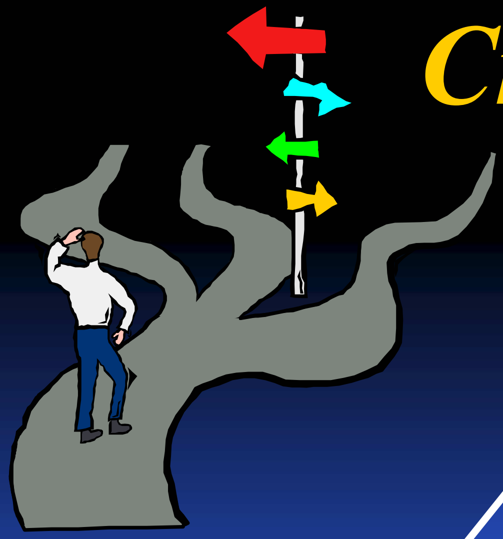
Challenging the Neurovestibular System

- 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.



Sensory and Balance System

Critical Path Roadmap



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

🟥

🟦

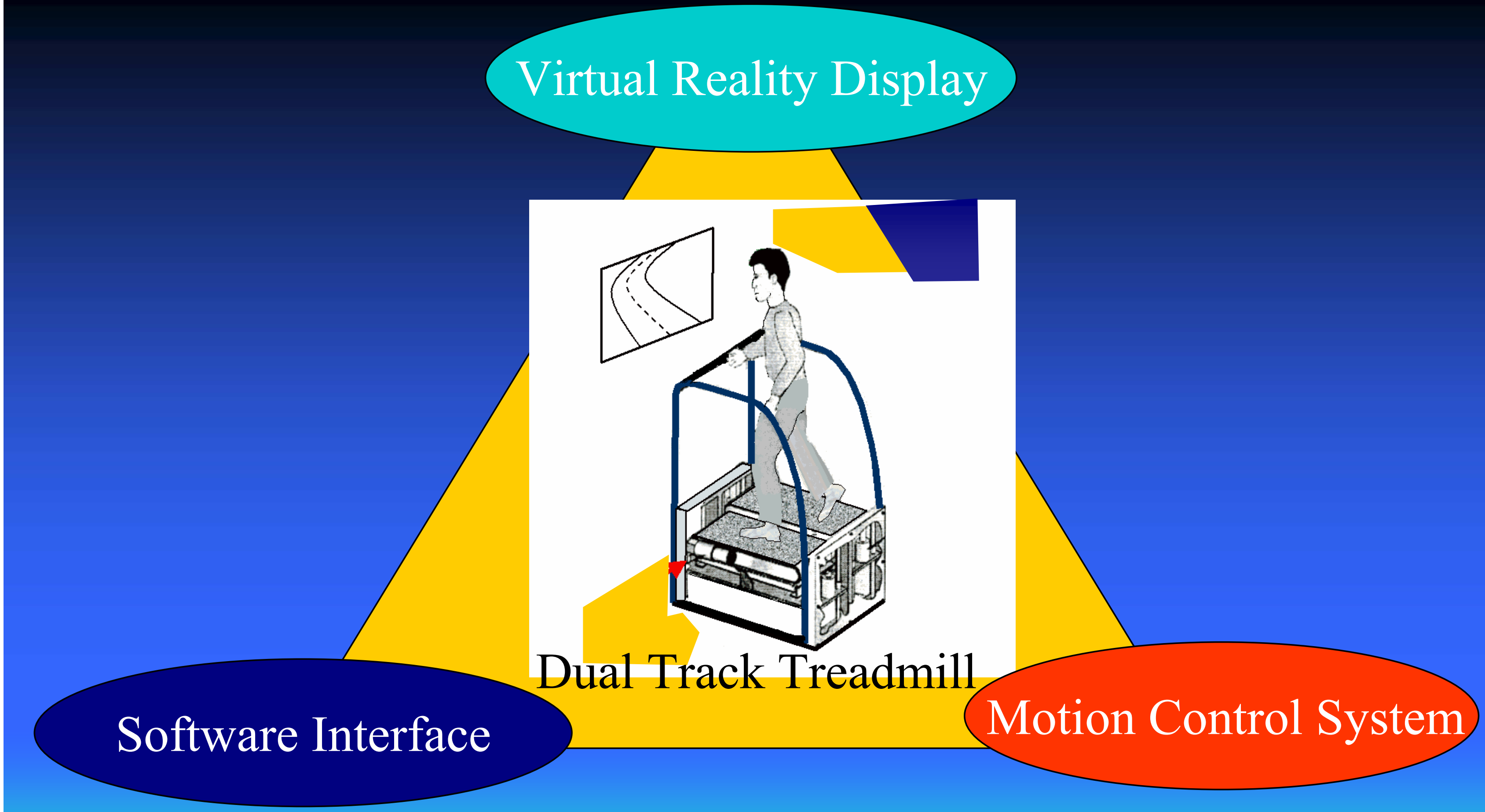
🟨

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



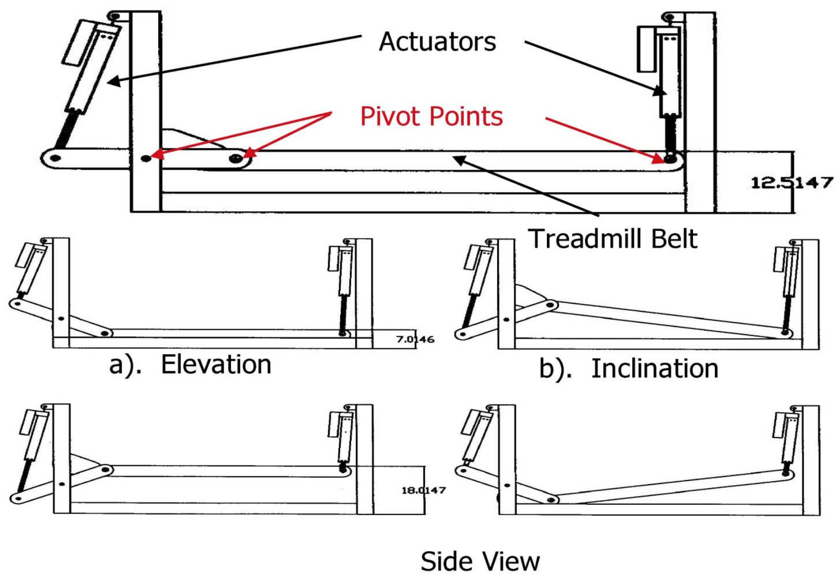
Virtual Reality Display

Dual Track Treadmill

Software Interface

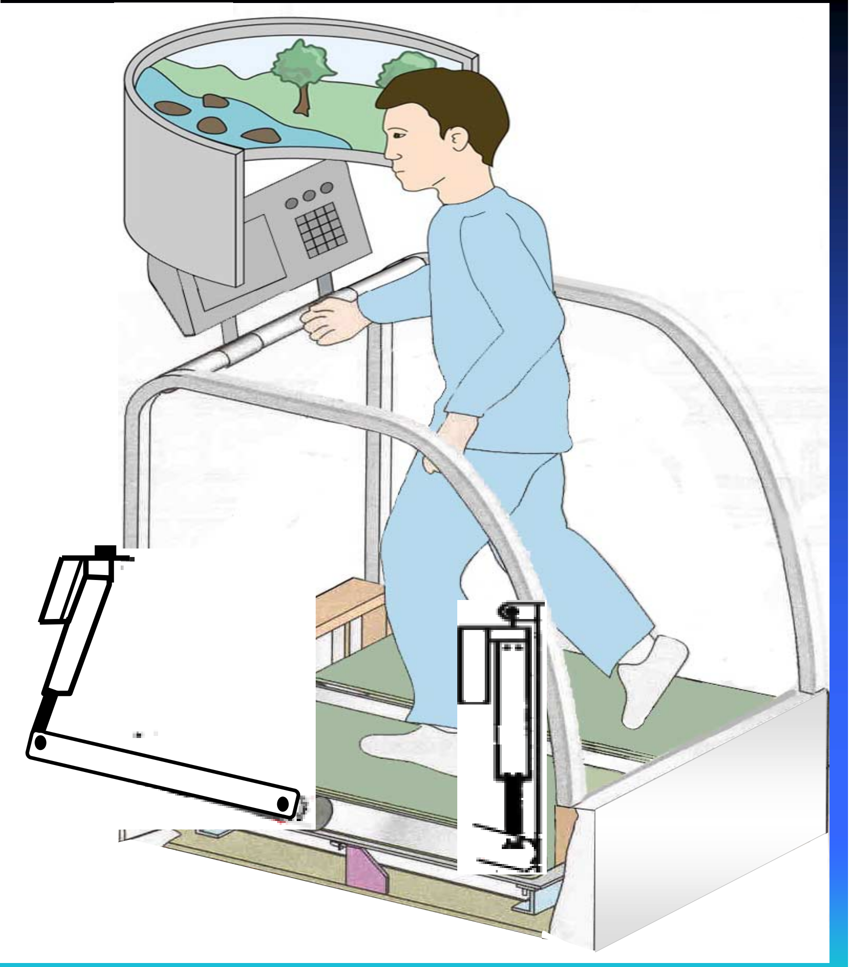
Motion Control System

Dual Track Treadmill



Side View

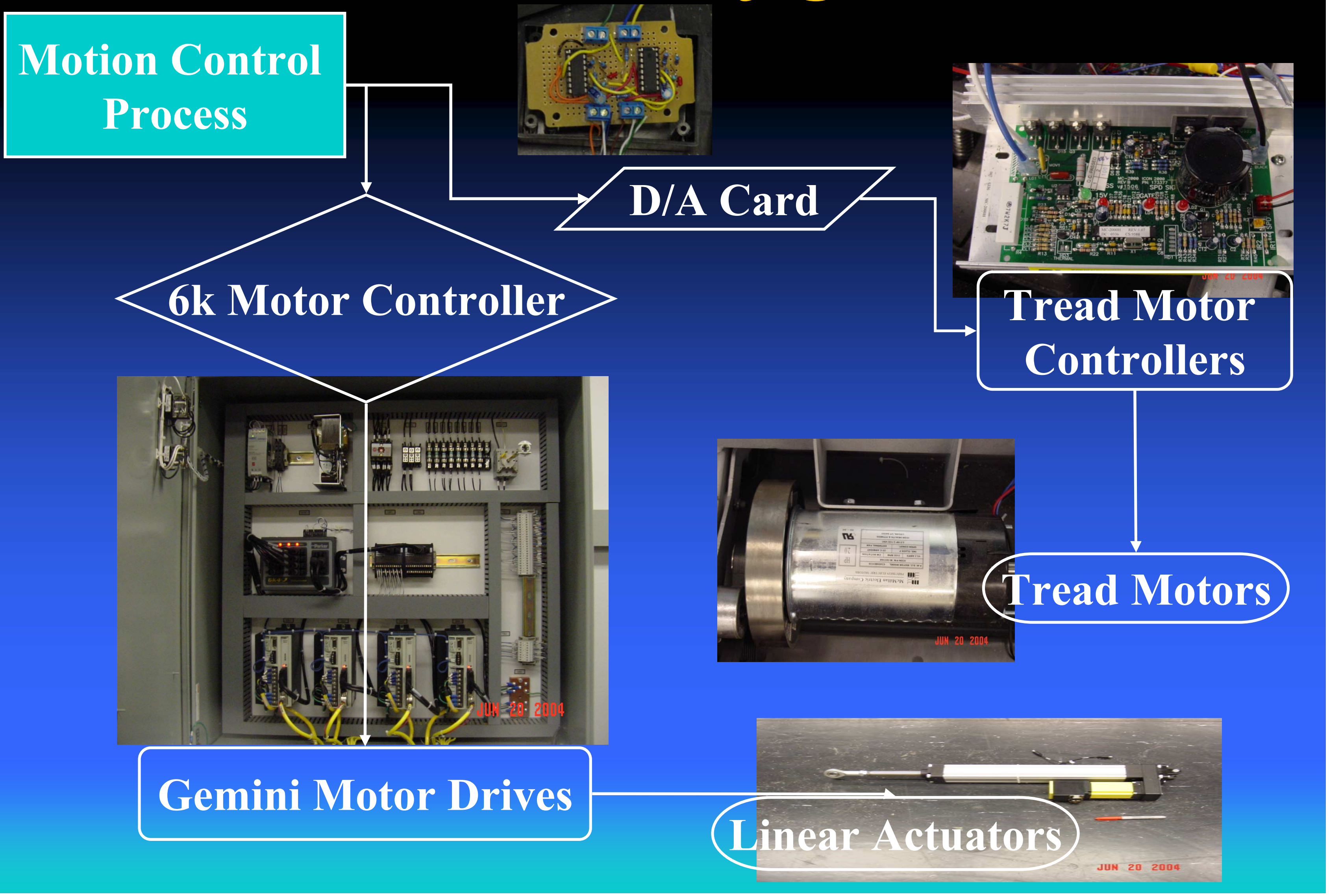
- Independently operated tracks
    - Speed
        - Curves
    - Elevation
        - Stairs
        - Rough terrain
    - Inclination
        - Hills



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.

Hardware Configuration



Motion Control Process

D/A Card

6k Motor Controller

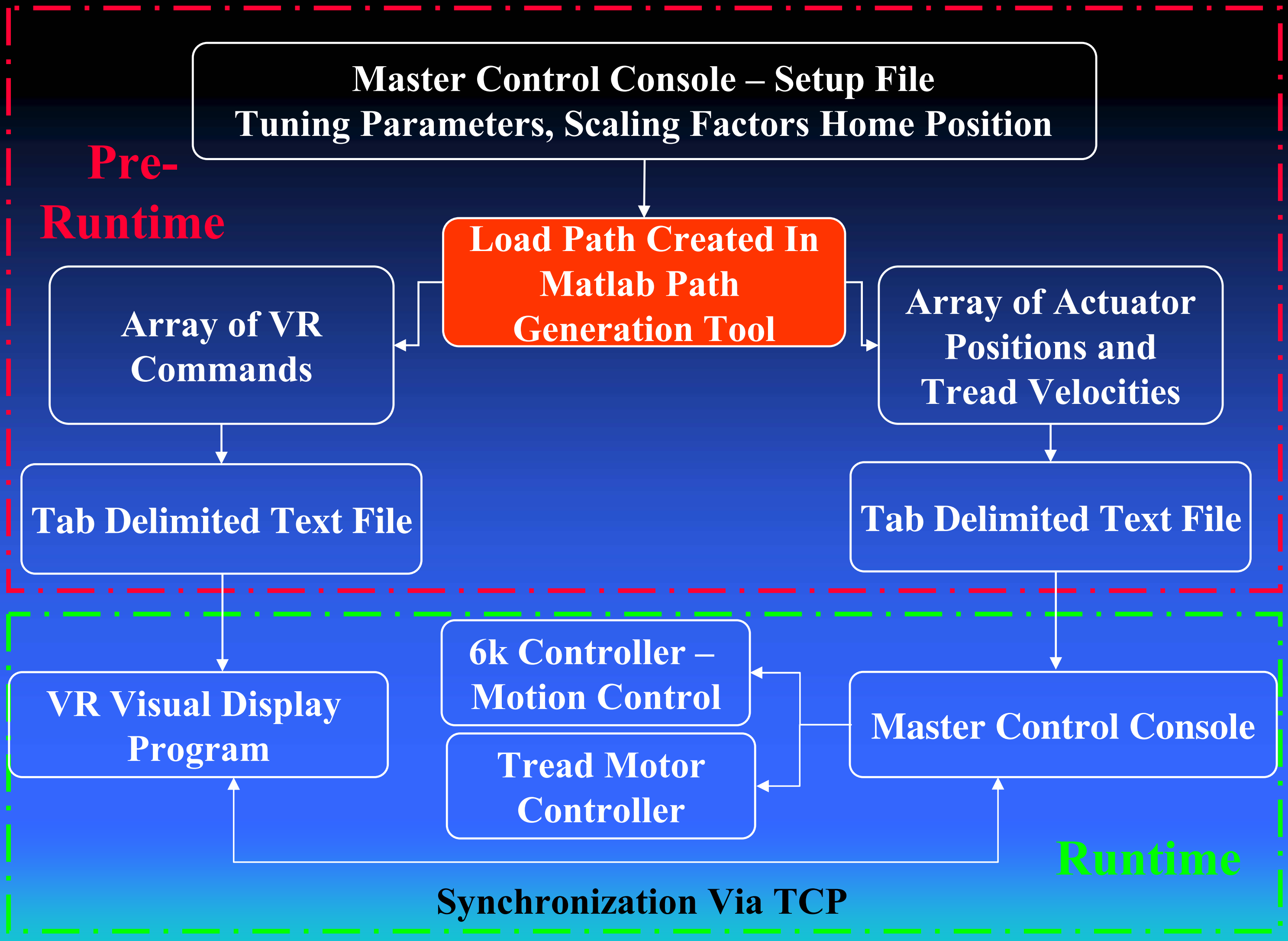
Tread Motor Controllers

Tread Motors

Gemini Motor Drives

Linear Actuators

Software Overview



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

Pre-Runtime

Load Path Created In Matlab Path Generation Tool

Array of VR Commands

Array of Actuator Positions and Tread Velocities

Tab Delimited Text File

Tab Delimited Text File

VR Visual Display Program

6k Controller – Motion Control

Tread Motor Controller

Master Control Console

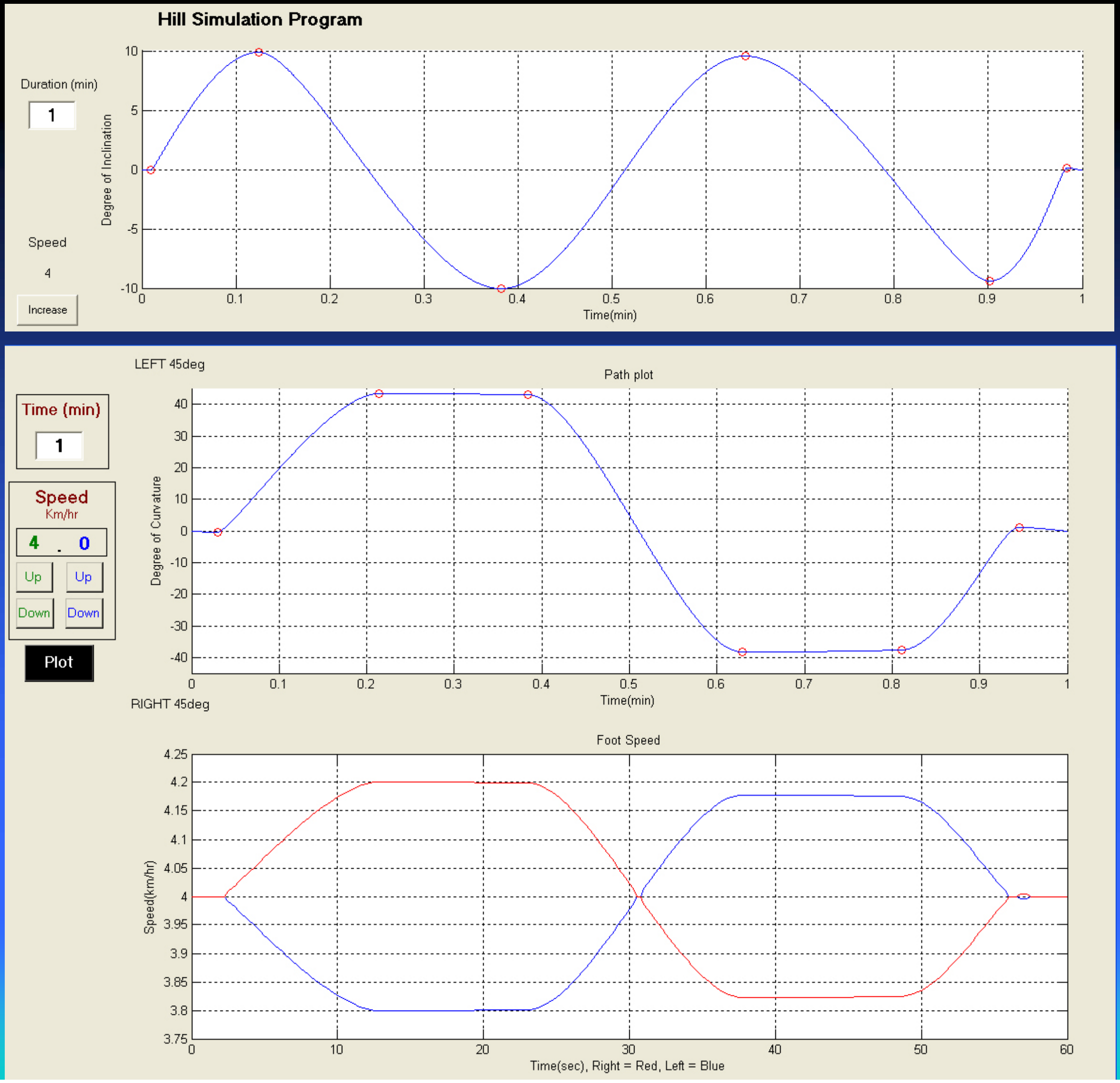
Runtime

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: 4

LEFT 45deg

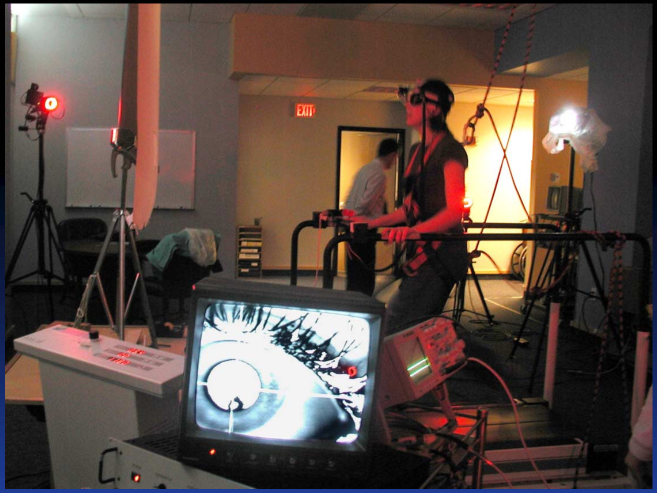
Time (min): 1

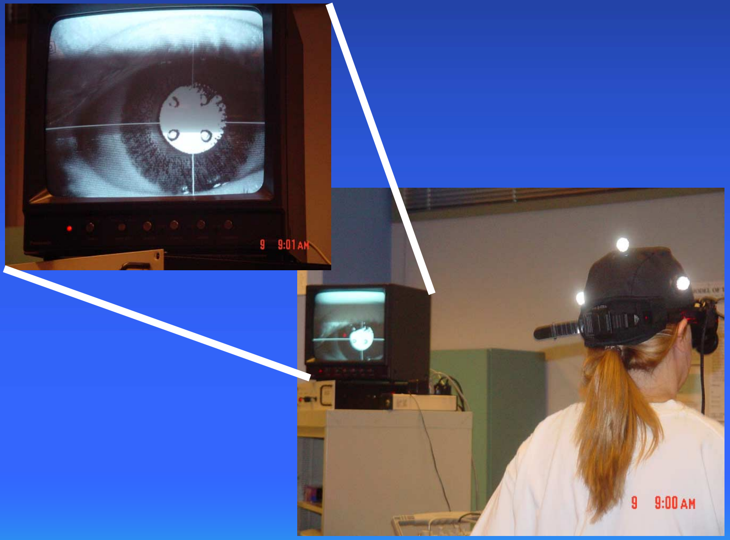
Speed Km/hr: 4 . 0

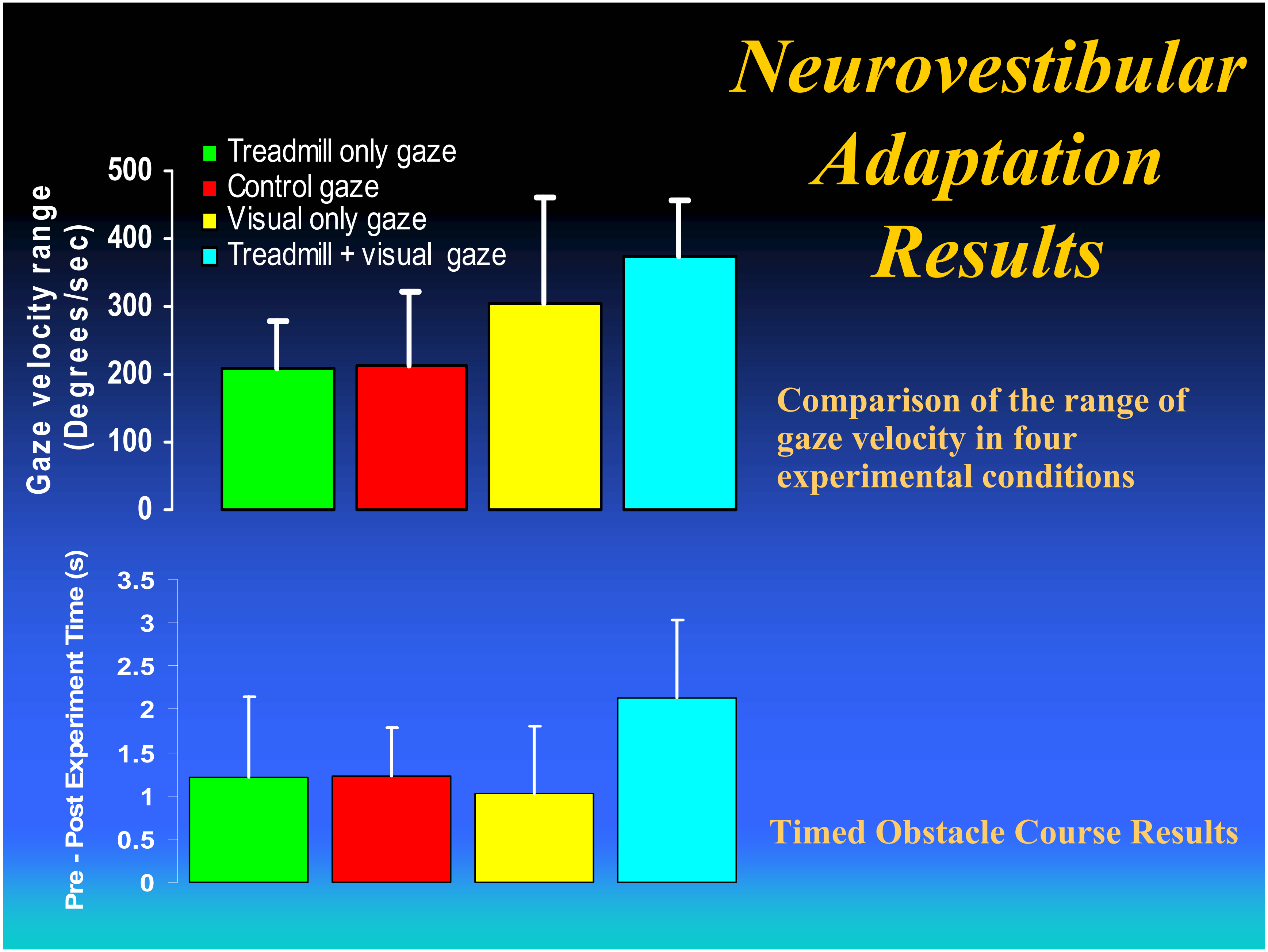
RIGHT 45deg

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
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- Ari Levine
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- Brian Sauer

NUCLEATE BOILING HEAT TRANSFER UNDER MICROGRAVITY CONDITIONS - POOL AND FLOW BOILING

Vijay K. Dhir
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 separtors,

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.

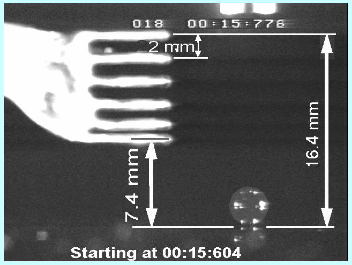
APPROACH

- 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

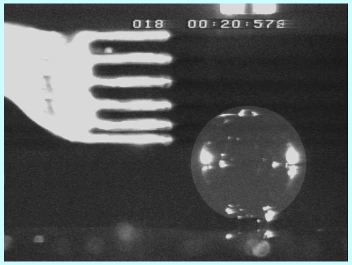
EXPERIMENTS IN THE LOW GRAVITY ENVIRONMENT OF THE KC-135 AIRCRAFT

POOL NUCLEATE BOILING

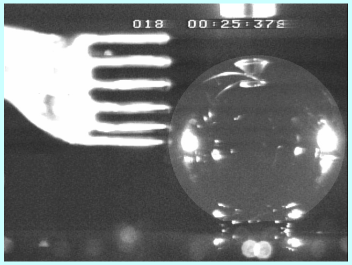
Bubble Growth – Lift off Cycle



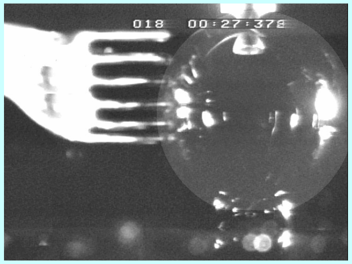
t = 0.17 s



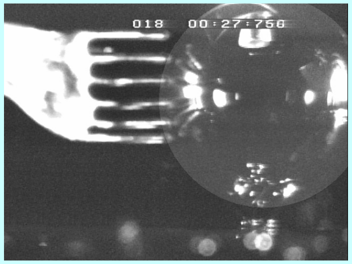
t = 4.97 s



t = 9.77 s (Max. base)



t = 11.77 s

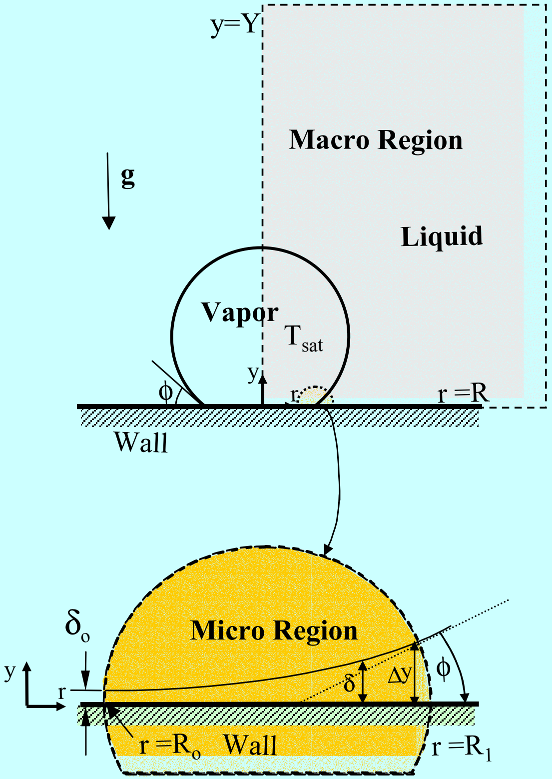


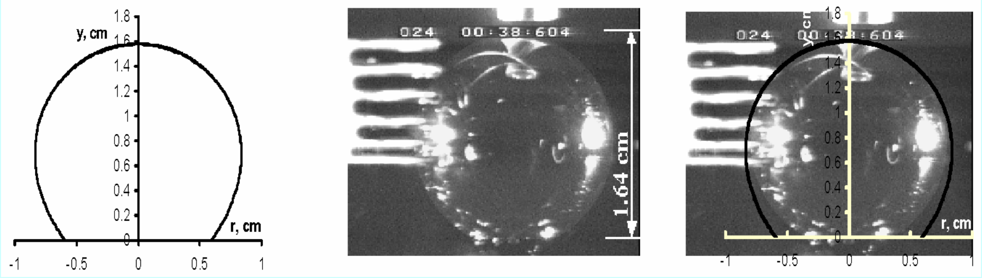
t = 12.15 s (Departure)

$$\Delta T_{sub} = 0.3\ ^{o}C,\ \Delta T_{w} = 4.2\ ^{o}C,\ g_{z} = 0.02\ g/g_{e}$$

POOL NUCLEATE BOILING (contd.)

Single Bubble – Numerical Simulations

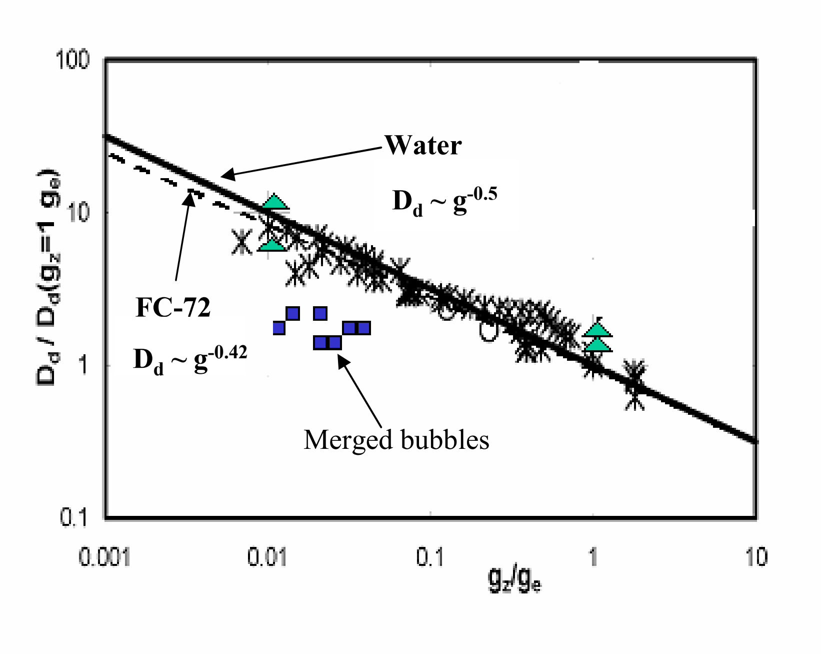




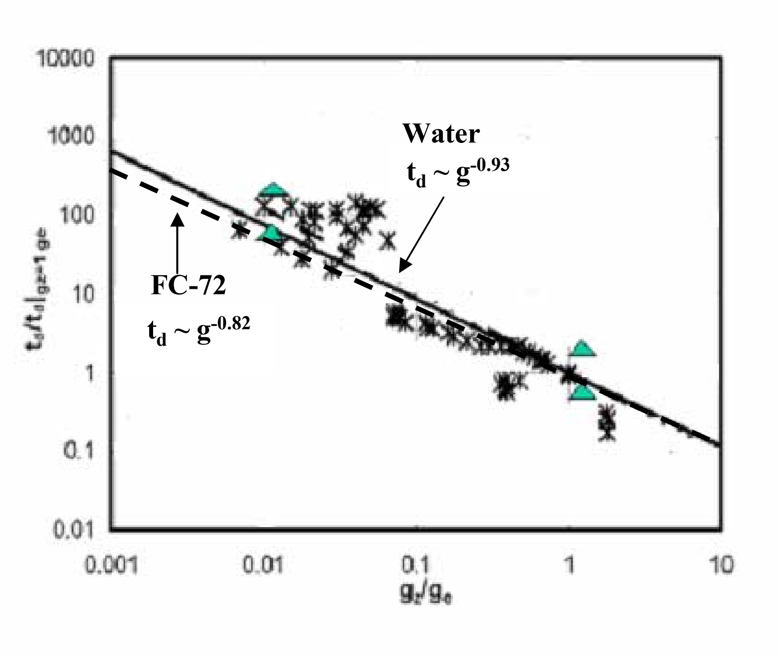
Comparison between measured and predicted bubble shapes for $\Delta T_w = 3.8°C$, $\Delta T_{sub} = 0.4°C$ and $g_z = 0.02\ g_e$

POOL NUCLEATE BOILING (contd.)

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



Lift off diameter

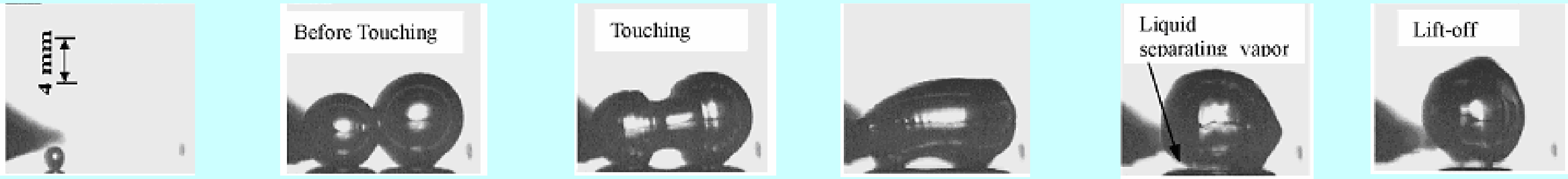


Growth period

POOL NUCLEATE BOILING (contd.)

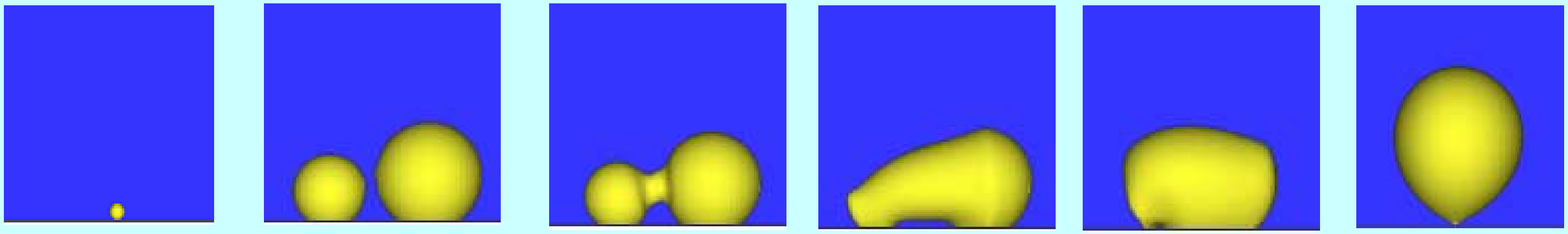
Bubble Merger

Experiments of Qiu *et al* (2000)



t=0.5 s **t=2.5 s** **t=2.9 s** **t=3.05 s** **t=3.15 s** **t=3.2 s**

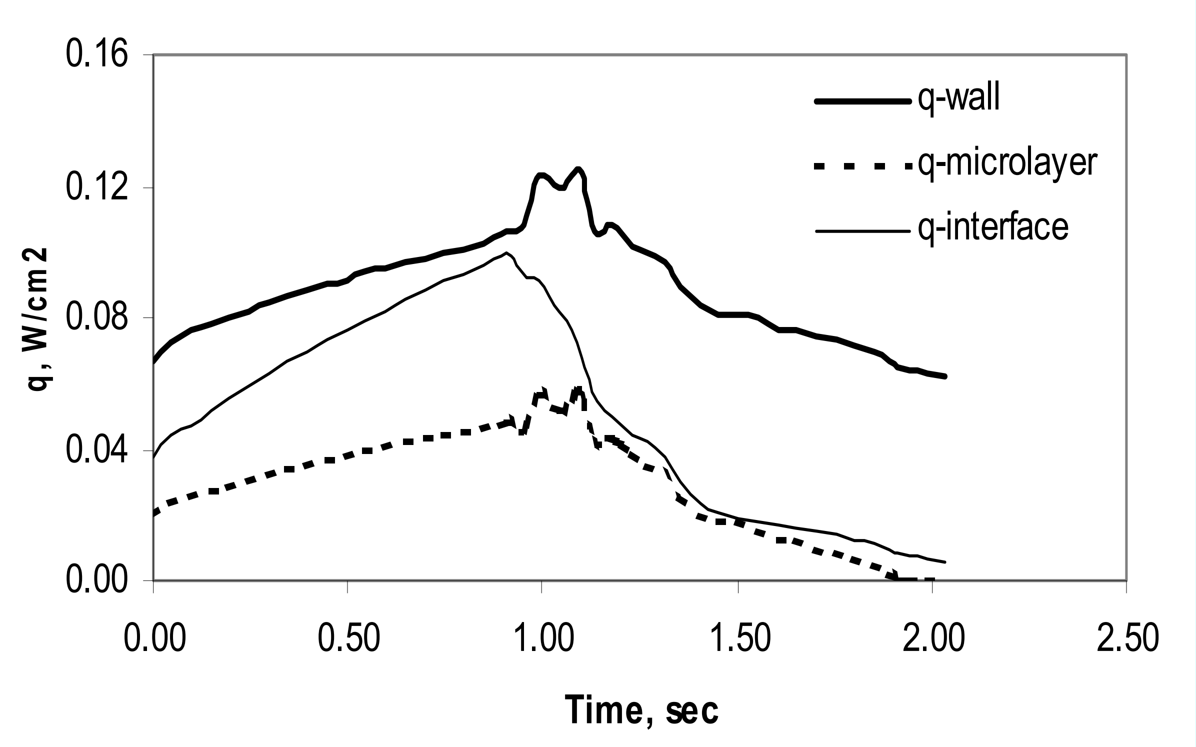
Numerical Predictions



Two bubble merger for water, $\Delta T_w = 5.0$ °C, $\Delta T_{sub} = 3.0$ °C, $g_z = 0.0033 g_e$, spacing = 7 mm

POOL NUCLEATE BOILING (contd.)

Bubble Merger – Heat Transfer



Five bubble merger for saturated water, $\Delta T_w = 7.0$ °C, $g_z = 0.01g_e$, spacing = 7 mm

POOL NUCLEATE BOILING (contd.)

Boiling eXperiment Facility (BXF)

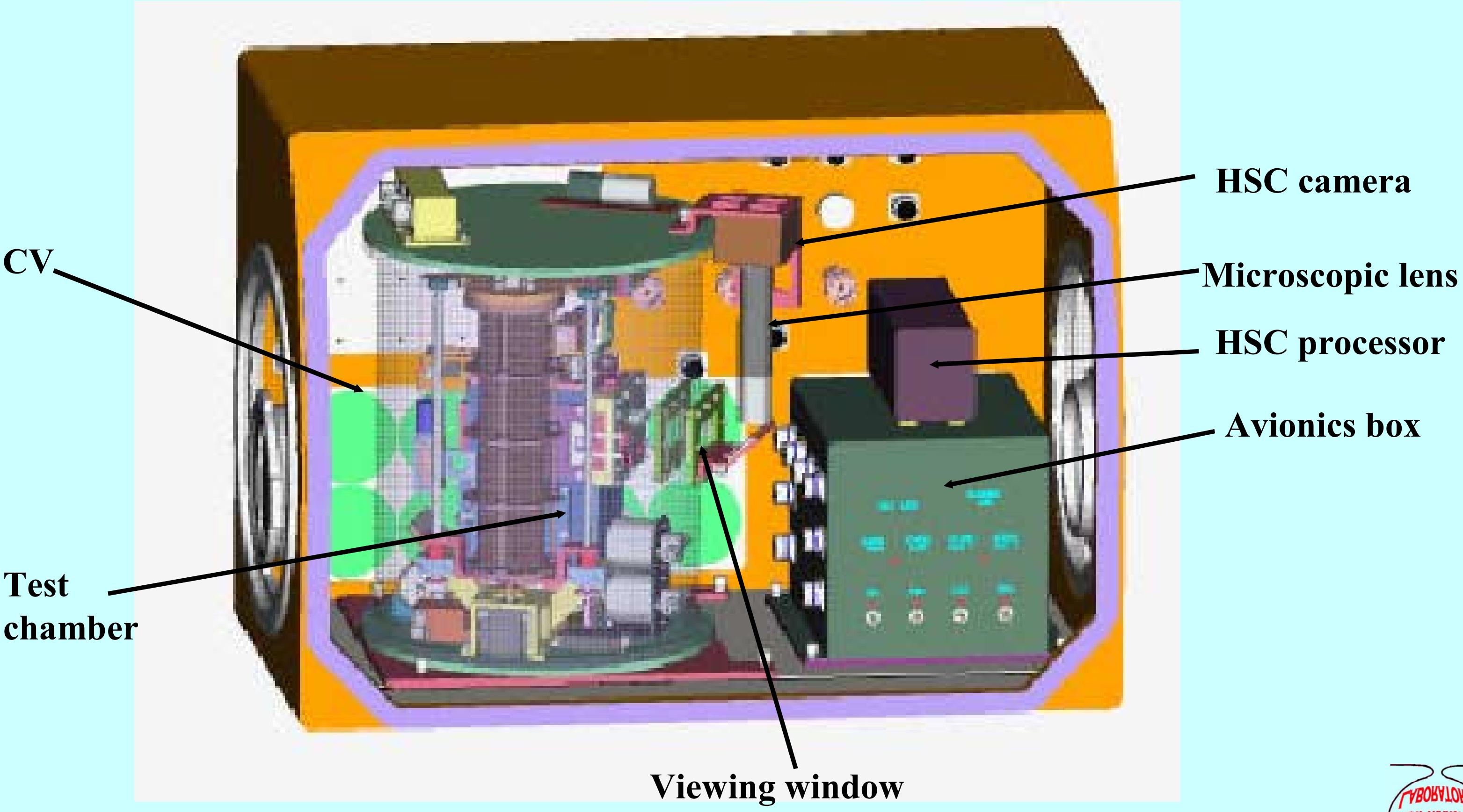
BXF is a multi-use apparatus designed to accommodate two fluid physics experiments

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.

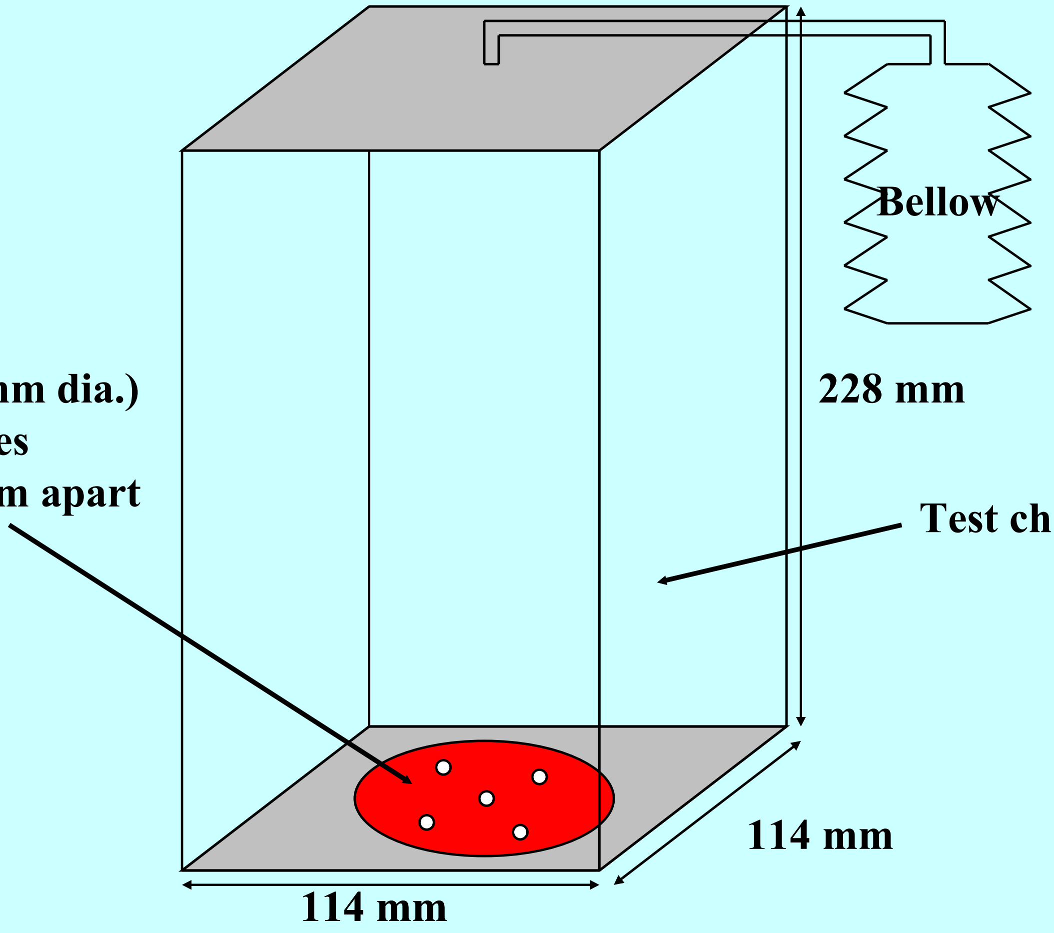
POOL NUCLEATE BOILING (contd.)

VIEW OF FLIGHT HARDWARE IN MSG



POOL NUCLEATE BOILING (contd.)

NPBX Test Chamber



Bellow

228 mm

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

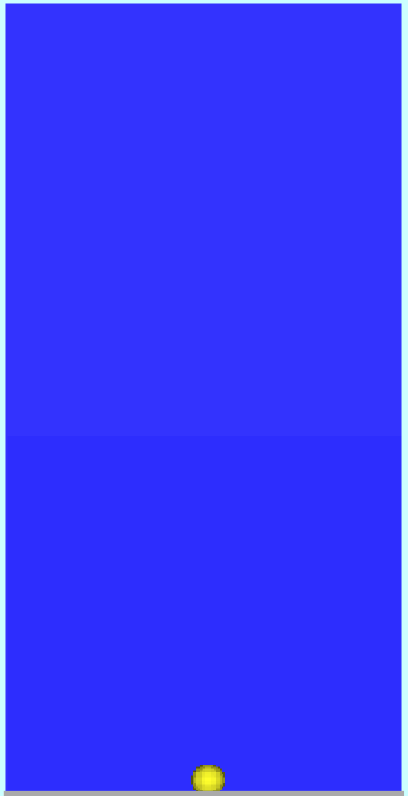
Test chamber

114 mm

114 mm

POOL NUCLEATE BOILING (contd.)

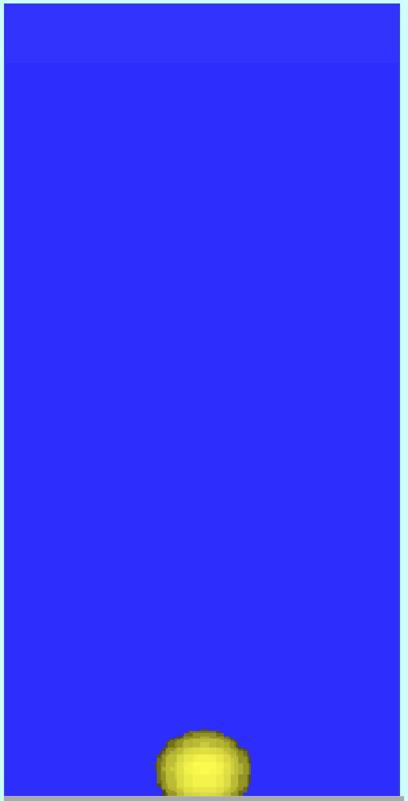
Single Bubble – Numerical Simulations



Click here to play movie

Saturated FC-72, $\Delta T_w = 10\ ^oC$
$\phi = 10^o$

$g = 10^{-5}\ g_e$



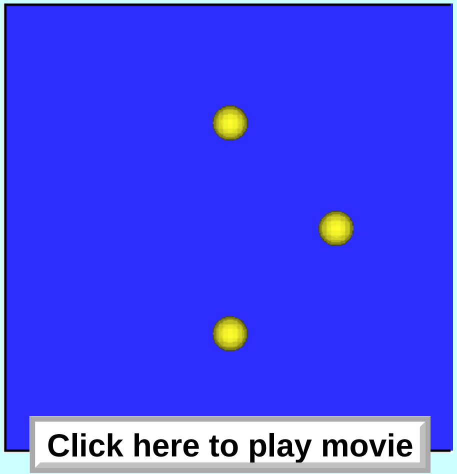
Click here to play movie

Saturated Water, $\Delta T_w = 10\ ^oC$
$\phi = 54^o$

POOL NUCLEATE BOILING (contd.)

Three Bubble Merger – Numerical Simulations

Top view

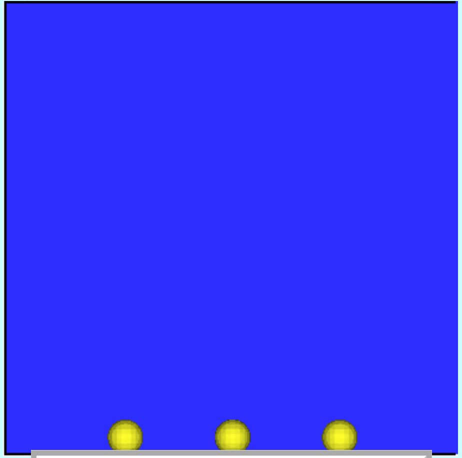


Click here to play movie

$g_z = 10^{-5}\ g_e$

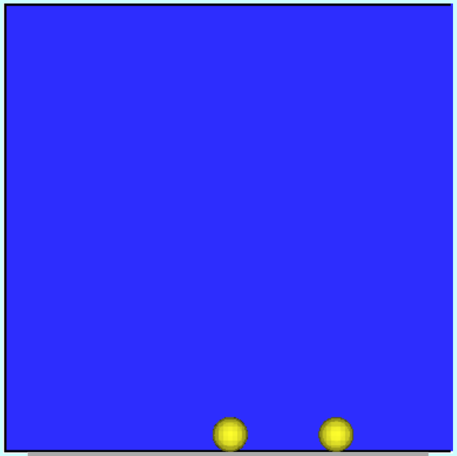
Fluid: Sat. FC-72

Front view



Click here to play movie

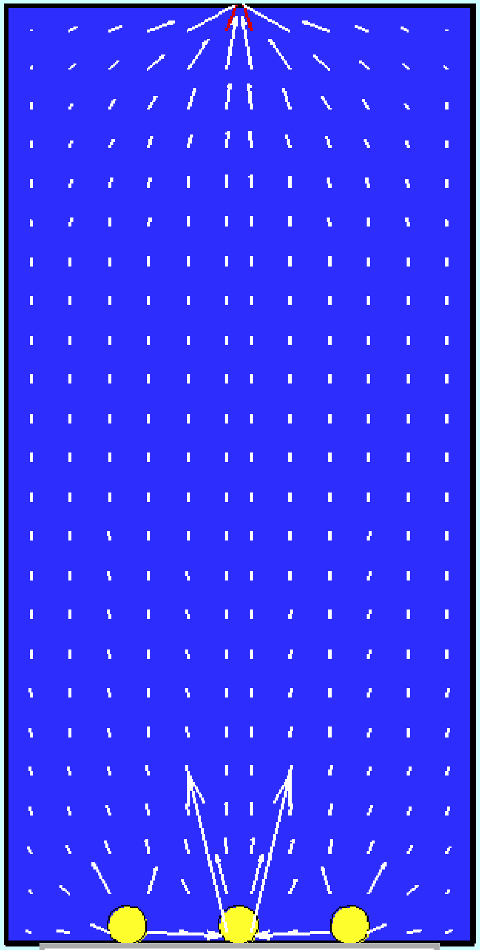
Side view



Click here to play movie

POOL NUCLEATE BOILING (contd.)

Five Bubble Merger – Numerical Simulations



Click here to play movie

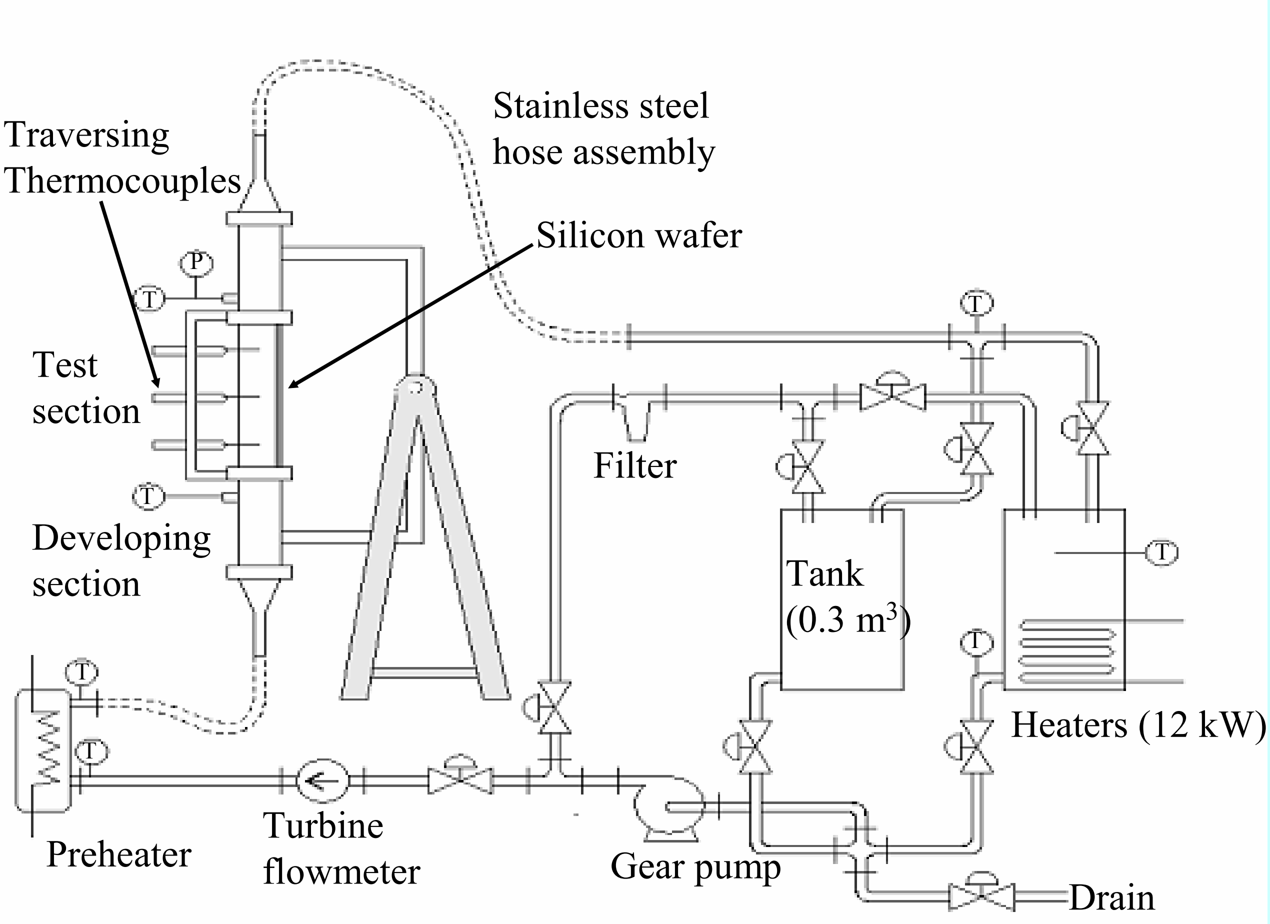
$g_z = 10^{-5}\ g_e$

Time lag = 0.5 sec

Fluid: Sat. FC-72

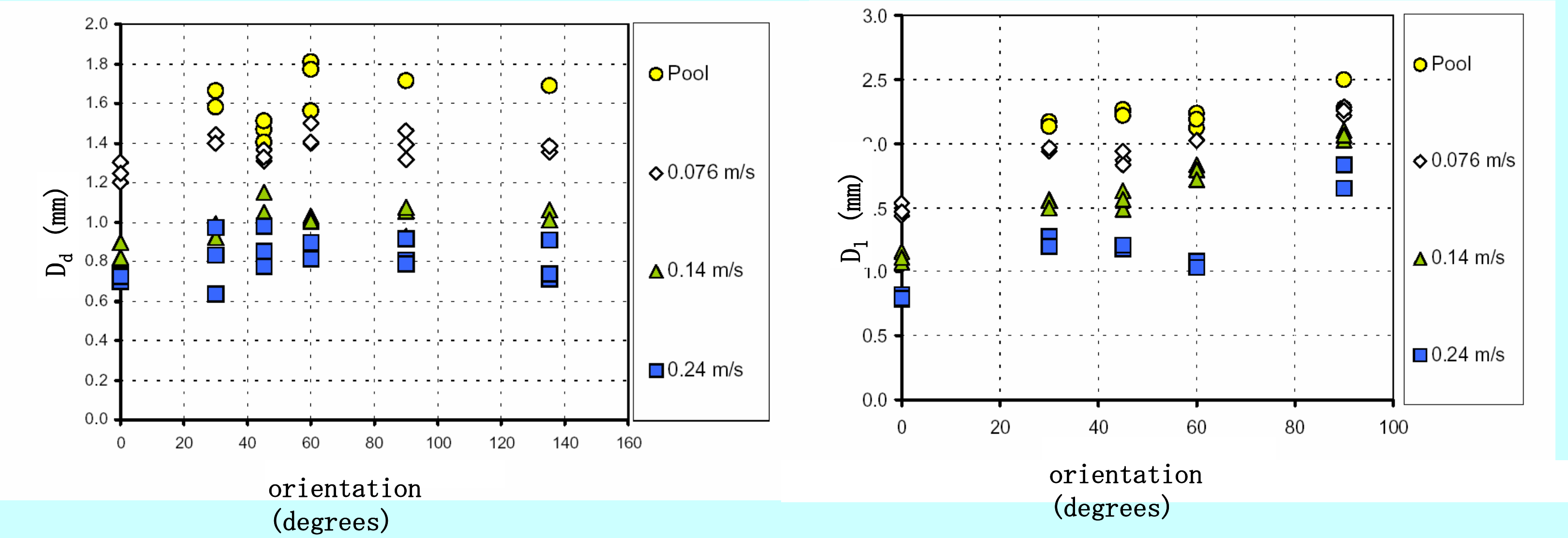
TRANSITION FROM POOL TO FLOW BOILING

Low Velocity Flow Boiling



FLOW BOILING (Contd.)

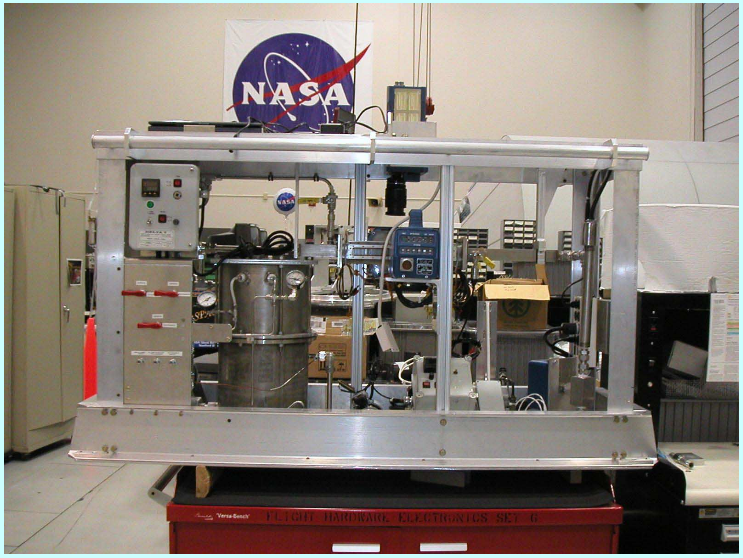
Low Velocity Flow Boiling – Earth Normal Gravity



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

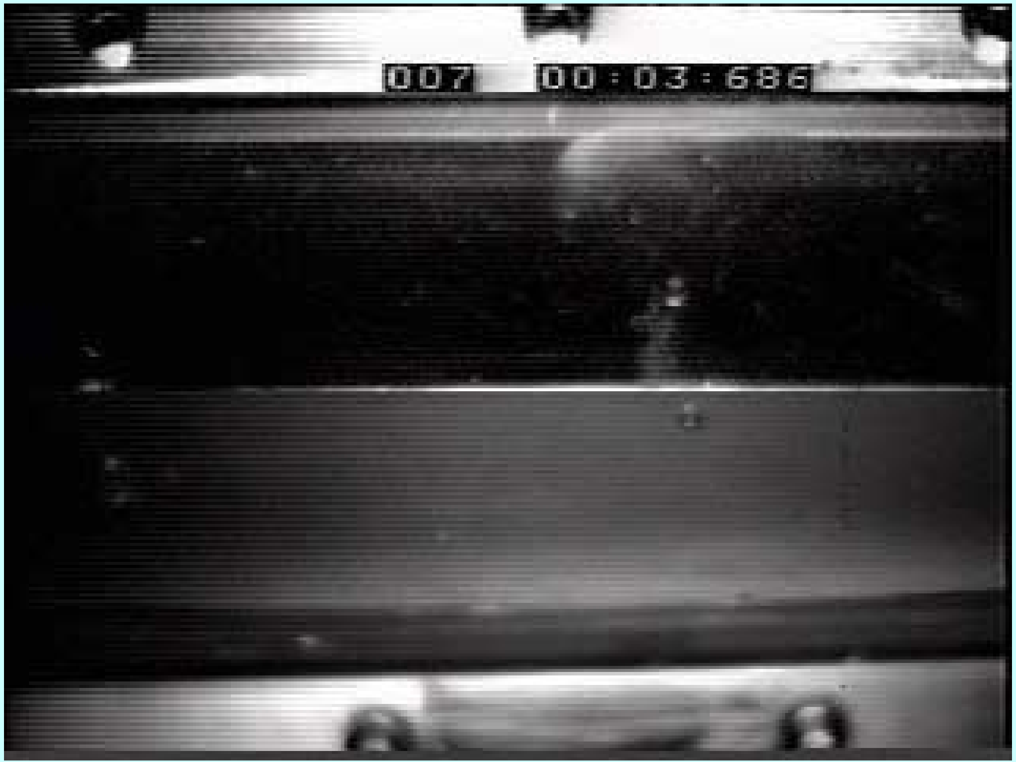
FLOW BOILING (Contd.)

Experimental Setup (KC-135)



FLOW BOILING (Contd.)

KC-135 Experiments



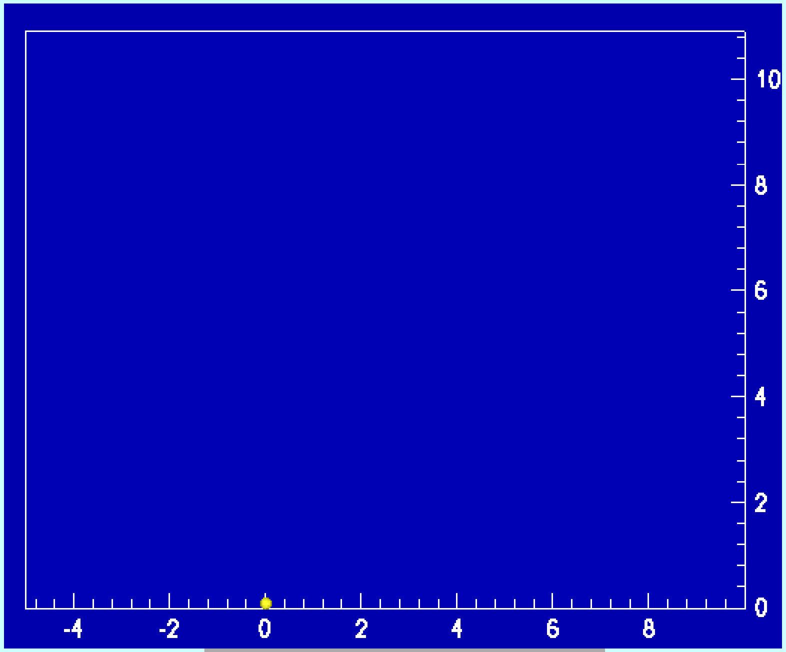
Click here to play movie

Fluid: water, $\Delta T_w = 6\ ^oC$, $\Delta T_{sub} = 0.5\ ^oC$, $g_z = 0.023g_e$

FLOW BOILING (Contd.)

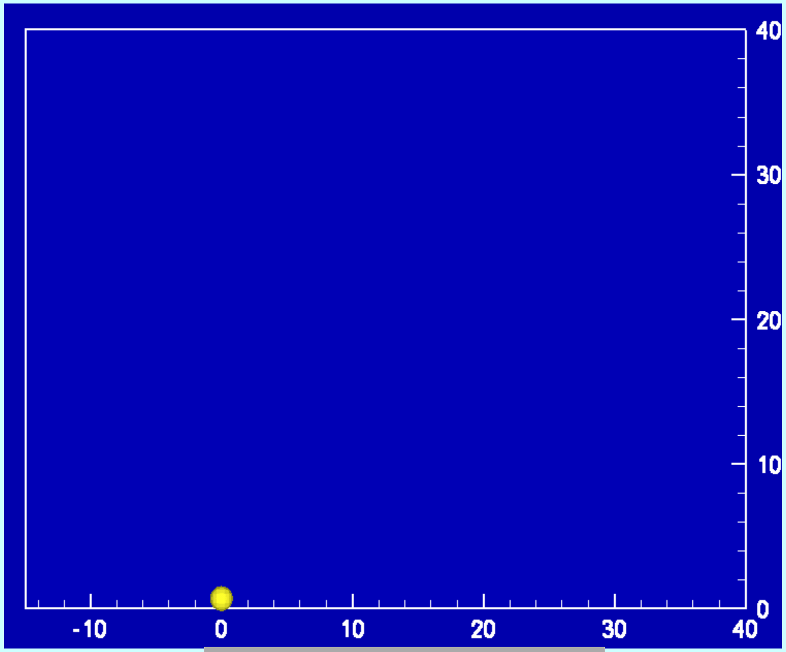
Low Velocity Flow Boiling - Numerical Simulation

$g_z = 1.0g_e$



Click here to play movie

$g_z = 0.02g_e$

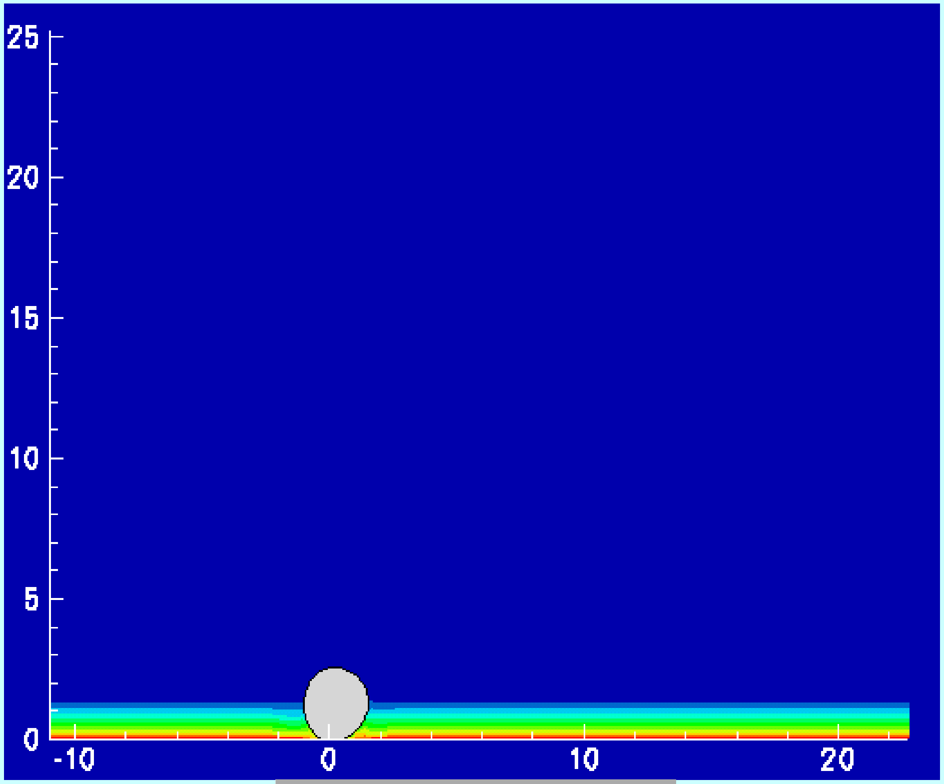


Click here to play movie

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

FLOW BOILING (Contd.)

Low Velocity Flow Boiling - Numerical Simulation



$g_z = 0.02g_e$

Click here to play movie

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

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 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 **P**ortable **U**nit for **M**etabolic **A**nalysis*

D.L. Dietrich, N.D. Piltch, J.R. Juergens, M.E. Lewis, M.J. Lichter, P.M. Struk, *NASA GRC*

R.D. Pettegrew, *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

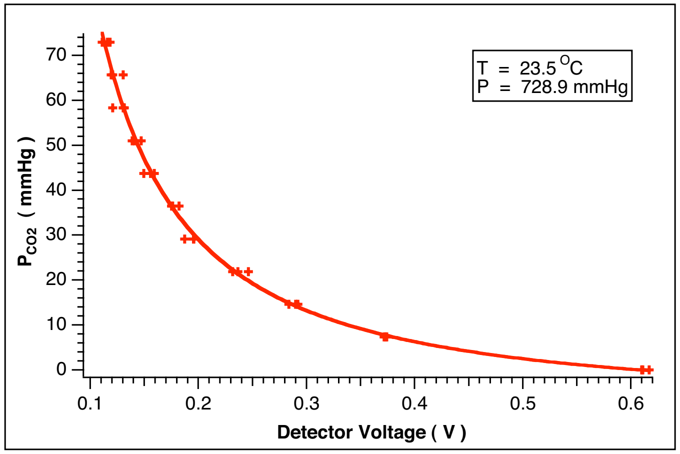
- Breath by breath analysis *and* within breath analysis
    - Design goal is 10 Hz (minimum)
- Eliminate timing issues with existing fixed and portable units (sampling at mask instead of remotely)
- Utilize better oxygen sensor technology than exists with existing portable units (electrochemical cell)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

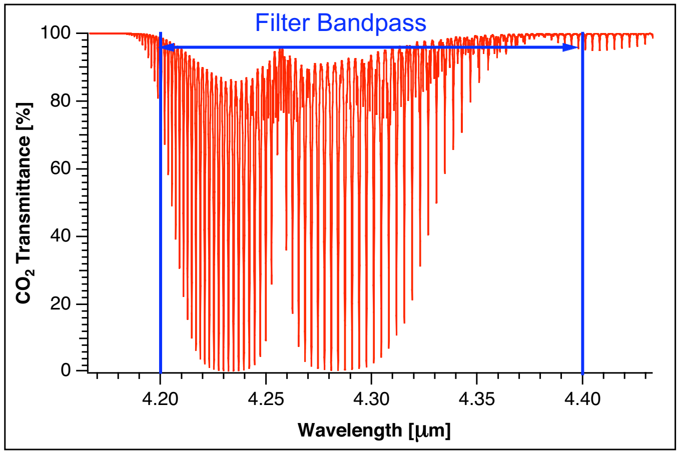
Specific Technologies

- 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

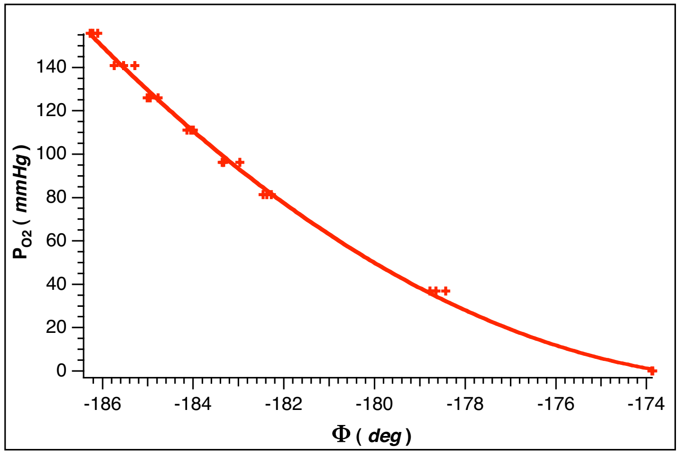


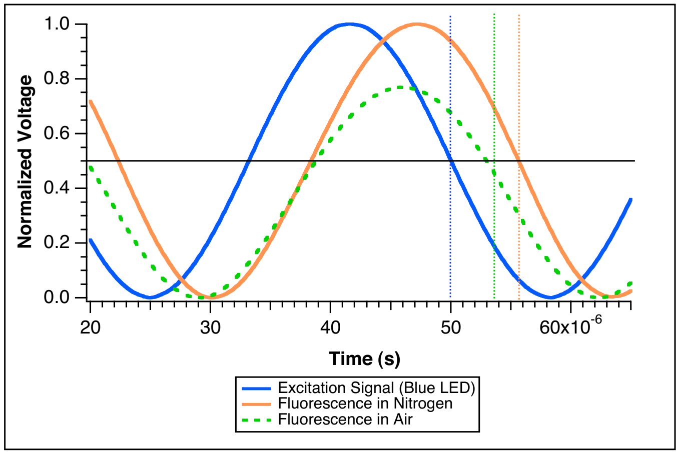


- Modulated IR source (currently incandescent-chopped)
- PbSe photoconductive detector (cooled)

Oxygen Subsystem

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



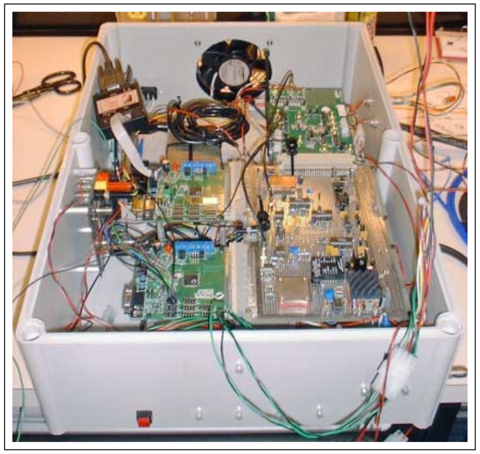


Measuring phase shift is:

- 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" x 15" x 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

ADVANCED LIFE SUPPORT WATER RECYCLING TECHNOLOGIES CASE STUDIES: VAPOR PHASE CATALYTIC AMMONIA REMOVAL AND DIRECT OSMOTIC CONCENTRATION

Michael Flynn
NASA Ames Research Center

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 theses 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
650-604-1163
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.

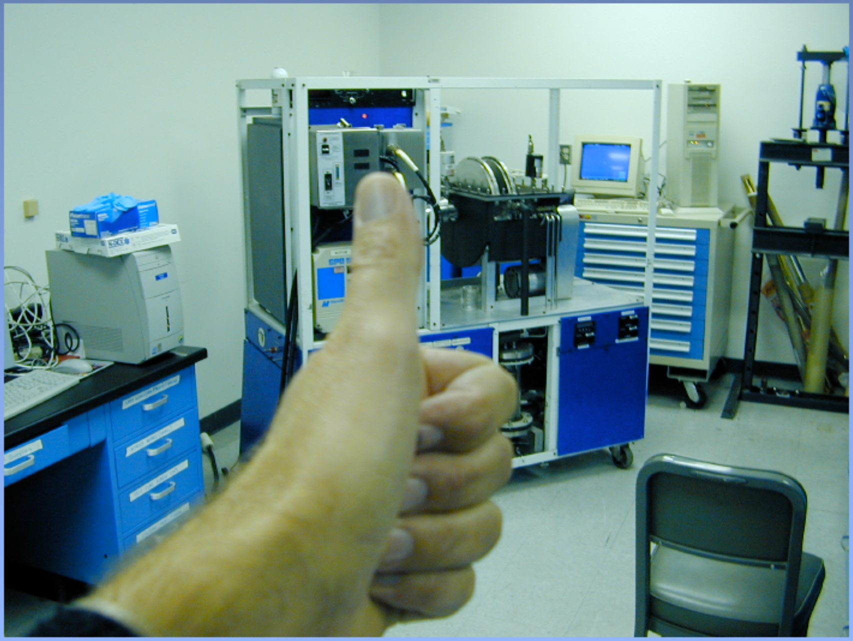
- Using the Mars Reference Mission as a baseline and Mars Pathfinder launch cost data, the cost of supplying water for this mission in the open loop case is over $11 Billion.

Assumptions: 6 astronauts, flow=3.18kg/hr, duration=960 days, launch Cost= $150,000/kg

Advanced Life Support

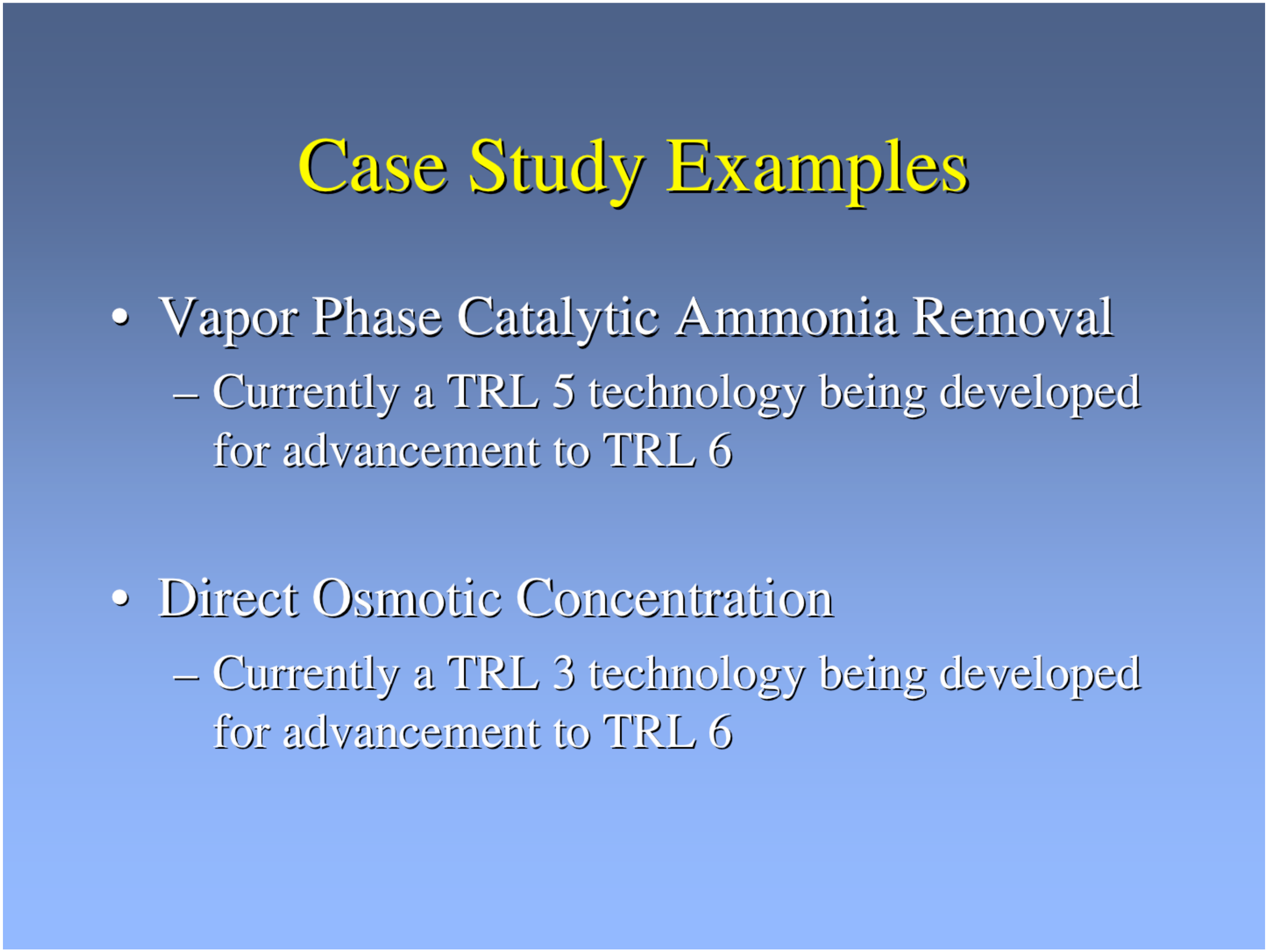
- The ALS program supports fundamental research into the development of new technologies.
- It supports the development of these technologies to high technology readiness levels (TRL 5-6).
- It has not adequately supported the validation of the microgravity performance of these technologies (TRL 7 to 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

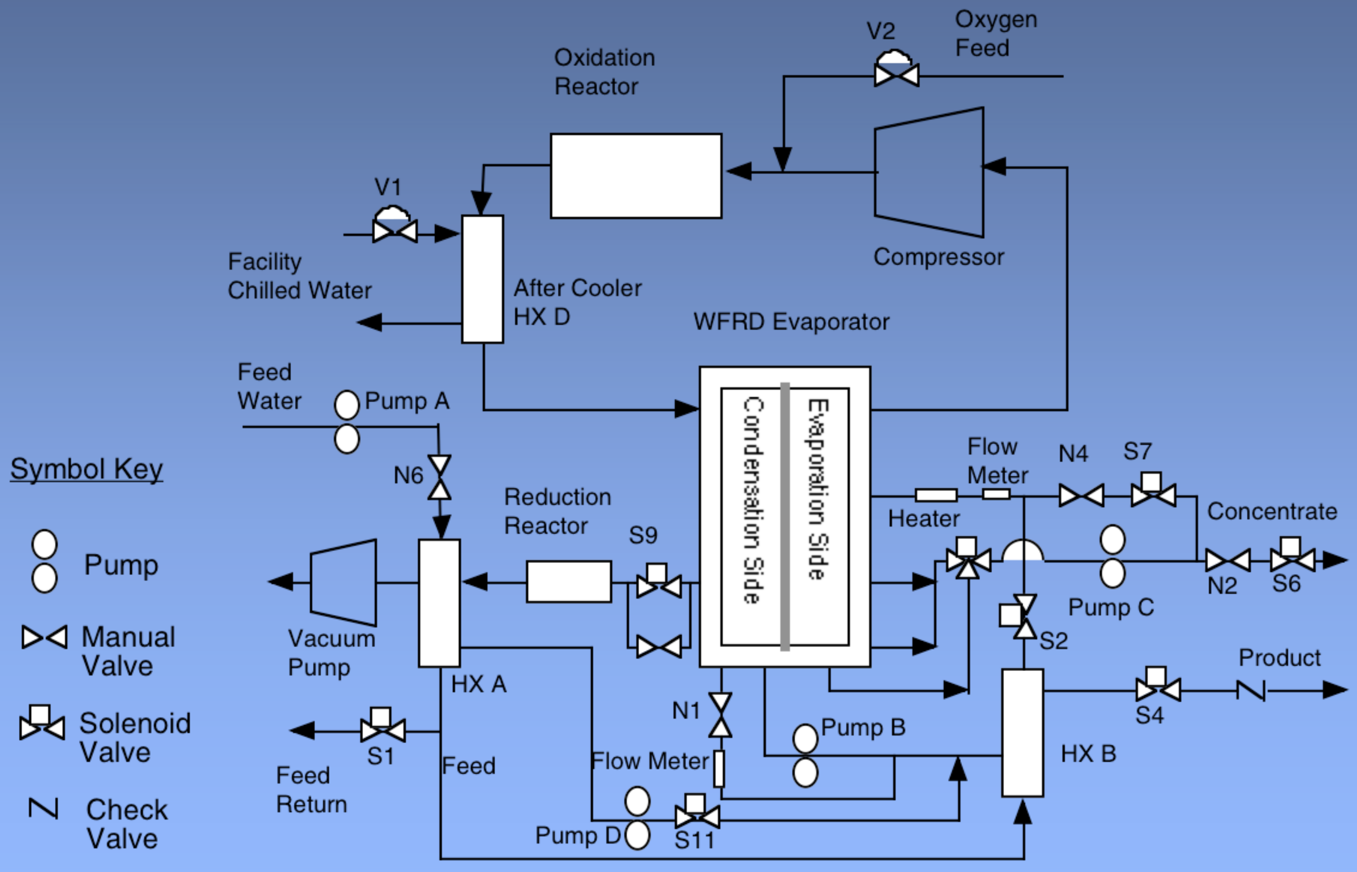
- Vapor Phase Catalytic Ammonia Removal
  - – Currently a TRL 5 technology being developed for advancement to TRL 6
- Direct Osmotic Concentration
  - – Currently a TRL 3 technology being developed for advancement to TRL 6

Vapor Phase Catalytic Ammonia Removal (VPCAR)

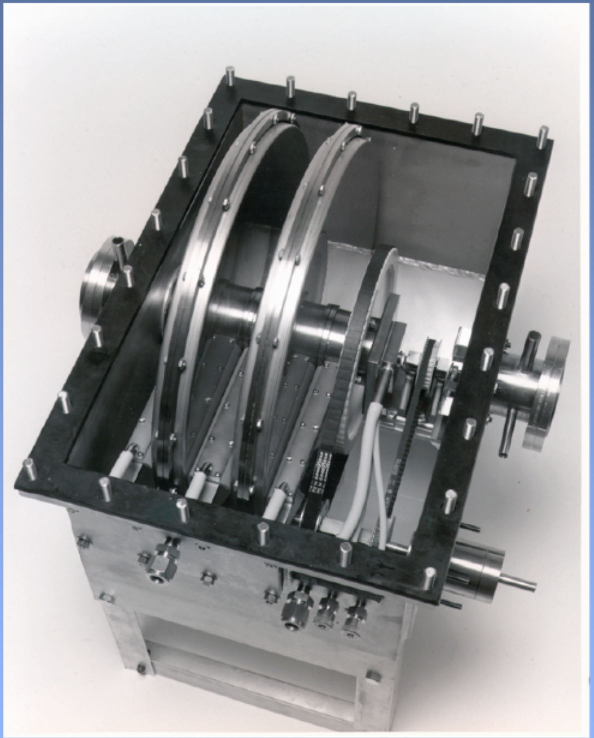
Vapor Phase Catalytic Ammonia Reduction

- 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 single volume comparable to a single Space Station rack.
- The technology has been the subject of many NASA trades studies and peer reviews.

VPCAR Flow Diagram

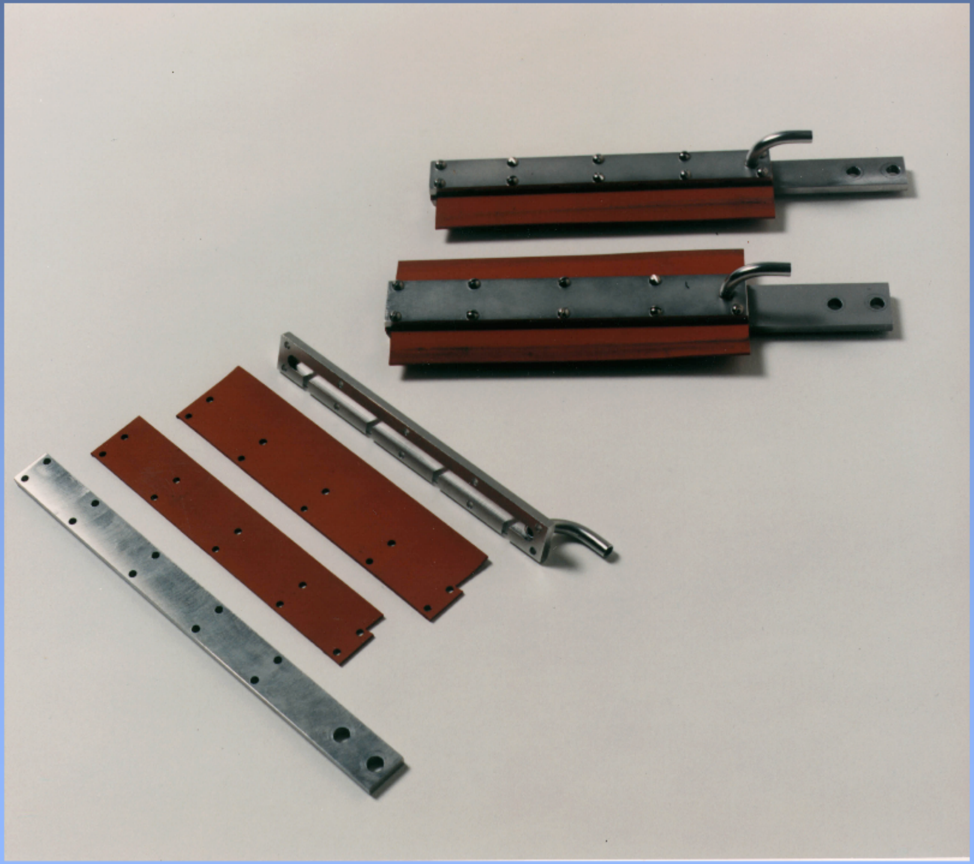


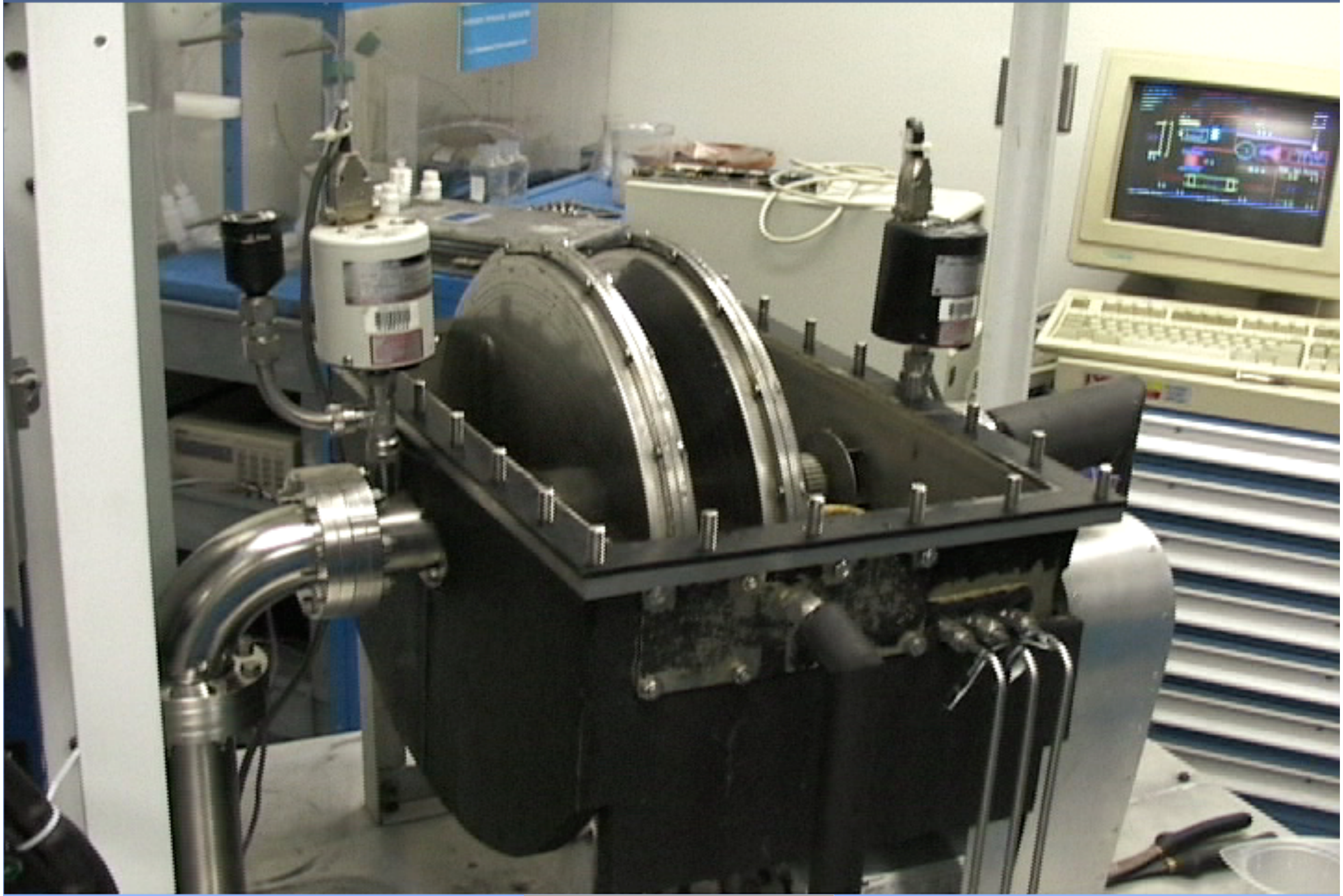
WFRD Components



Rotor Assembly

Wiper Blades





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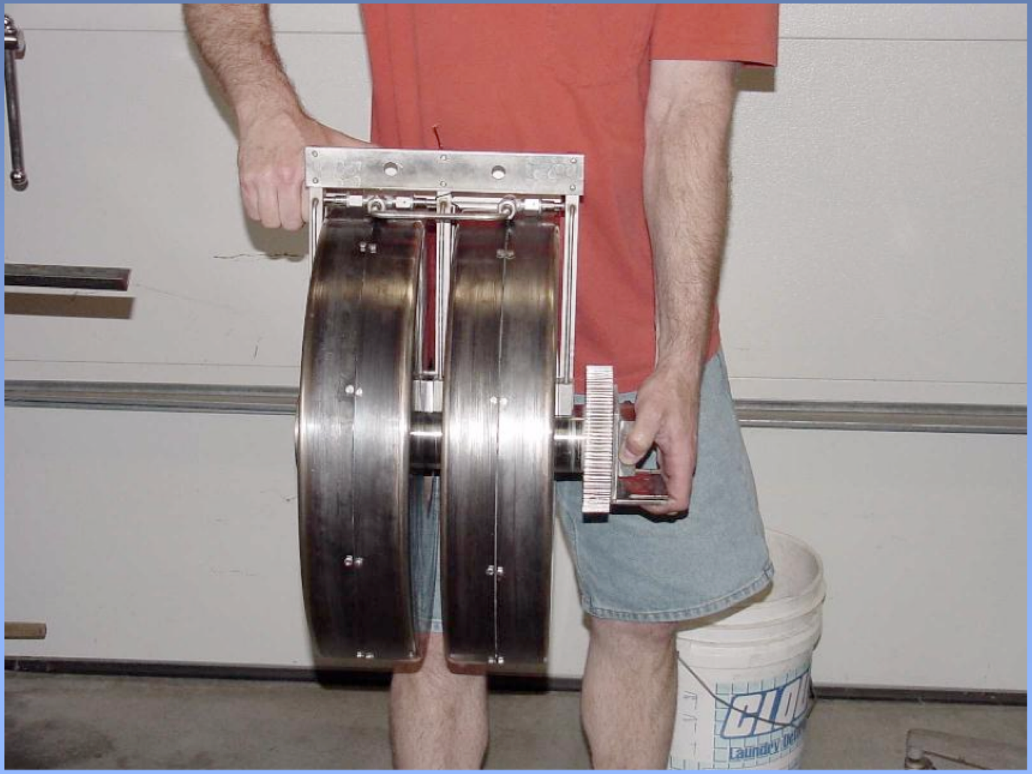
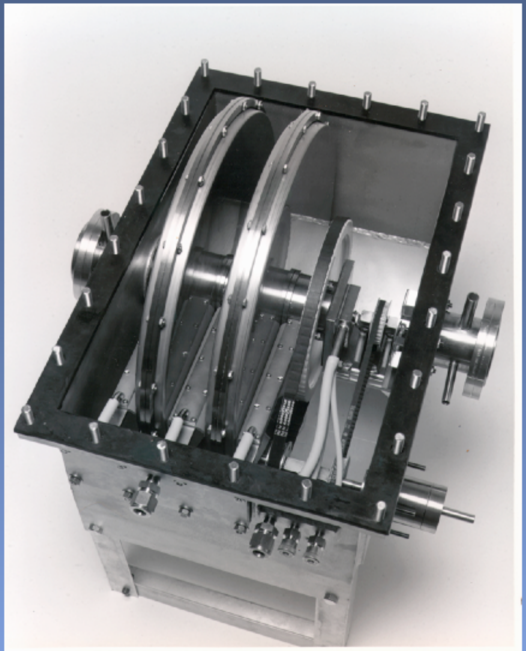
Microgravity Evaporator

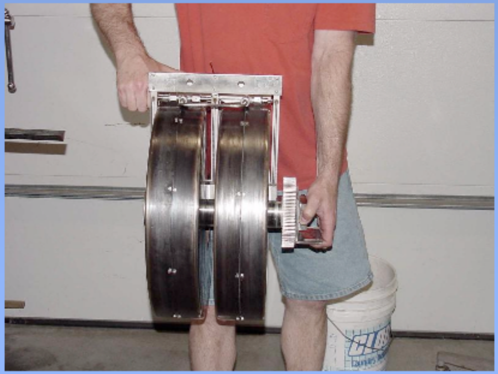


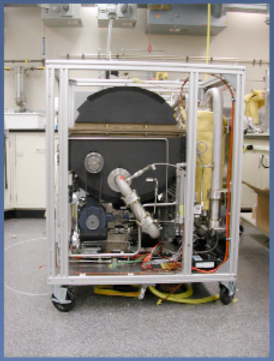

Click here to play movie

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



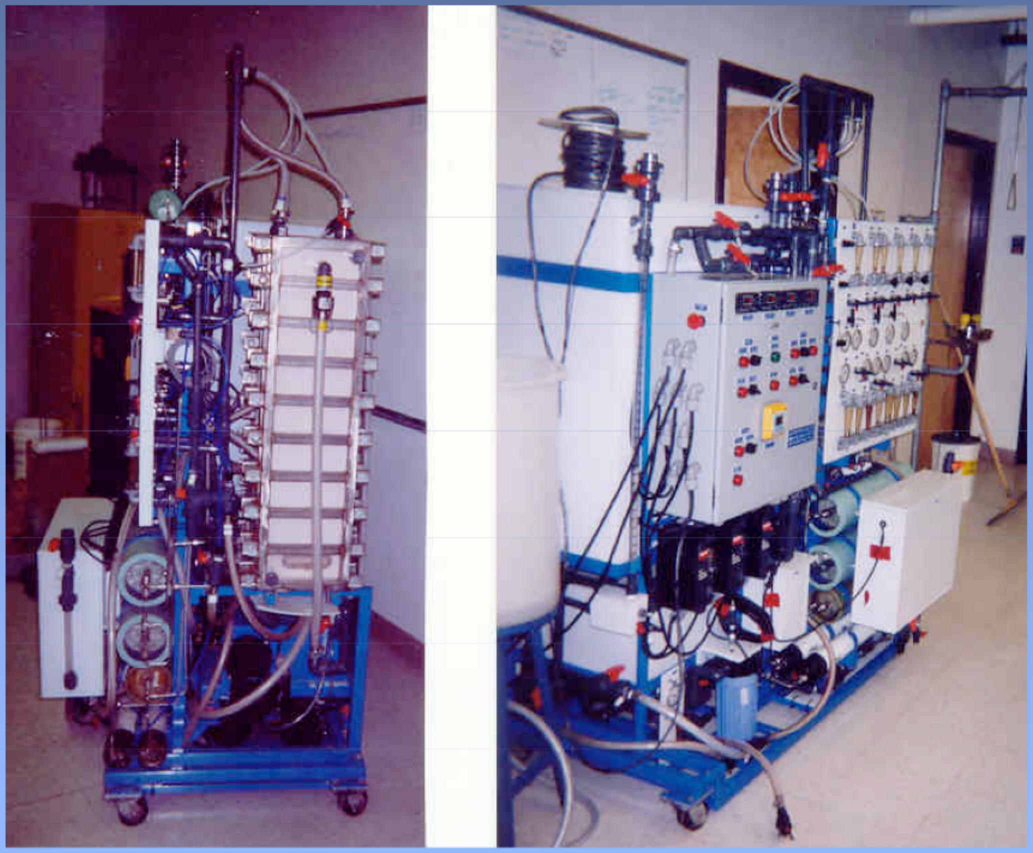




VPCAR Systems Flight Verification Topics (Cont.)

- 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

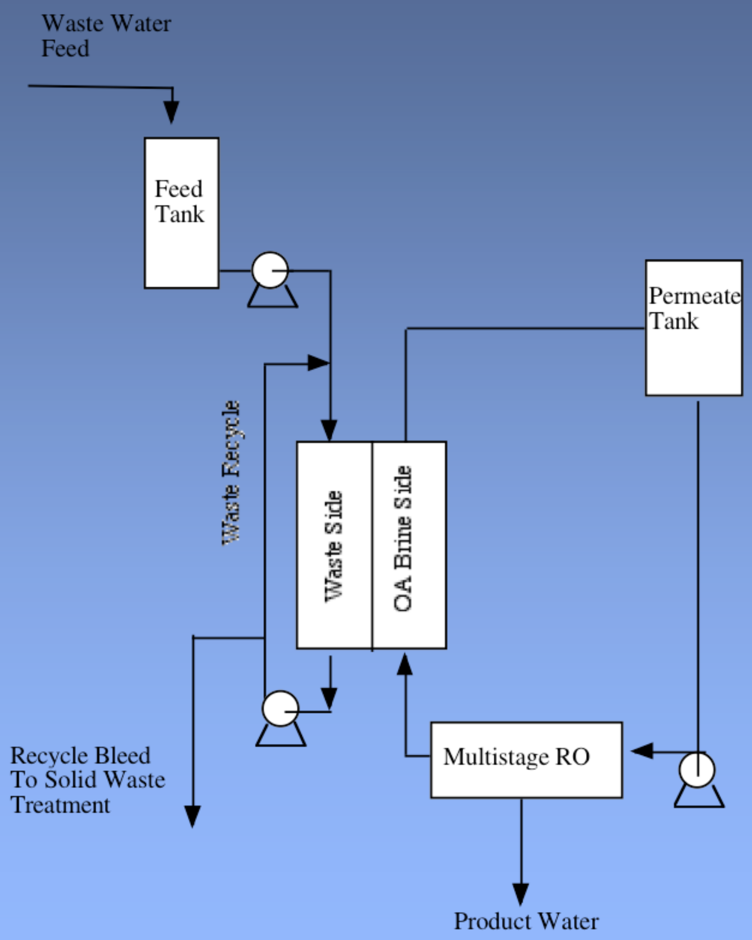
Direct Osmotic Concentration (DOC)



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 Recycle

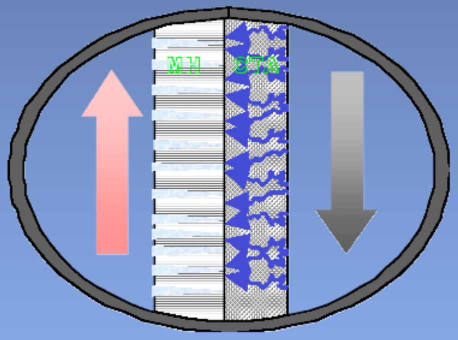
Waste Side

OA Brine Side

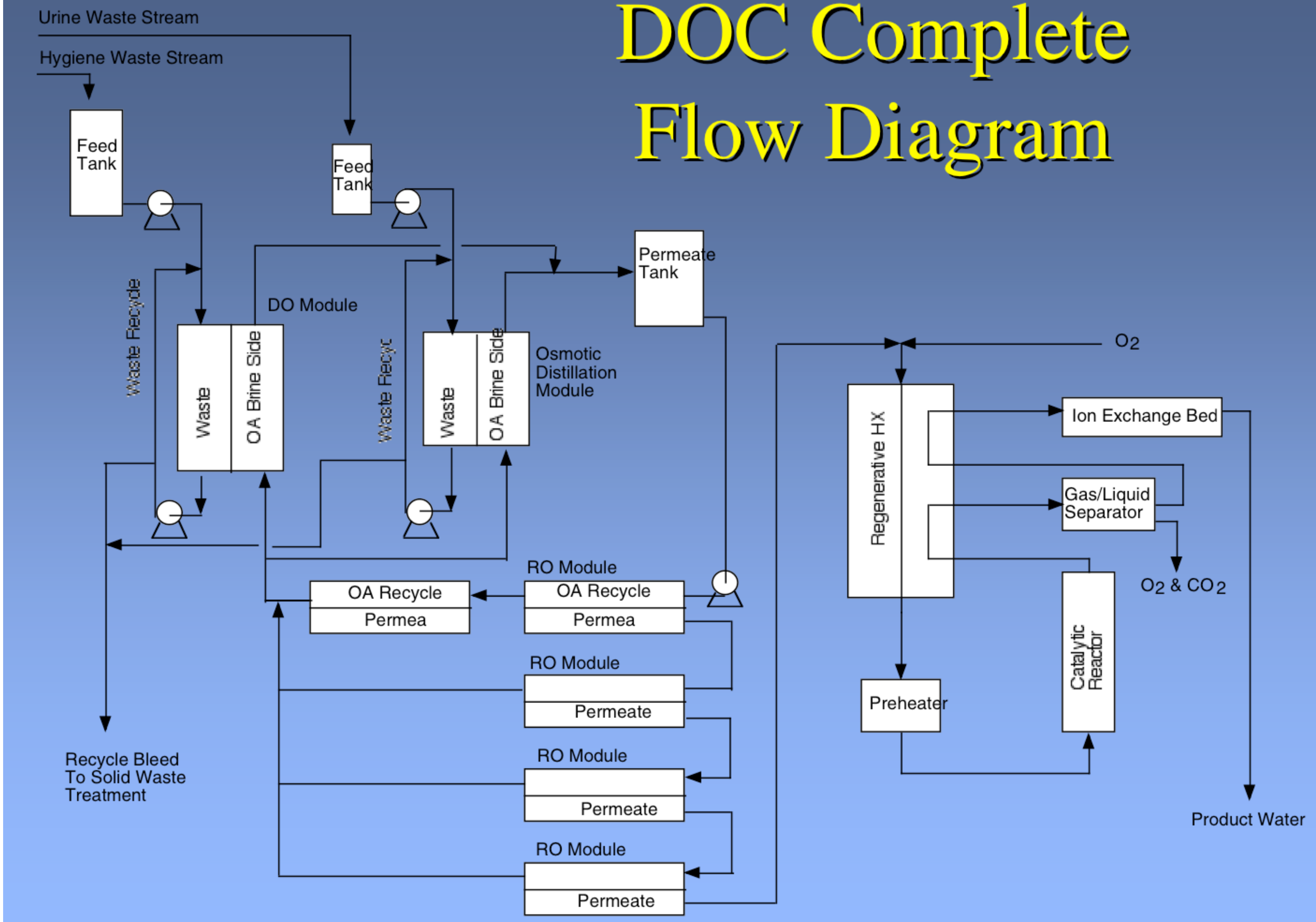
Multistage RO

Recycle Bleed To Solid Waste Treatment

Product Water



DOC Complete Flow Diagram



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 cm^2), square region of the upper plate. The narrow channel was filled a model airway lining fluid. Phosphate buffered saline including 0.1 mg/mL $CaCl_2$ and $MgSO_4$ (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 calcein 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, γ, 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, $\nabla \mathbf{P} = \mu \nabla^2 u$ and $\nabla \bullet u = 0$, were solved using the boundary element method. The interfacial stress condition applied at the air-liquid interface was $|\sigma \bullet \hat{n}| = \gamma \kappa \hat{n}$, where $\sigma = -P\mathbf{I} + \mu(\nabla u + \nabla u^T)$ was the stress tensor, $\hat{n}$ was the unit normal, and κ 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

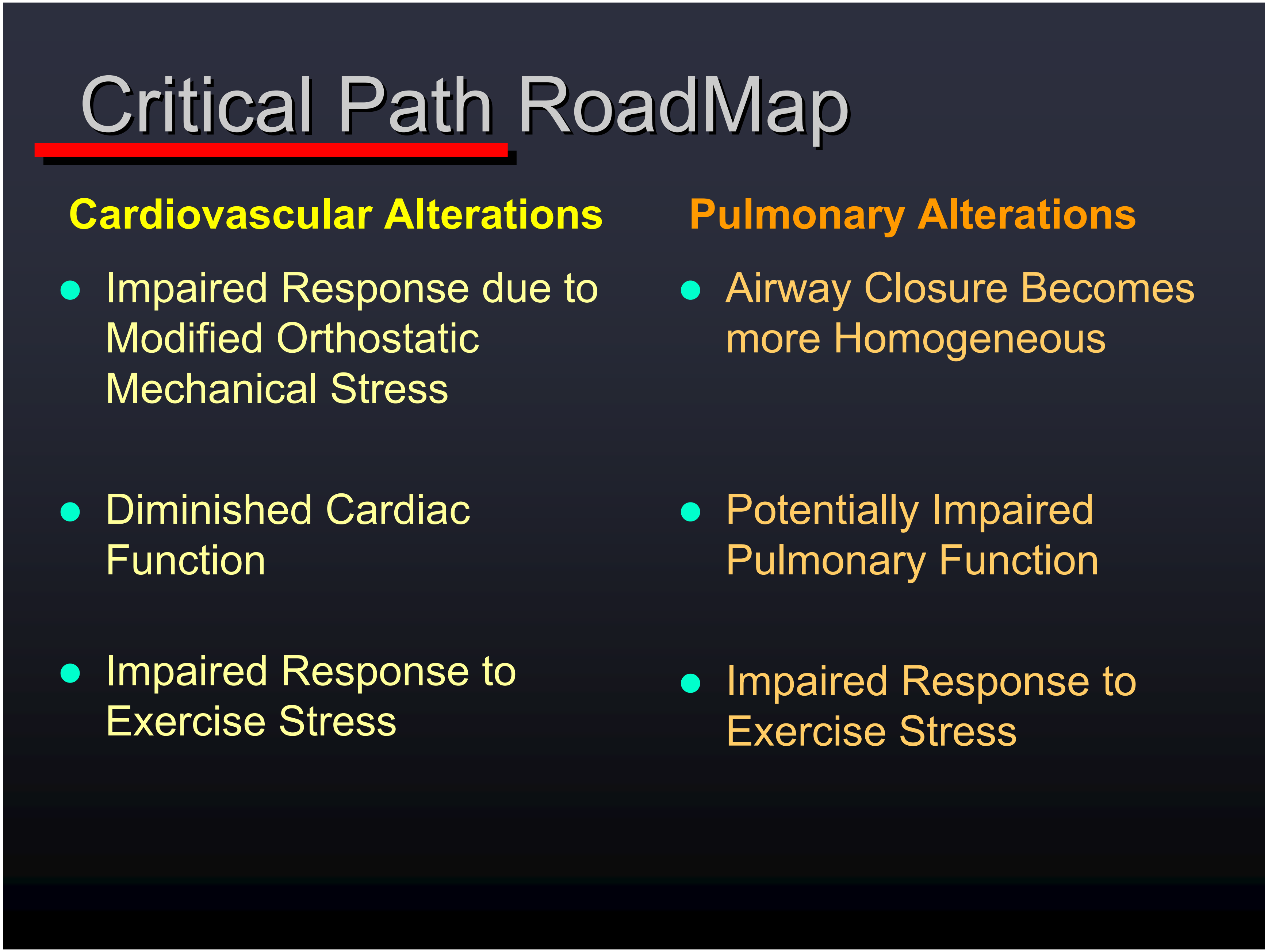
For each condition the average number of injured cells per square centimeter was measured. For the saline-occluded channels, bubble progression at both velocities produced significantly increased numbers of injured cells when compared to the control. The slow velocity resulted in a 66-fold increase in the number of injured cells and the fast velocity produced a 20-fold increase. The addition of Infasurf 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

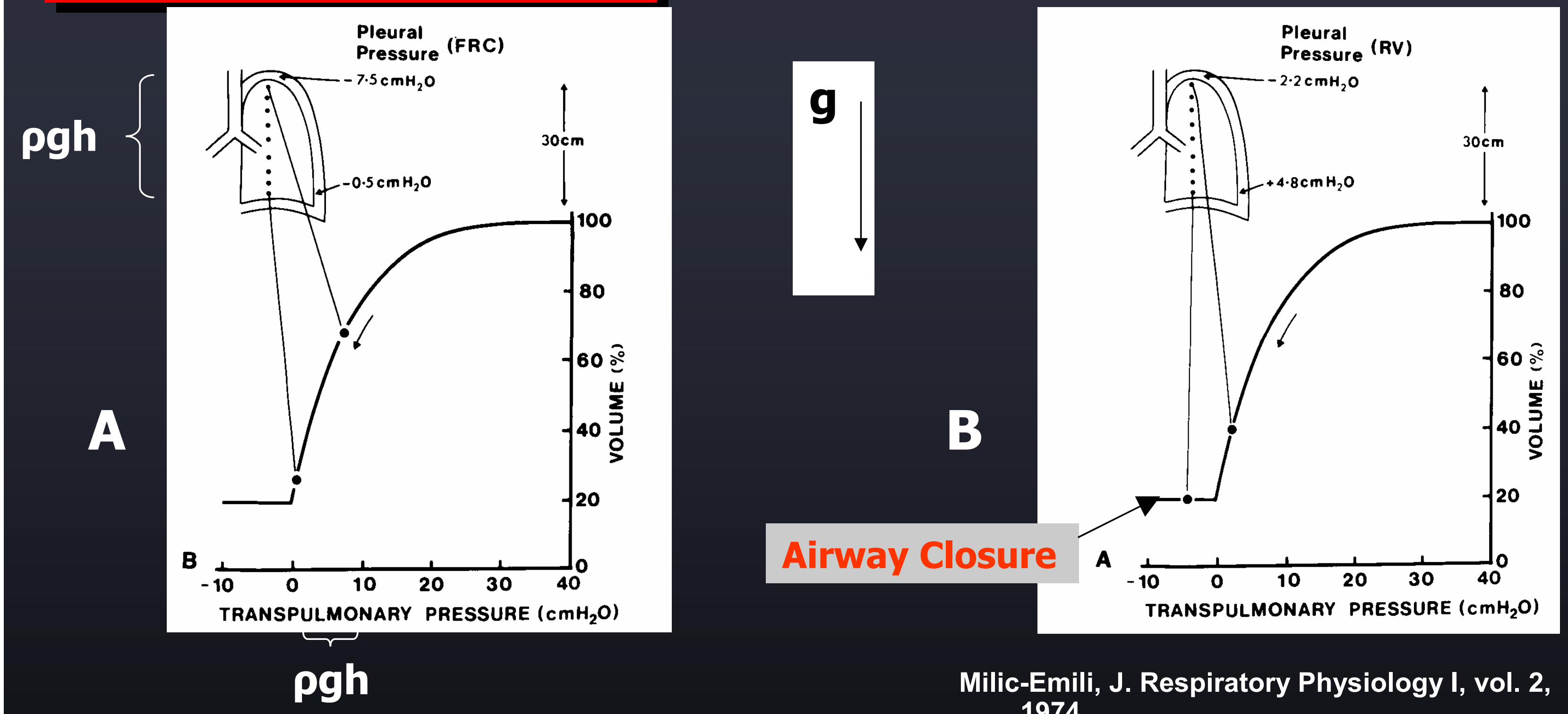
Cardiovascular Alterations

- 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



Milic-Emili, J. Respiratory Physiology I, vol. 2, 1974

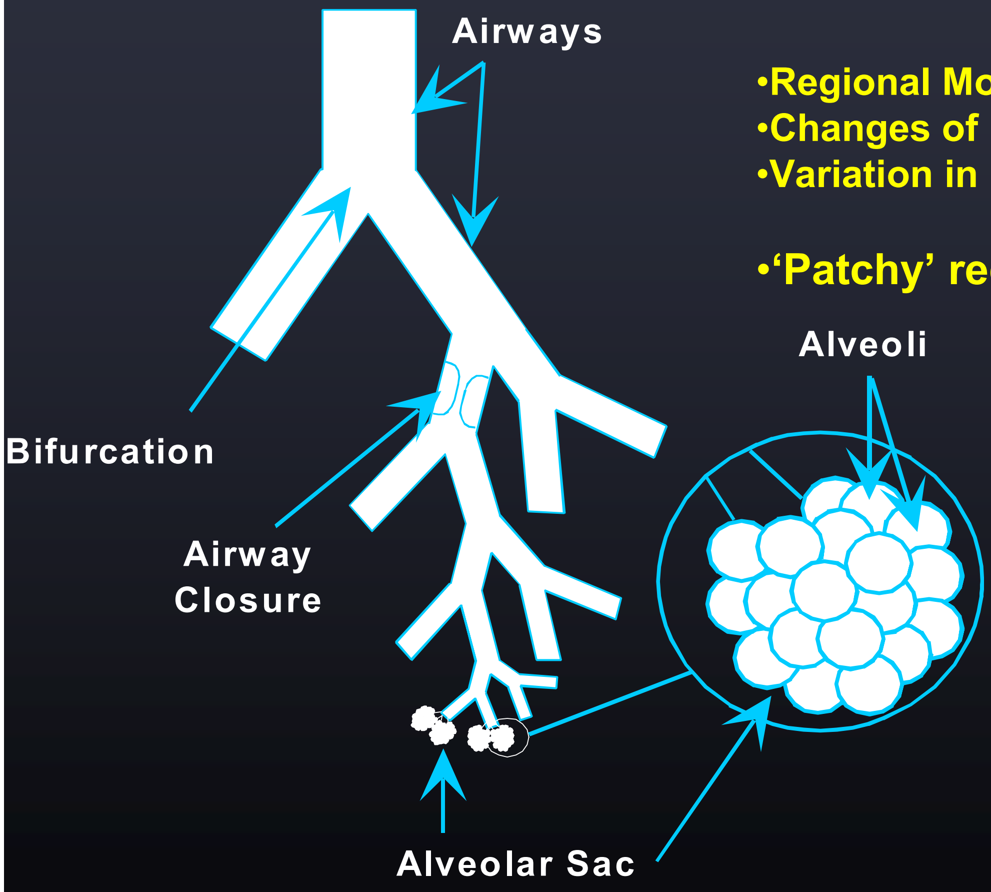
- **(A) At FRC the lower region is less expanded, but more compliant so it receives larger portion of ventilation**
- **(B) At RV the lower lung regions experience airway closure**

Airway Closure in Microgravity

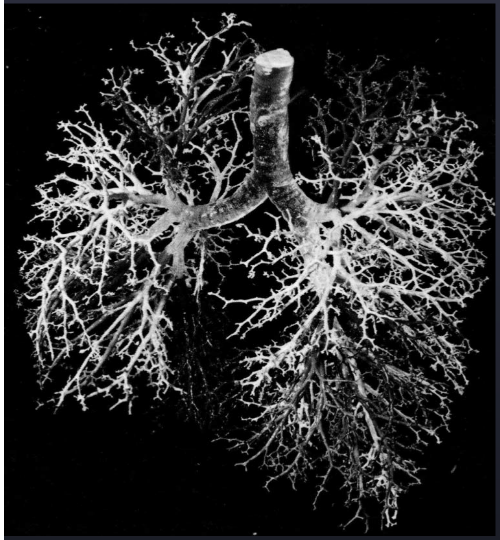
MICROGRAVITY CAUSES:

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

- ‘Patchy’ regions of airway collapse

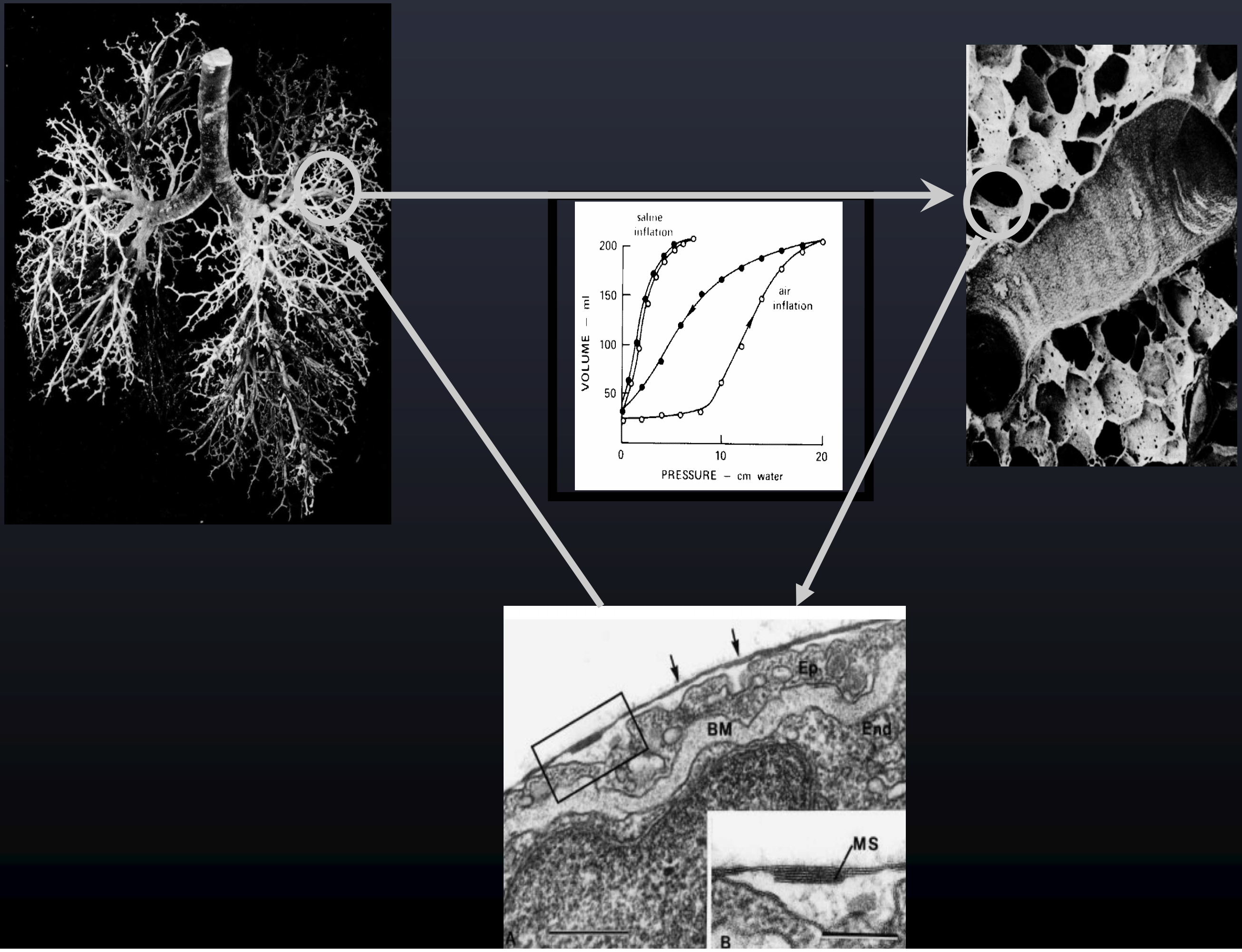


Related Terrestrial Syndromes



- •Infant Respiratory Distress Syndrome
- •Acute Respiratory Distress Syndrome
- •Ventilator-Induced Lung Injury

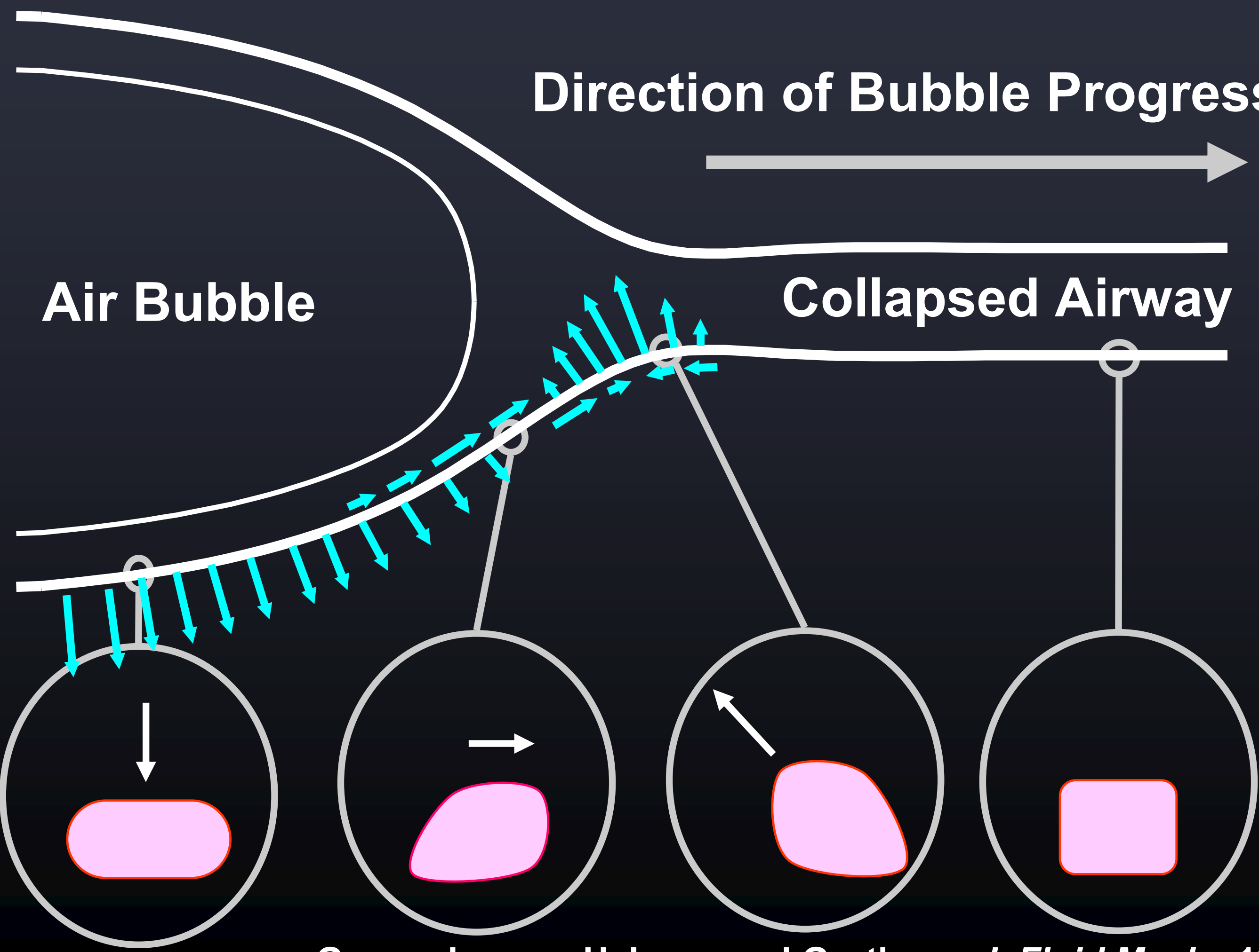
Pulmonary Multiscale Interactions



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



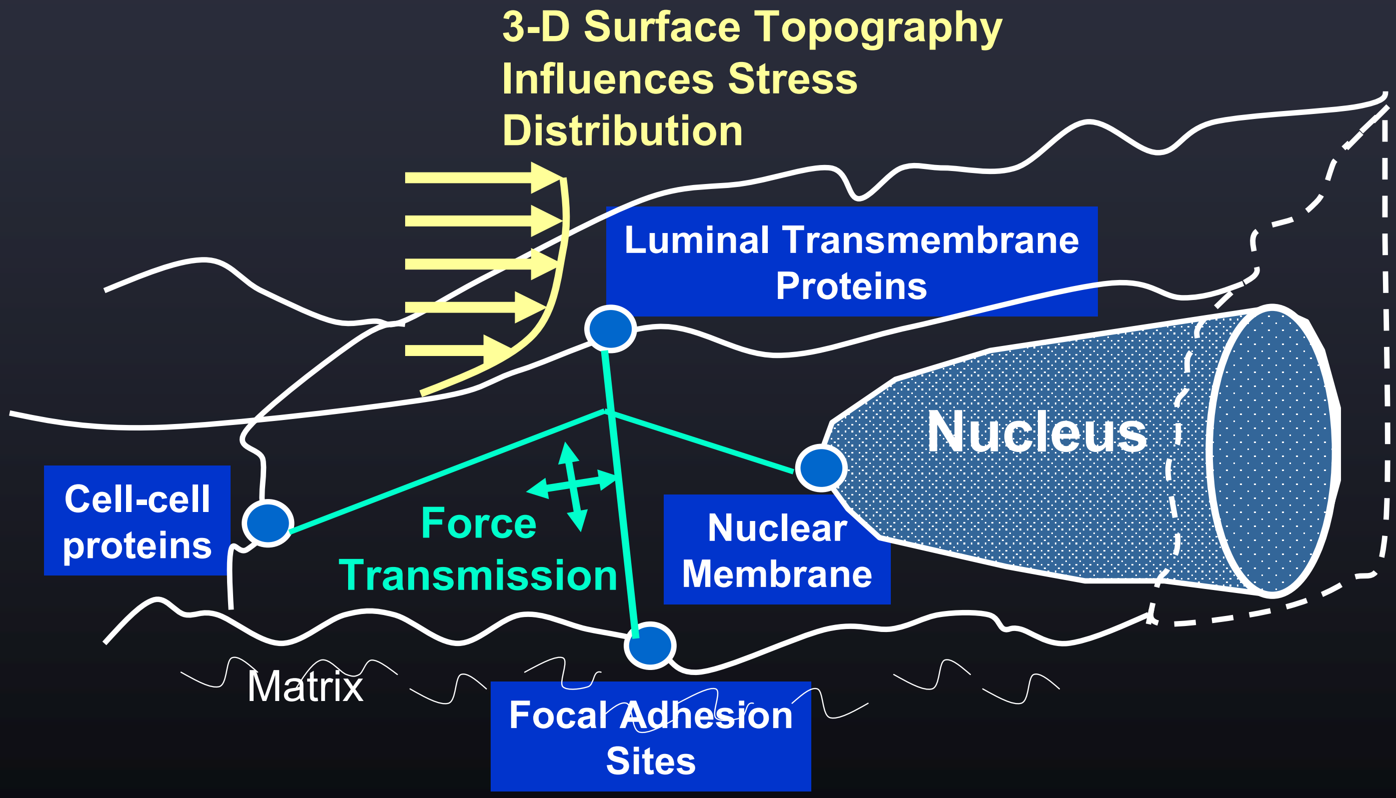
Direction of Bubble Progression

Air Bubble

Collapsed Airway

Gaver, Jensen, Halpern and Grotberg, *J. Fluid Mech.*, 1996

Mechanisms of Cell Mechanotransduction and Damage



3-D Surface Topography Influences Stress Distribution

Luminal Transmembrane Proteins

Nucleus

Cell-cell proteins

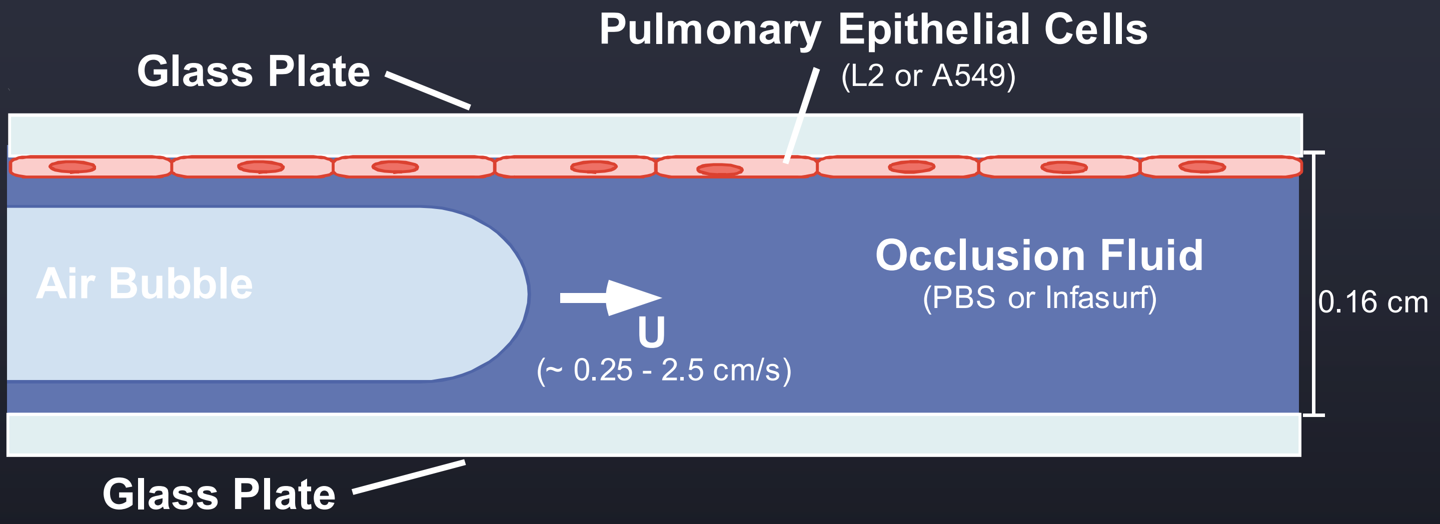
Force Transmission

Nuclear Membrane

Focal Adhesion Sites

Adapted from Davies,
Physiol. Rev., 1995

Cell Culture Experiments



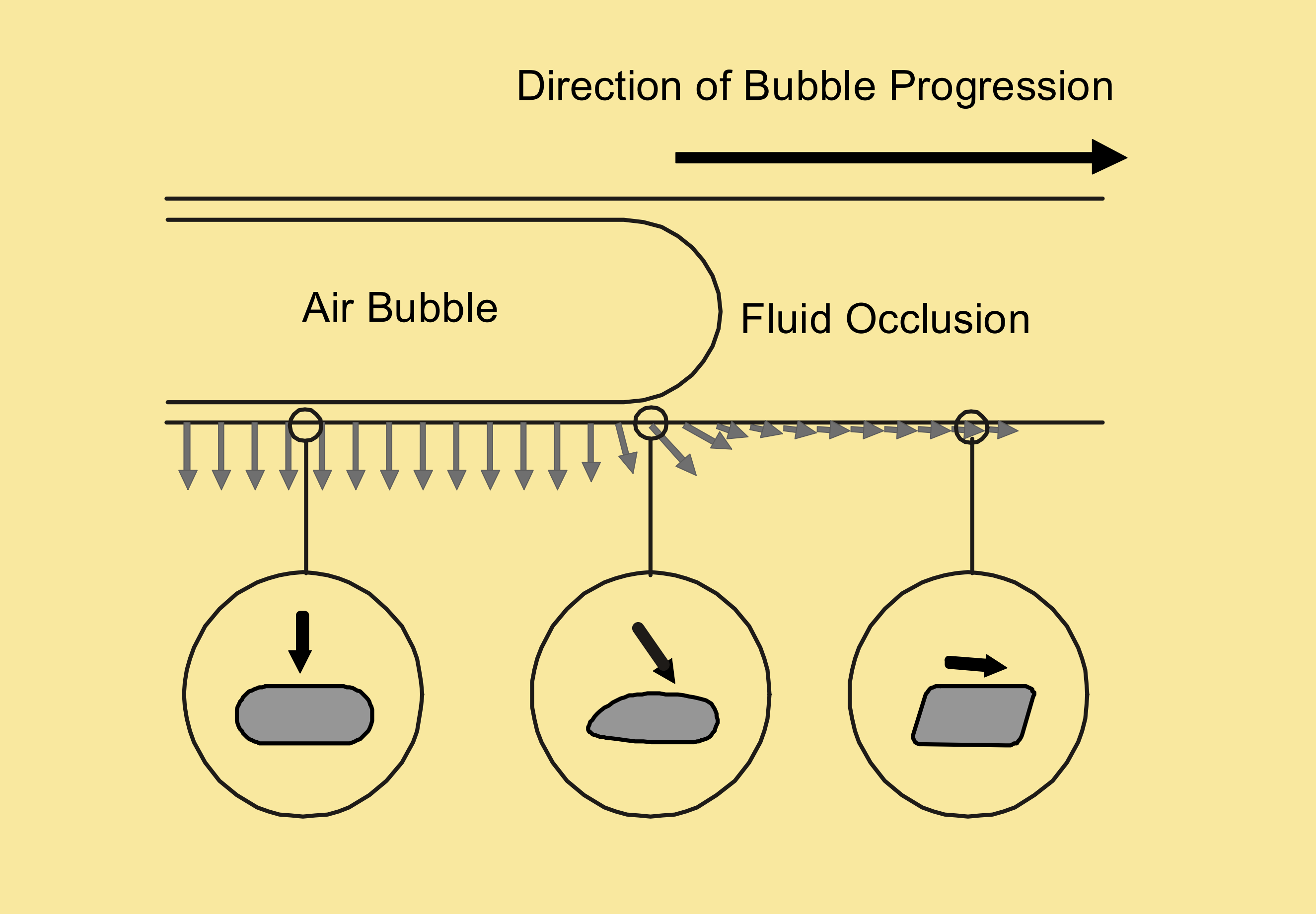
Lung epithelial cells were:

- 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

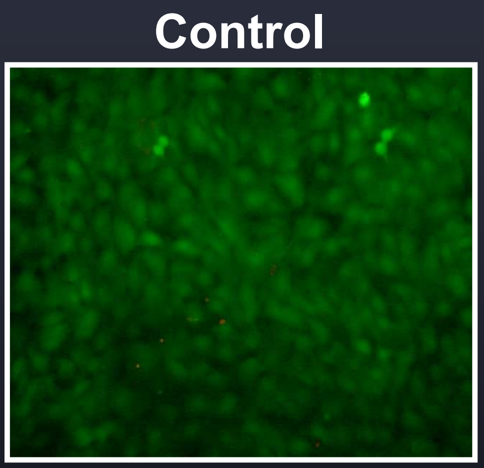
- **Lung epithelial cells (CRL-149, ATCC) cultured to confluence on glass microscope slides.**
- **The channel dimensions were 2.5 x 7.0 x 0.17 cm.**
- **Two velocities (0.27 and 2.7 cm/s) were assessed.**
- **Two occlusion fluids were assessed:**
  - **phosphate buffered saline (PBS) and**
  - **1 mg/mL Infasurf (ONY, Inc., Buffalo, NY) in PBS.**
- **Cellular trauma was quantified using fluorescent staining (Live/Dead Kit, Molecular Probes).**

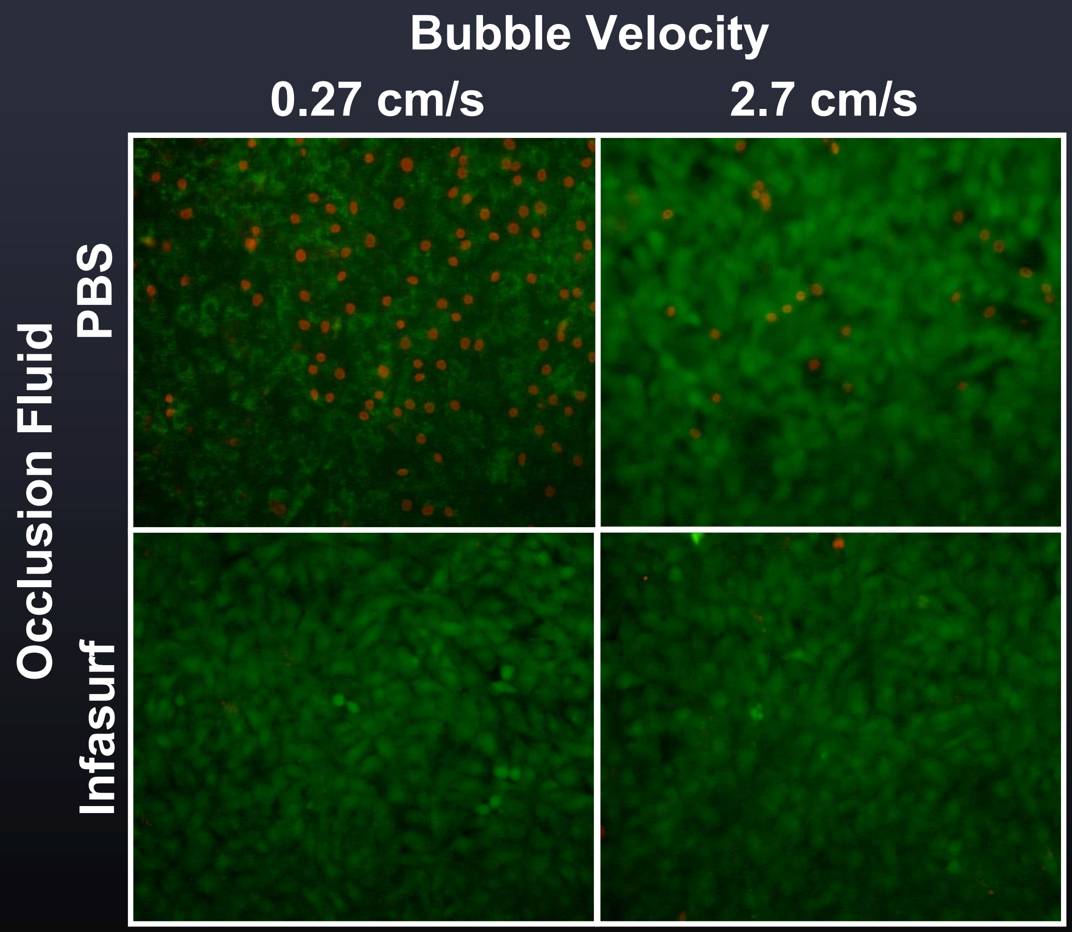
Stress Field – Rigid Channel

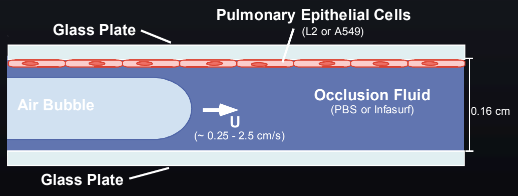


Injury by a Single Bubble Progression

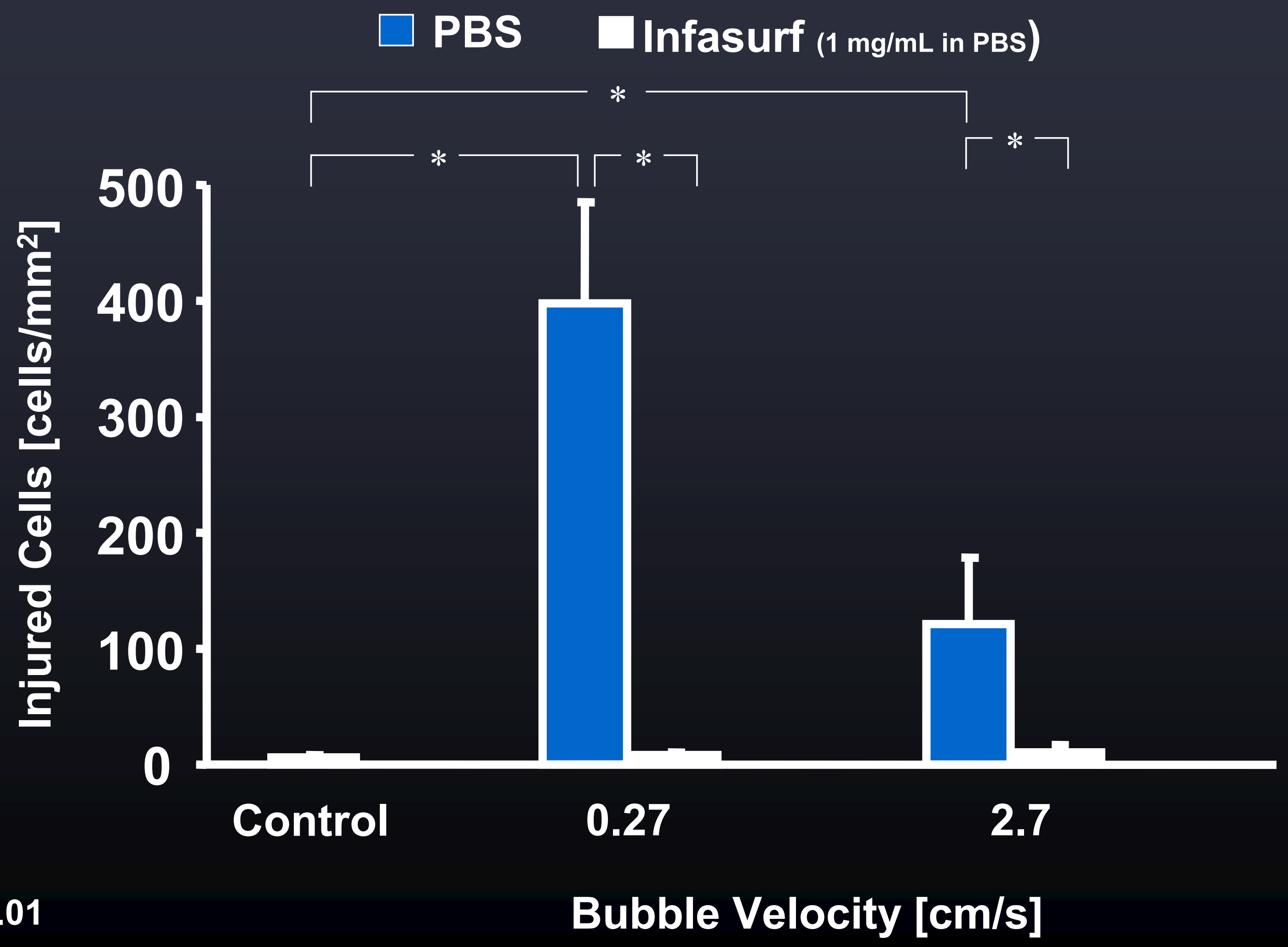
(L2 cells, Live/Dead Kit)







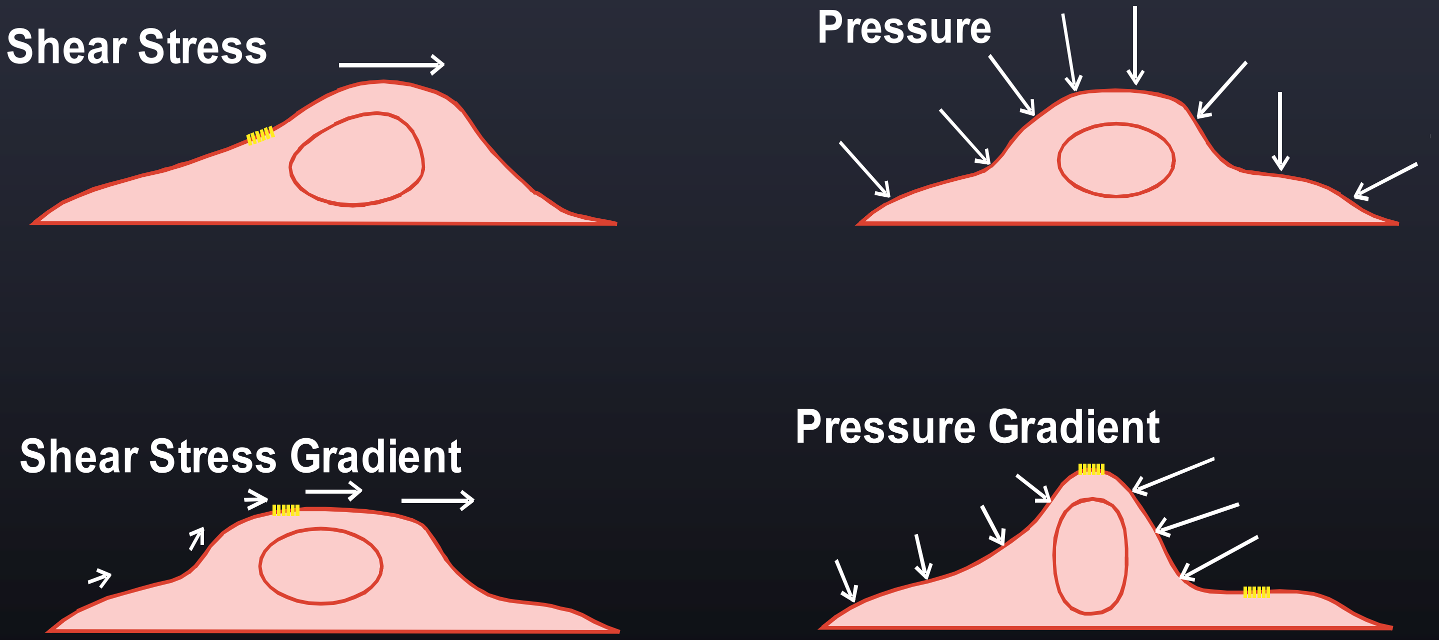
Injury by a Single Bubble Progression (L2 cells, Live/Dead Kit)



n = 5

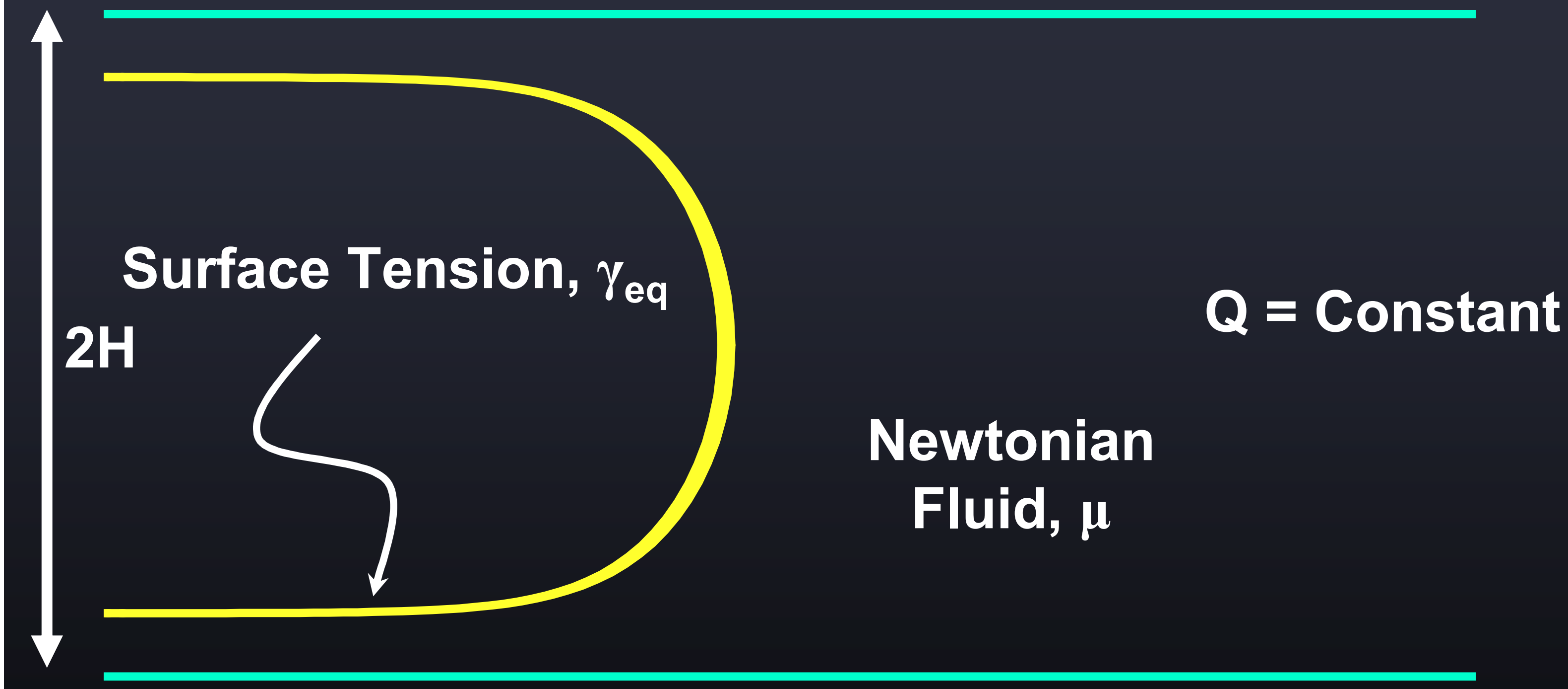
* $p < 0.01$

Mechanisms of Cell Membrane Wounding



The Flow Model

Steady Flow of a Semi-Infinite Bubble in a Channel



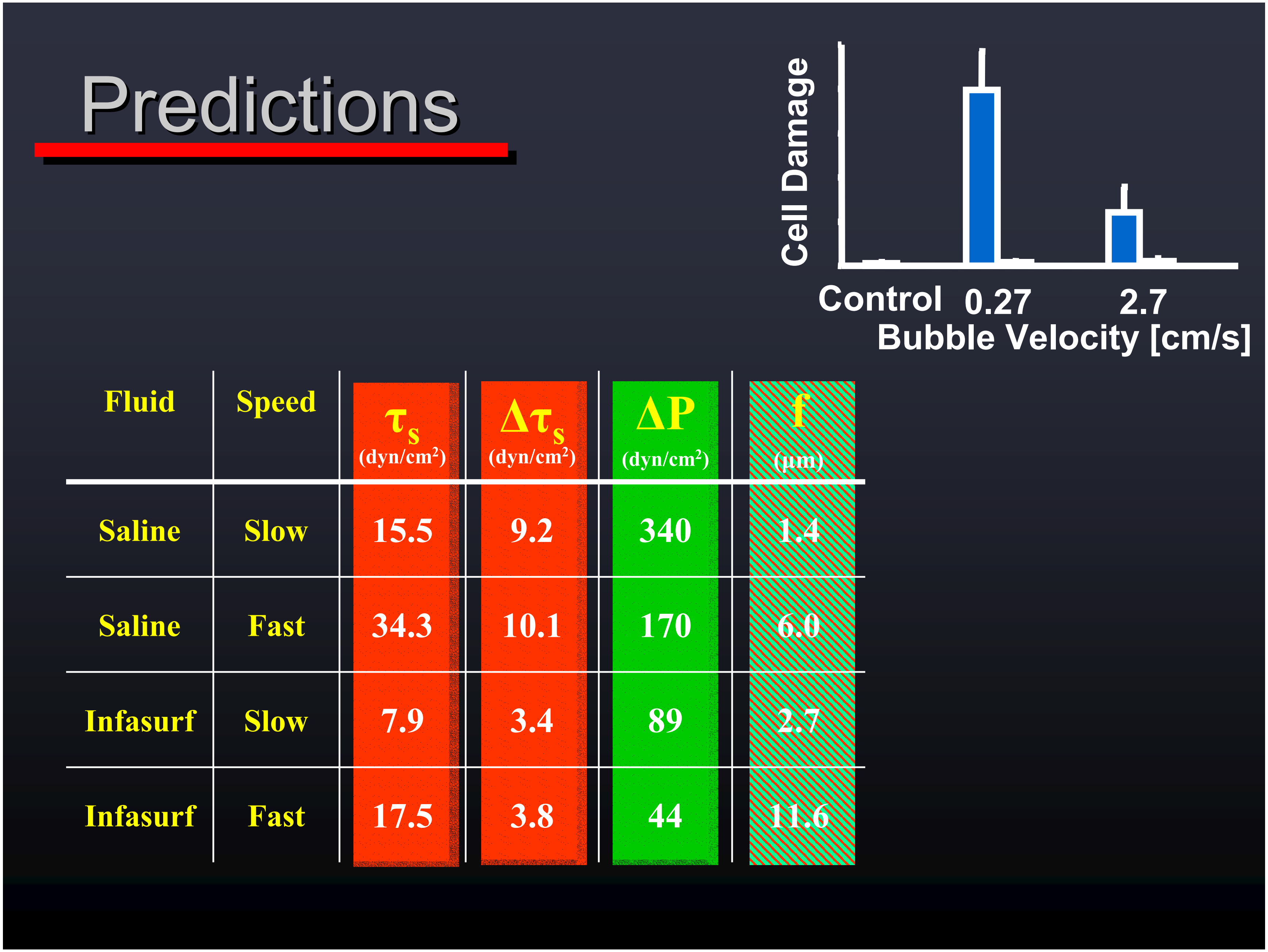
Surface Tension, γ_{eq}

2H

Q = Constant

Newtonian Fluid, μ

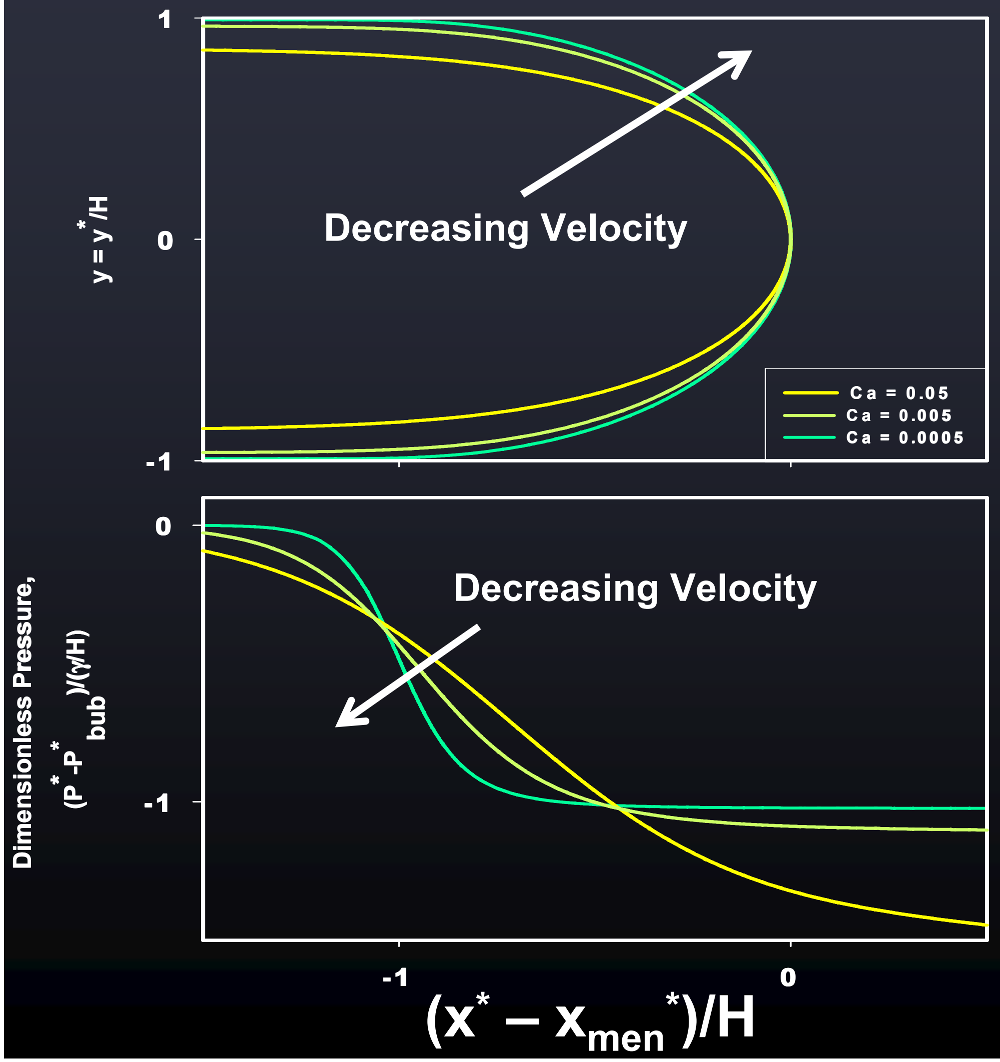
Governing Parameter: $$Ca = \frac{\mu U}{\gamma_{eq}}$$

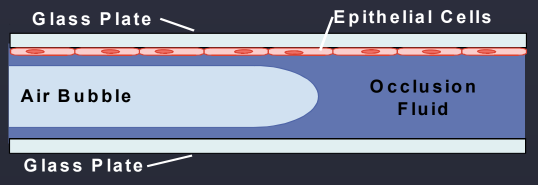


Predictions

Fluid	Speed	τ_s (dyn/cm^2)	$\Delta\tau_s$ (dyn/cm^2)	ΔP (dyn/cm^2)	f (μm)
Saline	Slow	15.5	9.2	340	1.4
Saline	Fast	34.3	10.1	170	6.0
Infasurf	Slow	7.9	3.4	89	2.7
Infasurf	Fast	17.5	3.8	44	11.6

Predictions of Cell Normal Stresses





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.

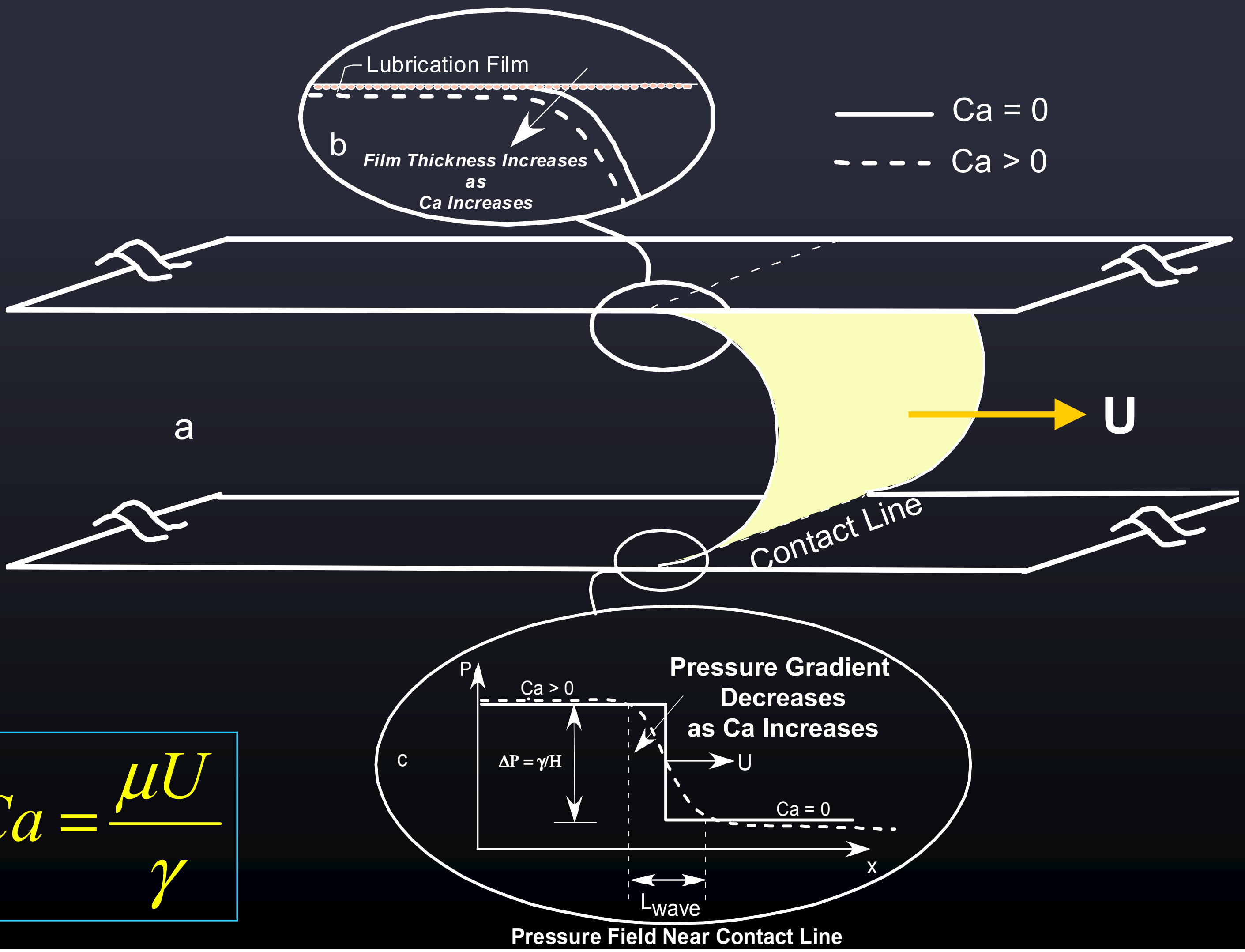
Hypothesis:

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
  - $\mu = 8\text{x}10^{-3}$ g/(cm s) (PBS)
  - $\mu = 8\text{x}10^{-2}$ g/(cm s) (PBS + 14% Dextran)
- Cellular trauma was quantified using fluorescent staining (Live/Dead Kit, Molecular Probes).

Traveling-Wave Behavior

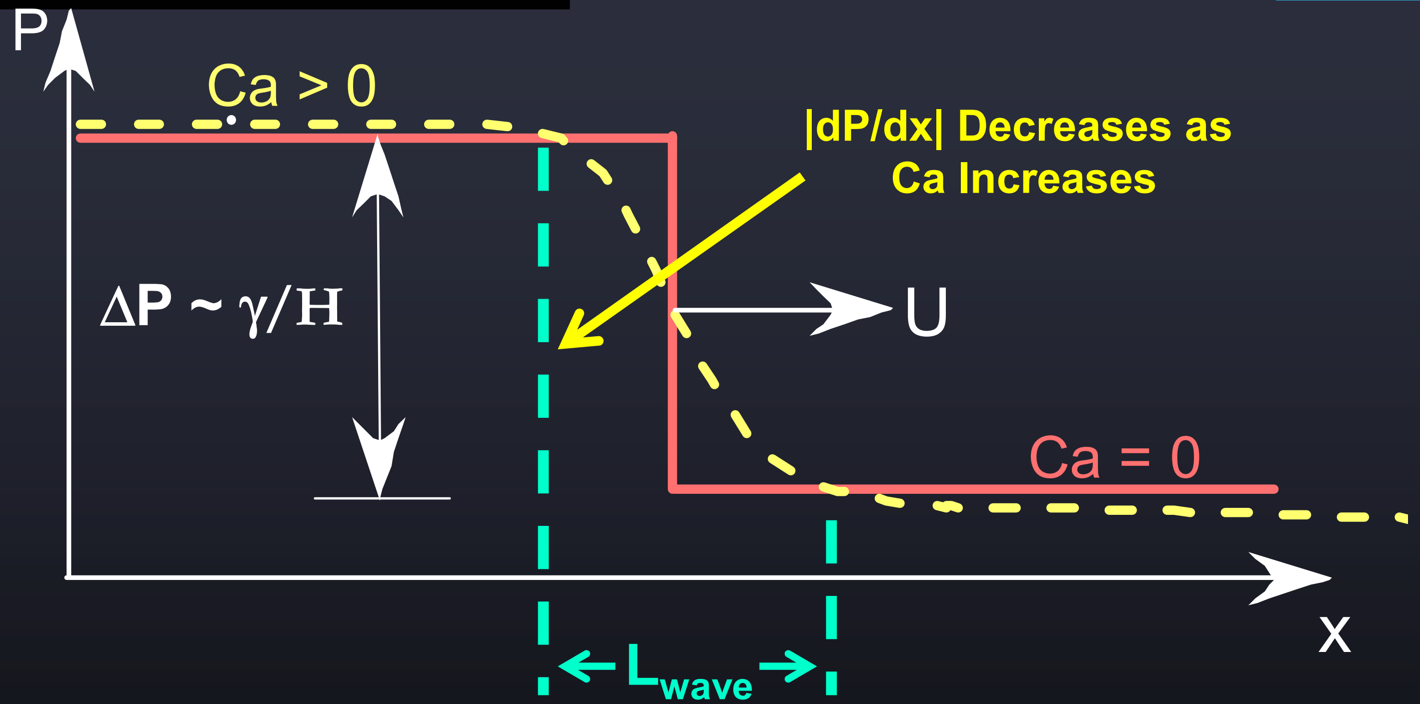


Pressure Field Near Contact Line

$$Ca = \frac{\mu U}{\gamma}$$

Traveling-Wave Behavior

$$Ca = \frac{\mu U}{\gamma}$$



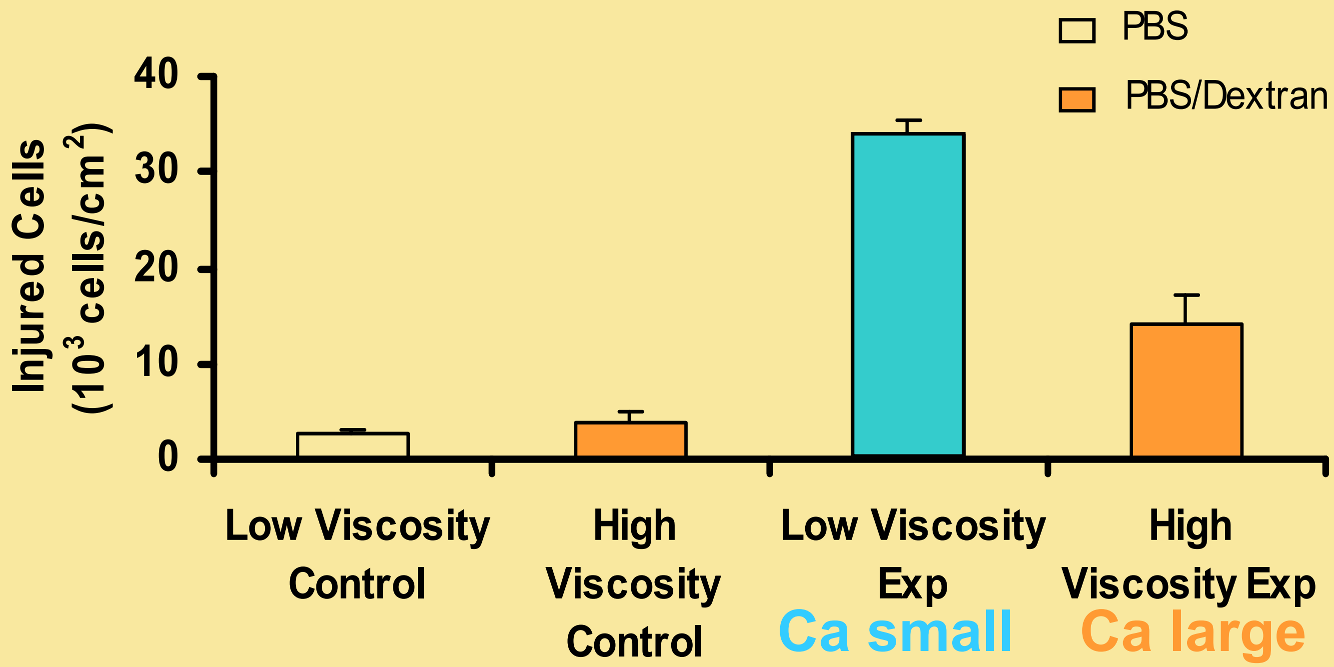
|dP/dx| Decreases as Ca Increases

Increases as Ca Increases

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

Pressure Gradient, not Exposure Duration, Determines Damage

$U = 0.34$ cm/s, $\mu_{Dextran} = 10\mu_{PBS}$



Ca small

$\frac{dP}{dx}\uparrow \tau_s \downarrow$

$t_{exp} \downarrow$

Ca large

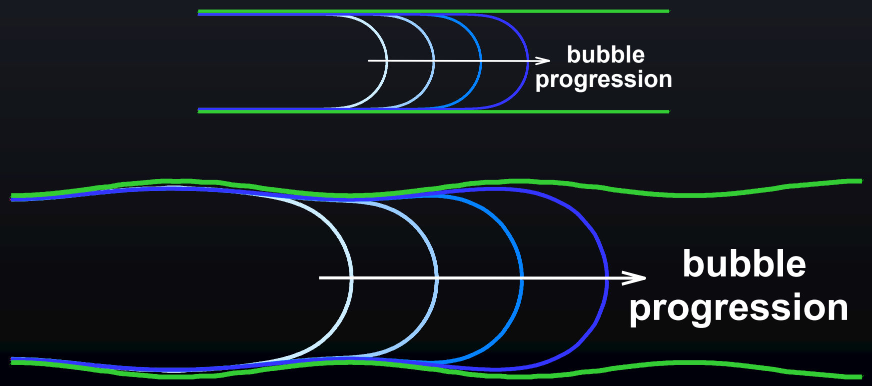
$\frac{dP}{dx}\downarrow \tau_s \uparrow$

$t_{exp} \uparrow$

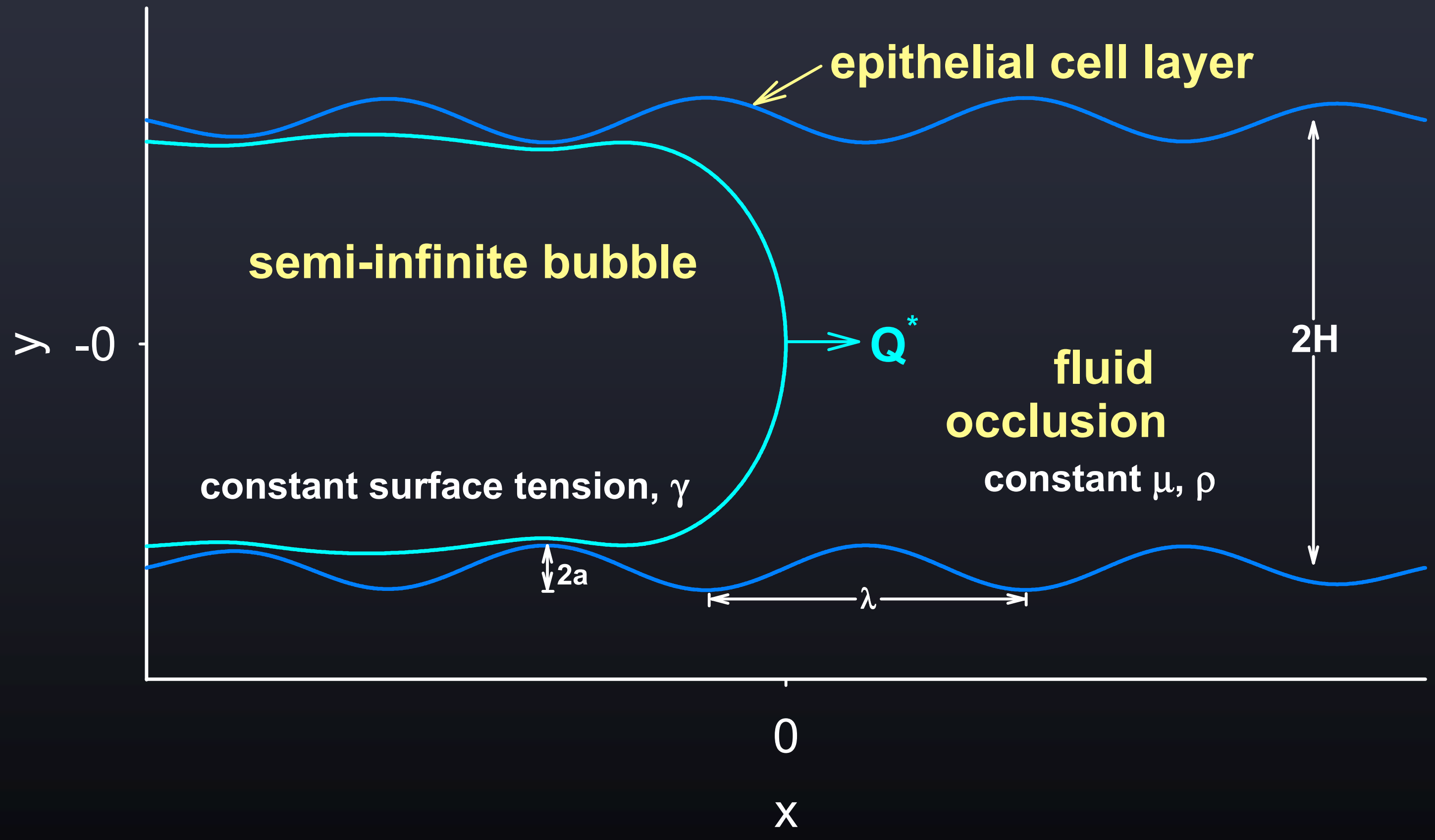
Kay *et al.*, JAP, 2004

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



epithelial cell layer

semi-infinite bubble

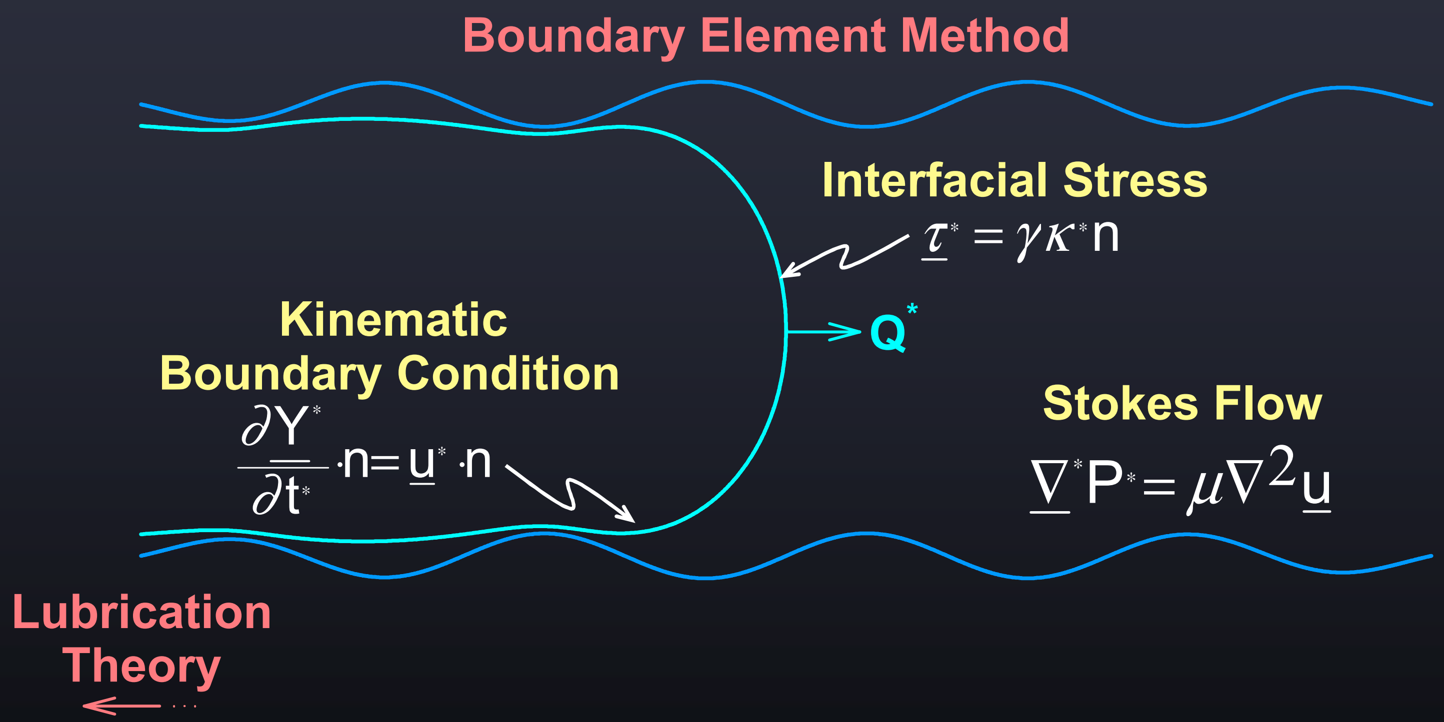
constant surface tension, γ

fluid occlusion

constant μ, ρ

- **Geometric Parameters:** $\varepsilon = a/H$ $\Lambda = \lambda/H$

Computational Model



Boundary Element Method

Interfacial Stress

$\underline{\tau}^* = \gamma\kappa^* n$

Kinematic Boundary Condition

$\frac{\partial \underline{Y}^*}{\partial t^*}\cdot n = \underline{u}^* \cdot n$

Stokes Flow

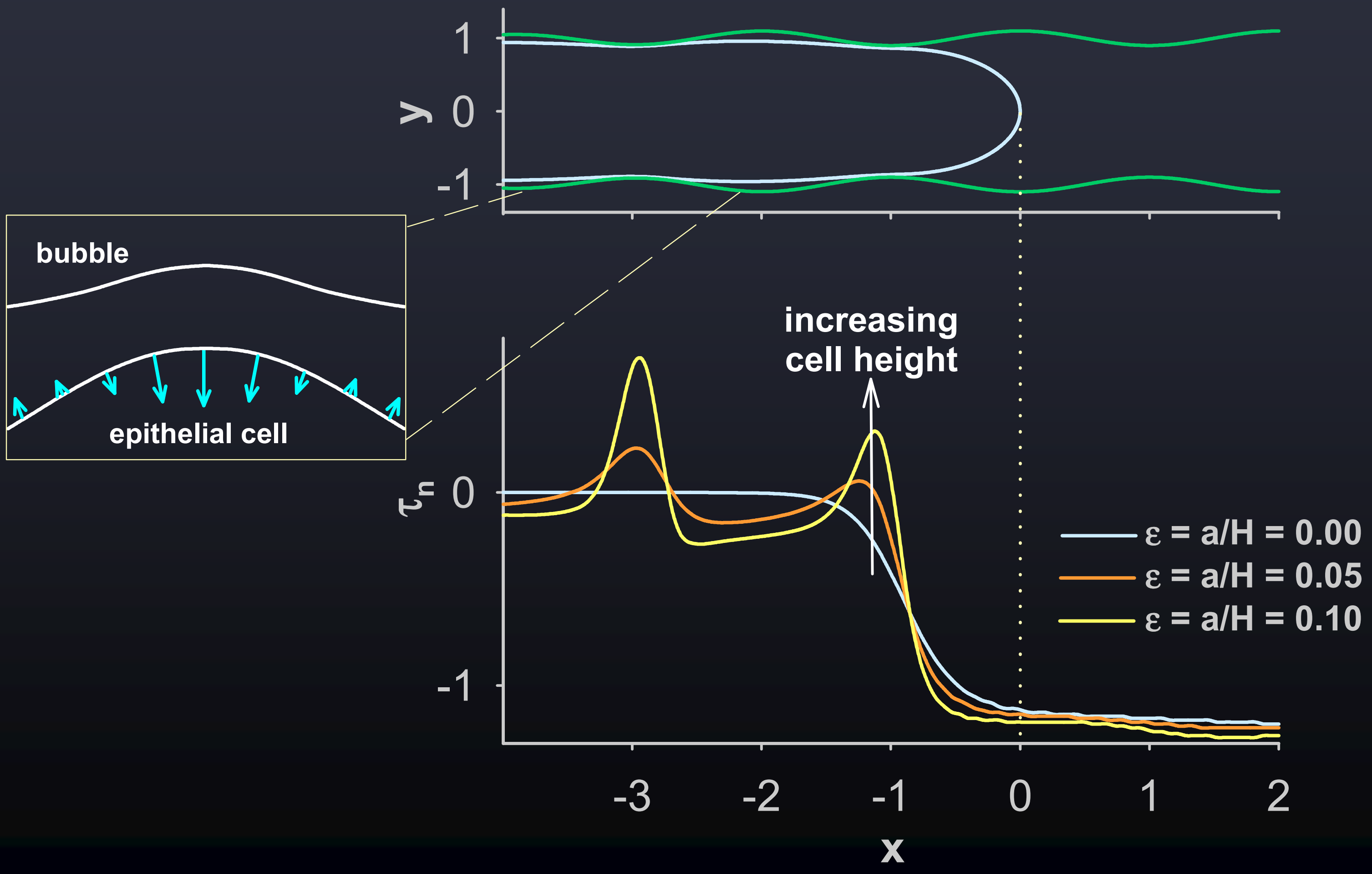
$\underline{\nabla}^* P^* = \mu\nabla^2 \underline{u}$

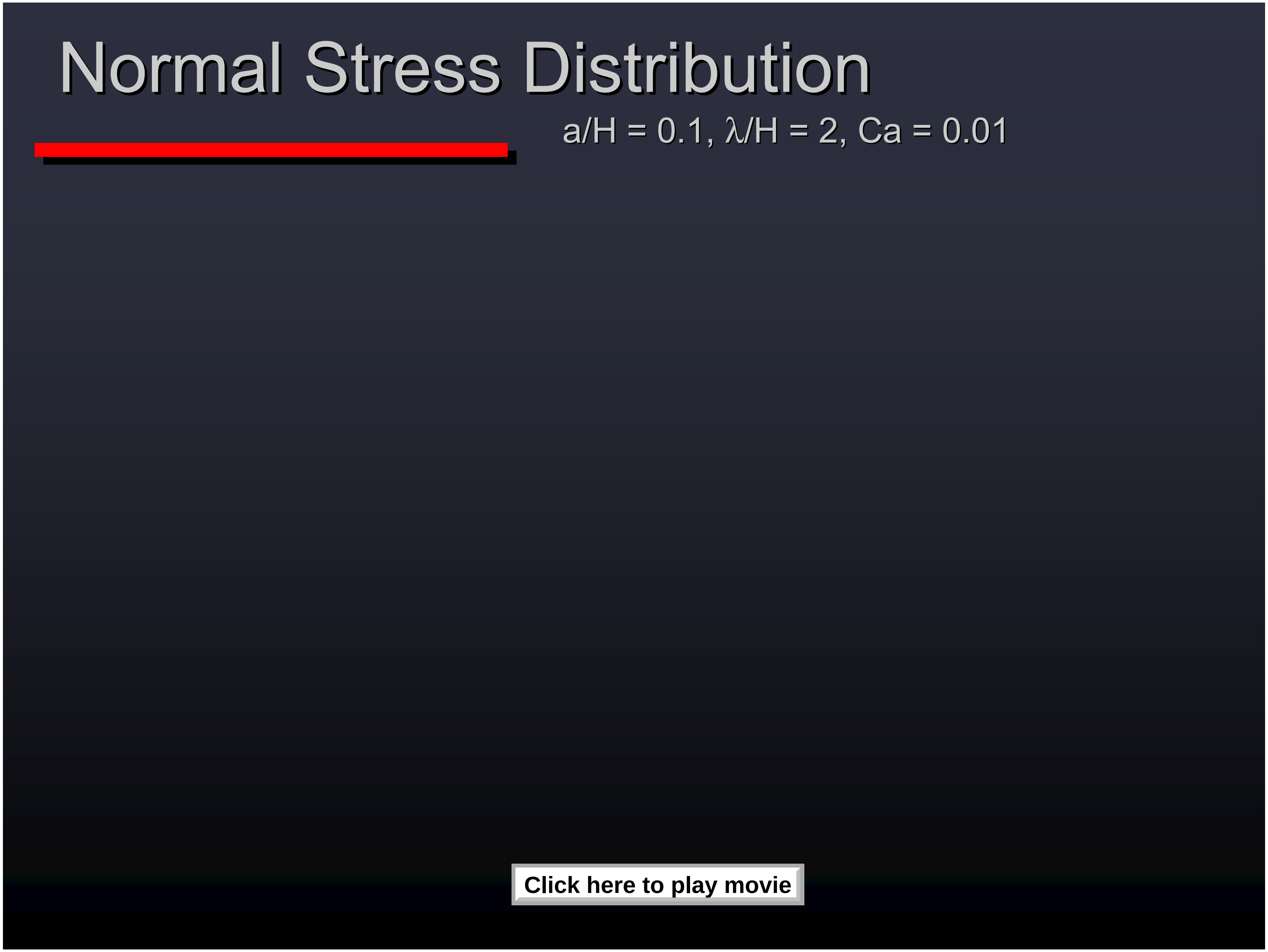
Lubrication Theory

- **Governing Parameter:** $Ca_Q = \frac{Q^*/2H}{\gamma/\mu}$

Normal Stress Distribution

λ/H = 2, Ca = 0.01



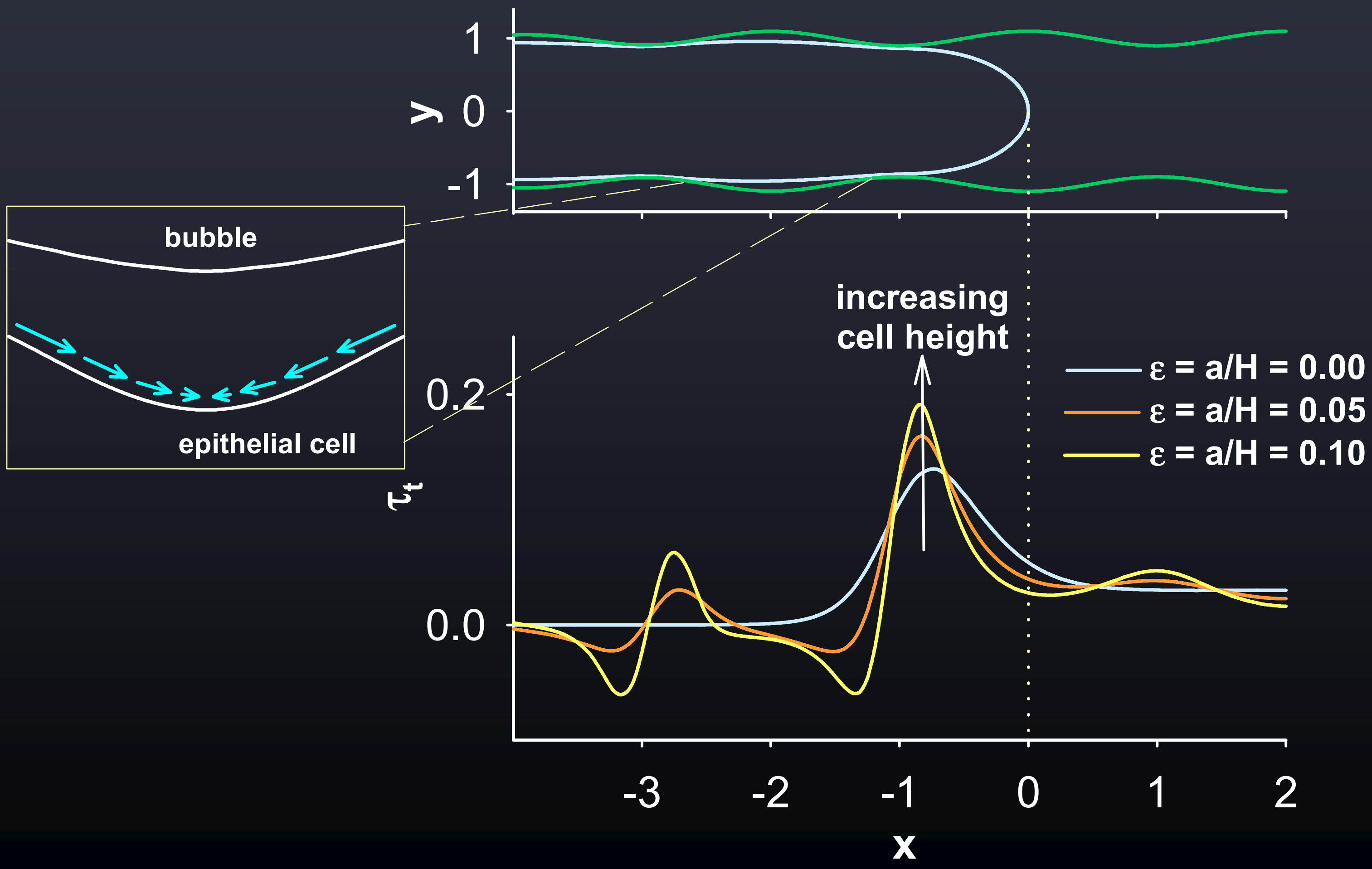


Normal Stress Distribution

$a/H = 0.1$, $\lambda/H = 2$, $Ca = 0.01$

Tangential Stress Distribution

$\lambda/H = 2$, $Ca = 0.01$



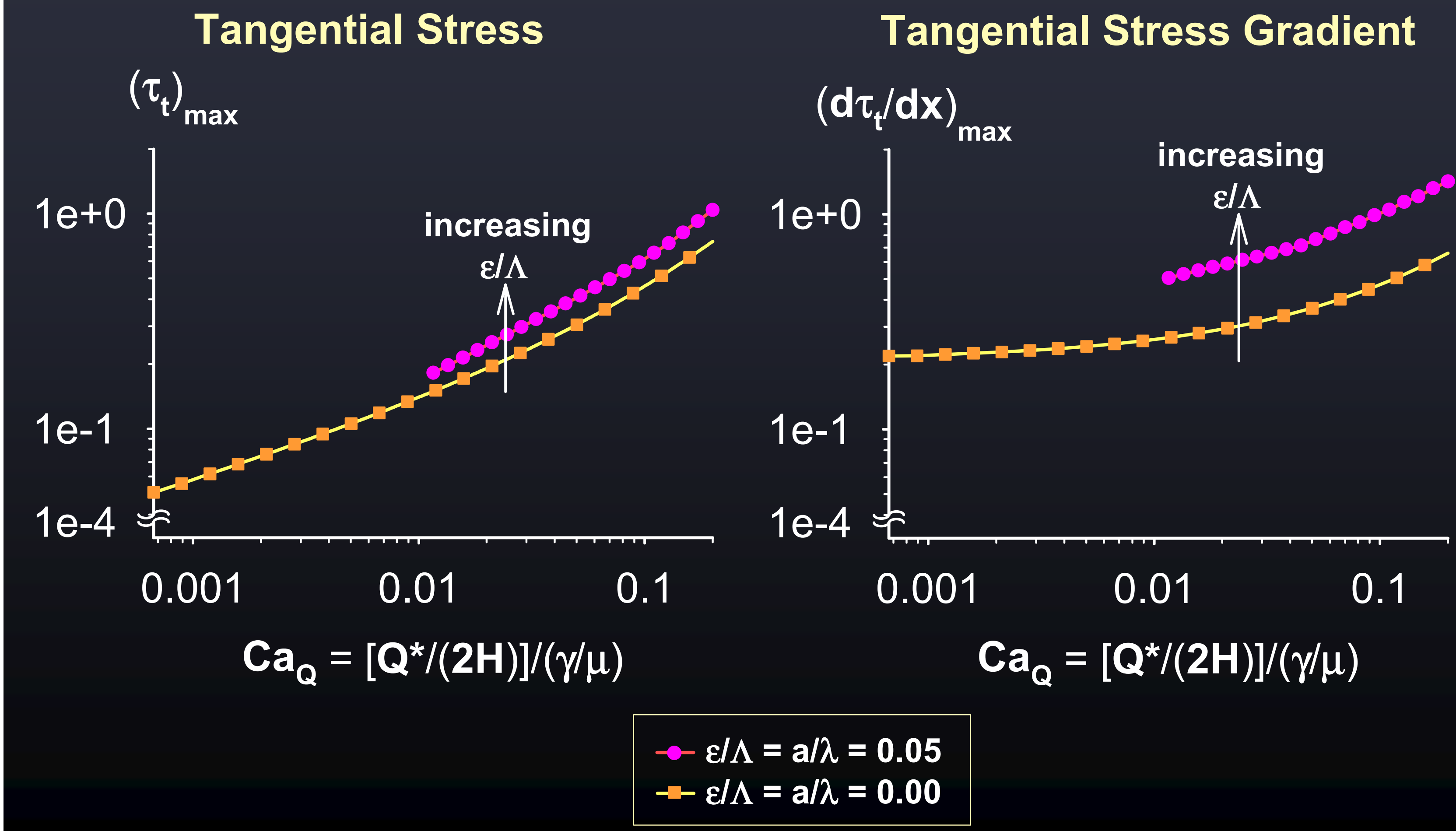
Tangential Stress Distribution

$a/H = 0.1$, $\lambda/H = 2$, $Ca = 0.01$

Click here to play movie

Ca_Q *vs.* Tangential Stress and Stress Gradient

$\varepsilon/\Lambda = 0.05$

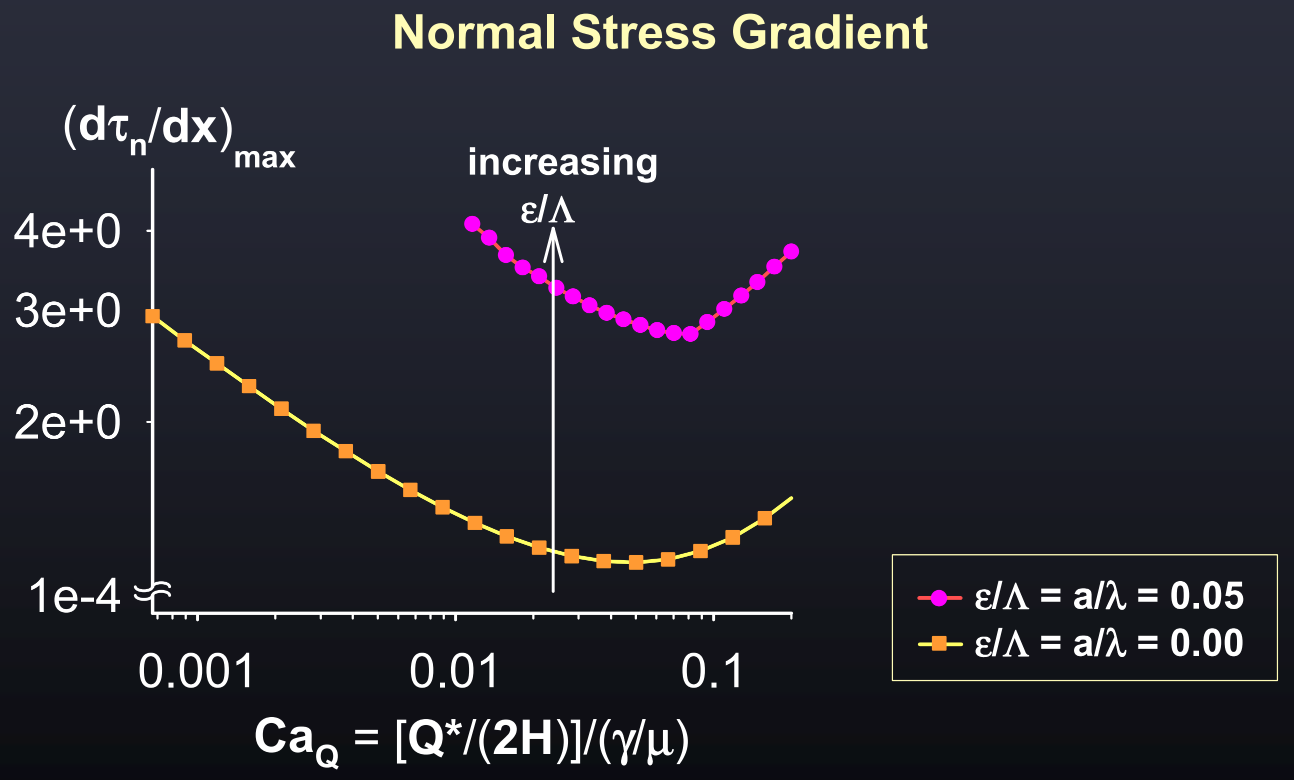


Tangential Stress

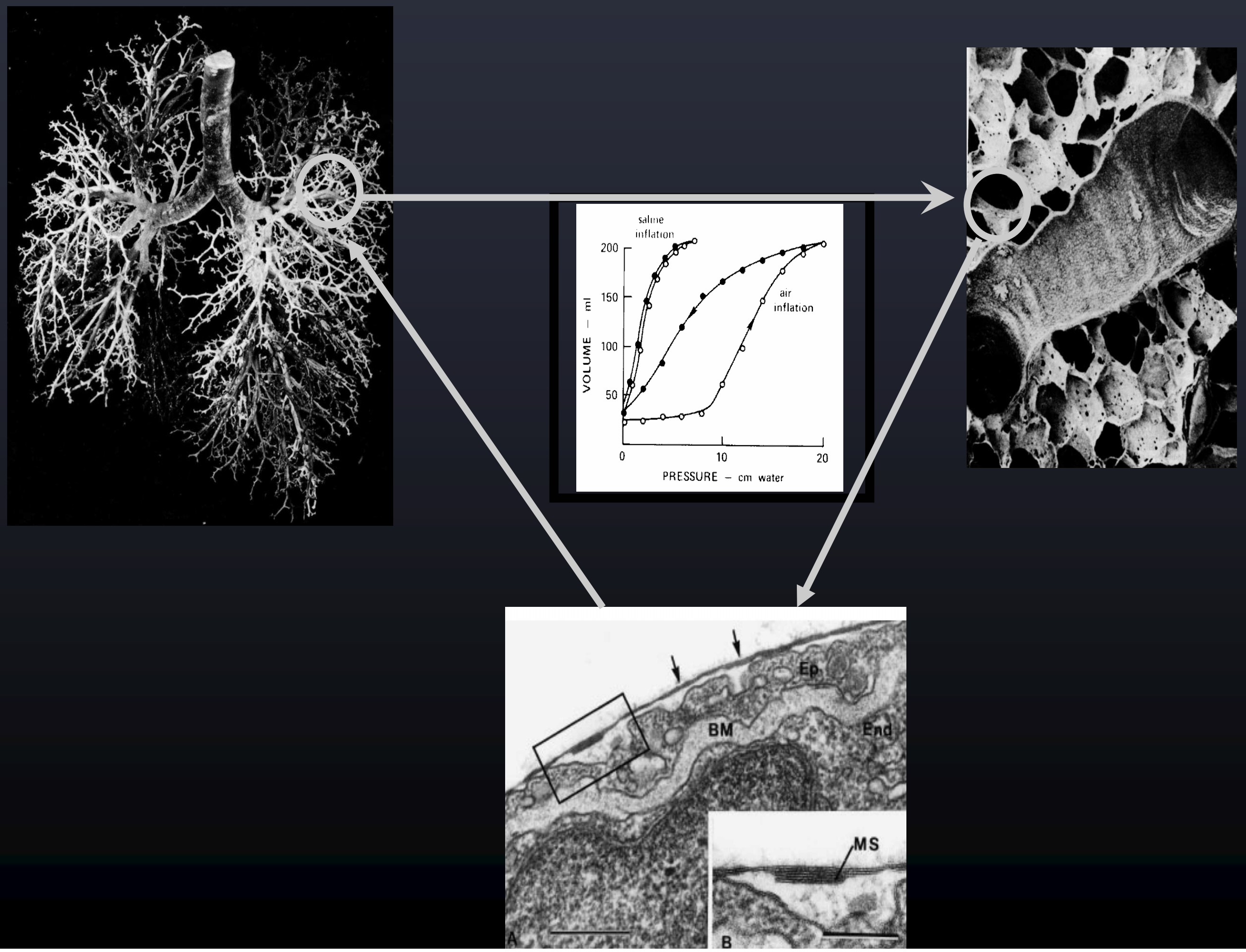
Tangential Stress Gradient

Ca_Q *vs.* Normal Stress Gradient

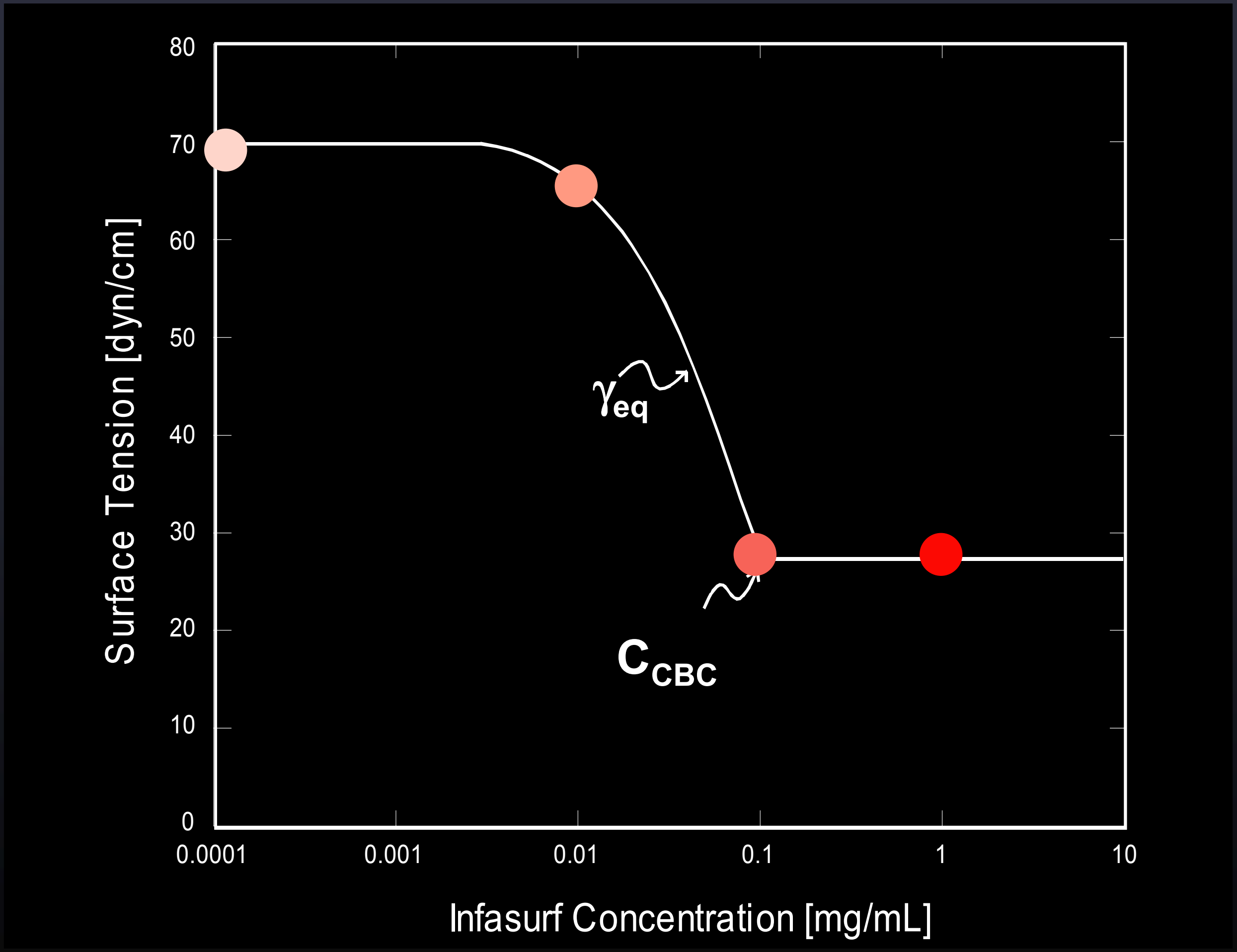
$\varepsilon/\Lambda = 0.05$



Surfactant Effects



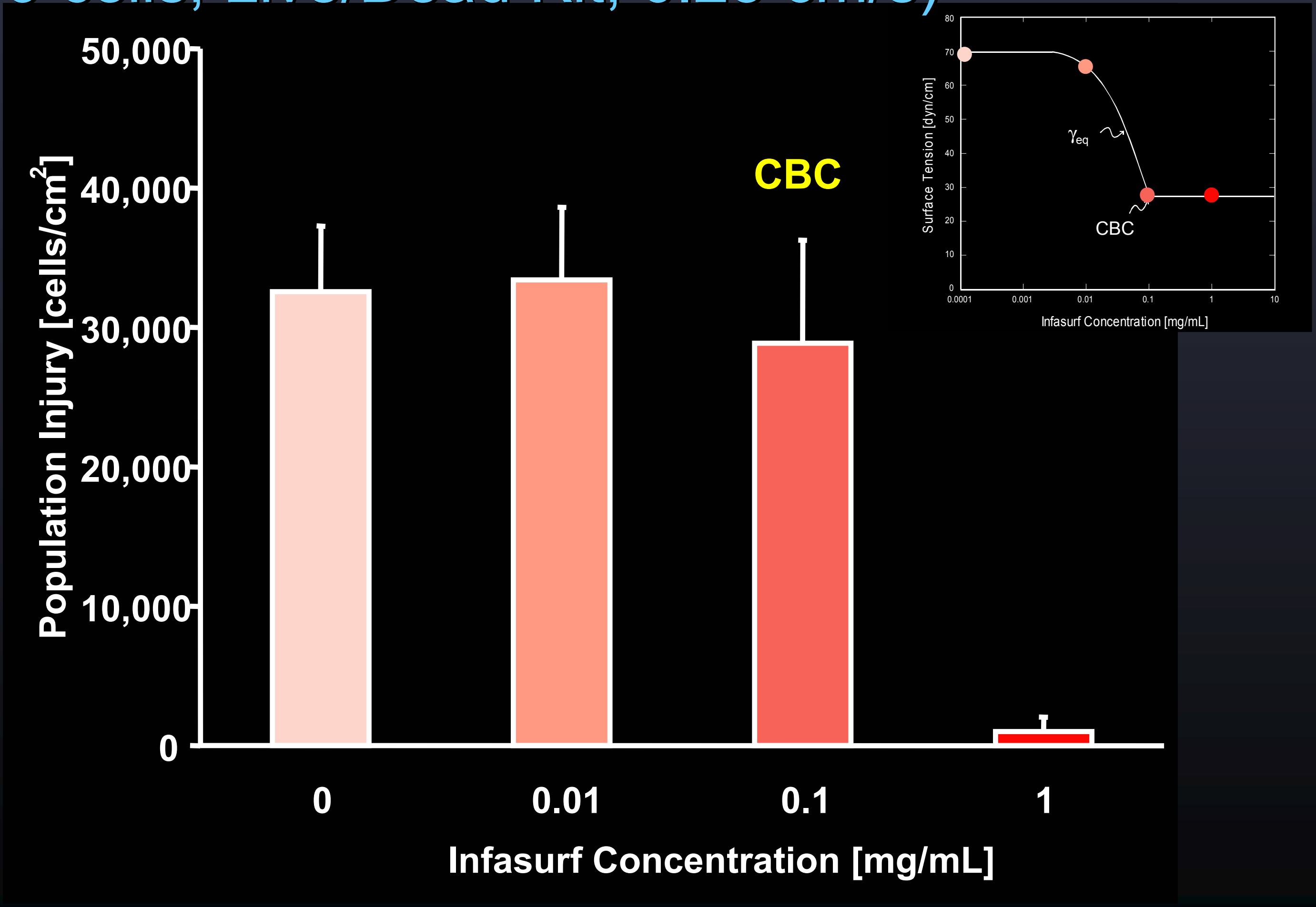
Equilibrium Equation of State (Infasurf)



Ghadiali, S. N. and D. P. Gaver, III (2000). J. Appl. Physiol. 88: 493-506.

Influence of Surfactant Concentration

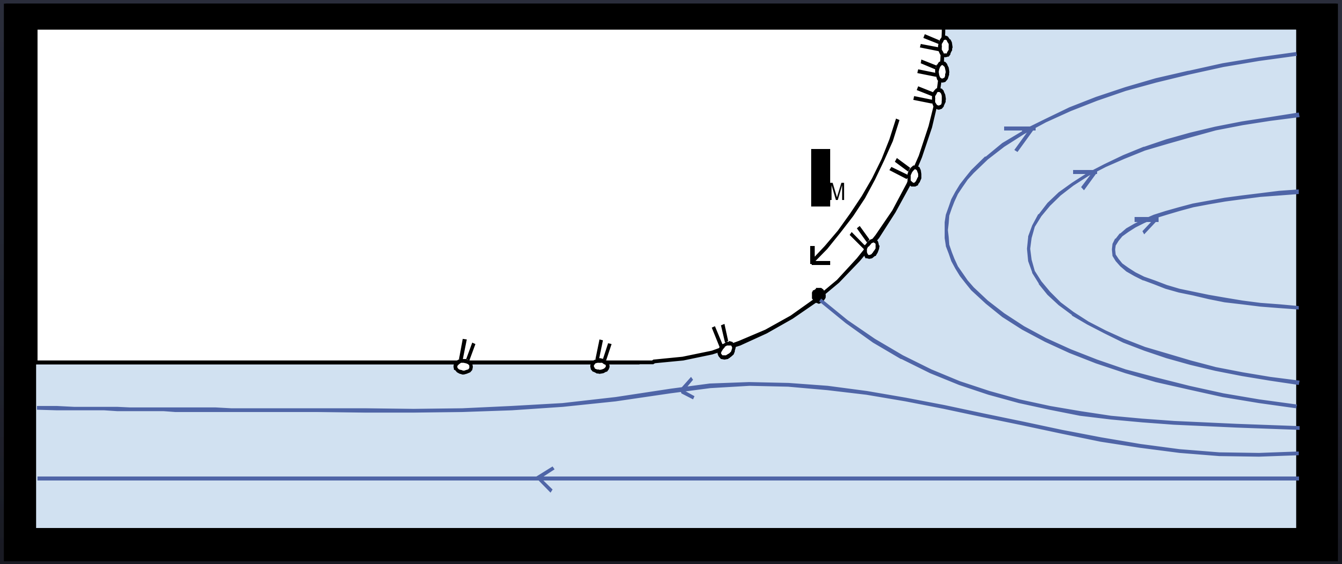
(A549 cells, Live/Dead Kit, 0.25 cm/s)



Correlation of Stress and Injury

Infasurf (mg/mL)	**Speed** (cm/s)	**Injury** (cells/cm^2)	τ_s (dyn/cm^2)	$\Delta\tau_s$ (dyn/cm^2)	ΔP (dyn/cm^2)	
0	0.25	++	13.1	4.8	163	✓
0.01	0.25	++	12.8	4.6	154	✓
0.1	0.25	++	7.1	1.9	48	?
1	0.25	-	6.7	1.8	44	✓

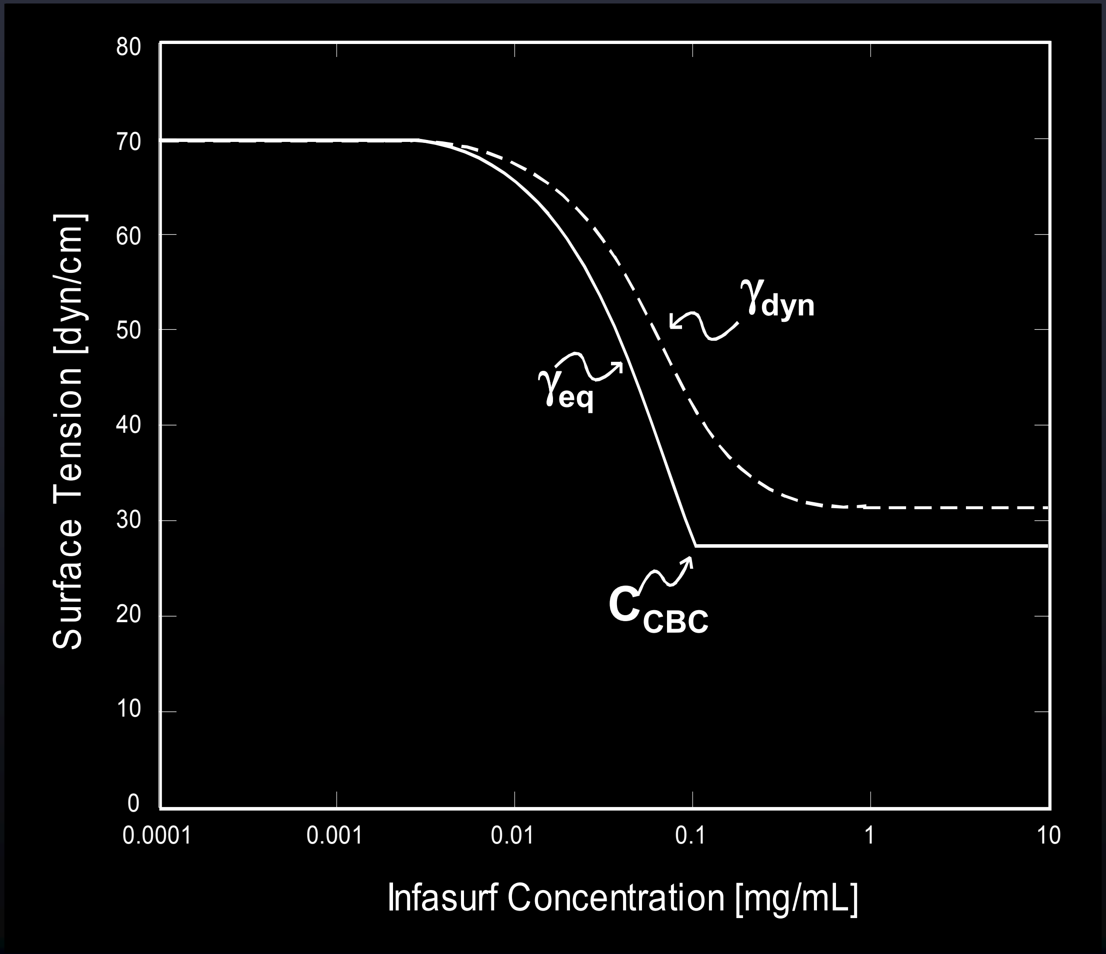
Influence of Non-Equilibrium Behavior of Infasurf



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



Ghadiali, S. N. and D. P. Gaver, III (2000). J. Appl. Physiol. 88: 493-506.

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 BIOCIDE 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

Paul Mudgett, Jeff Rutz, and John Schultz
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

NASA Bioscience and Engineering Institute **University of Michigan**

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

space

- Development of a new generation of Bioengineers

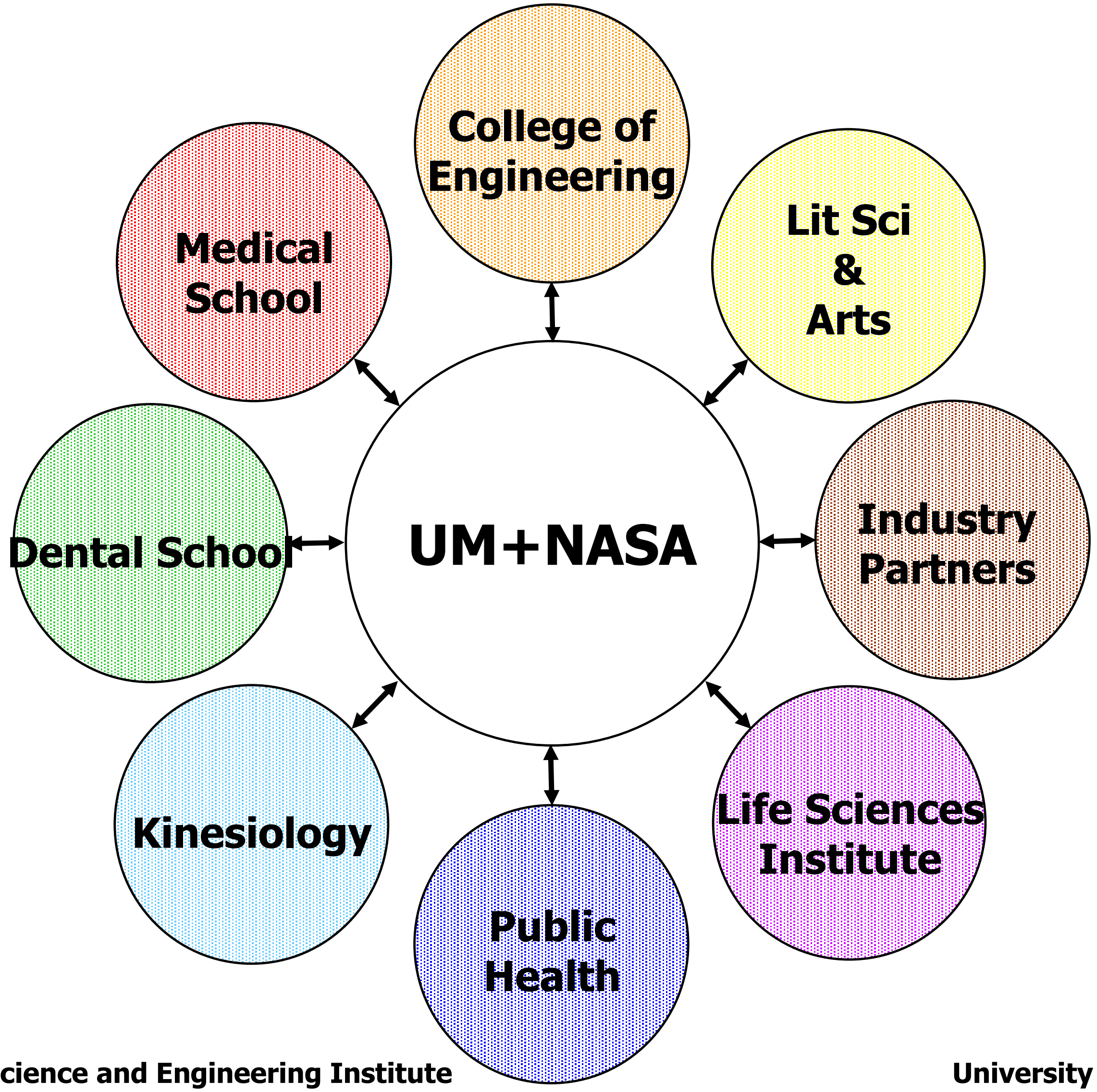
^

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

College of Engineering

Lit Sci & Arts

Industry Partners

Life Sciences Institute

Public Health

Kinesiology

Dental School

Medical School

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.

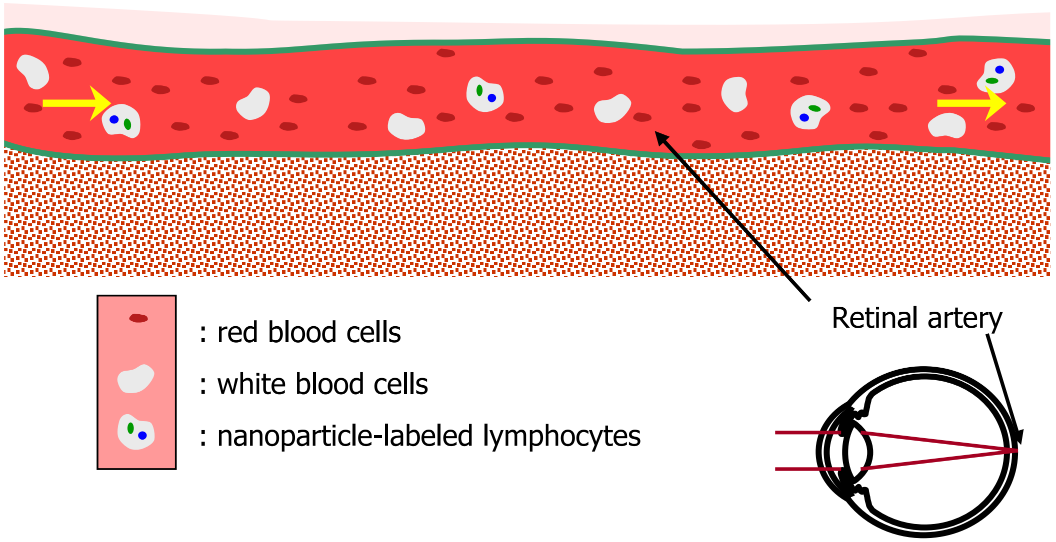
INCEPTION September, 2003

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**

MB1: Molecular Nanosystems to Monitor Astronaut Radiation Sickness

PI James Baker, M.D.

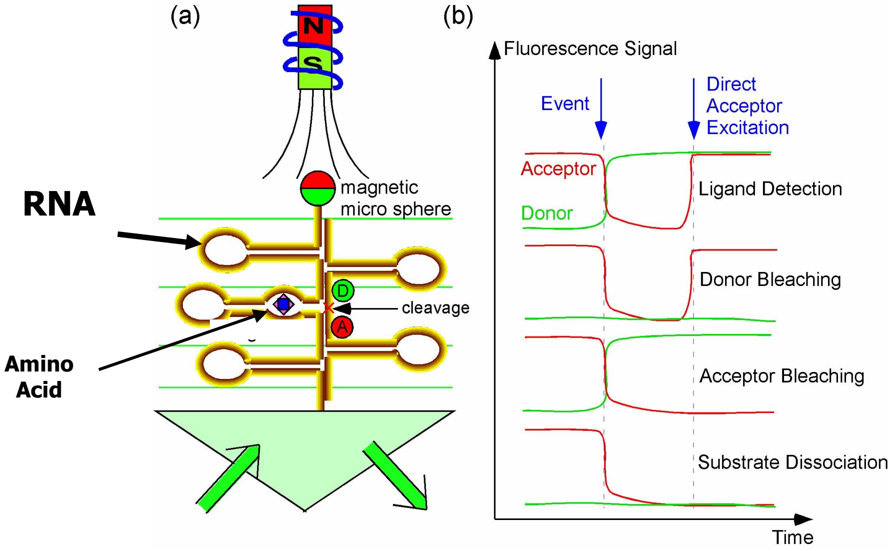
NBEI Goal Develop a device to quantify radiation effects and other physiological states in astronauts

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



Optical probe (TIRF)

Chris Meiners, Physics; Nils Walter, Chem

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

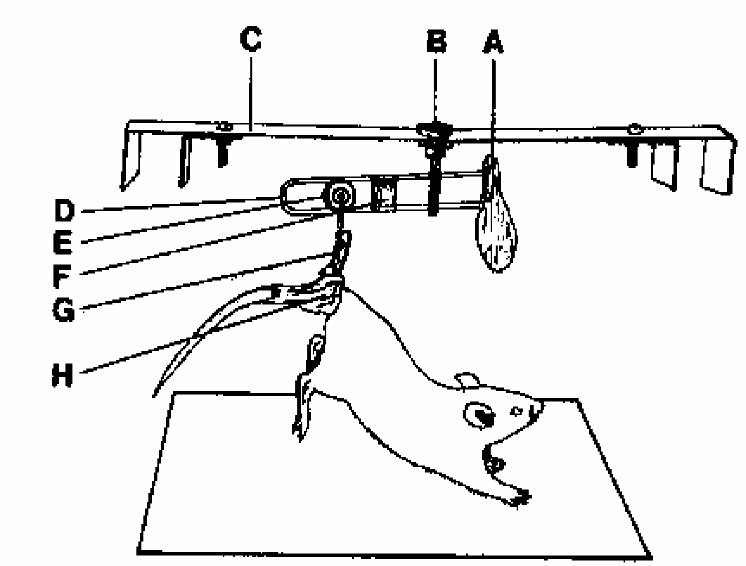
- Develop and validate a single molecule analysis system based on a TIRF microscope
- Adapt TIRF technology to a BioMEMS chip
- Validate single RNA molecule analysis with the TIRF microscope
- Complete a fully-functional biosensor chip to detect life

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

TB1: Effects of Hind-Limb Unweighting on Muscle Function

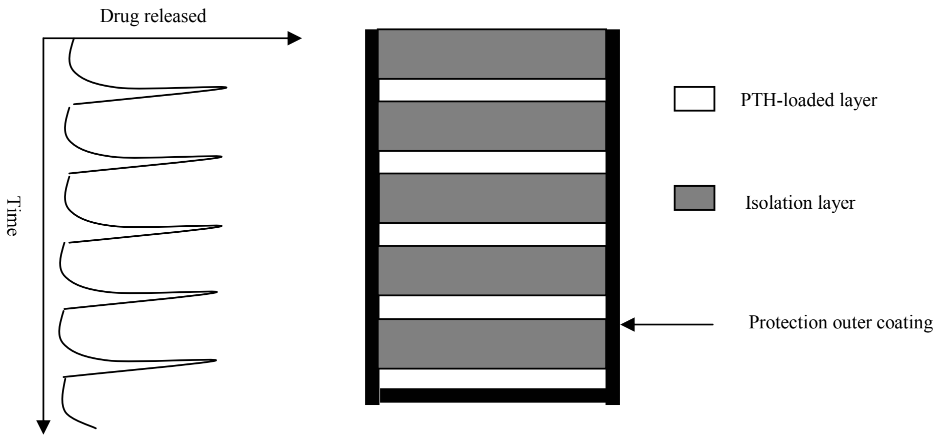
PI Robert G. Dennis, Ph.D./Susan Brooks, Ph.D.

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

Research Details

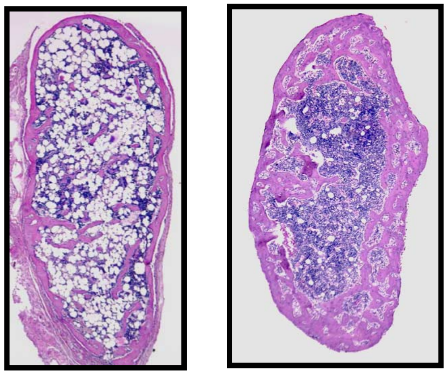
- Determine number of myogenic precursor (satellite) cells as a function of the duration of modeled microgravity due to hind limb suspension of rats.
- Assess effects of microgravity on satellite cells by observing growth dynamics in two dimensional cultures
- Grow in vitro functional muscle tissue from 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 counter-measure 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

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

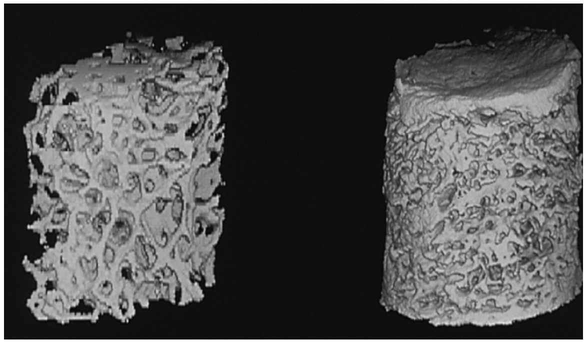
Research Details

- 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

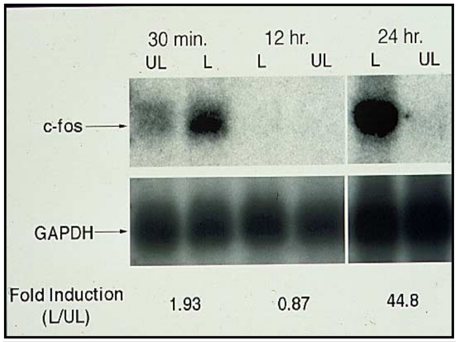
Project TB3: Mechanical signal transduction in bone under microgravity conditions.

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

Hydraulic loading chamber



control 12 weeks load



early gene response to single load

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

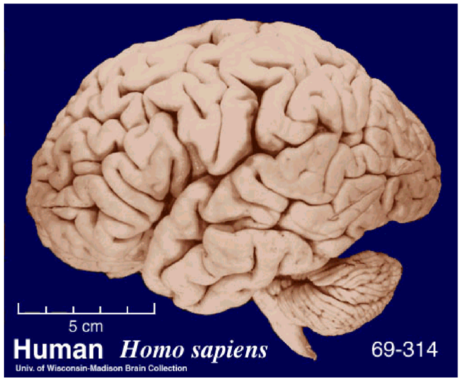
- Identify short and long term cellular and molecular events associated with mechanical stimulation from a hydraulically-controlled *in vivo* device
- Measure integrin-mediated signal transduction as a function of applied force and rate of force application
- Adapt *in vivo* rodent model for investigating mechanotransduction in a space flight environment

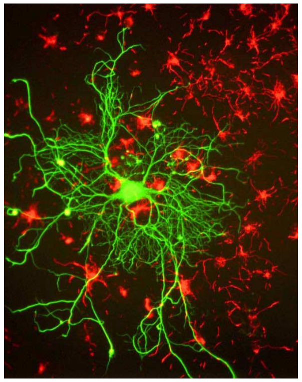
Research Theme: Transport Phenomena in Biology & Devices

Theme Leader: Ron Larson, PhD **Chem Eng (Chair)**

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

NASA Bioscience and Engineering Institute **University of Michigan**

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

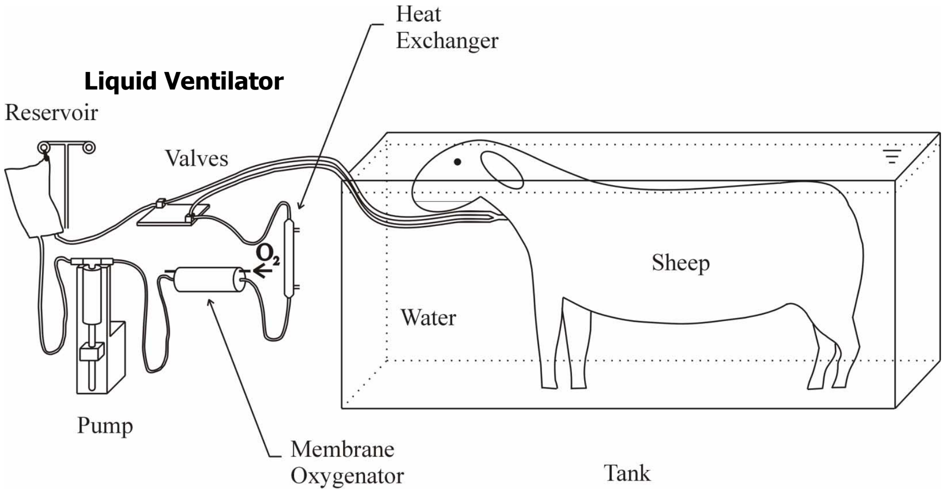
- Begin by developing microfluidic devices to vary fluid flow rates in the cell culture chamber to change shear stress and rate of nutrient delivery
- Include pulsatile flow to mimic physiological conditions and study how proliferation, differentiation, shape and death are affected by stress and nutrient 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.

Photograph courtesy of Alliance Pharmaceutical Corp., 1999

Rat breathing perfluorocarbon liquid spontaneously



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

NASA Bioscience and Engineering Institute **University of Michigan**

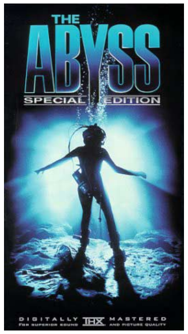
TP2: An Earth-Based Model of Microgravity Pulmonary Physiology

PI Ronald B. Hirschl, M.D.

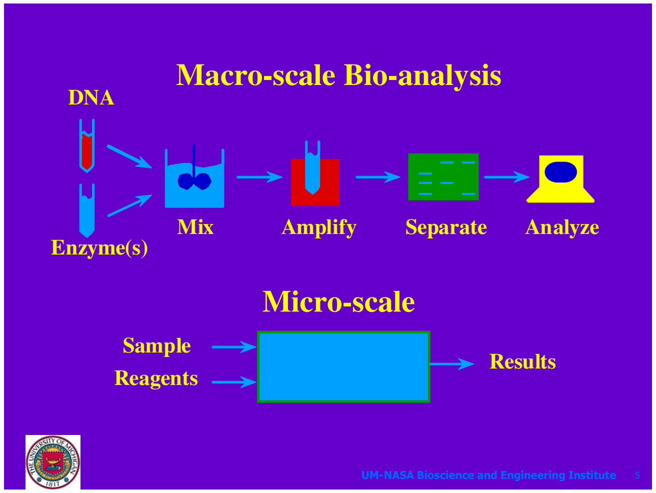
NBEI Goal Develop an experimentally verified model of microgravity respiration and incorporate with digital astronaut effort

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

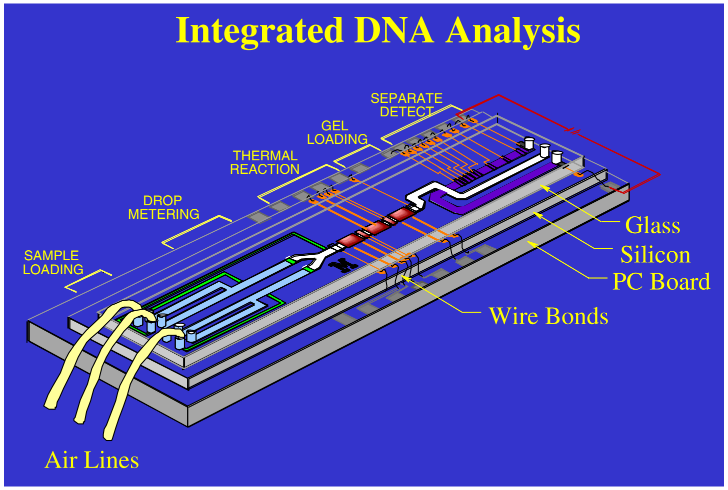


Project TP3: Lab-on-Chip devices: Portable medical diagnosis, initial studies on saliva to monitor astronaut health



Macro-scale Bio-analysis

Micro-scale



Integrated DNA Analysis

**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

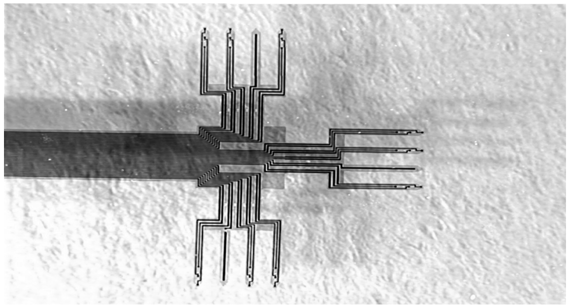
- Use cravicular fluid (saliva between teeth) because it has many serum markers present in blood and collection is non-invasive
- Characterize rheological properties of saliva for chip level analysis
- Study droplet evaporation and associated DNA stretching as a method of preparing the DNA for scission
- 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

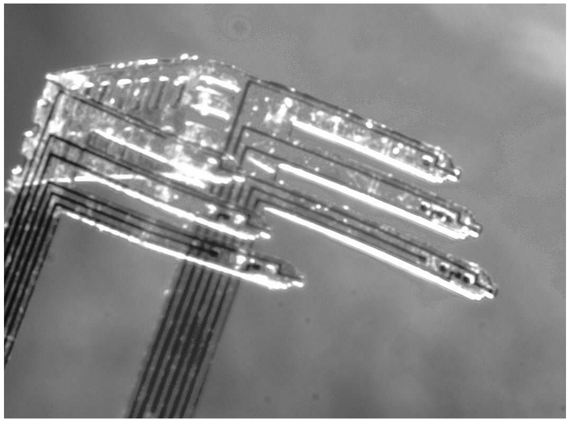
Research Theme: BioMEMS and Biomaterials

Theme Leader: Daryl Kipke, PhD **BME**

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





Zhao Chen, Chem
Daryl Kipke, BME
David Martin, MSE
Khalil Najafi, EECS

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 Partners

JOMED

Pfizer
Life is our life's work.

COLLAGENEX
pharmaceuticals

Alliance
PHARMACEUTICAL CORP.

caliper®

Lilly
INNOVATION IN MEDICINE

SIEMENS

C^3

ETHICON
a Johnson & Johnson company

INTRALASE

We bring good things to life.

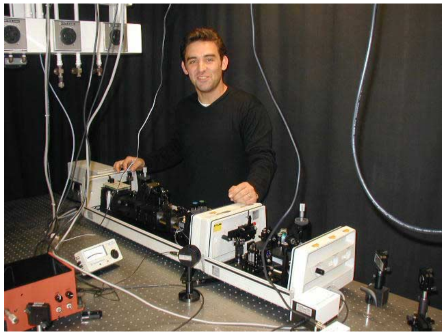
MICHIGAN
ECONOMIC DEVELOPMENT CORPORATION

PHILIPS

GUIDANT

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

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?

Gas-Liquid-Solid Flows: Critical Issues in Microgravity Fluids, Transport and Reaction Processes for Solid Waste Management

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

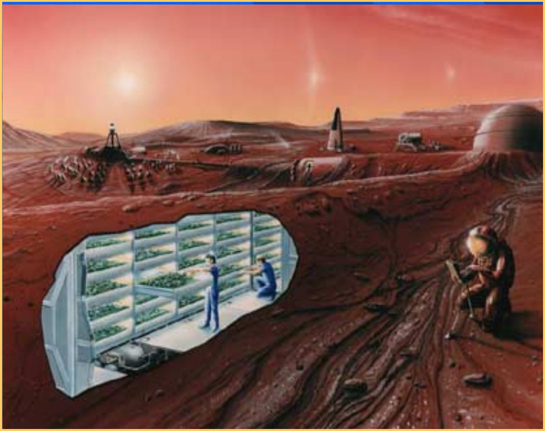
Solid Waste Processing / Resource Recovery

GOAL

Long missions, with little or no food production

Destroy hazardous or noxious wastes

Long missions using biological processors



Reclaim CO_2 and nutrients from waste for biological processors

Waste Composition

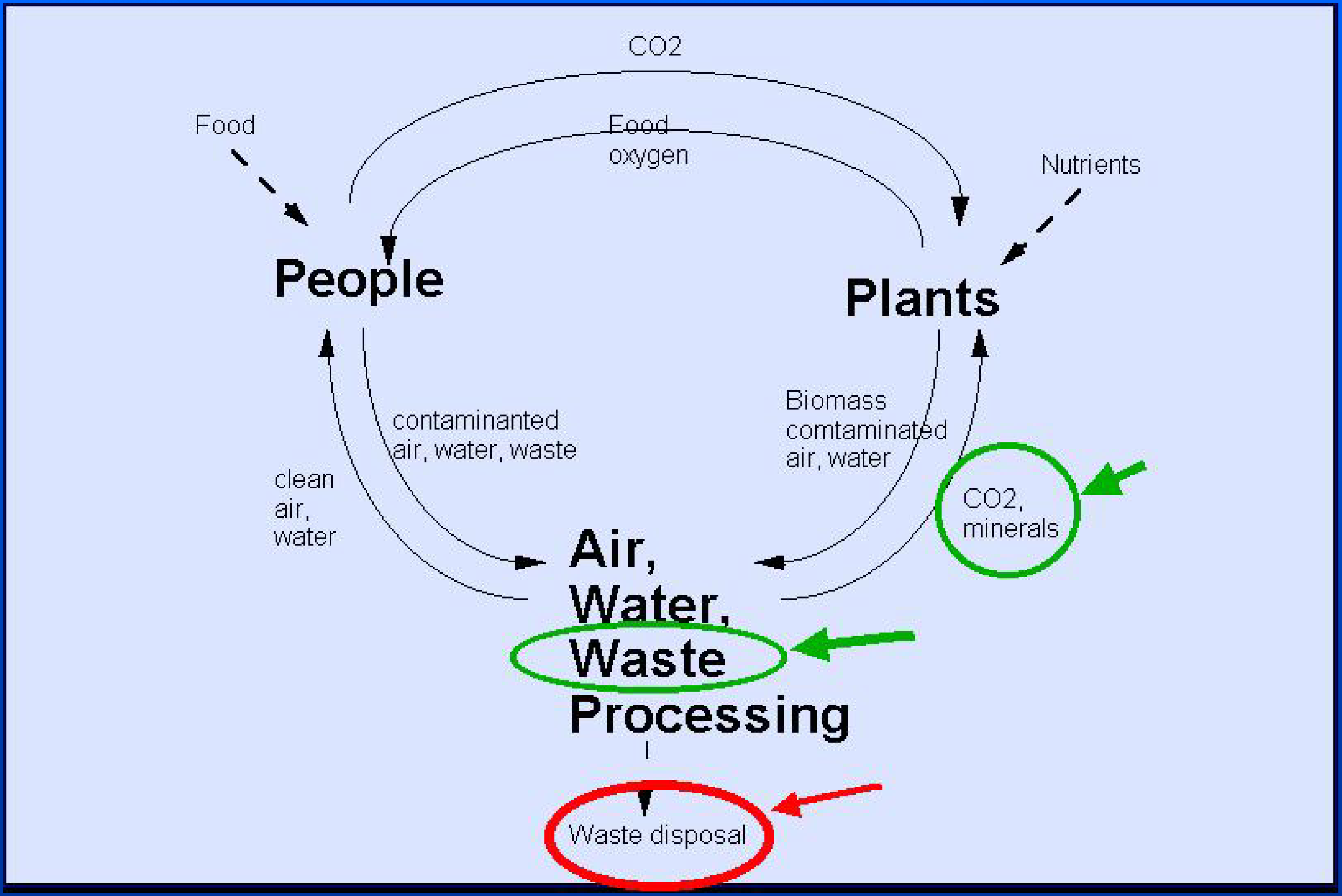
Planetary mission with crew of six is expected to generate solid waste at the rate of (NASA TM-2003-210785):

10-12 kg/day (dry)

25-30 kg/day (wet)

Feces	114 g/person-d
Urine	1562 g/person-d [Composition: 59 g solids, 1503 g water]
Toilet paper	28 g/person-d
Miscellaneous (skin cells, hair, sweat, etc.)	10.75 g/person-d
Mensus	113.4 g/female for each day of menstruation.
wipes	185 g/person-d
Paper documentation	77 g/person-d [Moisture content of 6%]
Clothing, towels and wash cloths	486 g/person-d [Moisture content of 8.5%]
Food packaging - adhered food	508 g/person-d
Others: **Wasted grown food** **Tape** **Inedible biomass** **Wasted EVA food sticks and packaging** **MAG's (diaper, feces & urine)**	

Closed Loop Life Support



CO2

Food

Food
oxygen

Nutrients

People

Plants

contaminanted
air, water, waste

Biomass
comtaminated
air, water

clean
air,
water

CO2,
minerals

**Air,
Water,
Waste
Processing**

Waste disposal

Potential Resource Recovery Objectives

- Water recovery
  - from wet wastes
  - from brines
- CO_2 recovery
  - supply photosynthetic requirements
  - O_2 generation/recovery
- Plant nutrient recovery
  - recycle nutrients to growth chambers
- Transform to beneficial products
  - activated carbon
  - food production substrate
  - structural materials - paper
  - fuel production (CH_4, C_2H_4)

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

http://gltrs.grc.nasa.gov/reports/2004/TM-2004-212940.pdf

Top Level Functional Operations

Generation → Initial Storage Container → Processor → Storage/ Disposal

Involves Variable dry/moist/wet solid flows with and without gas phase incorporation

- 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

J.C. Hermanson and S.M. Som
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

- [1] Strategic Research Workshop on Two-phase Flow, Fluid Stability and Dynamics: Issues in Power, Propulsion and Advanced Life Support Systems, Sponsored by Office of Biological and Physical Research, NCMR, NASA Glenn Research Center, Cleveland, Ohio, May 15, 2003.
- [2] Survey of Present and Future Challenges in Low-g Fluids Transport Processes, NASA Contract C-74461-N, Final Report to NASA Glenn Research Center, M.M. Weislogel, TDA Research, Inc., Wheat Ridge, CO.
- [3] National Research Council, Space Studies Board, Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies, National Academic Press, 2000.
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- [5] Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space, Sponsor NASA OLSMA, Host NASA GRC, Cleveland, July 25-26, 2000.
- [6] Workshop on Research Needs in Fluids Management for the Human Exploration of Space, Sponsored by NASA OLSMA, NASA Glenn Research Center, Cleveland, Ohio, Sept. 22, 2000.
- [7] Carpenter, B.M., Process Research in Support of the Human Exploration and Development of Space: Issues in Program Development, Space V, Space Engineering/Construction/Operations, Proceedings of the 5th International Conference on Space ’96, Vol. 1, pp 509-515, Albuquerque, NM, 1996.
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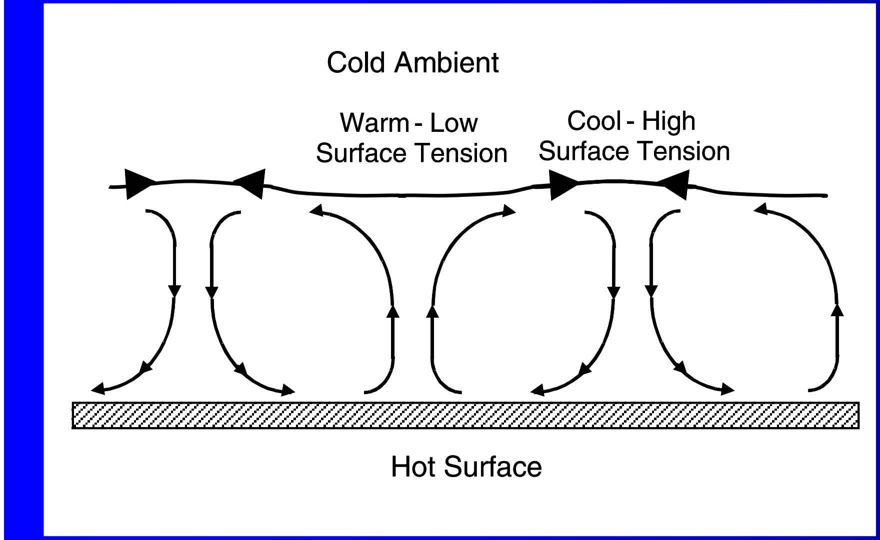
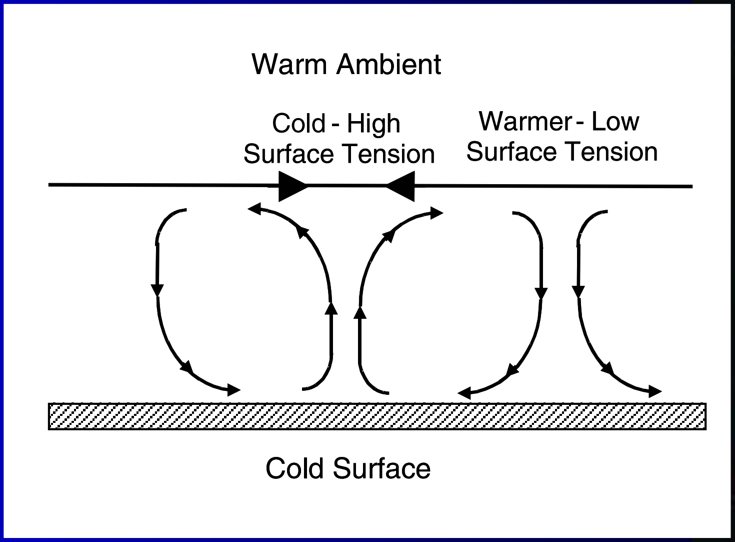
Condensation and Evaporation Research in Reduced Gravity is Enabling for AHST Technology Needs

- **Humidity Control**
  - Mechanisms which inhibit or exacerbate liquid film motion
  - Condensate control in ducts
  - Condensers/evaporators for crew atmosphere
- **Air Revitalization (O_2 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

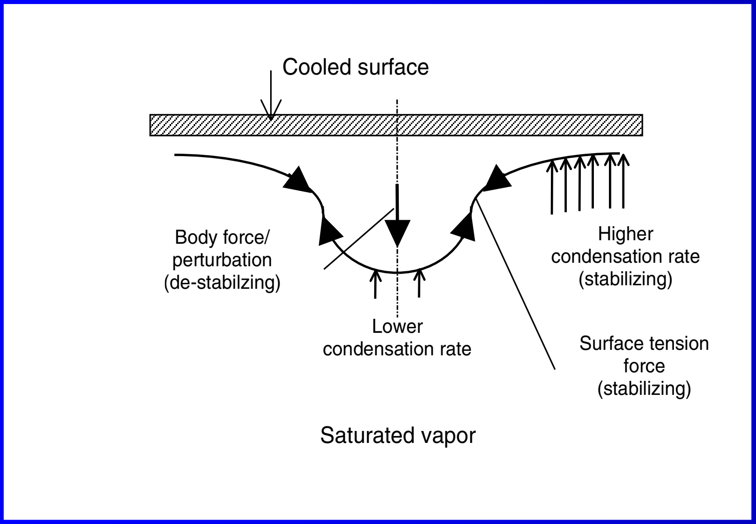




Evaporating film -
surface tension variations
de-stabilizing

Condensing film-
surface tension variations
stabilizing

Fluid Mechanisms in Condensing and Evaporating Films in Reduced Gravity



Cooled surface

Body force/
perturbation
(de-stabilzing)

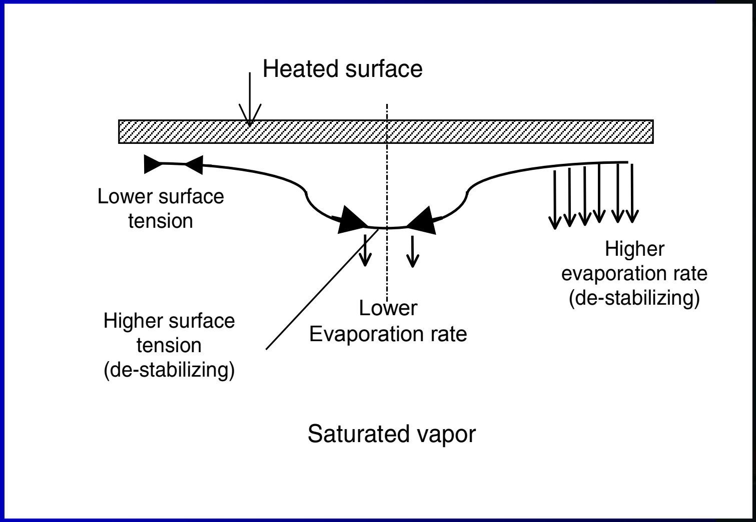
Higher
condensation rate
(stabilizing)

Lower
condensation rate

Surface tension
force
(stabilizing)

Saturated vapor

Condensing film in low-g



Heated surface

Lower surface
tension

Higher
evaporation rate
(de-stabilizing)

Higher surface
tension
(de-stabilizing)

Lower
Evaporation rate

Saturated vapor

Evaporating film in low-g

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)

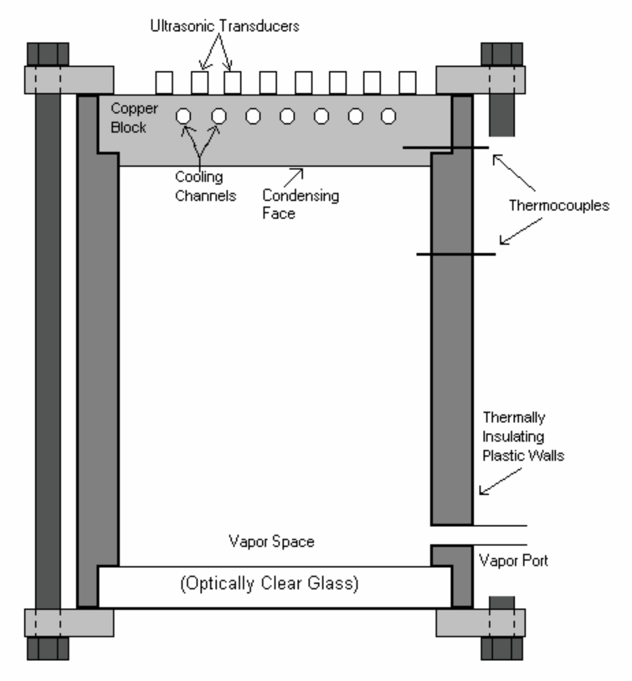
Experimental Configurations for Condensing Films

- **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)

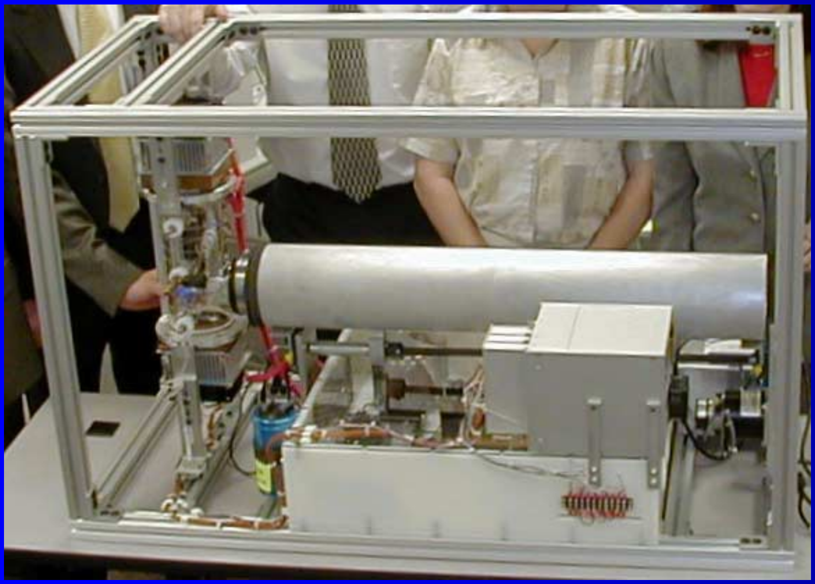
Laboratory Condensation Test Cell



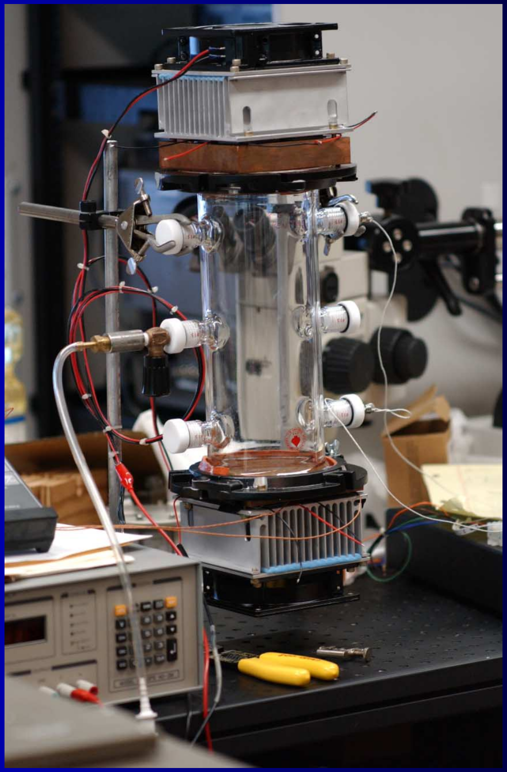
Schematic

Actual

Aircraft Experiment



Aircraft rig with
volume control system



A/C rig test cell with dual
thermoelectric elements

Condensation Study
Current Test Conditions

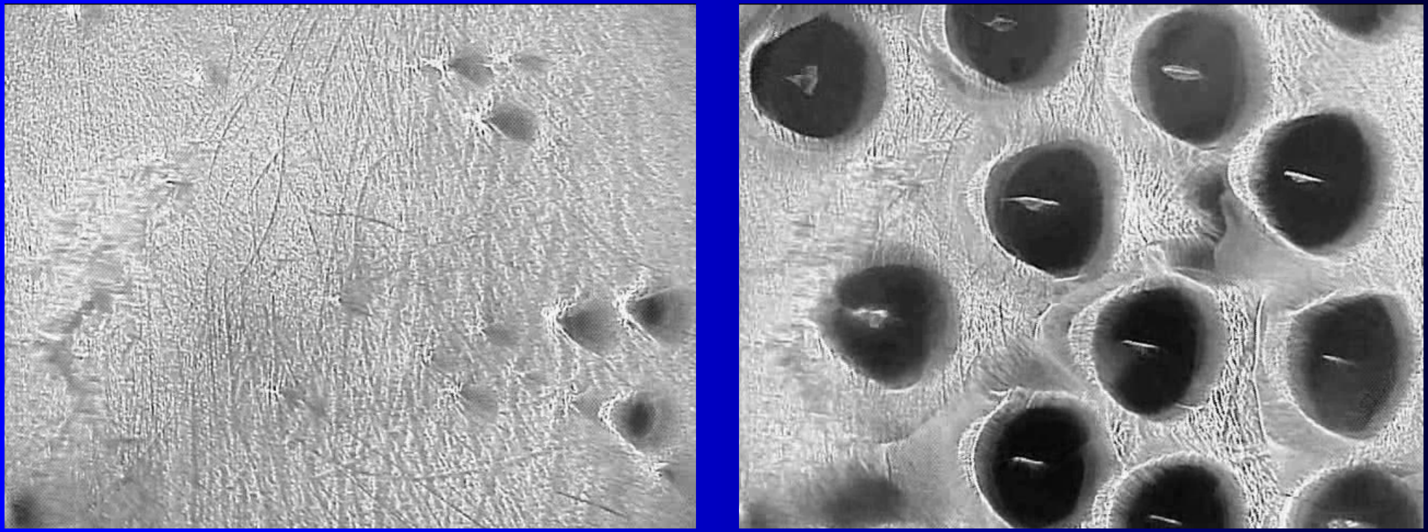
- **Condensation experiments**
  - 10 cm diameter cooled brass plate
  - Fluids: Methanol and n-pentane
  - Enclosed test cell, typical operating pressure 50-70 kPa
  - Subcooling range $T_{sat} - T_{wall} = 4 - 16$ C
- **“Pumped film” experiments**
  - 10 cm diameter perforated stainless plates
  - 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 *n*-pentane Film in Unstable (-1g) Configuration

$T_{wall} = 11$ C, $T_{sat} = 17$ C, $P_{sat} = 50$ kPa



At start of condensation

37 s after the start of condensation

Condensing n-Pentane Film in Normal Gravity (-1g) at Constant Pressure

Click here to play movie

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

Click here to play movie

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

Cycle period 180 s; video rate 2.4 x real time

Non-condensing “Pumped” Film in Normal Gravity (-1g)

50 cSt Silicone Oil

Click here to play movie

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)

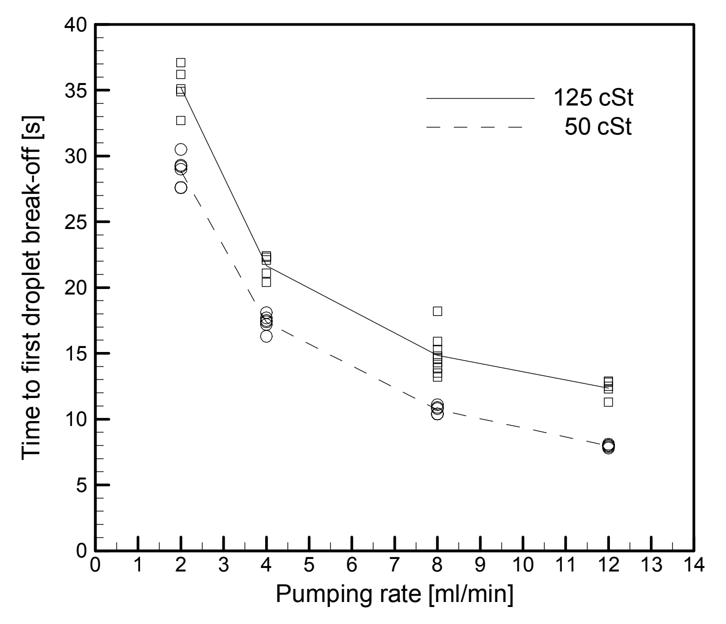
50 cSt Silicone Oil

Click here to play movie

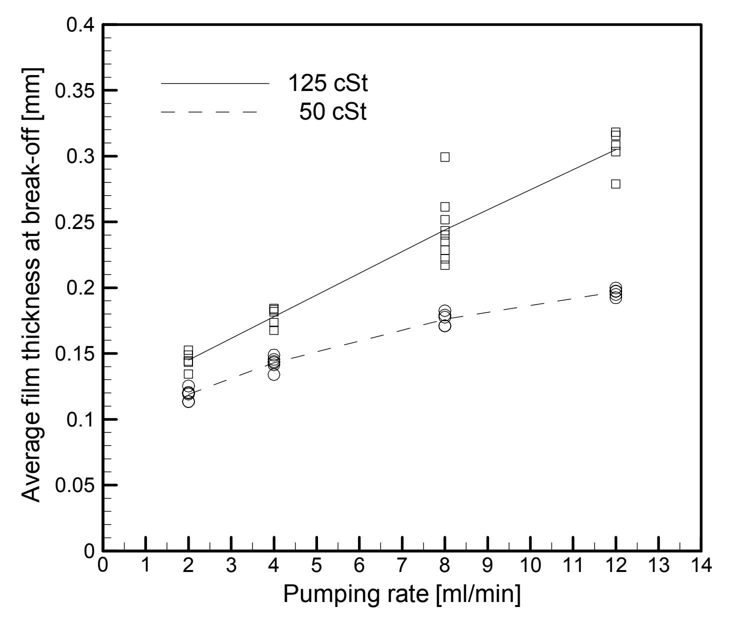
Pumping rate 12 ml/min
→ average film growth rate = 24.7 µm/s
Video rate 0.4 x real time

Non-condensing "Pumped" Film in Normal Gravity (-1g)

Silicone Oil

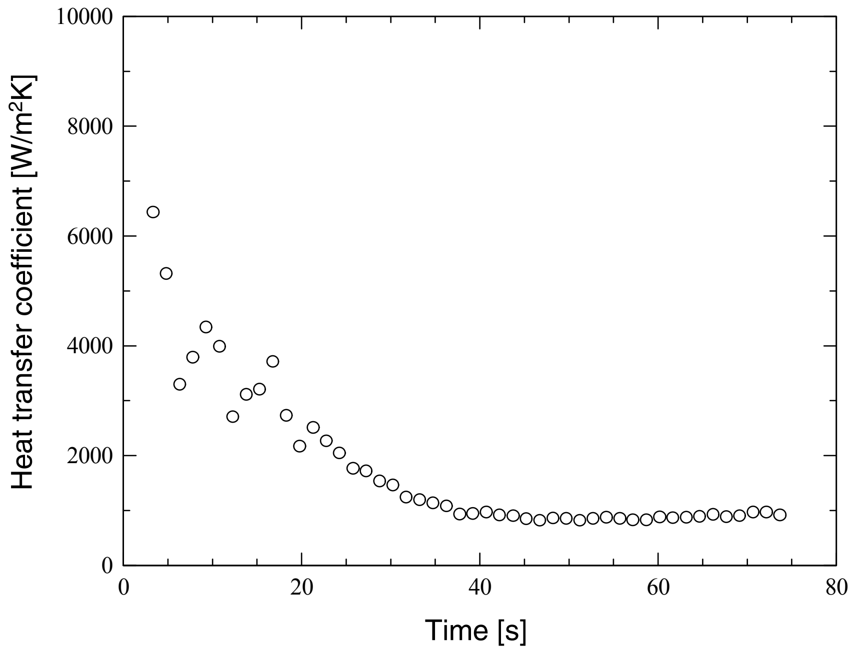


Time to first droplet break-off decreases with increasing pumping rate



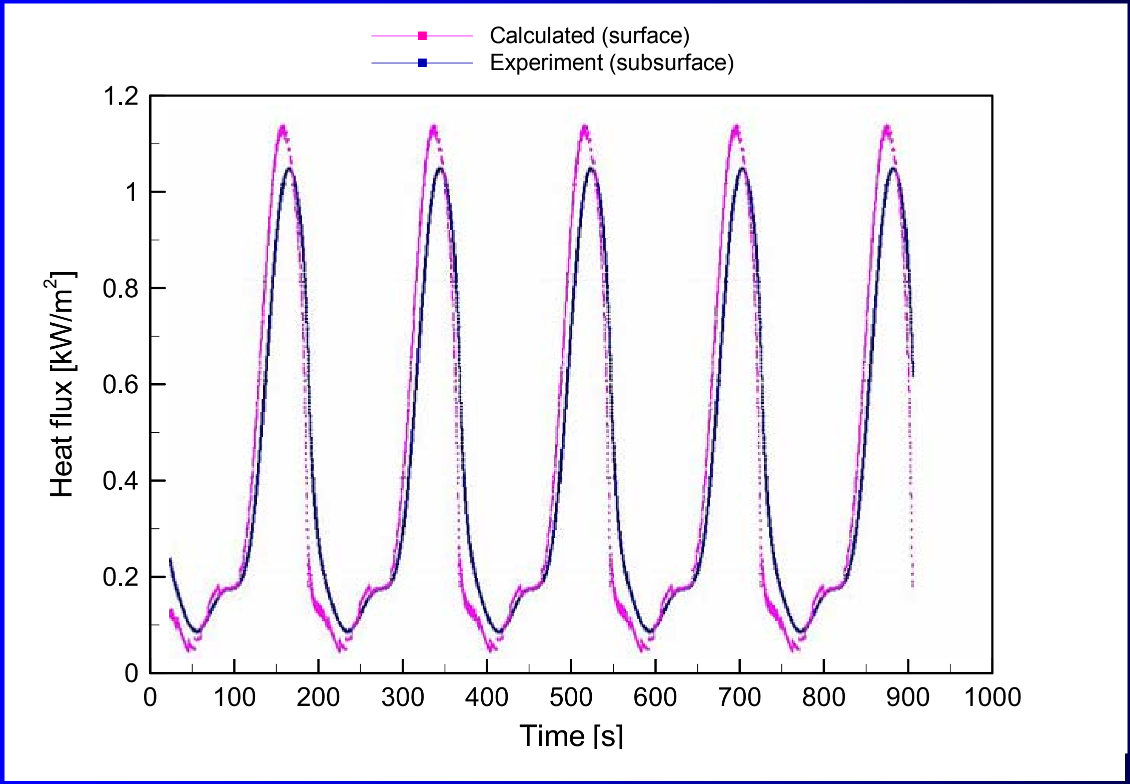
Film thickness at first droplet break-off increases with increasing pumping rate

Heat Transfer Coefficient in Developing, Unstable Condensing Film in Normal Gravity



Unstable (-1g) condensing n-pentane film
T_{wall} = 11 C, T_{sat} = 17 C, P_{sat} = 50 kPa

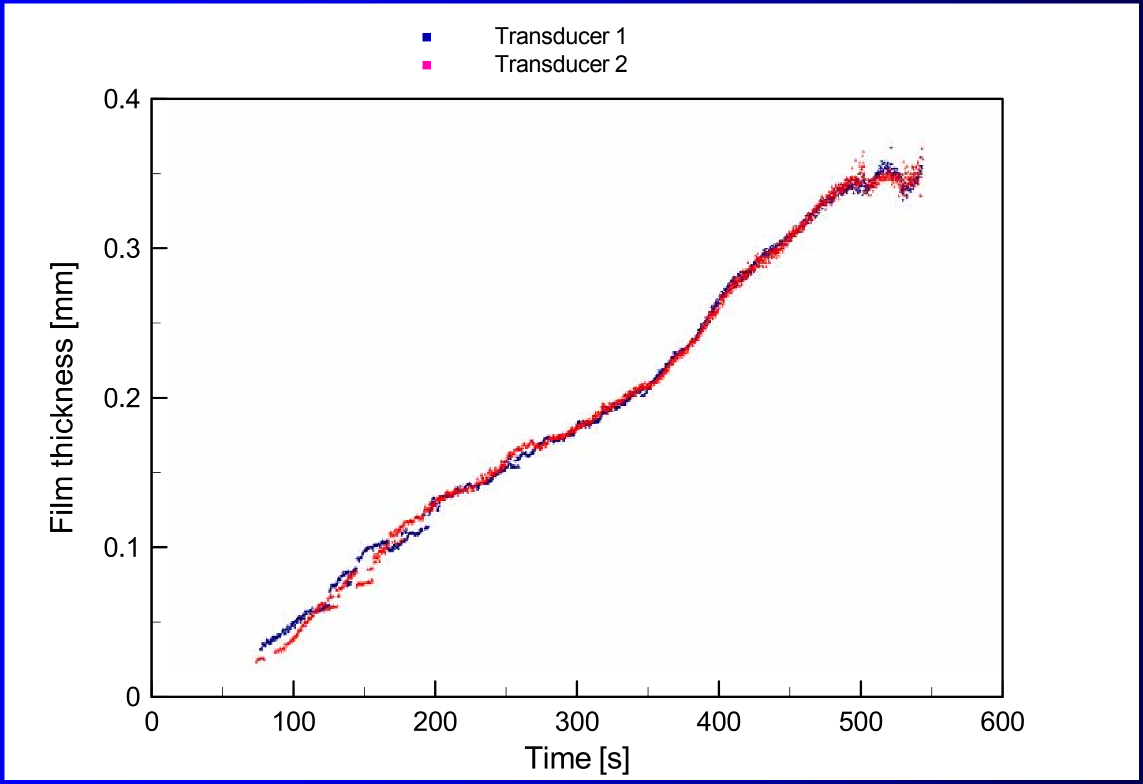
Heat Transfer for Unsteady Condensing Film (-1g)



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

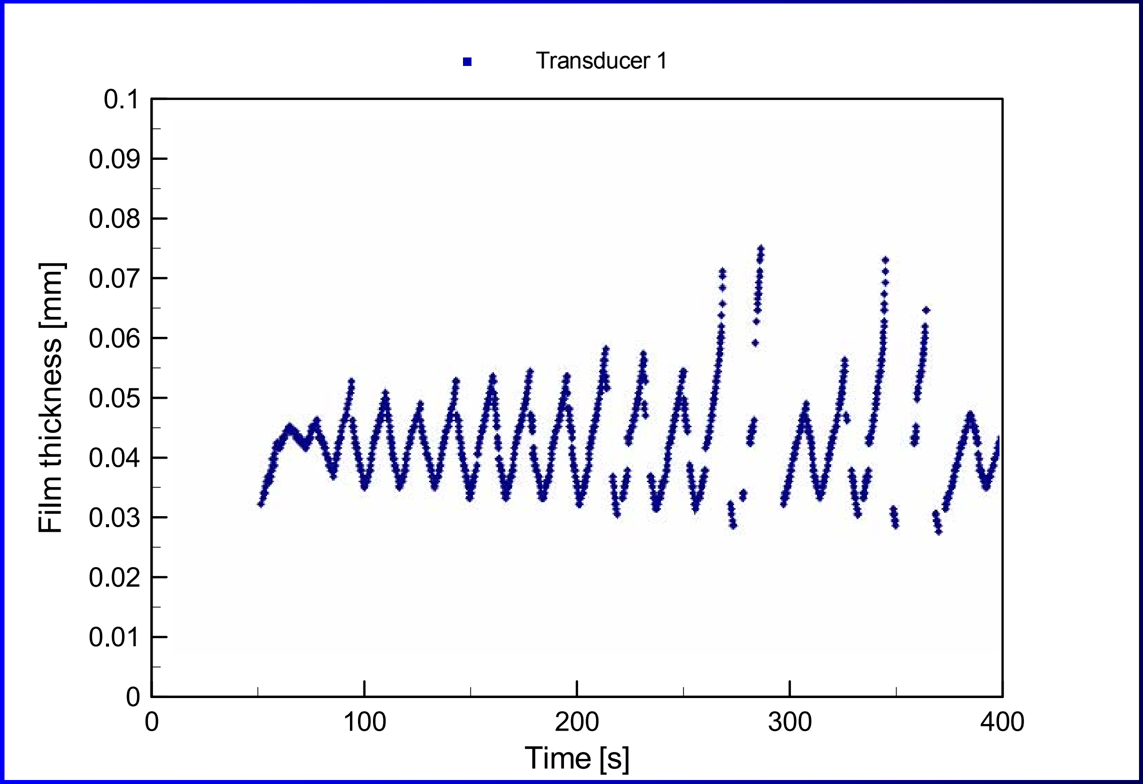
Ultrasound Measurement of Film Thickness

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



Ultrasound Measurement of Film Thickness

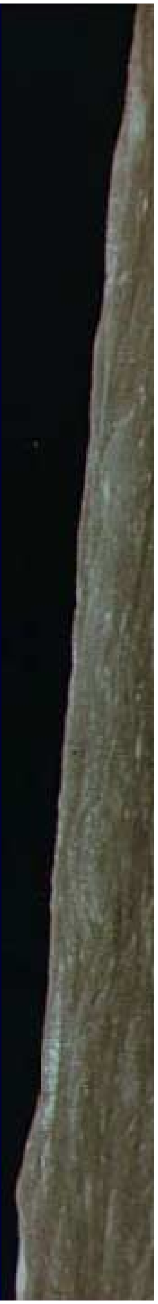
N-pentane Film, Unstable (-1g) Configuration



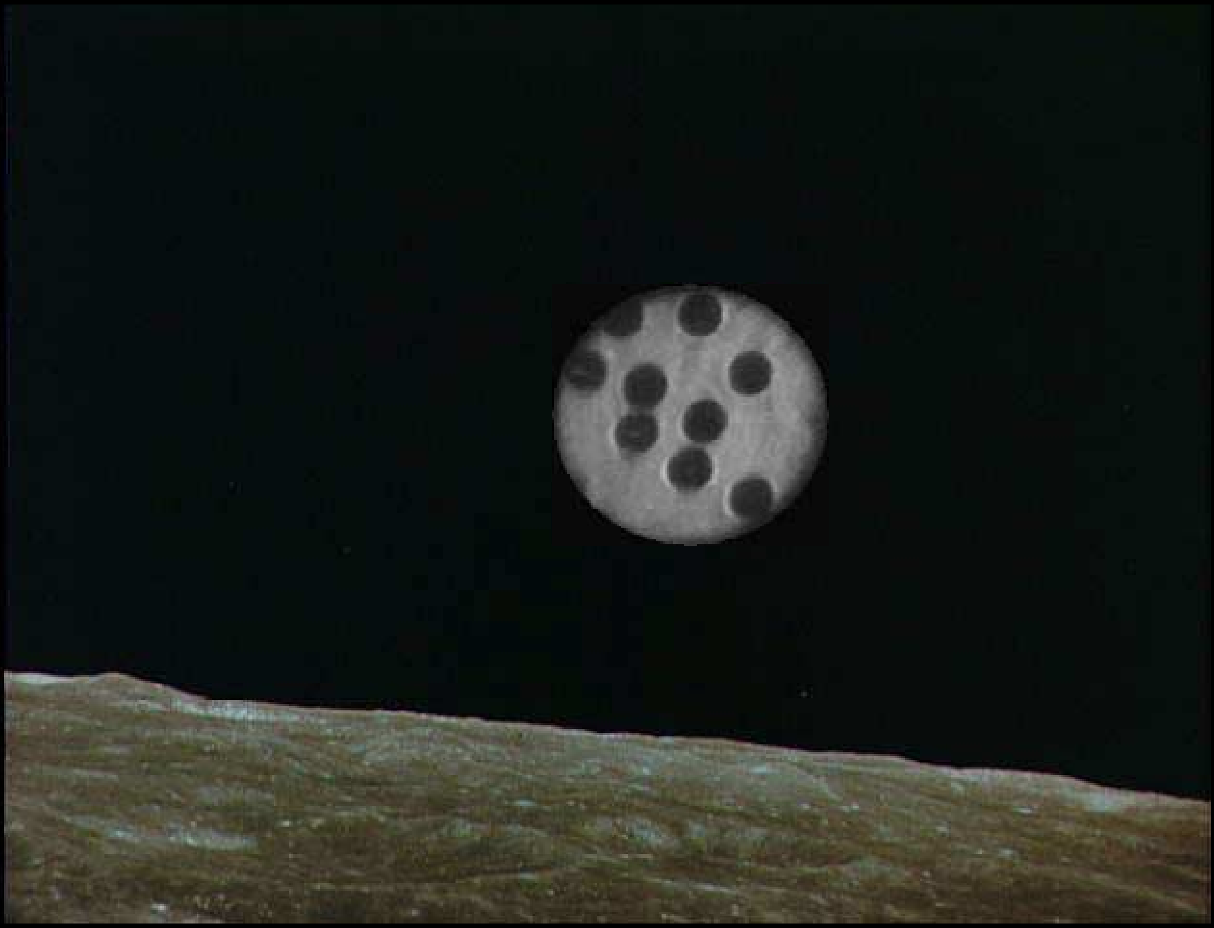
Summary

- **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
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FLEX - *Flammability and Extinction Investigations*

Michael C. Hicks

NASA Glenn Research Center

June 23, 2004

FLEX - *Flammability and Extinction Investigations*

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- Forman Williams, UCSD
- Craig Myhre & NASA Engineering Team

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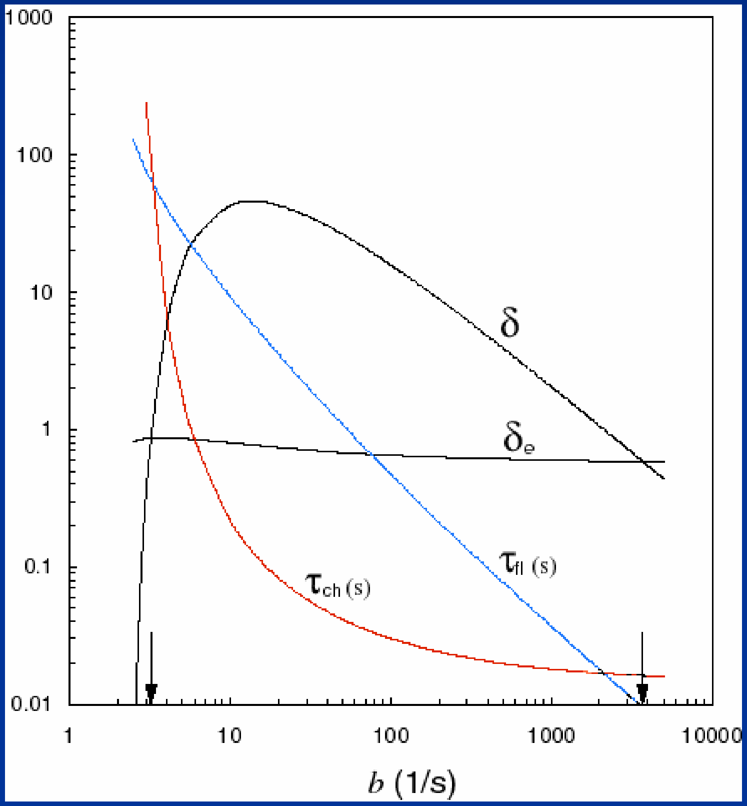
Diffusive and Radiative Extinction of Diffusion Flames



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

Similar extinction scenarios for different flow configurations:

* Counter-flow
* Cup-burners
* Droplet combustion

Nayagam and Williams, 28th Combustion Symposium 2000

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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

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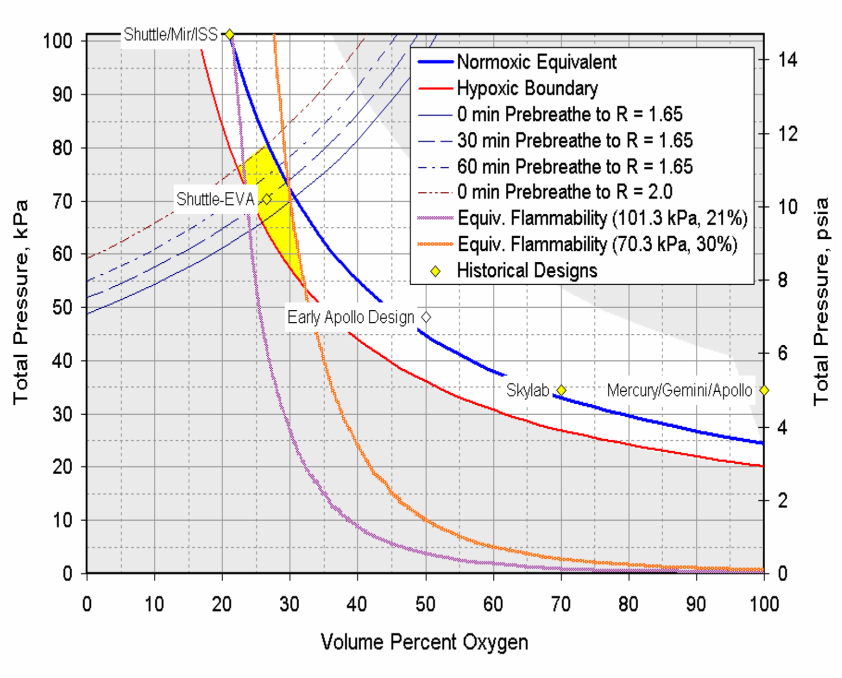
Organizing questions where "droplet combustion" may play a ***significant*** *role:*

1. What is the O_2 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



Conference Workshop on
Strategic Research to Enable NASA's Exploration Missions
June 22-23, 2004

FLEX - *Flammability and Extinction Investigations*

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 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 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.

FLEX - *Flammability and Extinction Investigations*

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 O_2 concentrations
- tests initially performed in quiescent conditions (freely deployed droplet) using N_2 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 (O_2 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

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

Typical Test Matrix:

Test number: 50
Fuel types: methanol, n-heptane
Total pressures: 0.5 atm, 0.75 atm, 1.0 atm
Diluent: N_2 or other
Droplet Sizes: 2.0 mm - 5.0 mm
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

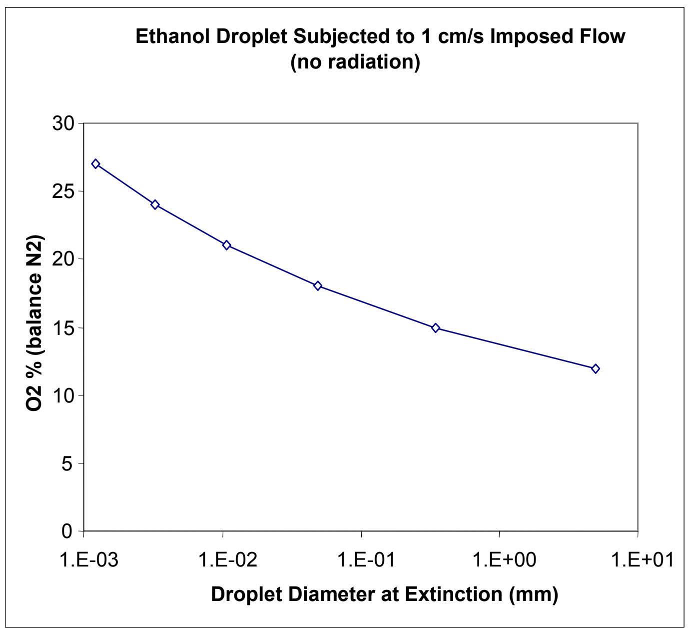
Science Data:

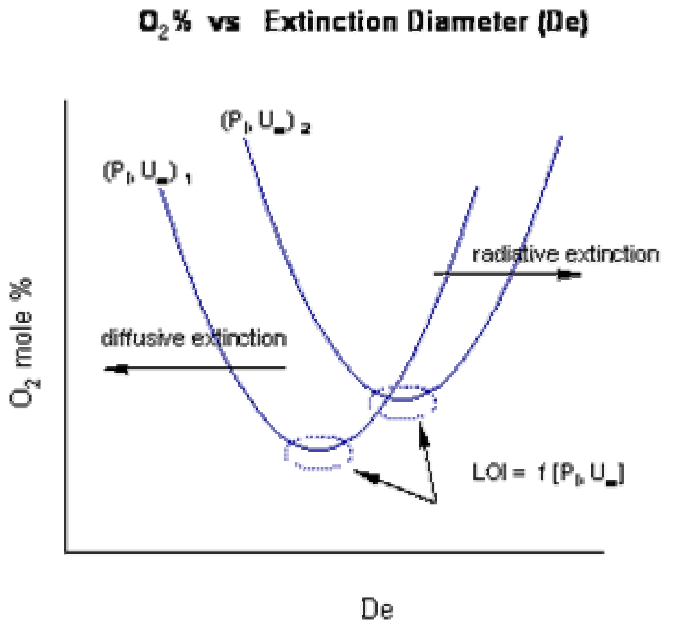
- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions

FLEX - *Flammability and Extinction Investigations*

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





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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.

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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.

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2. Suppressant Effectiveness Studies (cont) :

Proposed Test Matrix:

Test number: 178

Fuel types: methanol, n-heptane

Total pressures: 0.75 atm, 0.85 atm, 1.0 atm

Suppressants: He, CO_2, Halon, etc.

Diluent: N_2 and other

Droplet Sizes: 2.0 mm - 5.0 mm

Flow: 0 cm/s - 3cm/s

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

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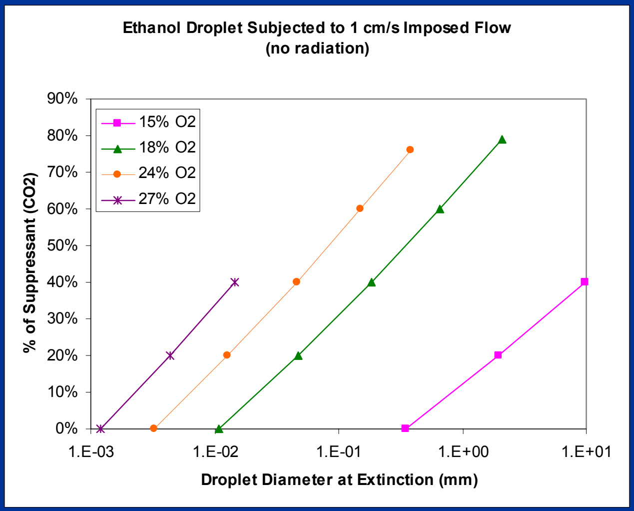
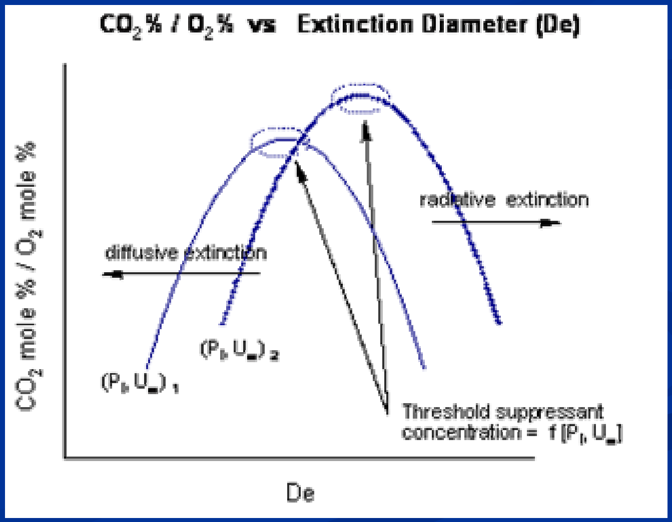
2. Suppressant Effectiveness Studies (cont) :

- simplified theory (e.g., AEA) correlates De with suppressant concentration with a range of O_2 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 ??).





FLEX - *Flammability and Extinction Investigations*

3. *Gas Phase Radiative Absorption Investigation:*

Rationale:

- Gaseous CO_2 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 CO_2 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 CH_4 when radiative reabsoprtion 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 CO_2 may have been injected into inaccessible spaces (e.g., behind an experimental rack).
- Temperatures of the gaseous CO_2 would be elevated creating conditions where smoldering particles, dislodged from a primary fire site, would be kept at elevated temperatures and possibly re-ignite.

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3. *Gas Phase Radiative Absorption Investigation (cont.):*

Approach :

- droplets will initially be freely deployed in atmospheres of 21% O_2 with varying levels of diluent comprising mixtures of CO_2/N_2
- concentrations of CO_2 up to 75% (i.e., CO_2 displaces only N_2)
- 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)

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3. Gas Phase Radiative Absorption Investigation (cont.):

Proposed Test Matrix:

Test number: 40

Fuel types: methanol, n-heptane

Total pressures: 1.0 atm, 2.0 atm, 3.0 atm

Suppressants: CO_2

Diluent: N_2

Droplet Sizes: 5.0 mm

Flow: 0 cm/s

Diagnostics:

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

Science Data:

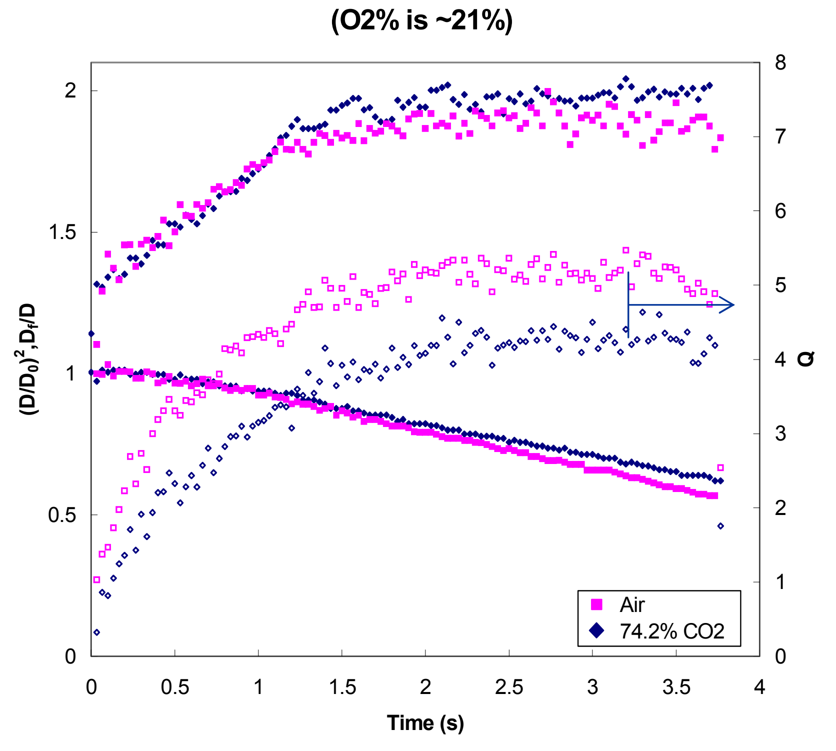
- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions and suppressant concentrations

FLEX - *Flammability and Extinction Investigations*

3. Gas Phase Radiative Absorption Investigation (cont.):

- preliminary results from recent testing show high concentrations of CO_2 (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

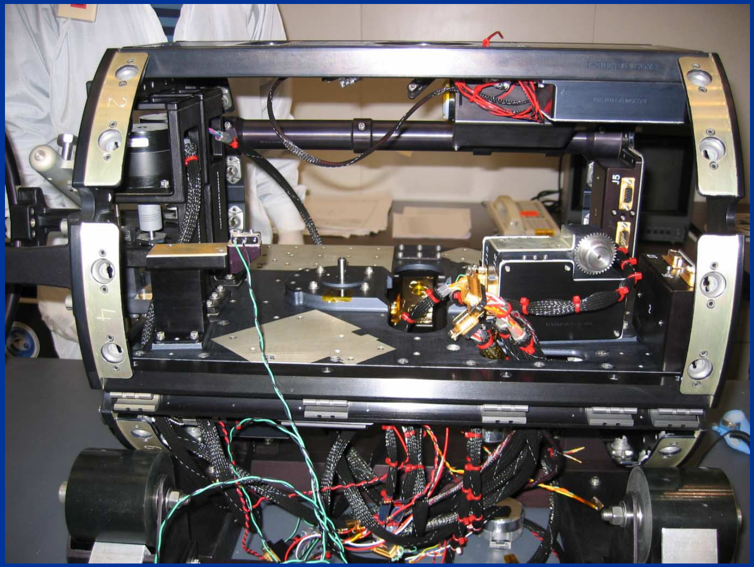
Drop Tower Results with Methanol Droplets (O2% is ~21%)

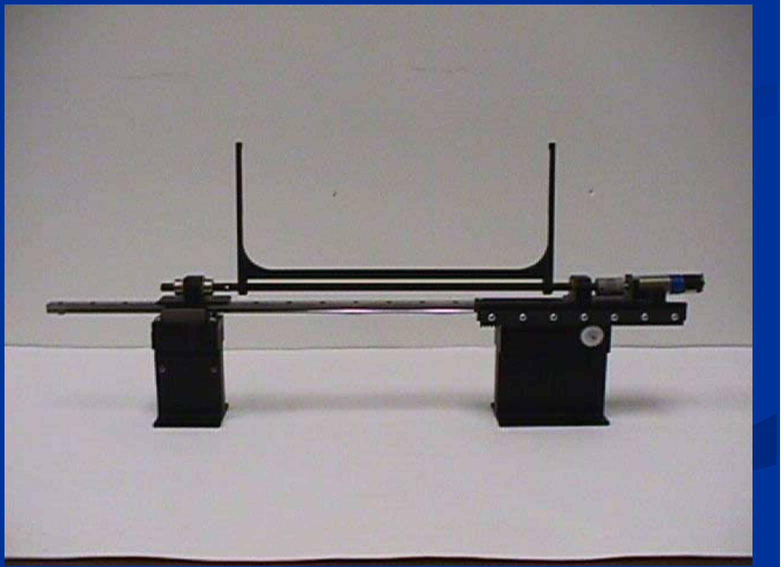


FLEX - *Flammability and Extinction Investigations*

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.





FLEX - *Flammability and Extinction Investigations*

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 O_2 % and pressures for NASA spacecraft

- Space Shuttle Orbiter Cabin
  - maximum during normal operations 25.9% O_2, 14.5 psia
  - during EVA preparation: 30% O_2, 10.2 psia
- Space Shuttle Orbiter Payload Bay: 20.9% O_2, 14.7 psia (Ground)
- Space Station Internal: 24.1% O_2, 14.5 psia
- Space Station Airlock: 30% O_2, 10.2 psia
- Space Station External: 20.9% O_2, 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

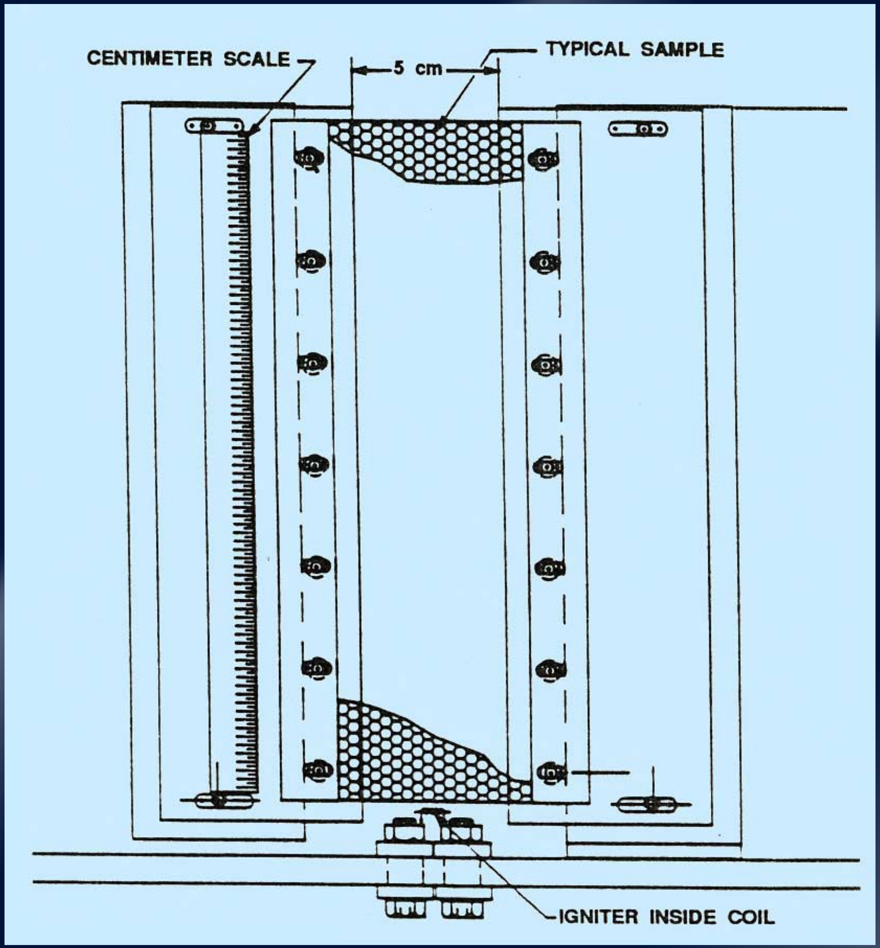
Required materials tests are conducted per NASA STD 6001

- 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

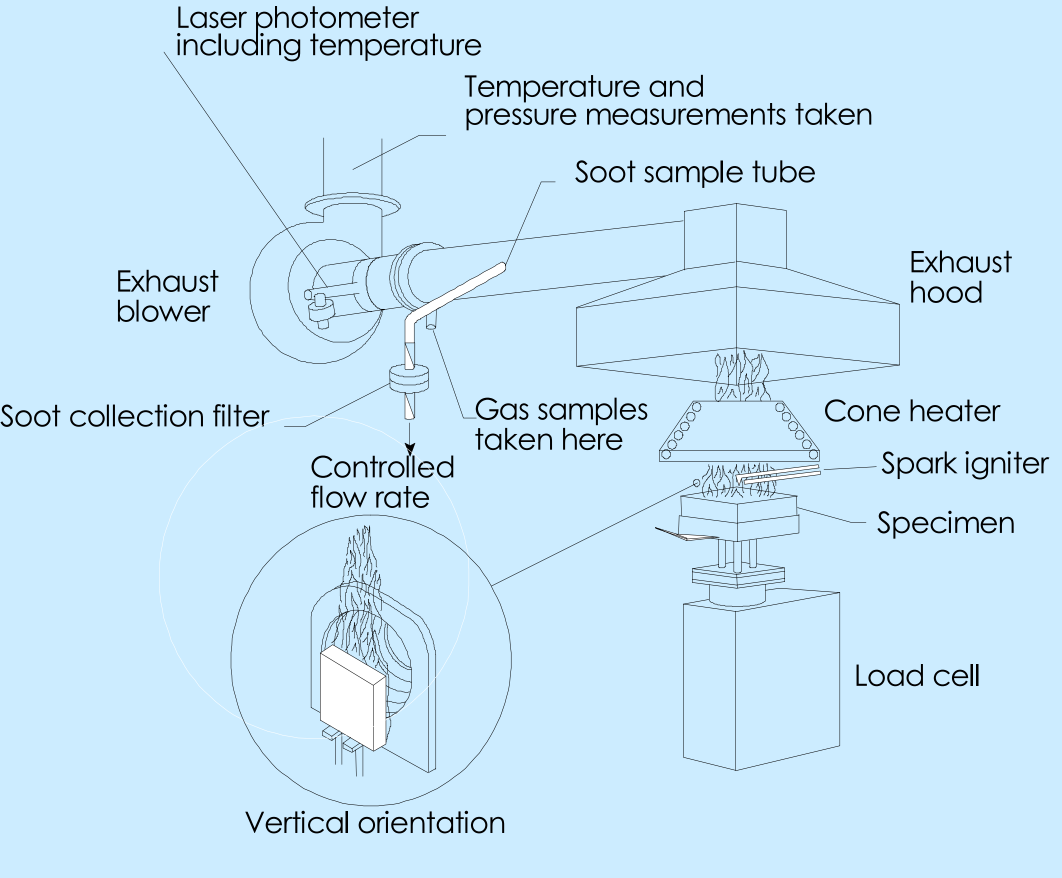
- Test method based on the relationship between materials heat of combustion and the amount of oxygen required for combustion

- 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/m^2) under flowing oxygen/nitrogen mixtures
- Sample is autoignited, or burning can be initiated by a spark ignition

Test 2 (Continued)



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)

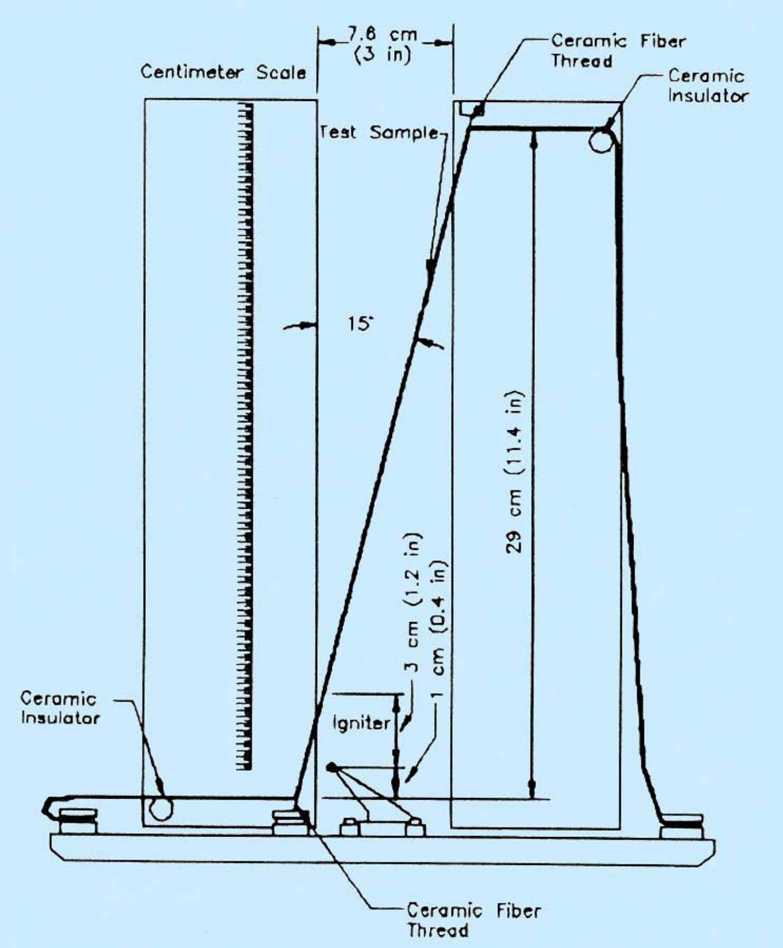
Data obtained:

- 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

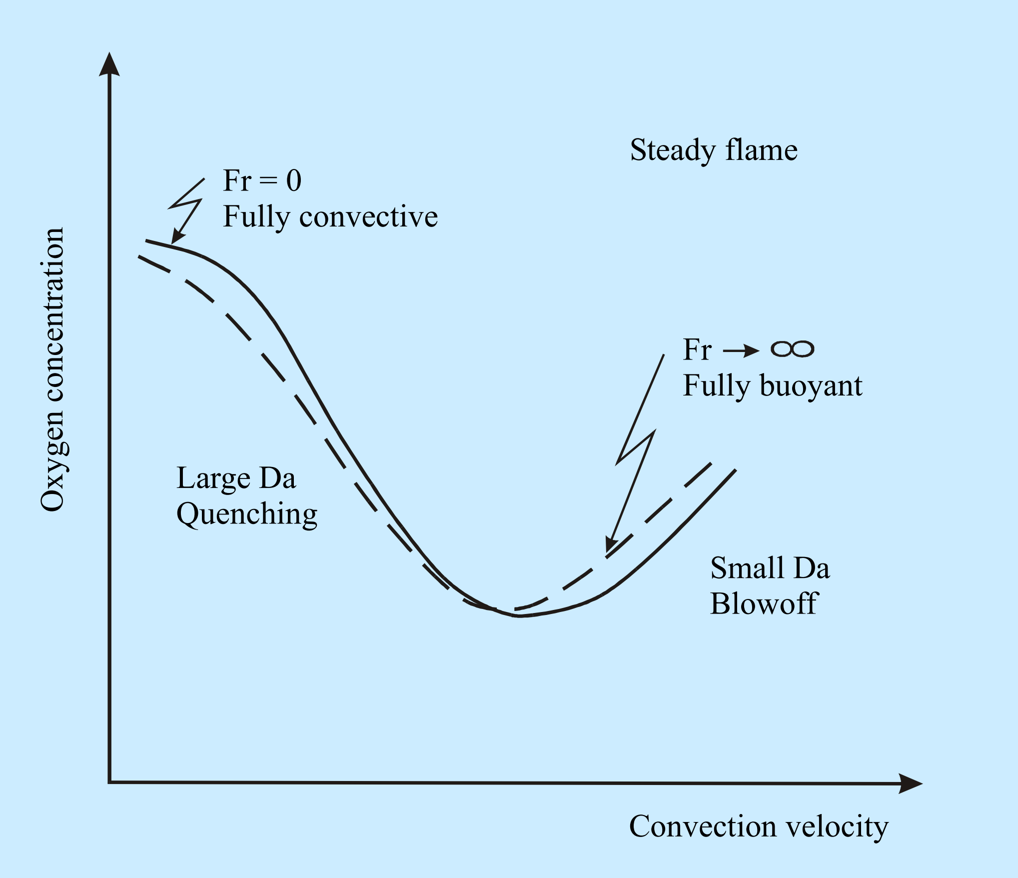
How is NASA test data used for materials selection?

- Pass/fail criteria
- Material usage agreements

Some issues

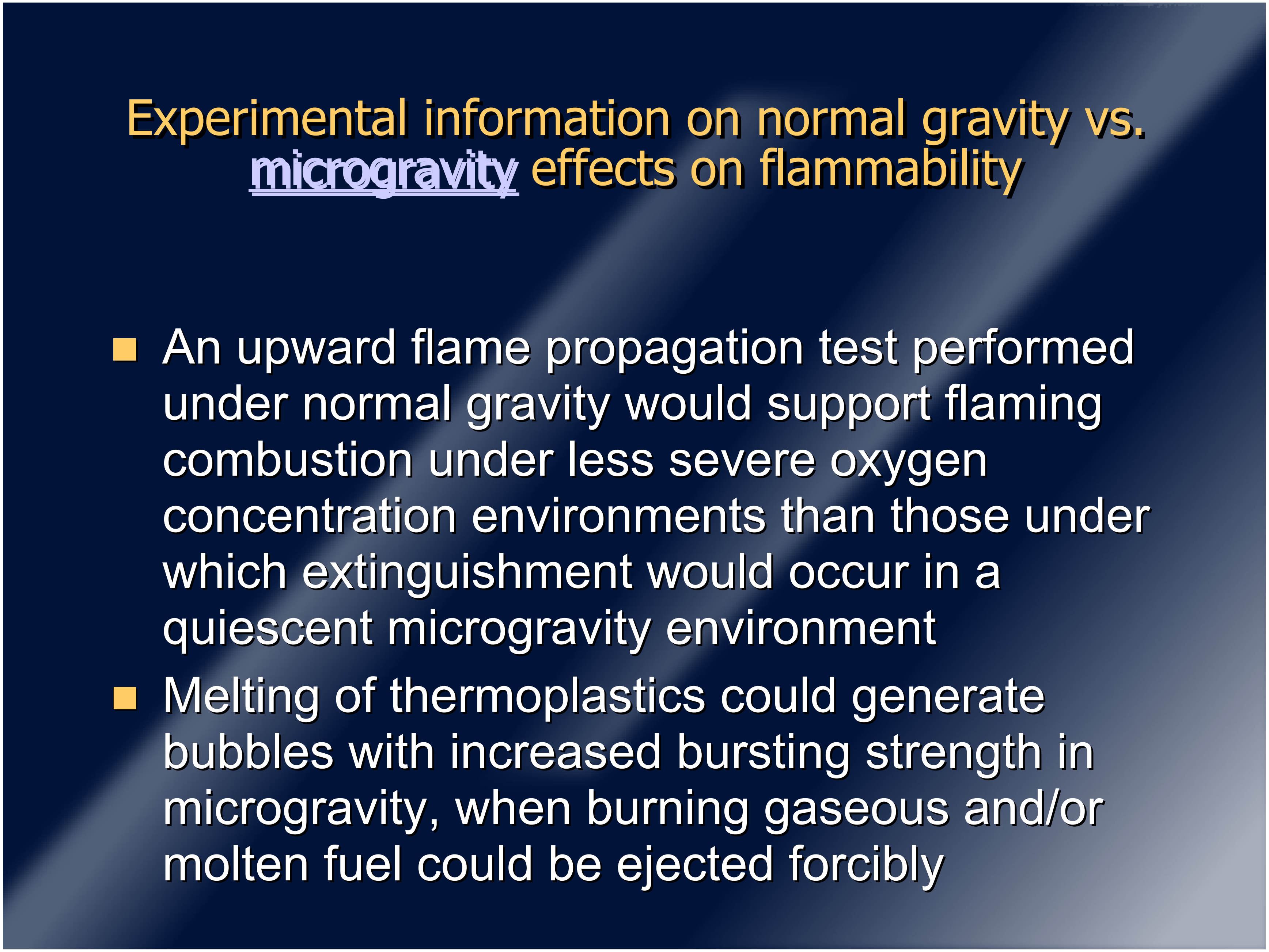
- Simulation by ground tests of spacecraft conditions (correlation between ground test data and real life)
  - Quiescent environment vs. forced convection
  - Normal gravity vs. microgravity

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

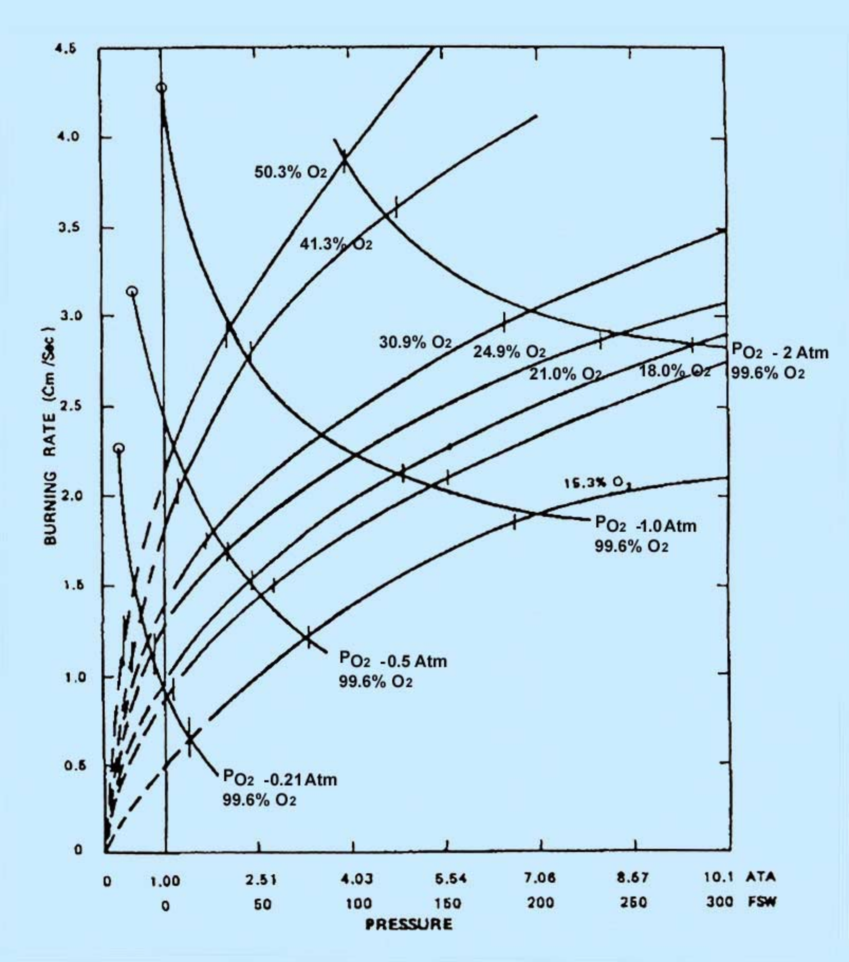
  Example:

  30.0% O_2, 10.2 psia (pO_2 = 3.06 psia)

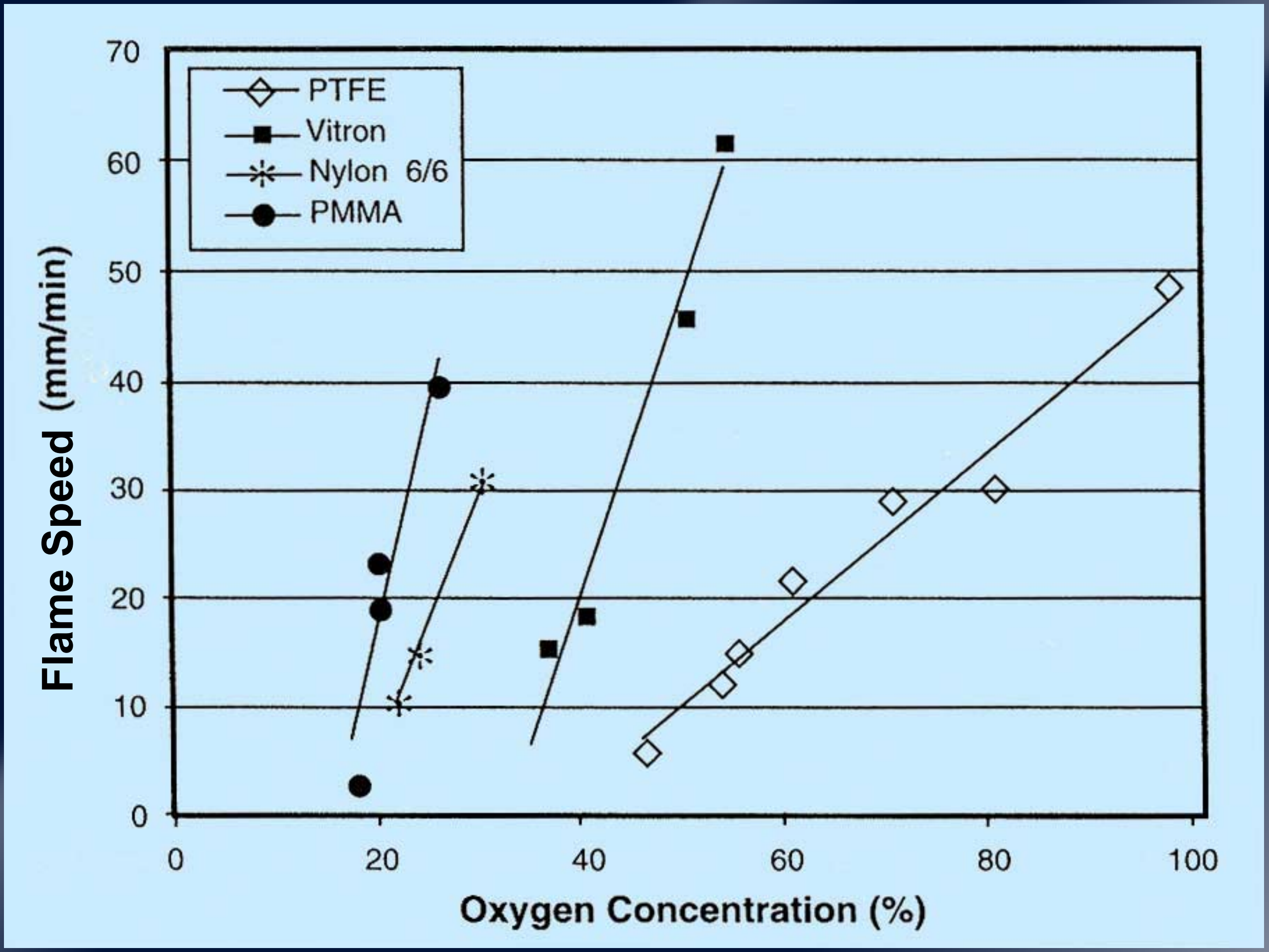
  21.9% O_2, 14.7 psia (pO_2 = 3.08 psia)

- Effects of oxygen concentration and total pressures on ignition and flammability characteristics

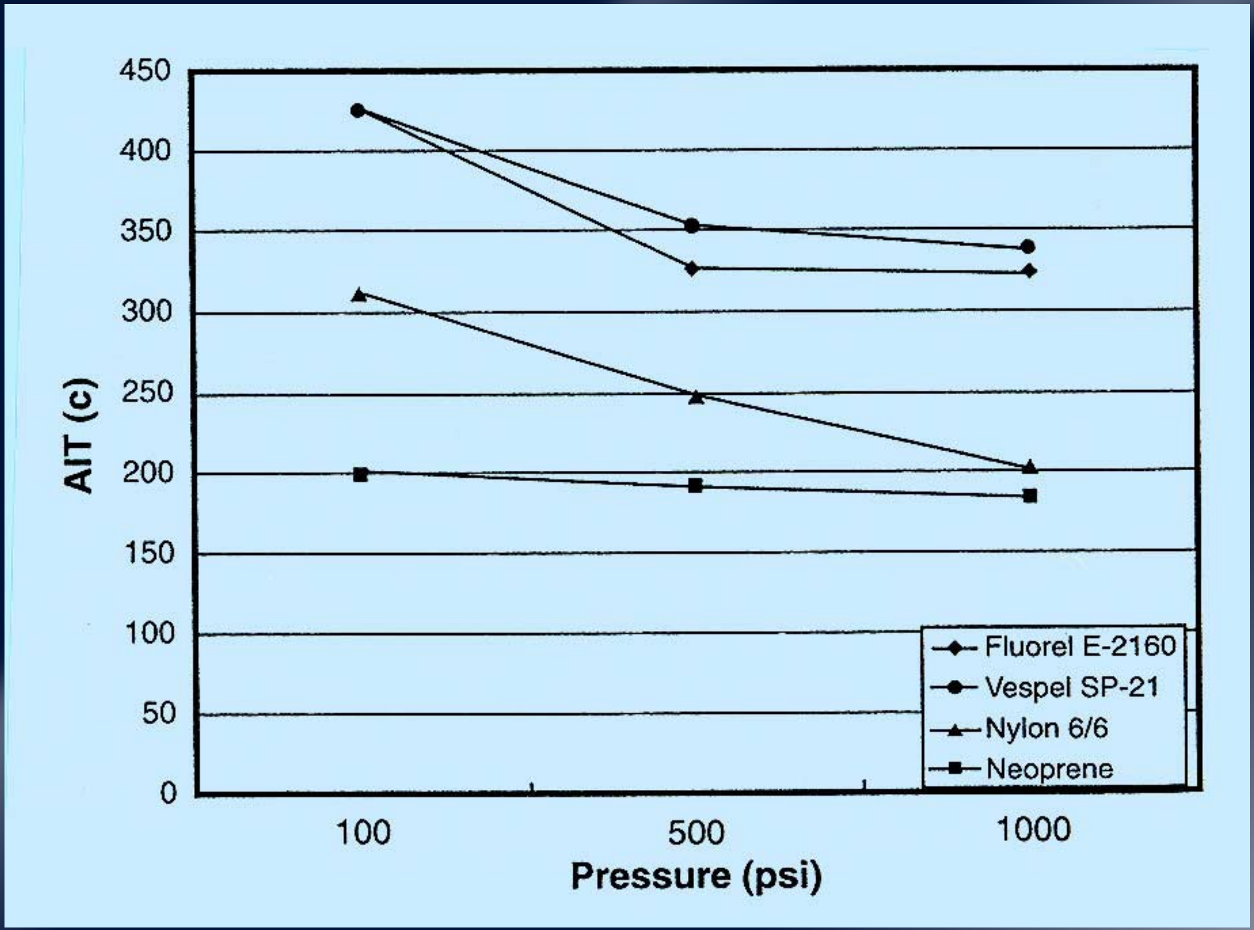
Flame speed - total pressure relationship



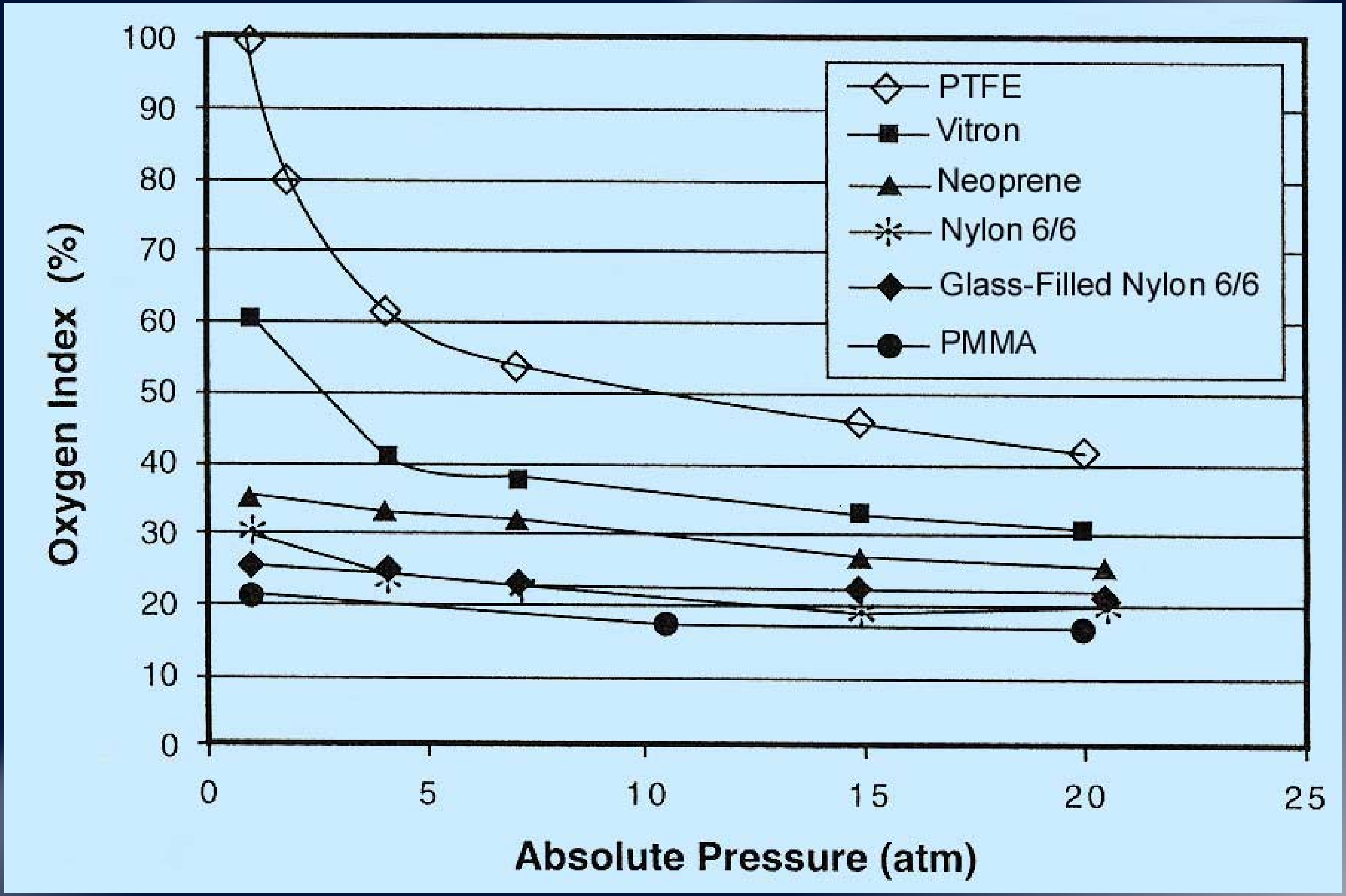
Flame speed - oxygen concentration relationship



Autoignition temperature - oxygen concentration and pressure effects

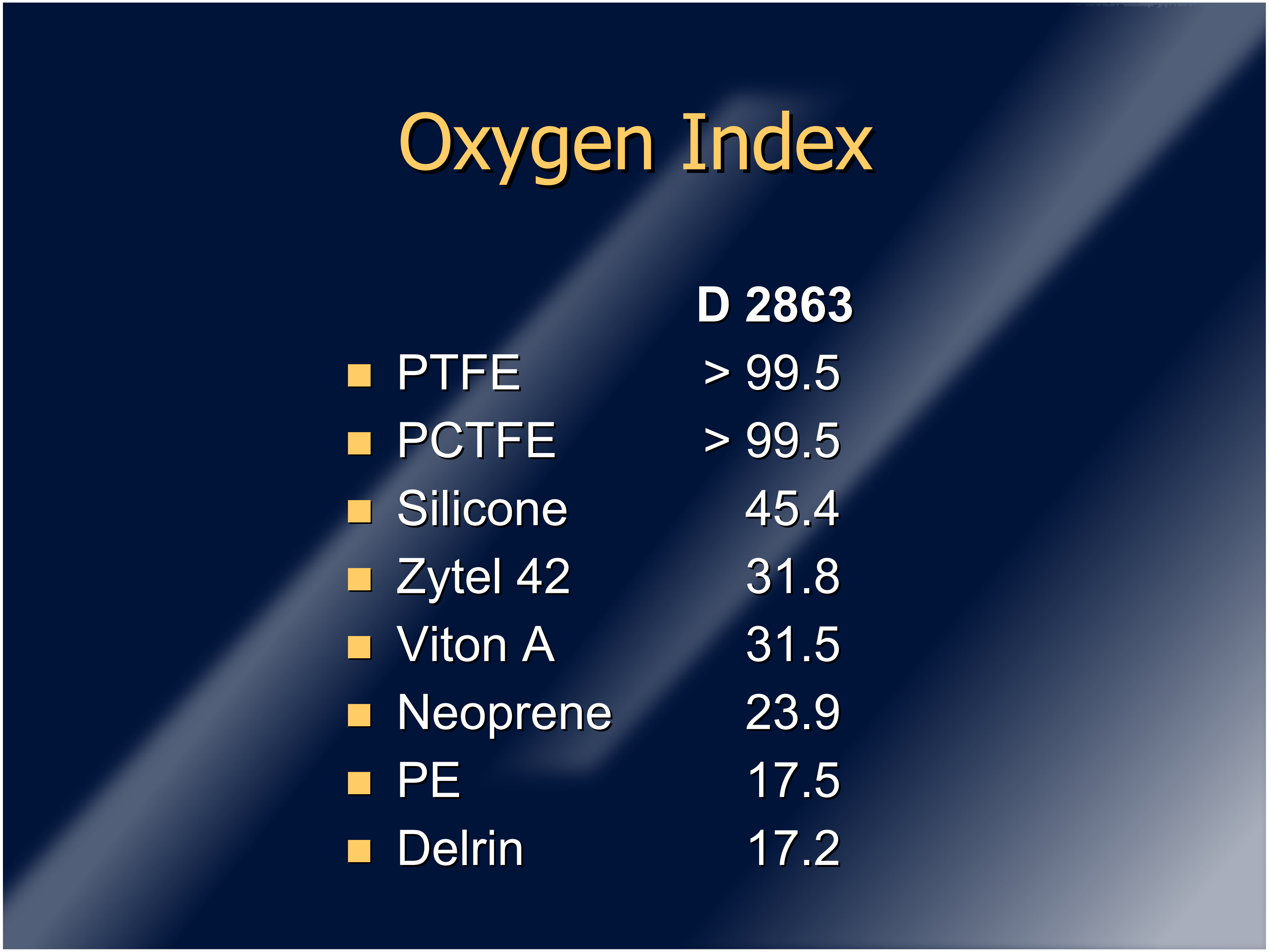


Limiting oxygen index - pressure effects



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

	D 2863	Upward LOI
PTFE	> 99.5	49.0
PCTFE	> 99.5	54.3
Silicone	45.4	23.5
Zytel 42	31.8	23.0
Viton A	31.5	22.5
Neoprene	23.9	17.5
PE	17.5	17.5
Delrin	17.2	11.5

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)

	20 kW/m^2	50 kW/m^2
Epoxy	337	62
Epoxy/fiberglass	320	57
Nylon 6/6	700	74
PEEK	NI	142
Phenolic/fiberglass	NI	165
Polyethylene	403	58
Polypropylene	120	27

Scudamore et al

E 1354 Autoignition time (s)

	25 kW/m²	**50 kW/m²**	**75 kW/m²**
polycarbonate	NI	99	44
polyethylene	141	70	35
PVC	485	421	69
Navy req	***300***	***150***	***90***
(minimum)	***- assumed***	***piloted?***	

Holbrow et al

Comparison of ignitibility in various tests

	UL94V 1mm thick	UL 94 V 2 mm thick	Min heat flux, kW/m^2
PTFE	V-0	V-0	33
PVC	V-1	V-2	8
PVC, FR	V-0	V-0	11

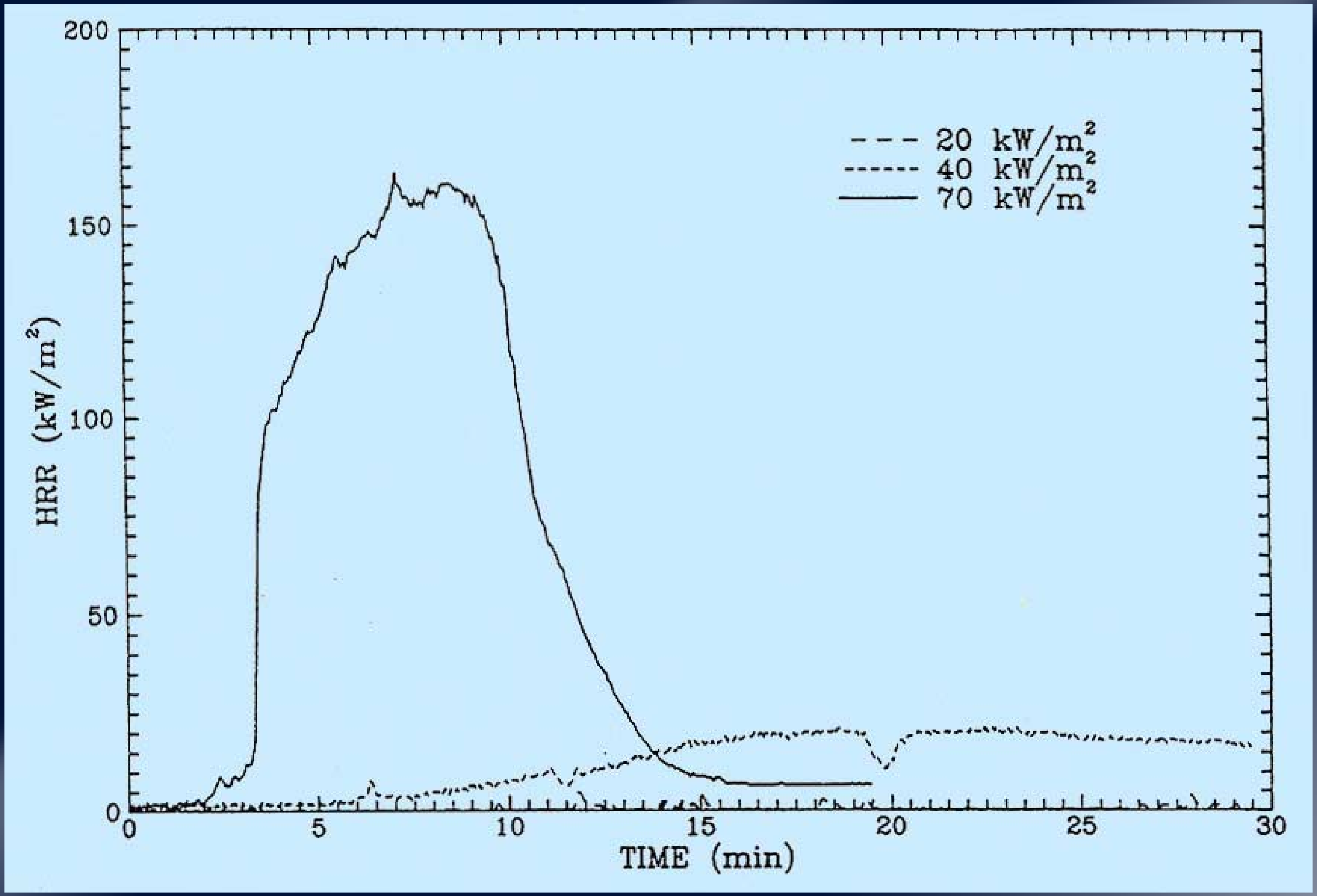
O’Neill et al.

E 1354 results at 70 kW/m^2

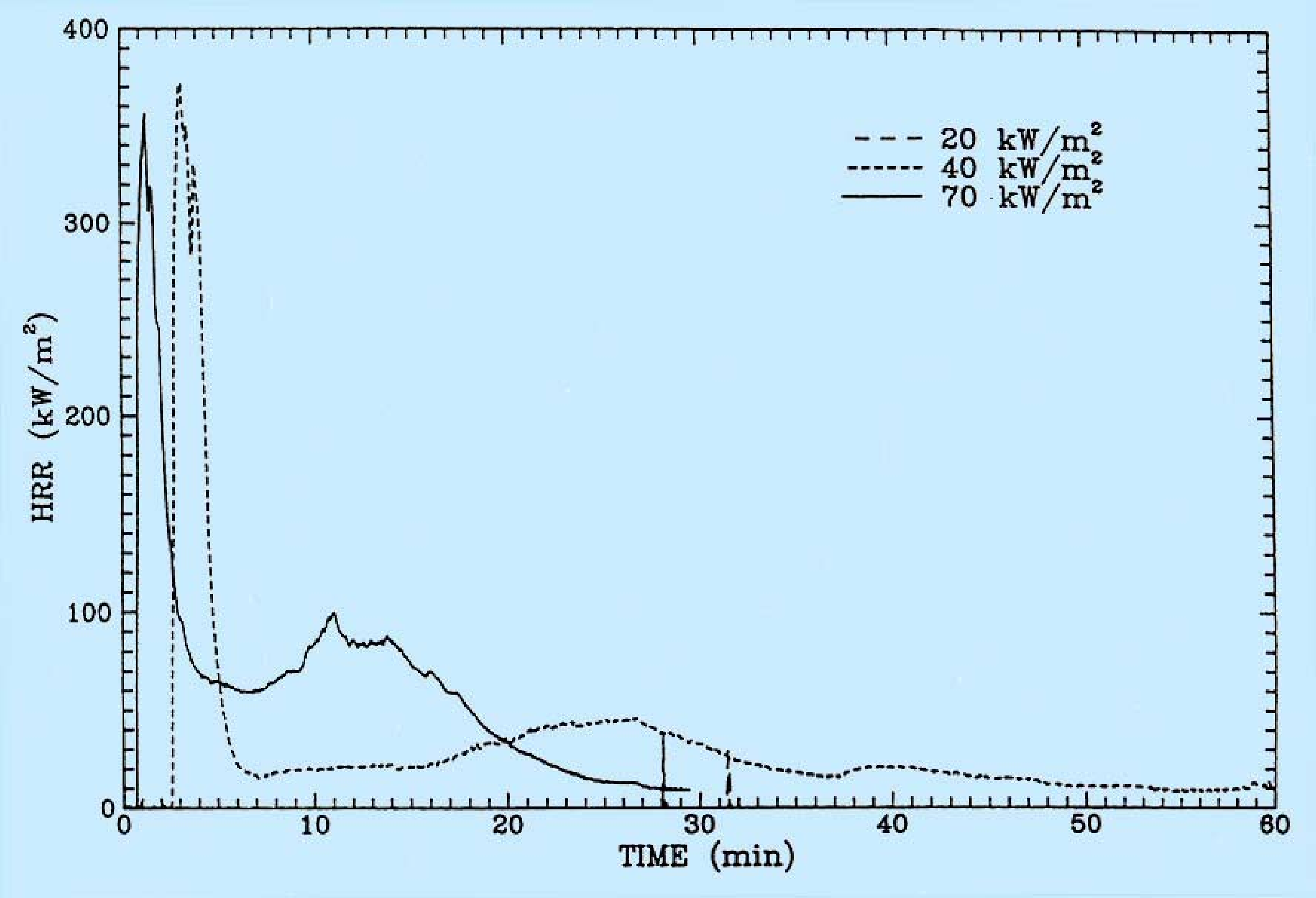
	TTI	PRHR	ARHR	TTI/RHR
PTFE	252	161	53	1.56
PCARB	75	342	115	0.22
PE	47	2735	911	0.02
XLPE	35	268	194	0.13
Navy req @ 75 kW/m^2	***90 minimum***	***100 maximum***	***100 maximum***	***-***

Babrauskas et al.

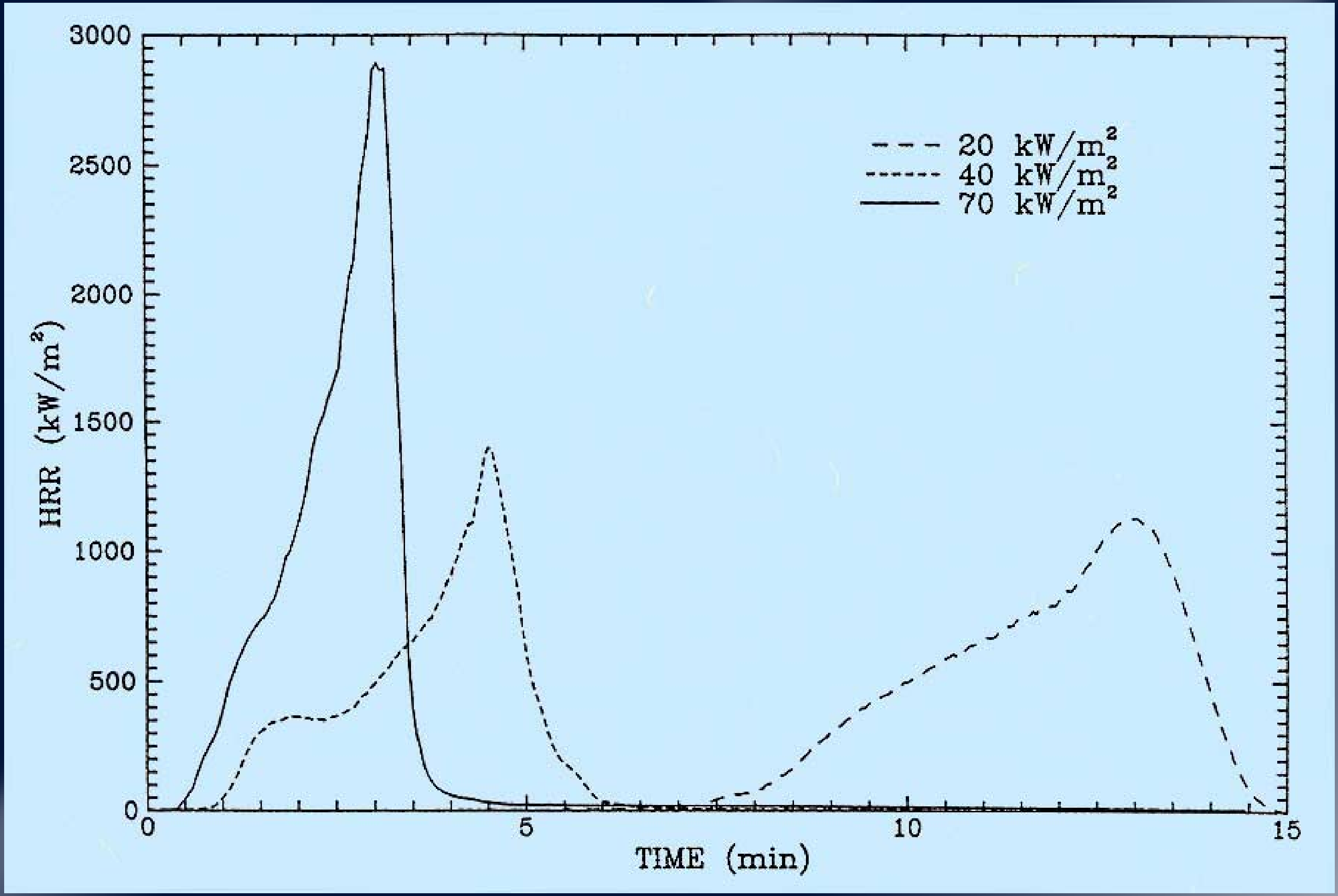
HRR vs. time for PTFE



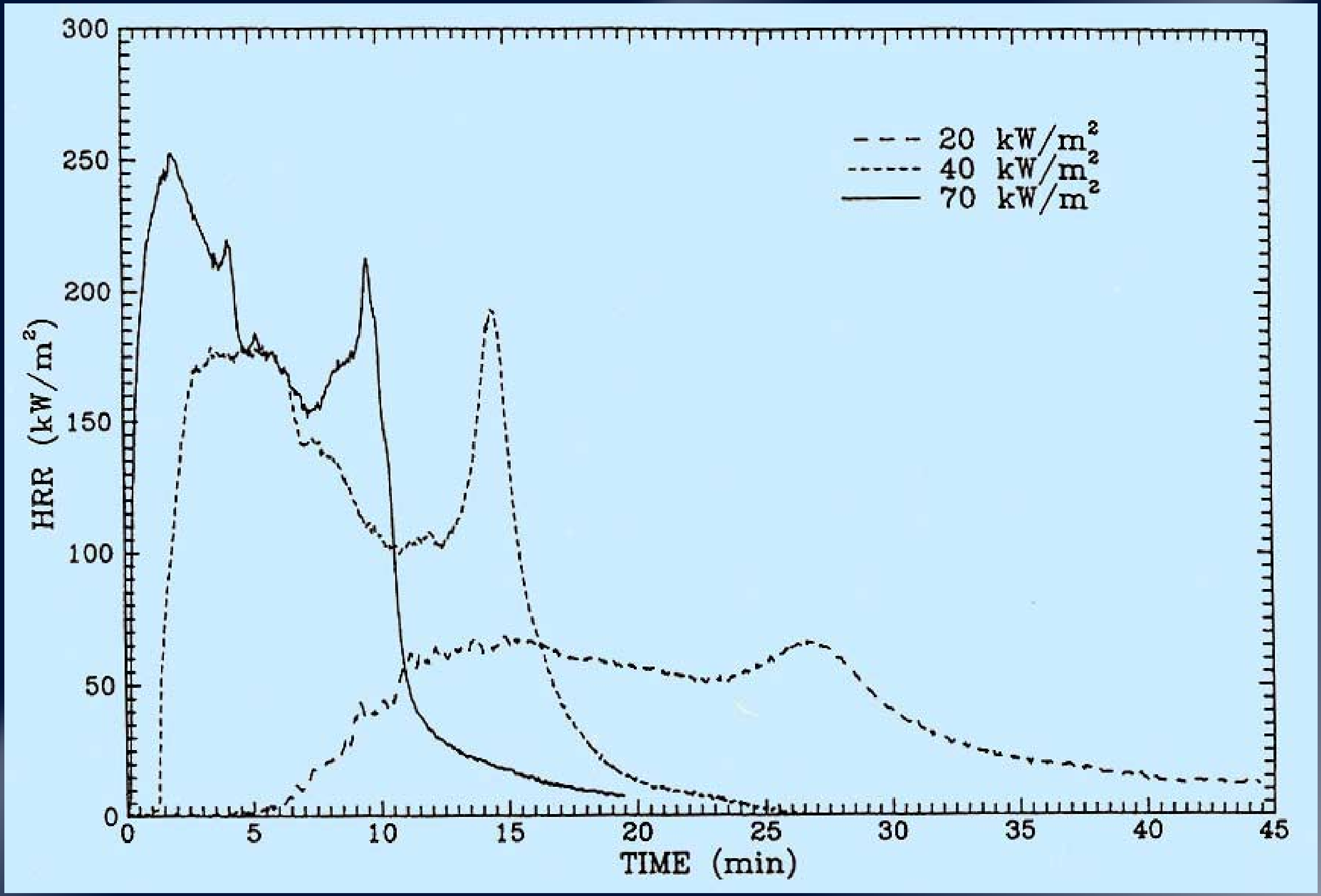
HRR vs. time for PCARB



HRR vs. time for PE



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/m^2
■ CO	200 ppm
■ CO_2	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_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

	Mil-Std-2223 - 3006/3007	NASA STD 6001	ASTM D 3032
Ranks/ Qualifies	Q	Q	R
7-wire bundle	X	X	X
400 Hz, 3 phase, 120/208 V	X	X	X – allows alternates

Arc tracking test methods comparison (continued)

	3006/3007	**NASA STD 6001**	**ASTM D 2223**
Arc initiation	Pre-damaged wires/RB	Graphite powder	Reciprocating blade (RB)
Voltage proof test	X	-	X
Visual damage	X	X	X
CB's tripped	X	-	X

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

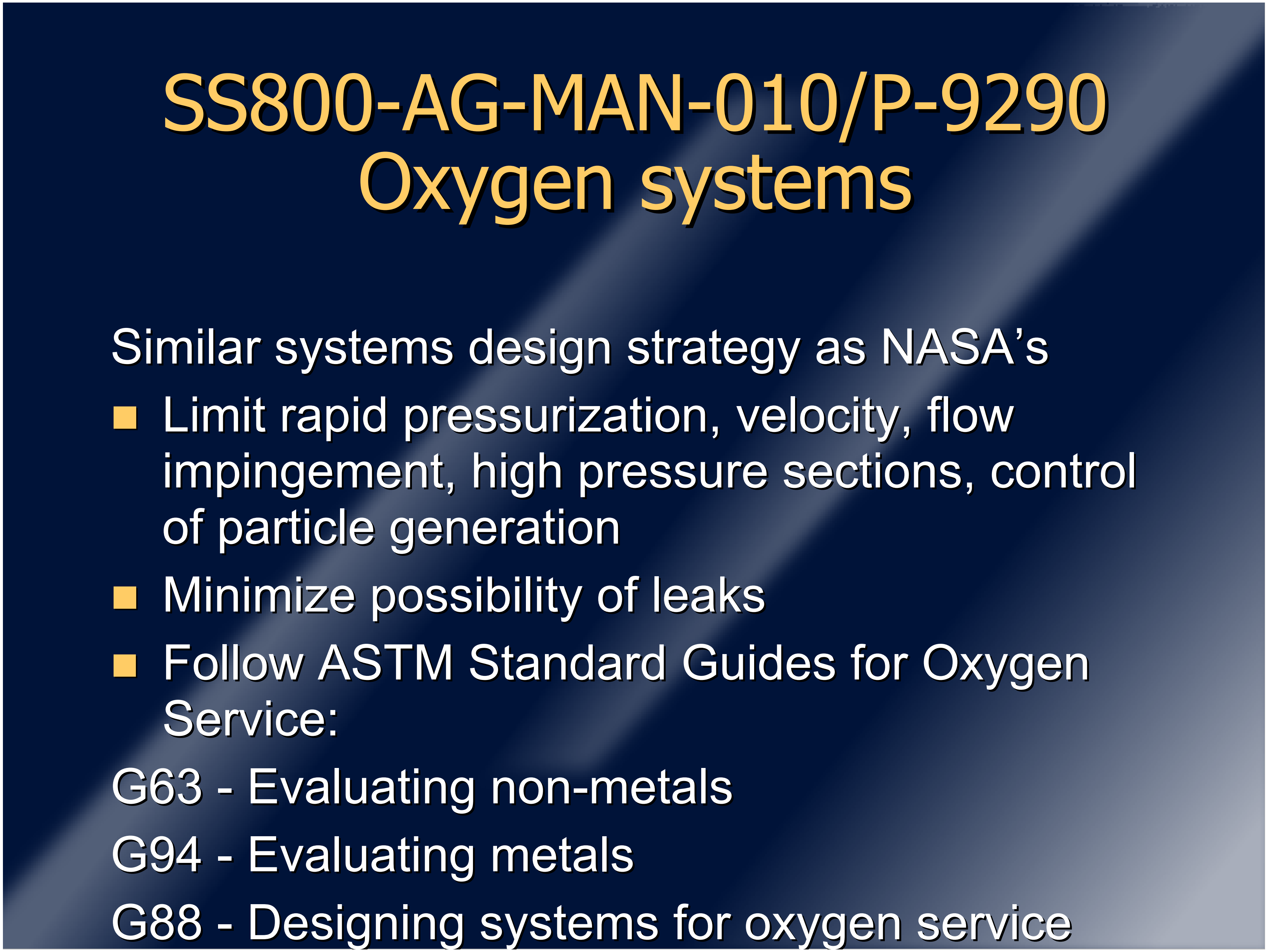
SS800-AG-MAN-010/P-9290 Category 3 Materials

- 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.



SS800-AG-MAN-010/P-9290 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.

INTERACTIONS, DEFORMATIONS AND BIOLUBRICATION OF LIQUID-LIQUID AND BIOFLUID INTERFACES

Jacob Israelachvili and Gary Leal
Department of Chemical Engineering, Materials Department, and Biomolecular Science & Engineering Program (BMSE), University of California at Santa Barbara (UCSB)
Santa Barbara, California 93106

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.

[1] Large deformations during the coalescence of fluid interfaces. Nianhuan Chen, Tonya Kuhl, Rafael Tadmor, Qi Lin and Jacob Israelachvili. Phys. Rev. Letters 92 (2004) 024501-04.
[2] Further studies on the effect of de-gassing on the dispersion and stability of surfactant-free emulsions. N. Maeda, K. Rosenberg, J. Israelachvili and R. Pashley. Langmuir 20 (2004) 3129-3137.
[3] Measurements of hydrophobic interactions at short-range. Tonya Kuhl, Qi Lin, Maria Tadmor, Jacob Israelachvili (submitted).

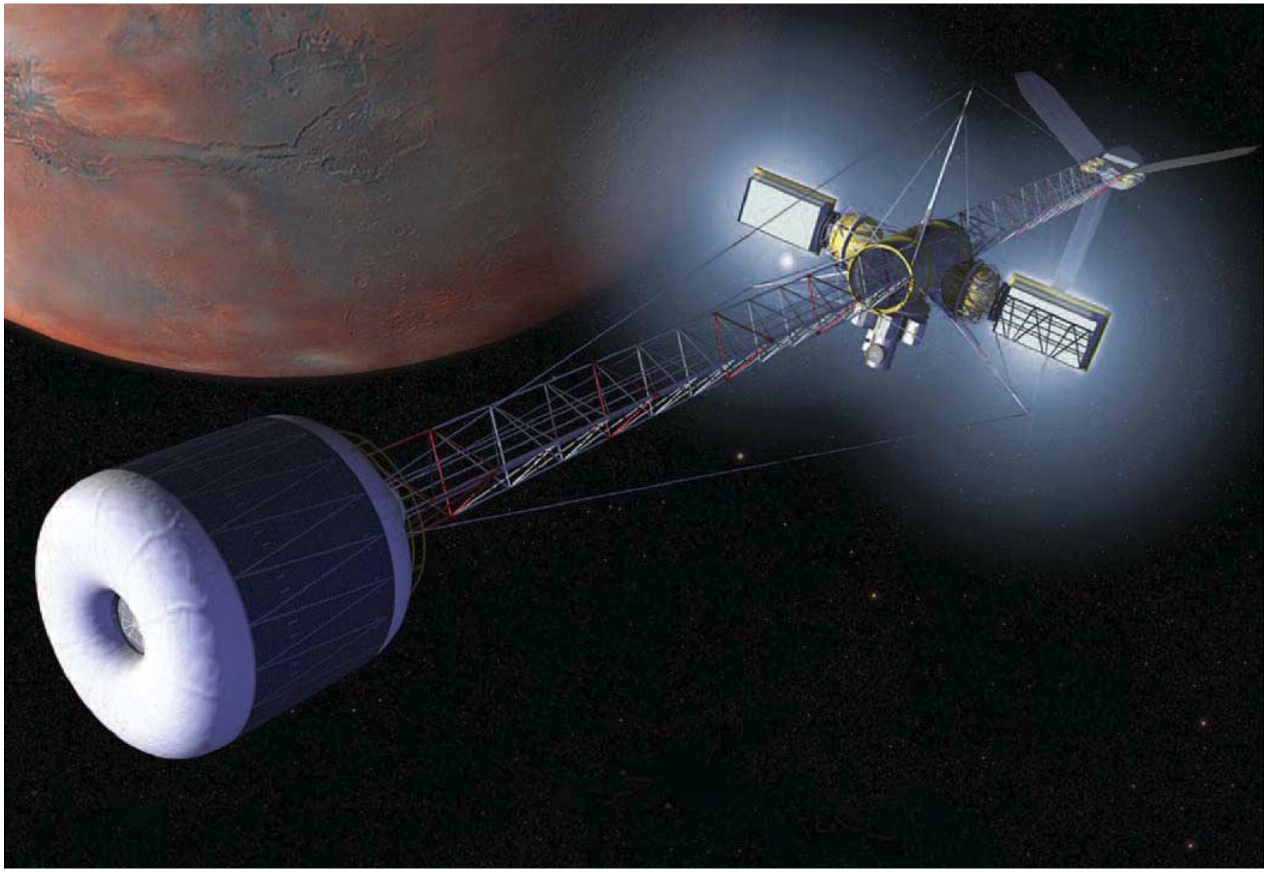
Advanced Environmental Monitoring Technologies

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

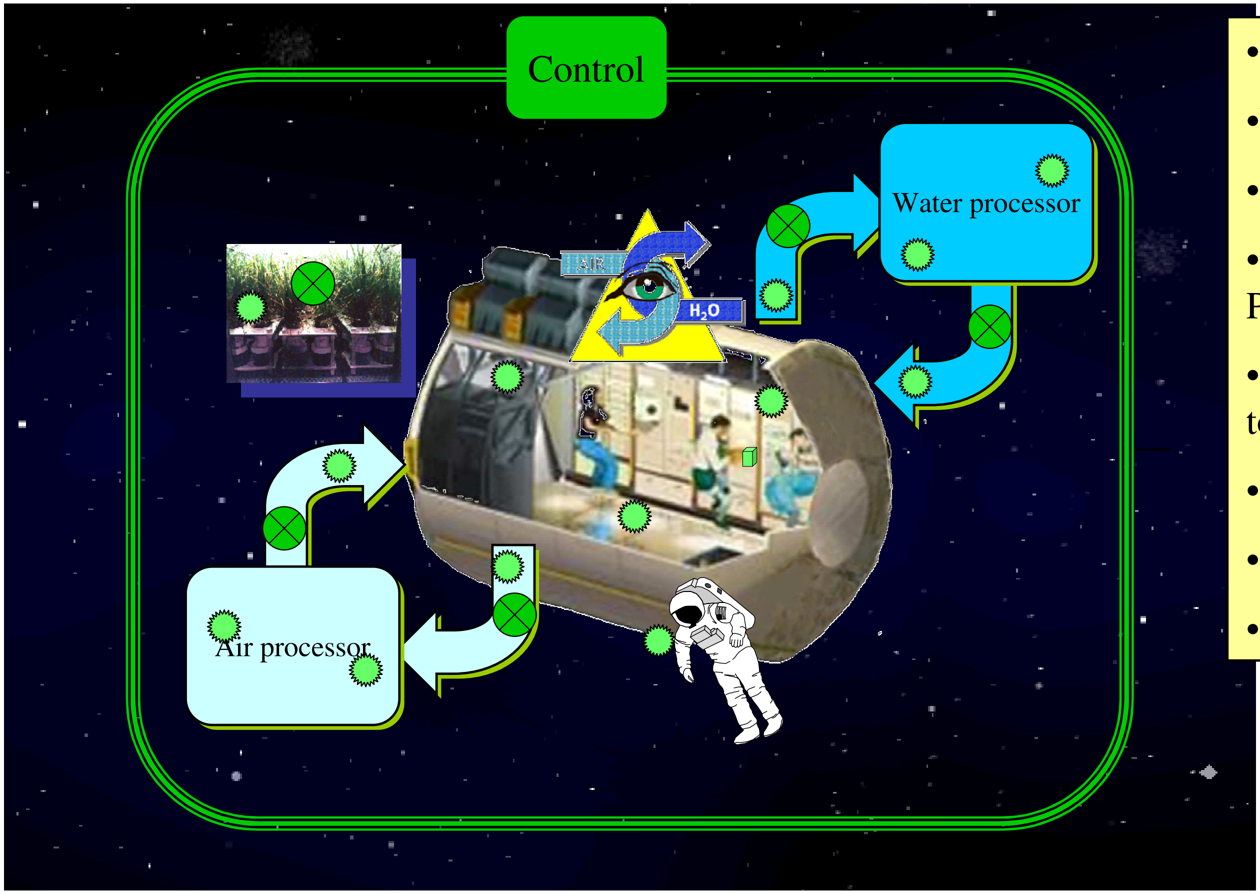
June 22, 2004

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Apollo 12 photograph , taken by lunar module pilot Alan Bean , mission commander Pete Conrad retrieves parts from the Surveyor.



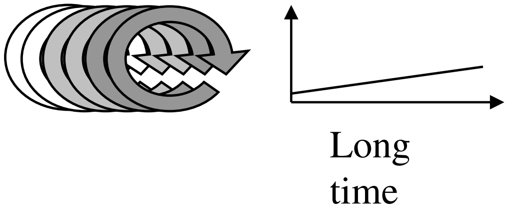
Monitoring & Controlling the environment



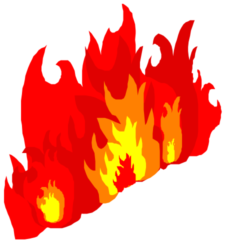
- Air
- Water
- Plant chambers
- Food and Food Preparation surfaces
- Gradual buildup of toxic species
- Hazardous events
- Chemical
- Biological

✹ sensors

⊗ actuators



COMPOUND	DETECTION LIMIT
PRIORITY 1	PPM
Acetaldehyde	0.1
Formaldehyde	0.01
Methanol	0.2
Dichloromethane	0.03
Perfluoropropane (F218)	10
Acetone	1
Octamethylcyclotetrasiloxane	0.05
2-Propanol	3
Freon 82	5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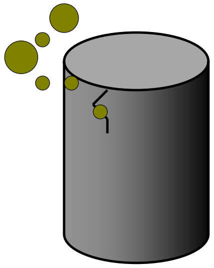
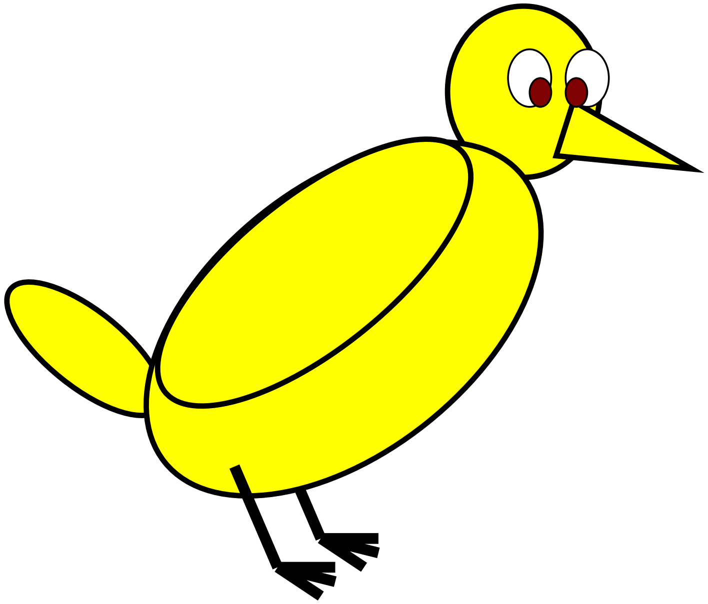


*microgravity combustion not shown

Gradual buildup of harmful chemical or microbials

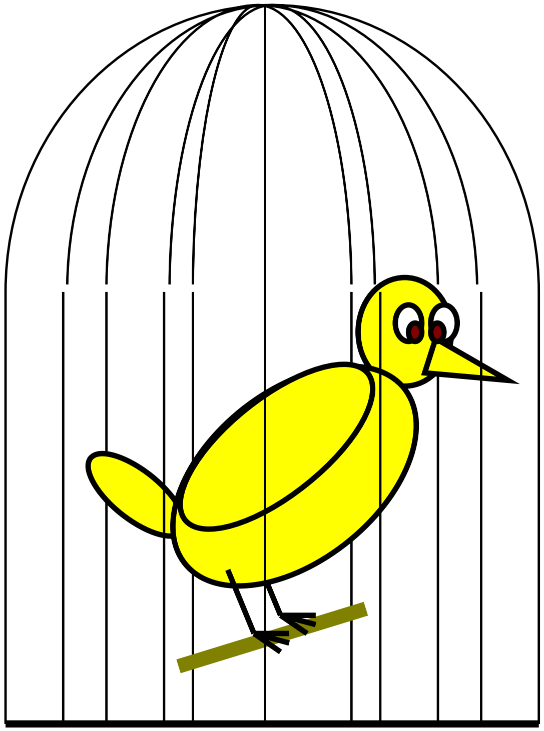
Hazardous event such as fire or leakage

ILLUSTRATIVE EXAMPLE:



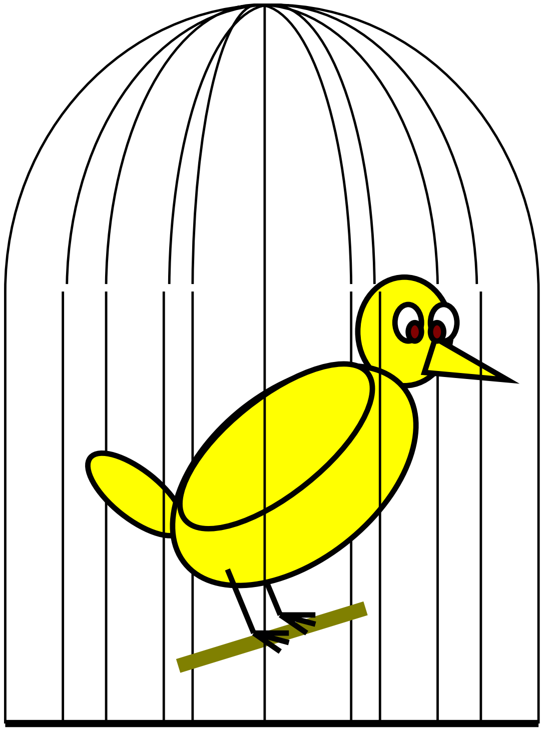
CANARY

Why a canary?



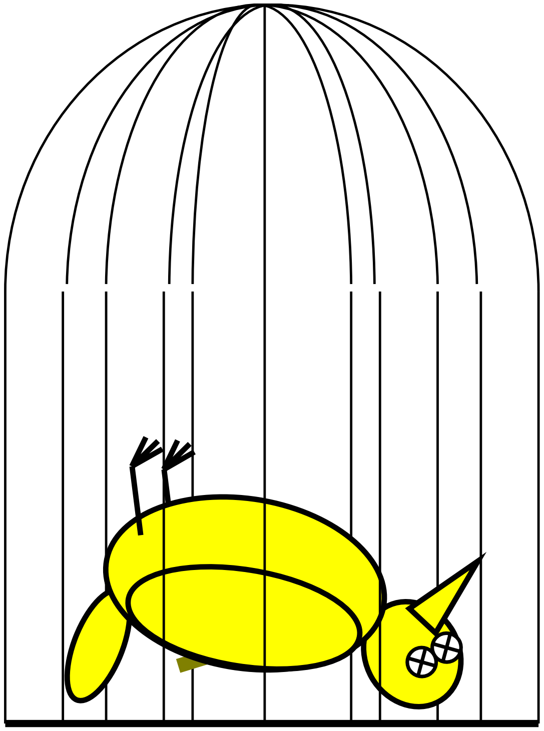
- •Continuous air monitor
- •Ground-based heritage
- •Doesn’t require skilled operator
- •Relatively low mass, low power
    - •Can consider placing in several locations
- •High sensitivity to many toxic gases
- •Multifunctional potential:
    - •air
    - •water
    - •food
    - •music
- •Probably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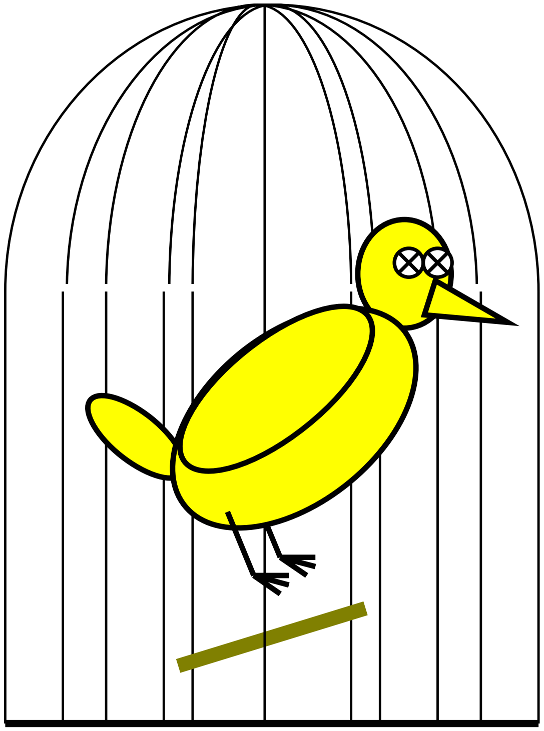
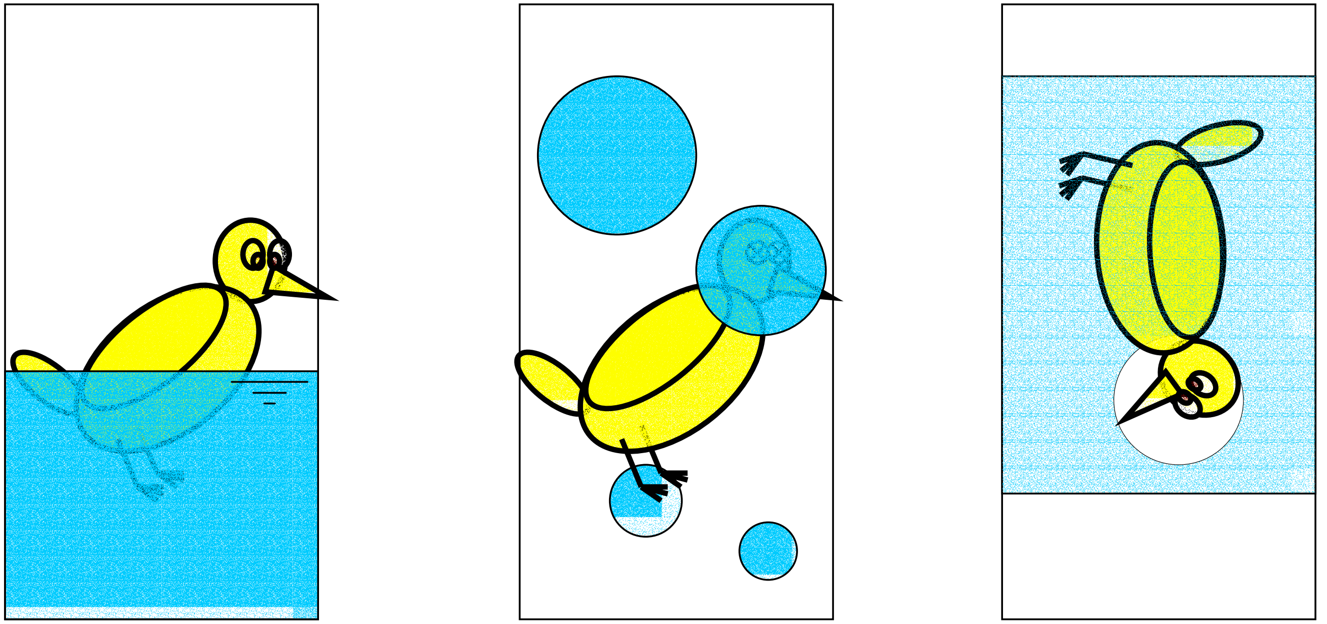
Why not a canary?



- 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?

A canary in water



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

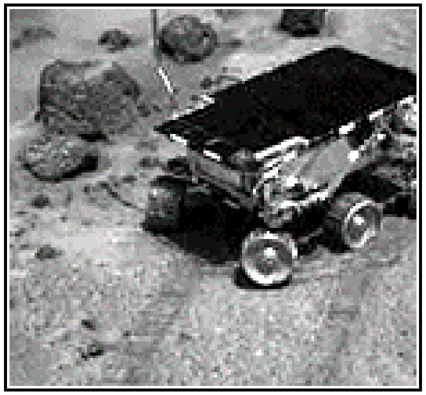
Ground-based Commercial technology

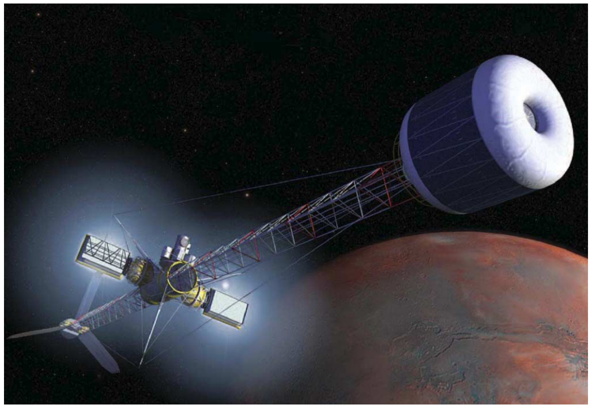
- •High mass
- •High power requirement
- •High operator skill
- •High capability
- •May require gravity

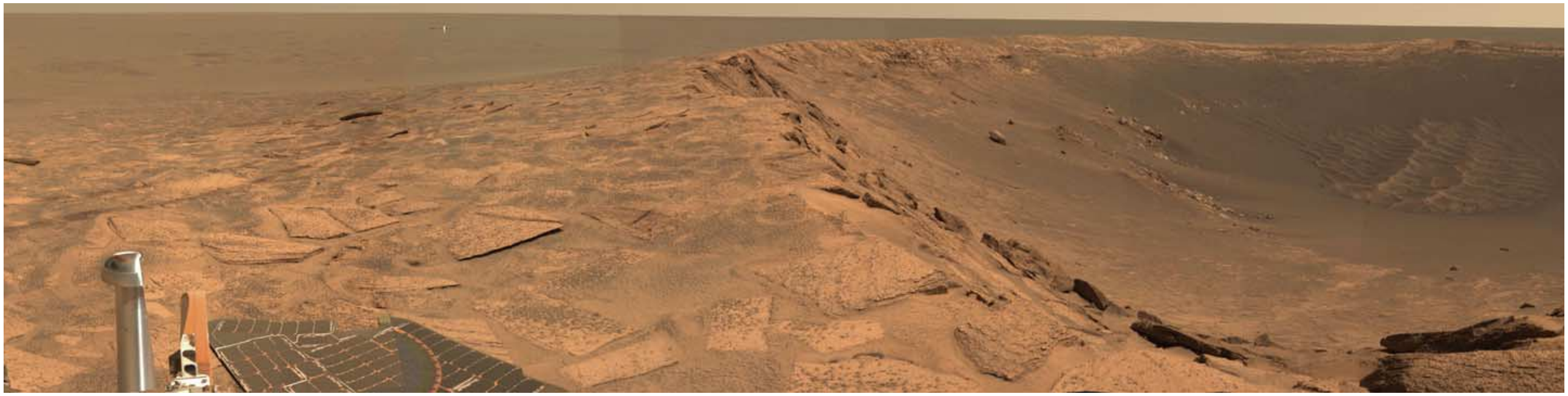
- •Lower mass
- •Lower power requirement
- •Low operator skill
- •Low capability
- •May require gravity

•Breakthroughs needed to achieve high capability and low mass/power plus autonomy

High Capability & Low Mass/Power + Autonomy = key to future SpaceFlight



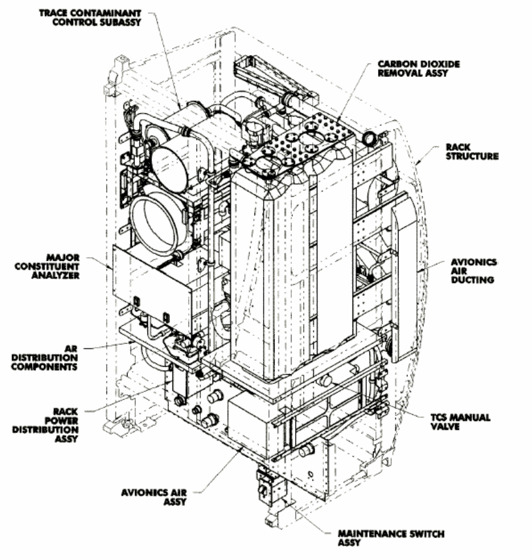




Current Practice: in flight

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

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



AR RACK FRONT ISOMETRIC VIEW
RACK FACEPLATES NOT SHOWN FOR CLARITY

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

2000-01-2345
International Space Station Carbon Dioxide
Removal Assembly Testing
James C. Knox

Current Practice: Post Flight

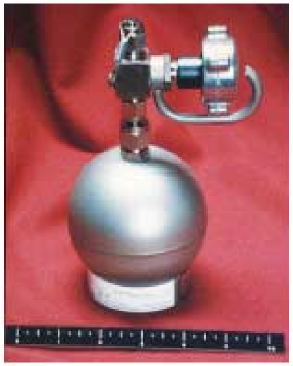
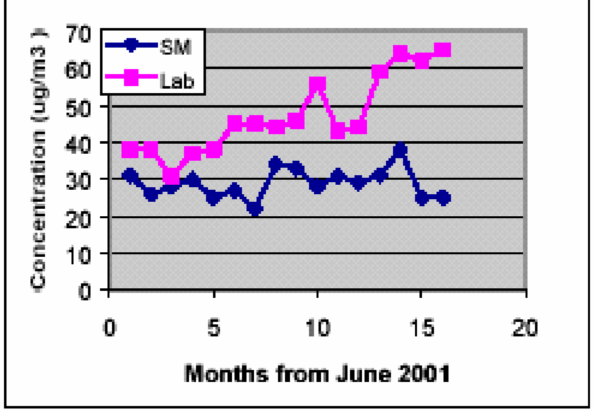


Figure 5: Grab Sample Container (GSC)

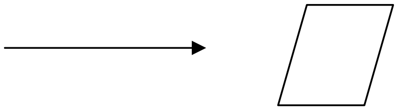
Grab Sample Bottles: Thorough analysis
By GCMS, over 100 species

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

Figure 1. Airborne Formaldehyde



Formaldehyde Badges



2.5 in x 2.5 in

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

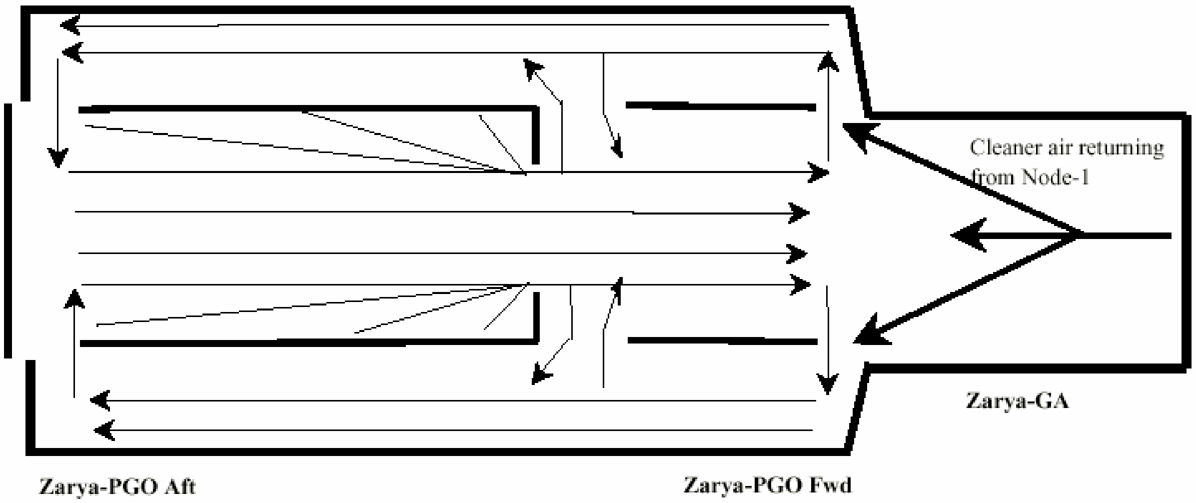
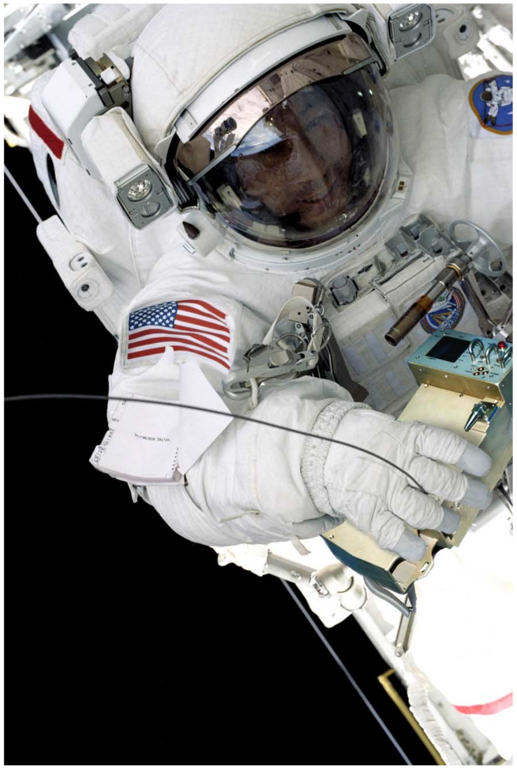


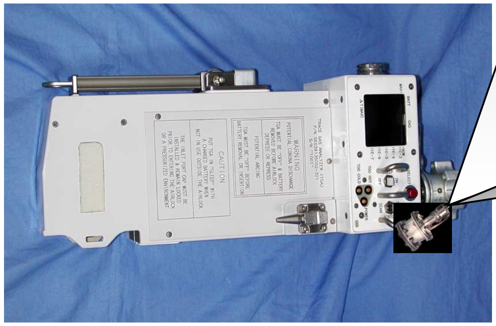
Figure 1. Overview of the airflow inside Zarya with opposed panels opened to 90 degrees. This diagram was adapted from Alibaruho et al. (1999) with addition of the flow arrows going from the walls toward the isle through open panels. The goal of the figure is to indicate the potential for disrupted airflow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

ICES 2000-01-2432 Toxicological Assessment of the
International Space Station Atmosphere
John James, et al

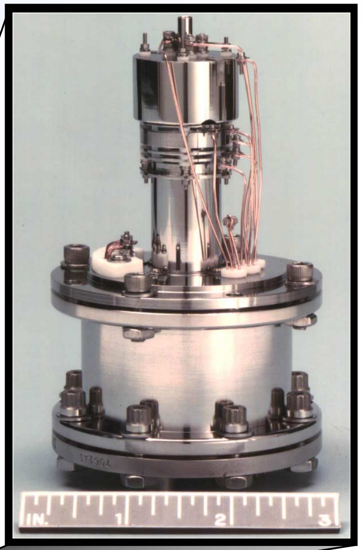
Miniature Mass Spectrometer for Planetary Exploration and Long Duration Human Flight

- **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**





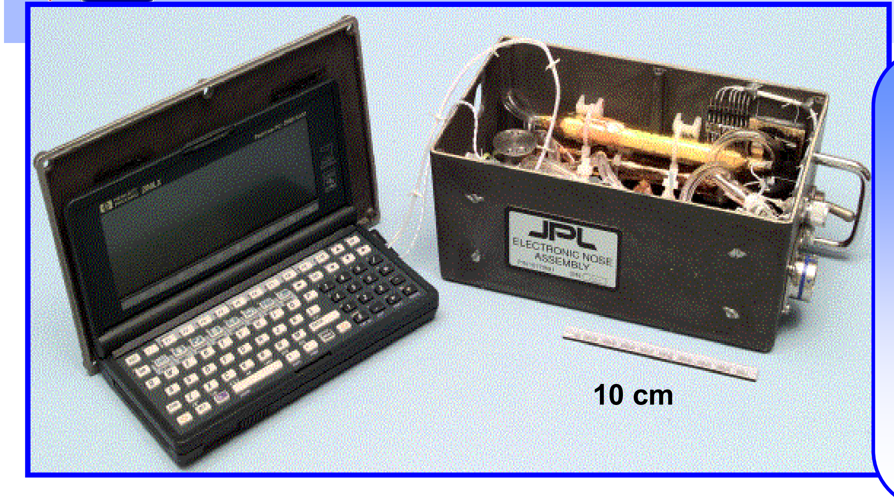
The QMSA Packaged as the Astronaut's Trace Gas Analyzer (TGA)



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

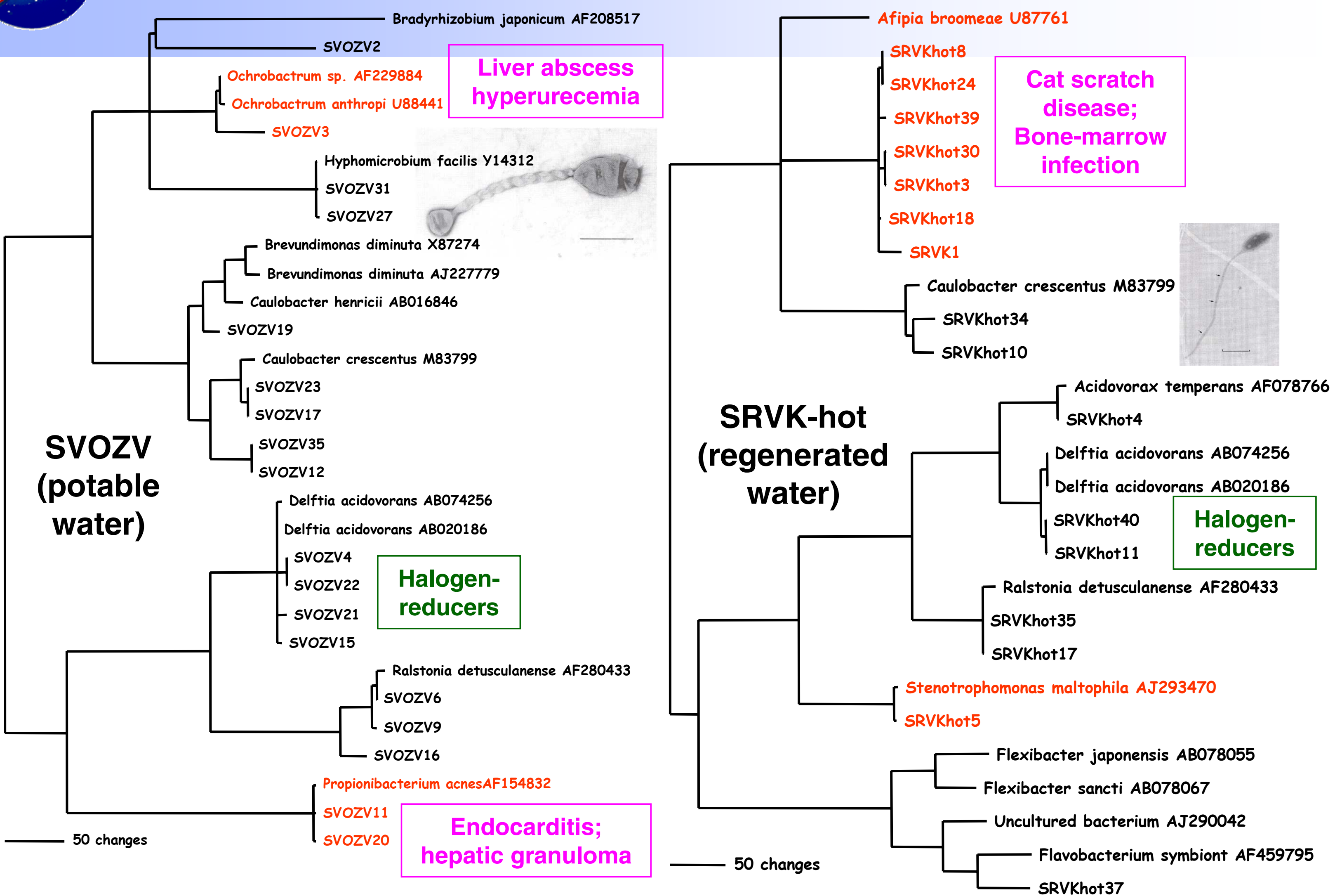
Optimized sensors, faster analysis, improved sensitivity

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



Darrell Jan JPL 02-13-03 21

Red clones are opportunistic pathogen

Preview of Porter

PARTICLE SEGREGATION IN COLLISIONAL SHEARING FLOWS

James T. Jenkins, PI
Department of Theoretical and Applied Mechanics
Cornell University, Ithaca, NY 14853

Michel Y. Louge, CoI
Sibley School of Mechanical and Aerospace Engineering
Cornell University, Ithaca, NY 14853

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.

Strategic Research to Enable NASA's
Exploration Missions Conference
Cleveland, 22-24 June, 2004

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

Human Support Technology Program

BCPR Risks relevant to HST

	AHST Risk Rating Criteria for System Performance Risks	
Rating		
R	Considerable potential for improvement in efficiency in many areas, or proposed missions may be infeasible without improvements.	
Y	Considerable potential for improvement in efficiency in a few areas	
G	Minimum or limited potential for improvement in efficiency.	

RISK NUMBER	Theme	Discipline	Risk Category	ISS (1yr)	Moon (30d)	Mars (30m)
7	HHC	Env Health	Define Acceptable Limits for Trace Contaminants in Air and Water	🟩	🟨	🟥
29	BH&P	SHFE	Mismatch between Crew Cognitive Capabilities and Task Demands	🟨	🟨	🟥
36	AHST	AEMC	Monitor Air Quality	Y	R	R
37	AHST	AEMC	Monitor External Environment	Y	R	R
38	AHST	AEMC	Monitor Water Quality	Y	R	R
39	AHST	AEMC	Monitor Surfaces Food and Soil	Y	R	R
40	AHST	AEMC	Provide Integrated Autonomous Control of Life Support Systems	G	Y	R
41	AHST	AEVA	Provide Space Suits and Portable Life Support Systems	G	Y	R
42	AHST	AFT	Maintain Food Quantity and Quality	Y	G	R
43	AHST	ALS	Maintain Acceptable Atmosphere	G	Y	R
44	AHST	ALS	Maintain Thermal Balance in Habitable Areas	G	Y	R
45	AHST	ALS	Manage Waste	G	Y	R
46	AHST	ALS	Provide and Maintain Bioregenerative Life Support Systems	G	Y	R
47	AHST	ALS	Provide and Recover Potable Water	G	Y	R
48	AHST	AHST	Inadequate Mission Resources for the Human System	Y	R	R
49	AHST	SHFE	Mismatch between Crew Physical Capabilities and Task Demands	G	Y	R
50	AHST	SHFE	Mis-assignment of Responsibilities within Multi-agent Systems	Y	Y	R

Human Support Technology Program

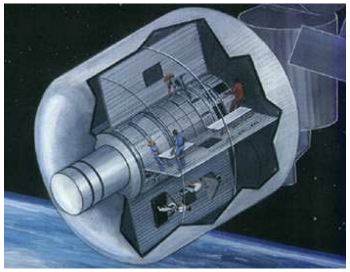
Research and Development Content

AHST

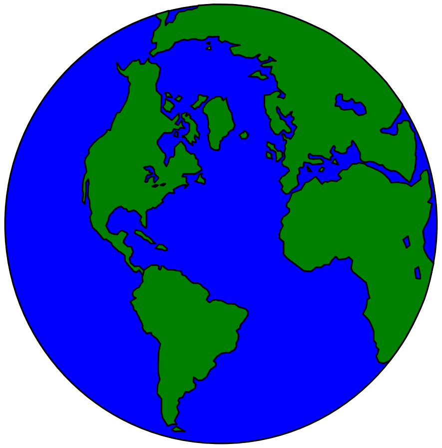
- *ADVANCED ENVIRONMENTAL MONITORING & CONTROL*
- *EXTRA-VEHICULAR ACTIVITIES TECHNOLOGY*
- *ADVANCED LIFE SUPPORT*
- *ADVANCED INTEGRATION MATRIX*
- *SPACE HUMAN FACTORS*

PSR

- 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

	Lunar Transit Vehicle (LTV)	Lunar Landing Vehicle (LLV)	Lunar Outpost (LO)	Mars Transit Vehicle (MTV)	Mars Landing Vehicle (MLV)	Mars Habitat (MH)	Pressurized Rover (PR)
Duration (Human Tended)	7 – 14 days (Roundtrip)	1 – 5 days	1 – 18 months	12 – 24 months (Roundtrip)	1 – 45 days	17 – 20 months	1 – 7 days
Air Revitalization	Open	Open	Closed	Closed	Open	Closed ISRU	Open
Water Recovery	Collection and Storage	Collection and Storage	Closed ISRU	Closed	Collection and Storage	Closed ISRU	Collection and Storage
Waste Management	Stored	Stored	Volume Reduction Mineralization Stabilization Resource Recovery	Volume Reduction Stabilization De-watering	Volume Reduction Stabilization	Volume Reduction Mineralization Stabilization Resource Recovery	Stored
Food Systems	Conventional Stored	Conventional Stored	Conventional Stored with Fresh Food Augmentation	Extended Shelf Life with Fresh Food Augmentation	Extended Shelf Life	Extended Shelf Life with Fresh Food Augmentation	Extended Shelf Life
Thermal Systems	LP-BR	LP-DR	HP-DR	HP-DR	LP-BR	HP-DR	LP-BR
System Configuration	System A	System A	System C	System B	System A	System C	System A

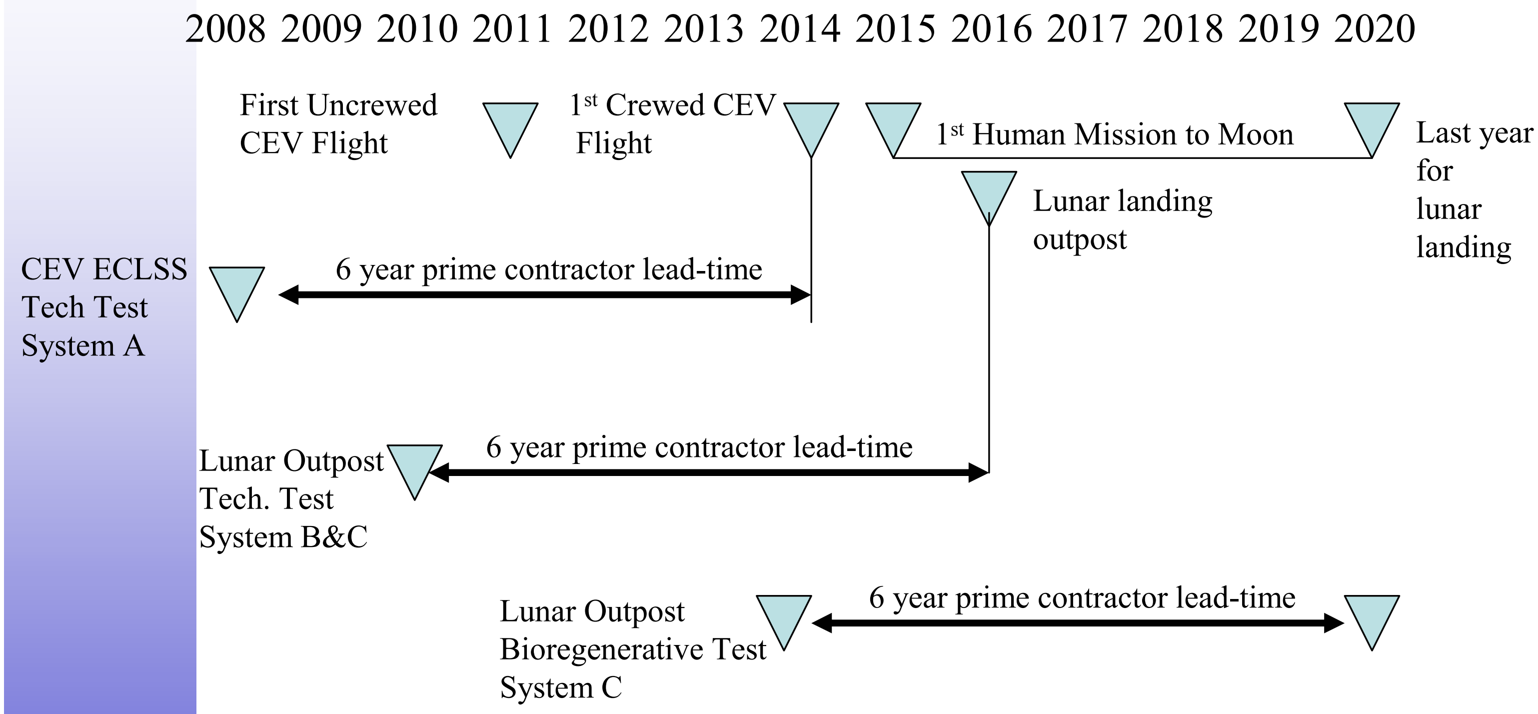
Closed Air is 75% by Mass
Closed Water is 90% by Mass
ISRU –Investigate and utilize as appropriate
Regenerative Systems will be selected over consumable systems

LP – Low Power HP – High Power
BR – Body Mounted Radiator
DR – Deployable Radiator

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

HST-Cleveland 22 June 2004 ET/RC

Exploration Timeline



2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

First Uncrewed CEV Flight

1st Crewed CEV Flight

1st Human Mission to Moon

Last year for lunar landing

Lunar landing outpost

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

Life Support Requirements
Mass Breakdown

(Per Person-Day)

DAILY INPUTS - NOMINAL

	kg
Oxygen	0.84
Food Solids	0.62
Water in Food	1.15
Food Prep Water	0.79
Drink	1.62
Hand/Face Wash Water	1.82
Shower Water	5.45
Clothes Wash Water	12.50
Dish Wash Water	5.45
Flush Water	0.50
TOTAL	30.74

5.02 - 30.74 kg per person-day

11.3 Metric Tons Per Person-Year

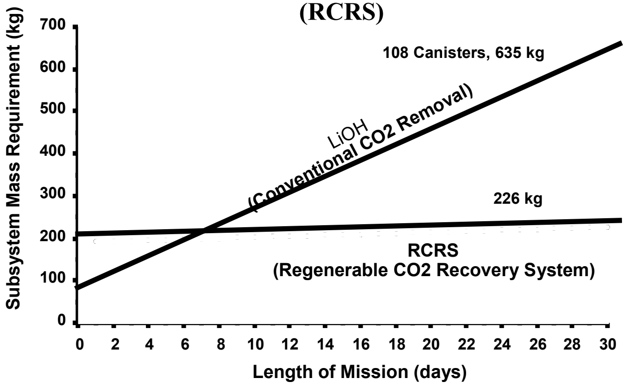
DAILY OUTPUTS - NOMINAL

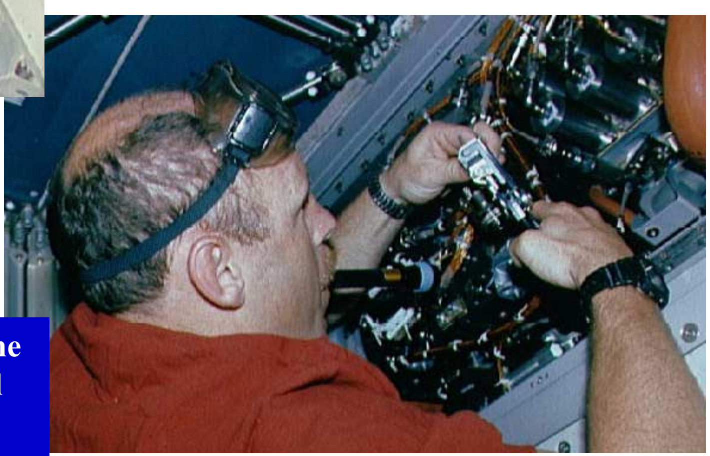
	kg
Carbon Dioxide	1.00
Respiration and Perspiration Water	2.28
Urine	1.50
Feces Water	0.09
Sweat Solids	0.02
Urine Solids	0.06
Feces Solids	0.03
Hygiene Water	6.68
Clothes Wash Water	11.90
Clothes Wash Latent Water	0.60
Other Latent Water	0.65
Dish Wash Water	5.43
Flush Water	0.50
TOTAL	30.74

Advanced Life Support

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

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





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

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***

Advanced Environmental Monitoring & Control (AEMC)

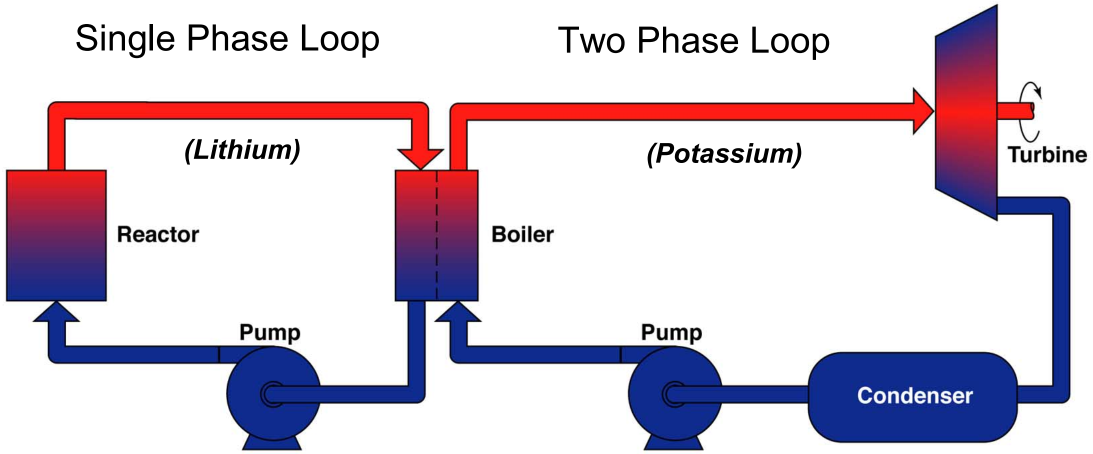
Goals and Objectives

- **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

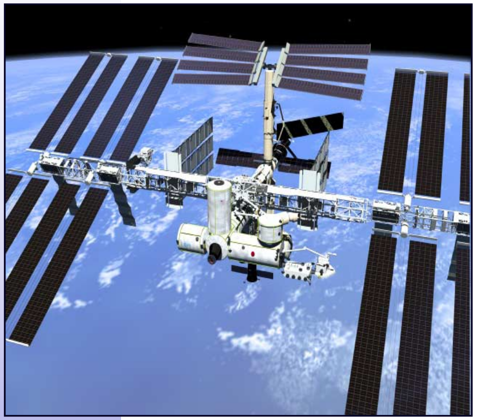
Strategic Research for Space Exploration
Two Phase Flow Facility - TΦFFy



Schematic Diagram of Two-Fluid, Liquid Metal Rankine Power Conversion System

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**

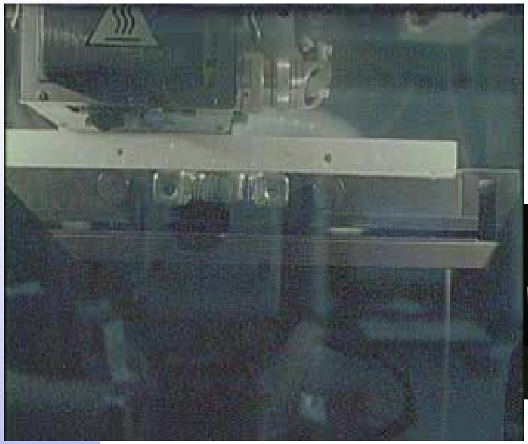
Fire Prevention, Detection, and Suppression

- 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

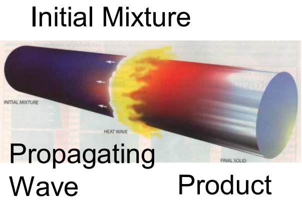
(LaRC/JSC)

In Situ SFF Deliverables

Project Plan Summary	Collaborators	FY '05	FY '06	FY '07	FY '08	FY '09	FY '10
Fabrication Technologies							
A. Combustion Synthesis Parts and Tools for	GRC, Purdue Univ, Col School of	▼ TRL 4	◆ Optimize Design	◆ Ceram/ Glass	◆ Prototype	◆ KC-135 Demo	▼ TRL 6
B. Electron beam Freeform Fabrication	LaRC, JSC	▼ TRL 3	◆ KC-135 Demo	◆ Portability	◆ Lrg Struc Repair	▼ TRL 5	

Self-Propagating High-Temp Synthesis

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



(GRC)

How will we conduct our Business?

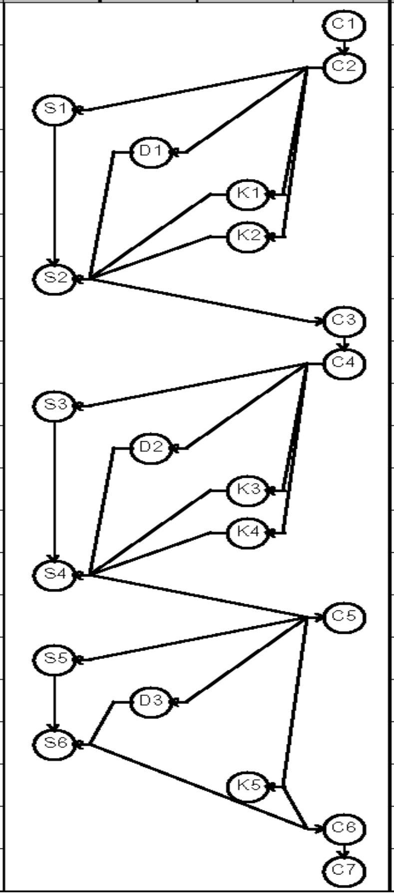
- Low TRL work through competitive NRAs
  - Long lead time items
- Rapid Technology Development Teams
  - Multi-disciplinary teams with clear objectives and deliverables
  - Mature technology to TRL 6
- Directed Research
  - Focused problems

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

Milestoneplan

S: Separator
D: Data System
K: Chemistry
C: Collaboration

Project nmbr.	
Project	Rapid Development of ISS Water Quality Sensors
Project code	
Project manager	
Milestoneplan name	Milestone Plan
Responsible	Supervisor
Approved by	



Planned	S	D	K	C	Code	Milestone
6/1/04				C1		Funding Received
8/31/04				C2		Kick-off Mtg and Req Review Completed
12/31/04	S1					Air-Water Separators Development Completed
12/31/04		D1				PC-based data system Development Completed
12/31/04			K1			Reagentless Calibration Development Completed
12/31/04			K2			Reagent Packaging Subsystem Completed
4/30/05	S2					SubsystemTesting and Refinement Completed
6/30/05				C3		KC-135 Subsystem Testing Completed
8/31/05				C4		Subsystem Evaluation Review Completed
12/31/05	S3					Bubble Mitigation Tech Refined & Selected
12/31/05		D2				PDA Data System Development Completed
12/31/05			K3			CSPE Methods Selected
12/31/05			K4			Reagent Shelf-life Tests Completed
3/31/06	S4					Integrated Prototype Design Completed
5/31/06				C5		Prototype Design Review Completed
9/30/06	S5					Fabricate Integrated Prototype Fabricated
9/30/06		D3				Barcode Scheme Development
12/31/06	S6					Integrated Prototype Ground Testing Completed
12/31/06			K5			Draft QA & Operating Procedures Prepared
3/31/07				C6		KC-135 Prototype Testing Completed
5/31/07				C7		Final Report and Prototype Delivered

Exploration EVA System

Lara Kearney
EVA Office
Johnson Space Center
June 22, 2004

Extravehicular
Activity
Office

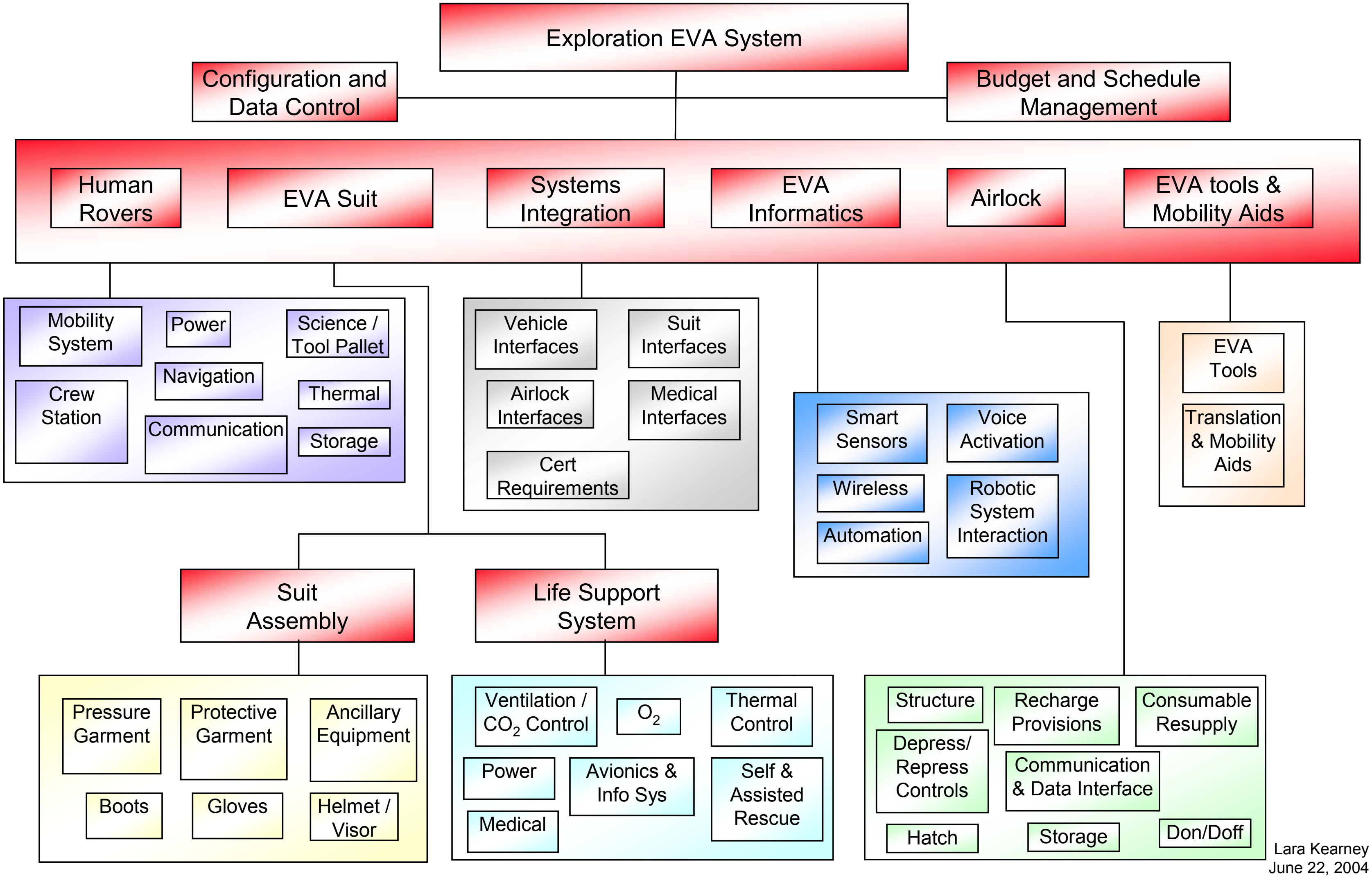
Exploration EVA System

- 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

Lara Kearney
June 22, 2004

Extravehicular
Activity
Office

Exploration EVA System



- Exploration EVA System
  - Configuration and Data Control
  - Budget and Schedule Management
  - Human Rovers
    - Mobility System
    - Power
    - Science / Tool Pallet
    - Navigation
    - Crew Station
    - Thermal
    - Communication
    - Storage
  - EVA Suit
    - Suit Assembly
      - Pressure Garment
      - Protective Garment
      - Ancillary Equipment
      - Boots
      - Gloves
      - Helmet / Visor
    - Life Support System
      - Ventilation / CO_2 Control
      - O_2
      - Thermal Control
      - Power
      - Avionics & Info Sys
      - Self & Assisted Rescue
      - Medical
  - Systems Integration
    - Vehicle Interfaces
    - Suit Interfaces
    - Airlock Interfaces
    - Medical Interfaces
    - Cert Requirements
  - EVA Informatics
    - Smart Sensors
    - Voice Activation
    - Wireless
    - Robotic System Interaction
    - Automation
  - Airlock
    - Structure
    - Recharge Provisions
    - Consumable Resupply
    - Depress/ Repress Controls
    - Communication & Data Interface
    - Hatch
    - Storage
    - Don/Doff
  - EVA tools & Mobility Aids
    - EVA Tools
    - Translation & Mobility Aids

Lara Kearney
June 22, 2004

Extravehicular Activity Office

Current State of EVA

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

Extravehicular
Activity
Office

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 +150F) • 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 ft^3 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

Lara Kearney
June 22, 2004

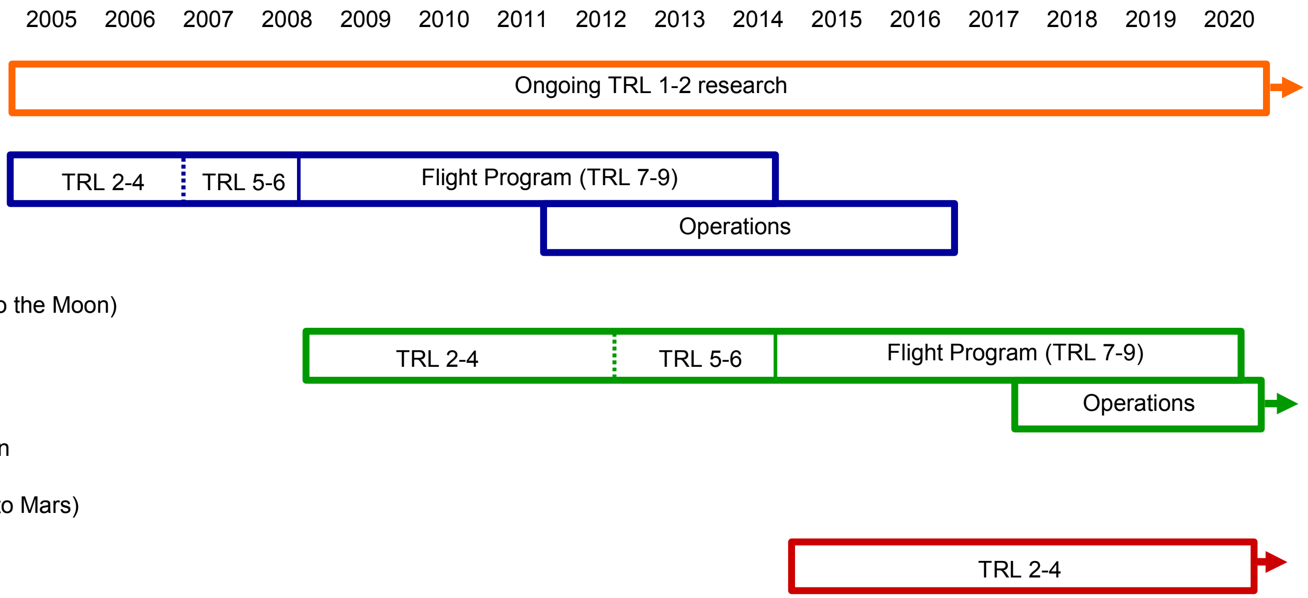
Exploration EVA System

- **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)

Extravehicular Activity Office

Exploration EVA System

- **The Exploration EVA System should follow a spiral development, in parallel with the CEV spirals**



Spiral I (2014 manned CEV)
  EVA suits
  Airlock/vehicle interfaces
  EVA tools/mobility aids

Spiral II (2020 manned mission to the Moon)
  EVA suits
  Airlock/vehicle interfaces
  Habitation interfaces
  EVA tools/mobility aids
  Human Rovers - 1st generation

Spiral III (2030 manned mission to Mars)
  EVA suits
  Airlock/vehicle interfaces
  Habitation interfaces
  EVA tools/mobility aids
  Human Rovers - 2nd generation

Lara Kearney
June 22, 2004

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*

CO$_2$ Removal
- *Cyclic absorption/regeneration*
- *Venting membranes*

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 II/Lunar Technology

Environmental Protection
- *Dust containment and removal*
- *Radiation protection*

Field Recharge & In-the-Field Servicing
- *O$_2$ 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 III/Mars Technology

CO$_2$ Removal
- *Laser CO$_2$ Decomposition*
- *Cryogenic CO$_2$ Removal*

Environmental Protection
- *Radiation protection*
- *Dust containment and removal*

Field Recharge & In-the-Field Servicing
- *O$_2$ 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 HEAT TRANSFER MECHANISMS IN EARTH AND LOW GRAVITY: BOUNDARY CONDITION AND HEATER ASPECT RATIO EFFECTS

Jungho Kim
University of Maryland
Dept. of Mechanical Engineering
College Park, MD 20742

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 μm^2 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

Jungho Kim
Dept. of Mechanical Engineering
University of Maryland
College Park, MD 20742

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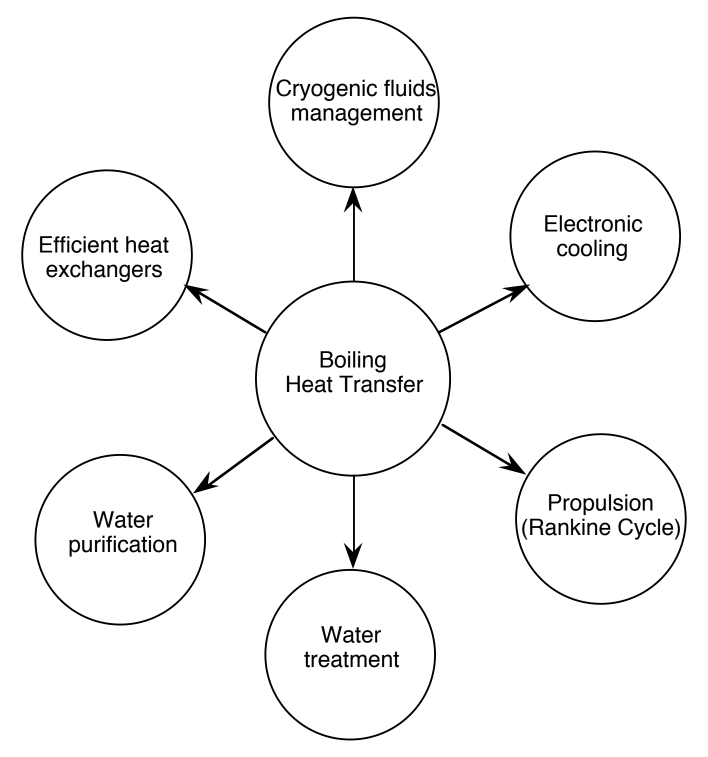
  Sam Hussey (Constant heat flux results)
  Glenda Yee (Constant heat flux results)
  John Yaniec

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



Boiling
Heat Transfer

Cryogenic fluids
management

Electronic
cooling

Propulsion
(Rankine Cycle)

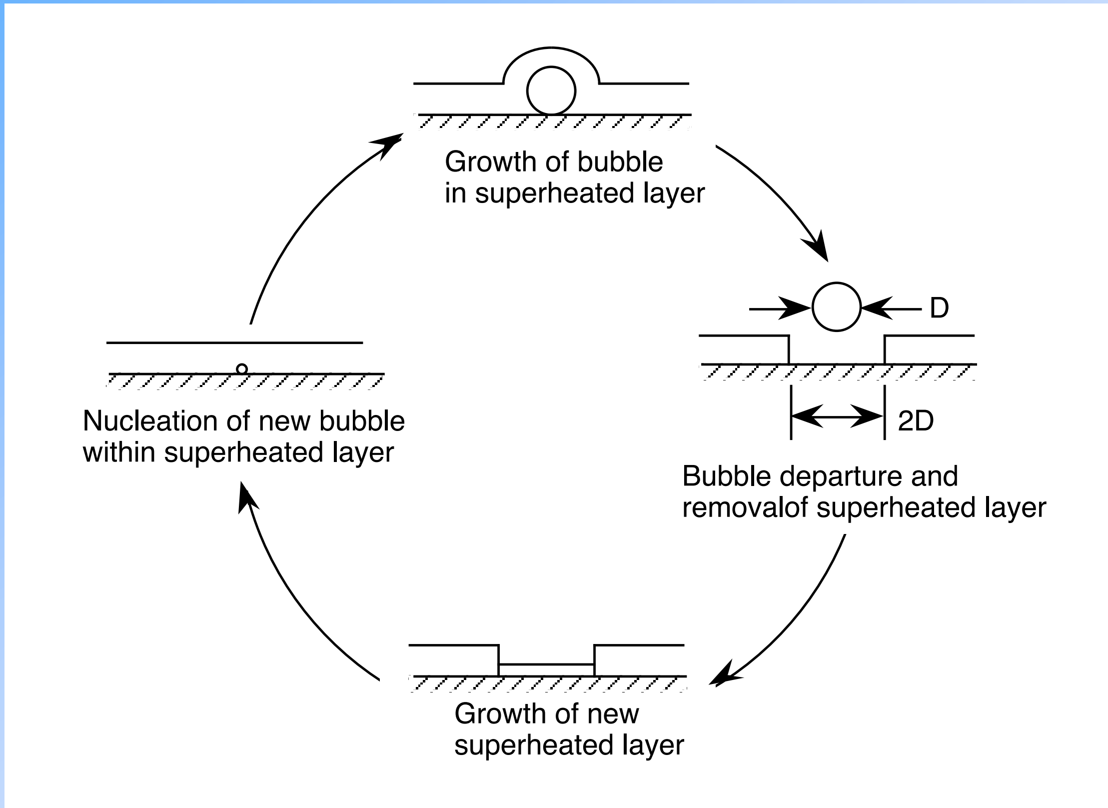
Water
treatment

Water
purification

Efficient heat
exchangers

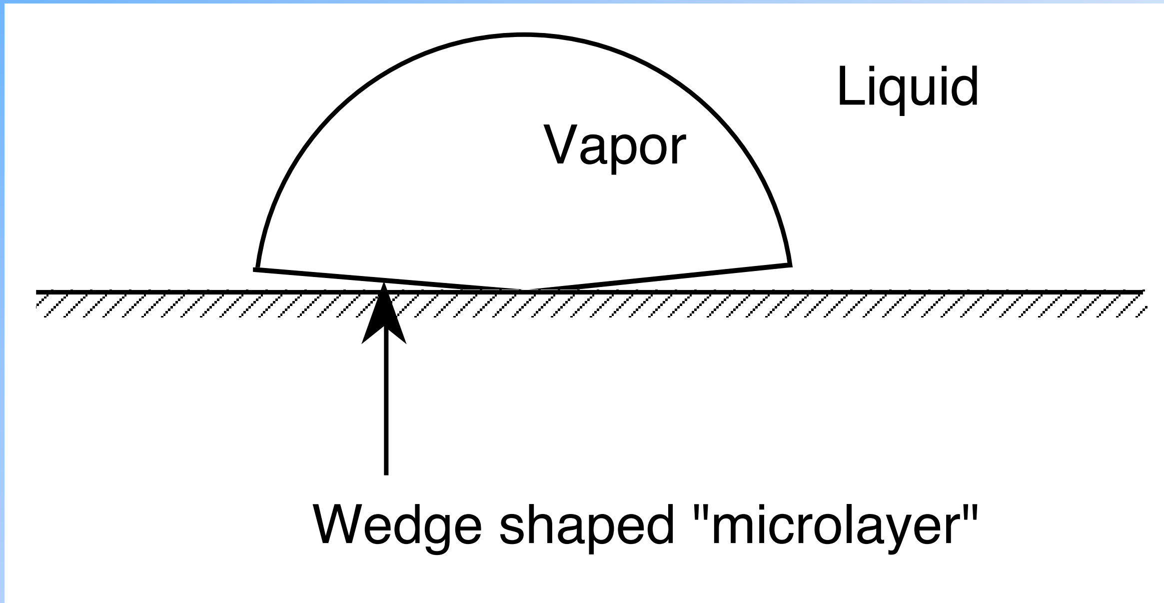
- **Provide fundamental understanding of gravity effects on boiling heat transfer mechanisms at various gravity levels so equipment and transfer processes can be designed efficiently.**

Model of Boiling: Mikic and Rosenhow (1969)



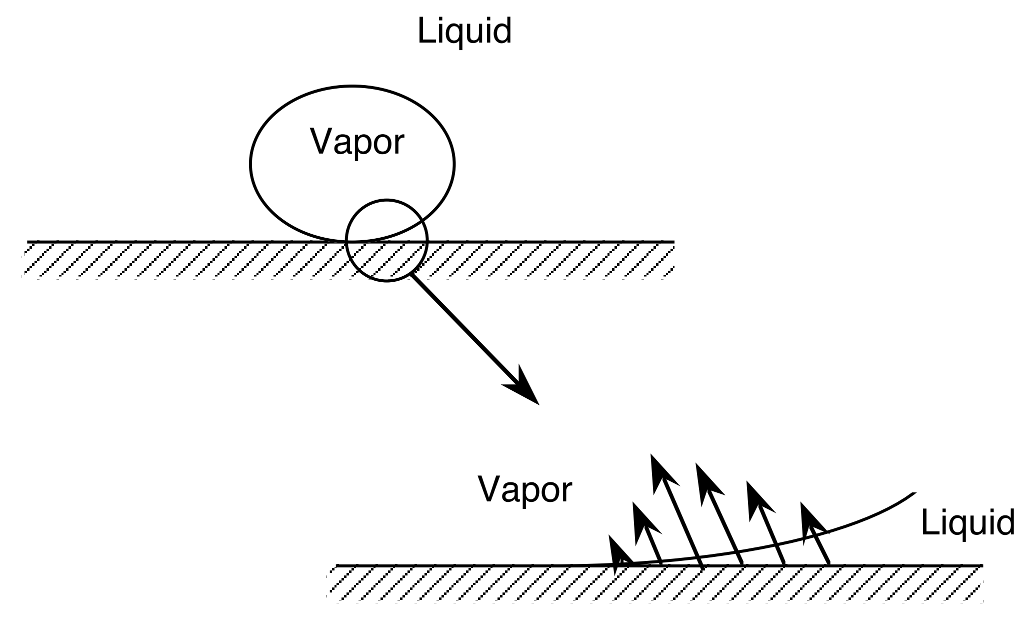
- **Heat transfer occurs primarily through conduction into liquid after bubble departs surface**

Model of Boiling: Microlayer Evaporation Model (Cooper and Lloyd–1969)



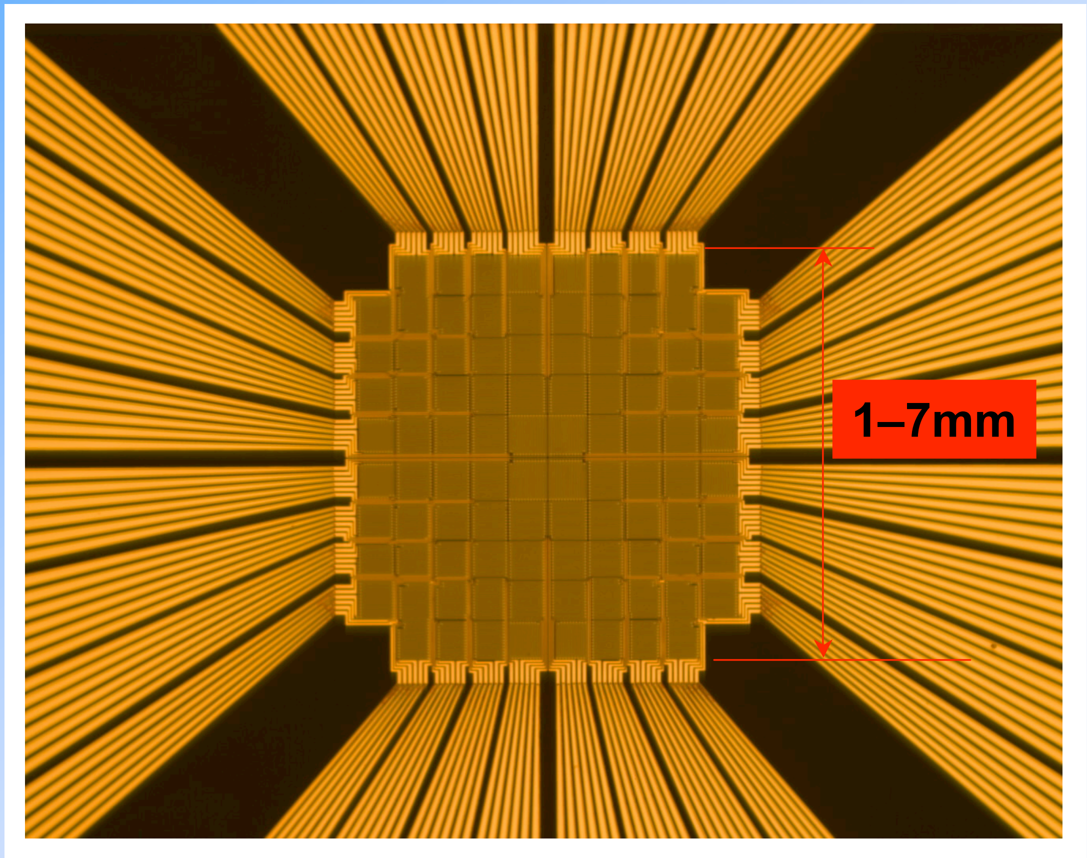
- **Heat transfer occurs primarily through evaporation of a thin film "microlayer" underneath bubble**

Model of Boiling: Contact Line Evaporation (Wayner, Stephan)

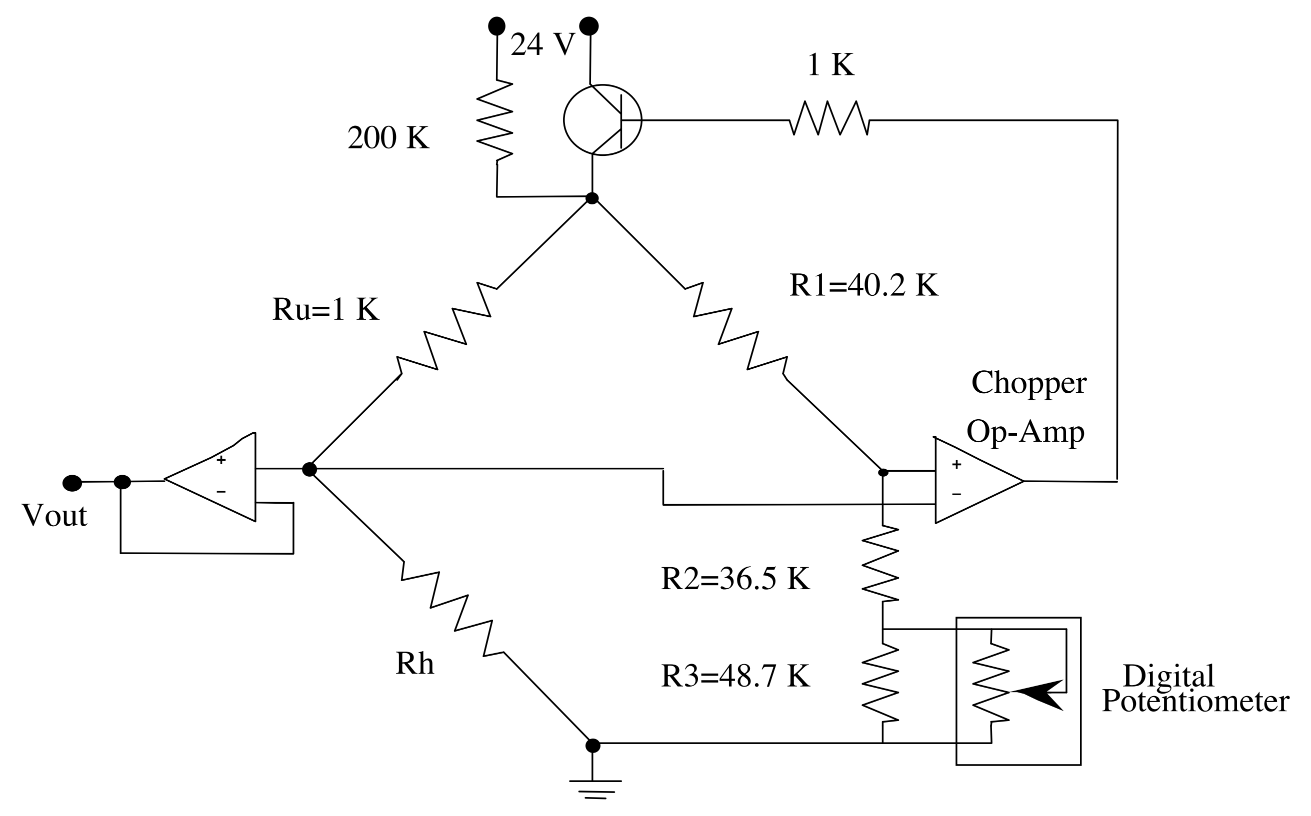


- **Heat transfer occurs primarily through conduction/evaporation of a thin meniscus at the three phase contact line**

Photograph of Heater Array

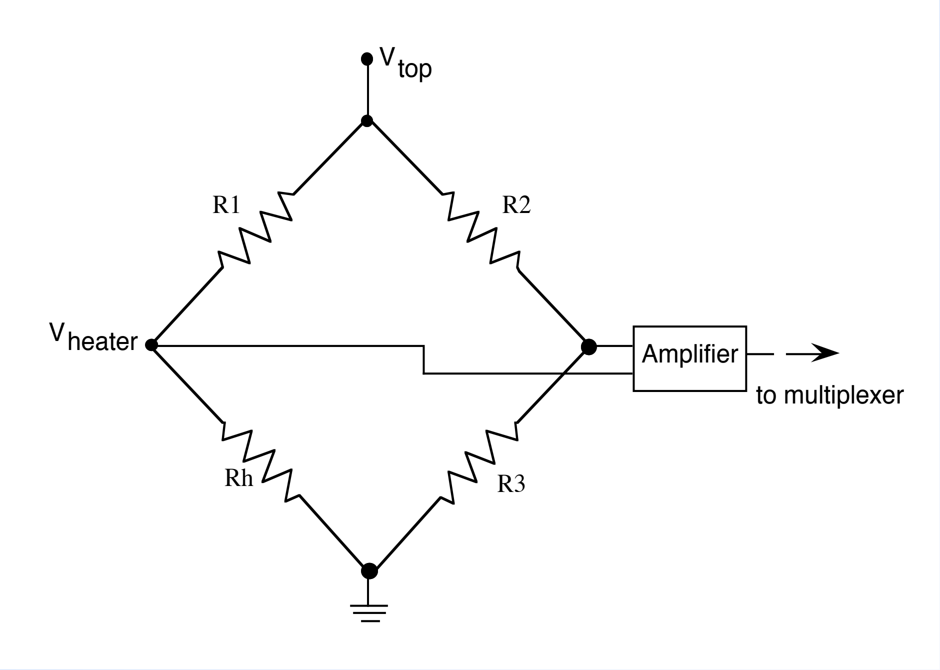


Feedback Control Circuit (Constant Temperature)



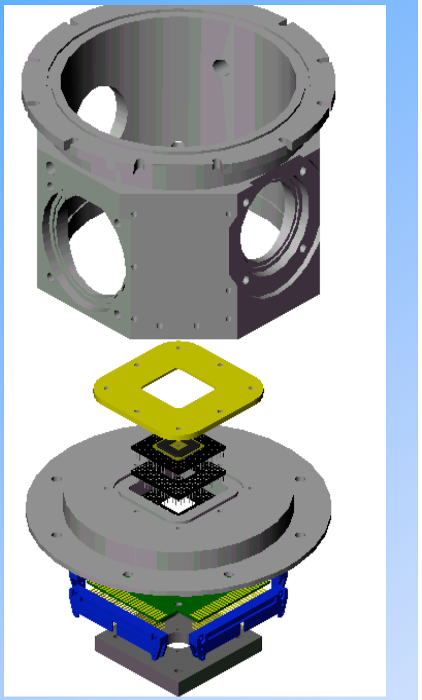
- **Feedback control circuit regulates heater temperature**
- **Frequency response up to 15 kHz.**

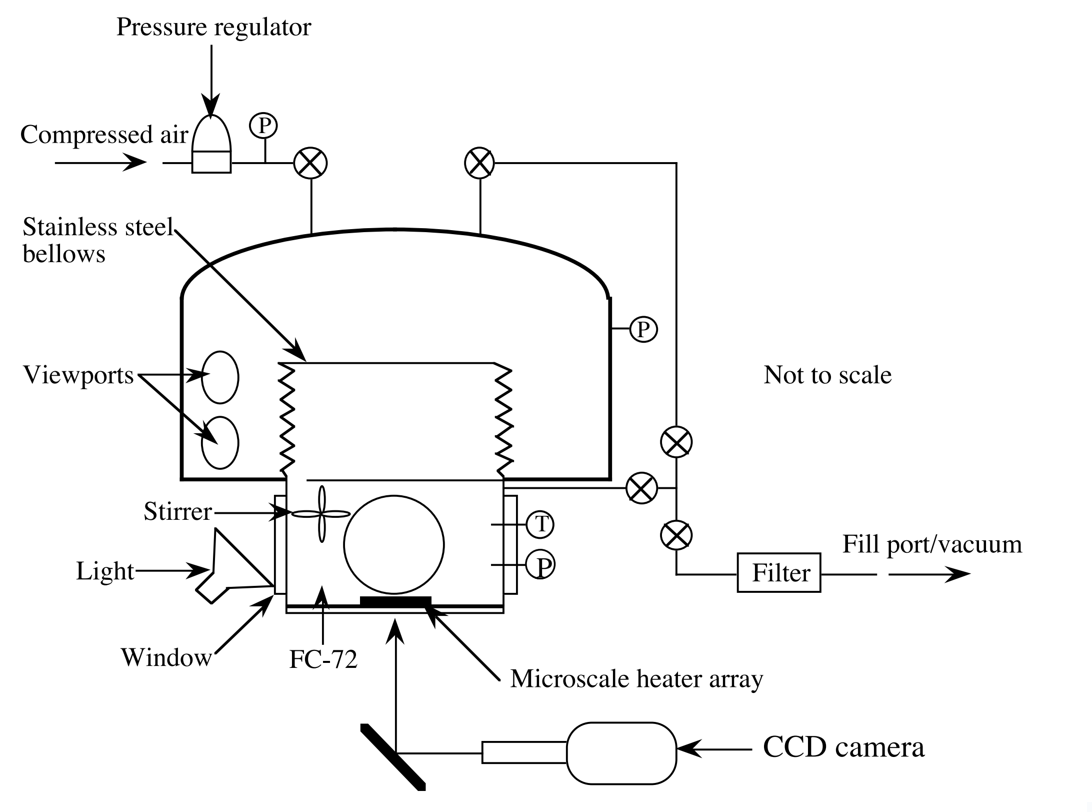
Schematic of Temperature Measuring Circuit (Constant Heat Flux)



- 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



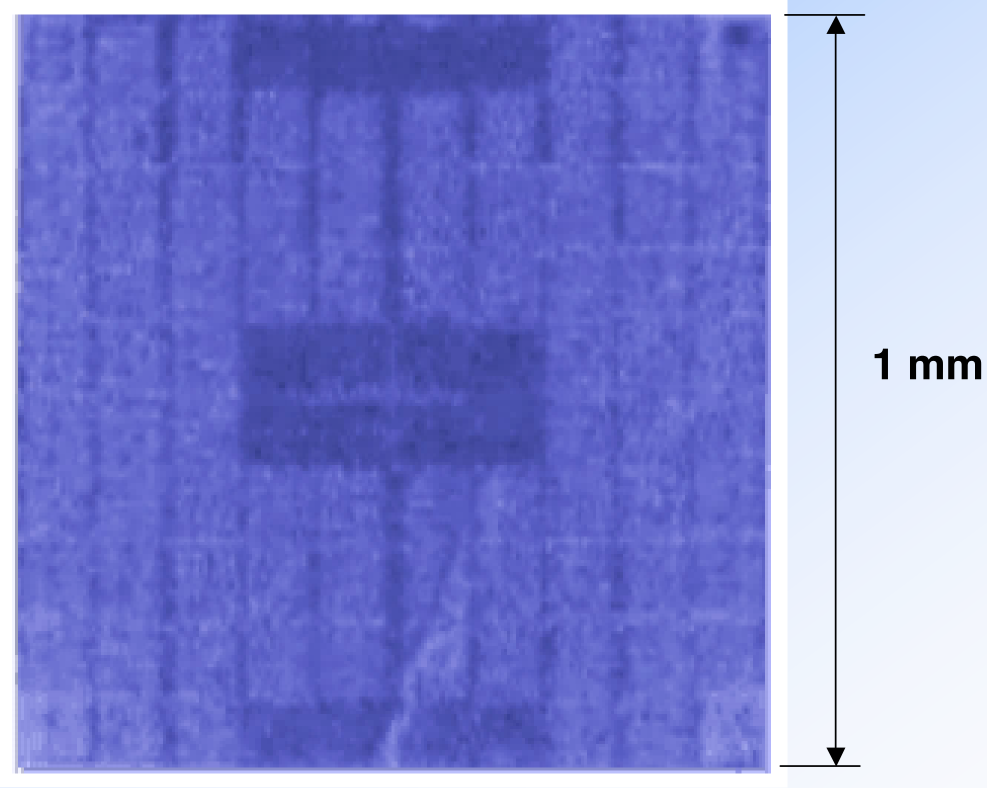


Experimental Results
(Earth Gravity)

Test Conditions for Constant Temperature Tests

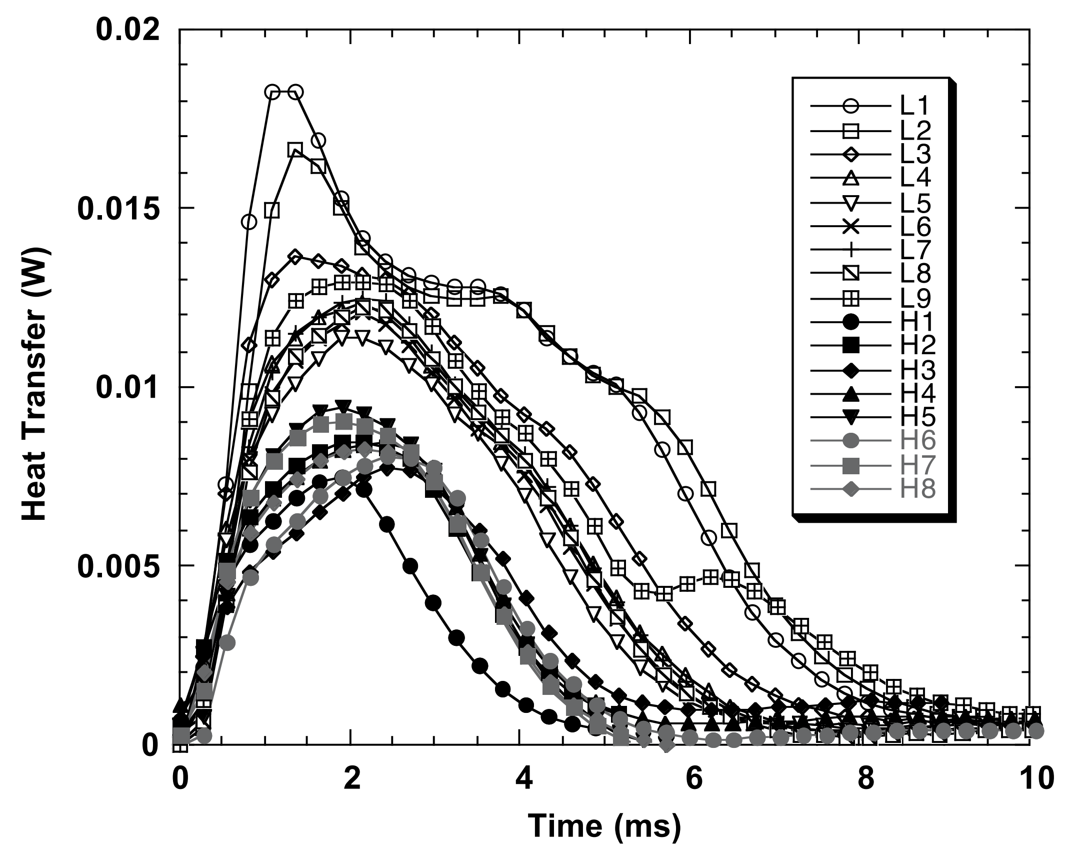
- **Fluid: FC-72**
- **Pressure=1 atm (T_{sat}=56.7 °C)**
- **Wall temperature=76 °C**
- **Bulk temperature=52 °C, 41 °C**

Heat Transfer Variation During Single Bubble Event



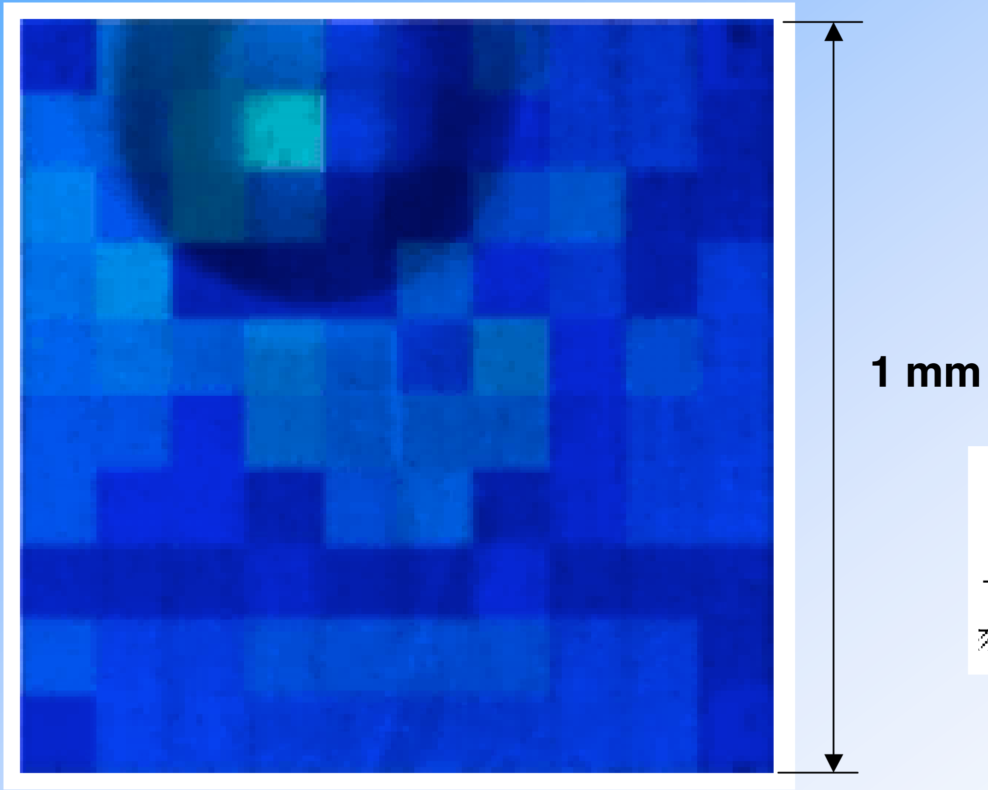
- Tbulk=52 °C

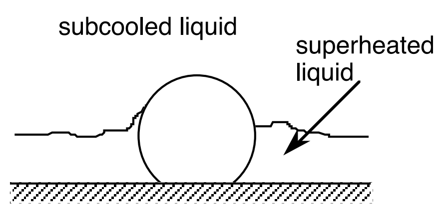
Single Bubble Heat Transfer



- Change in heat transfer profile observed for low subcooling case–may be linked to changes in baseline heat transfer.

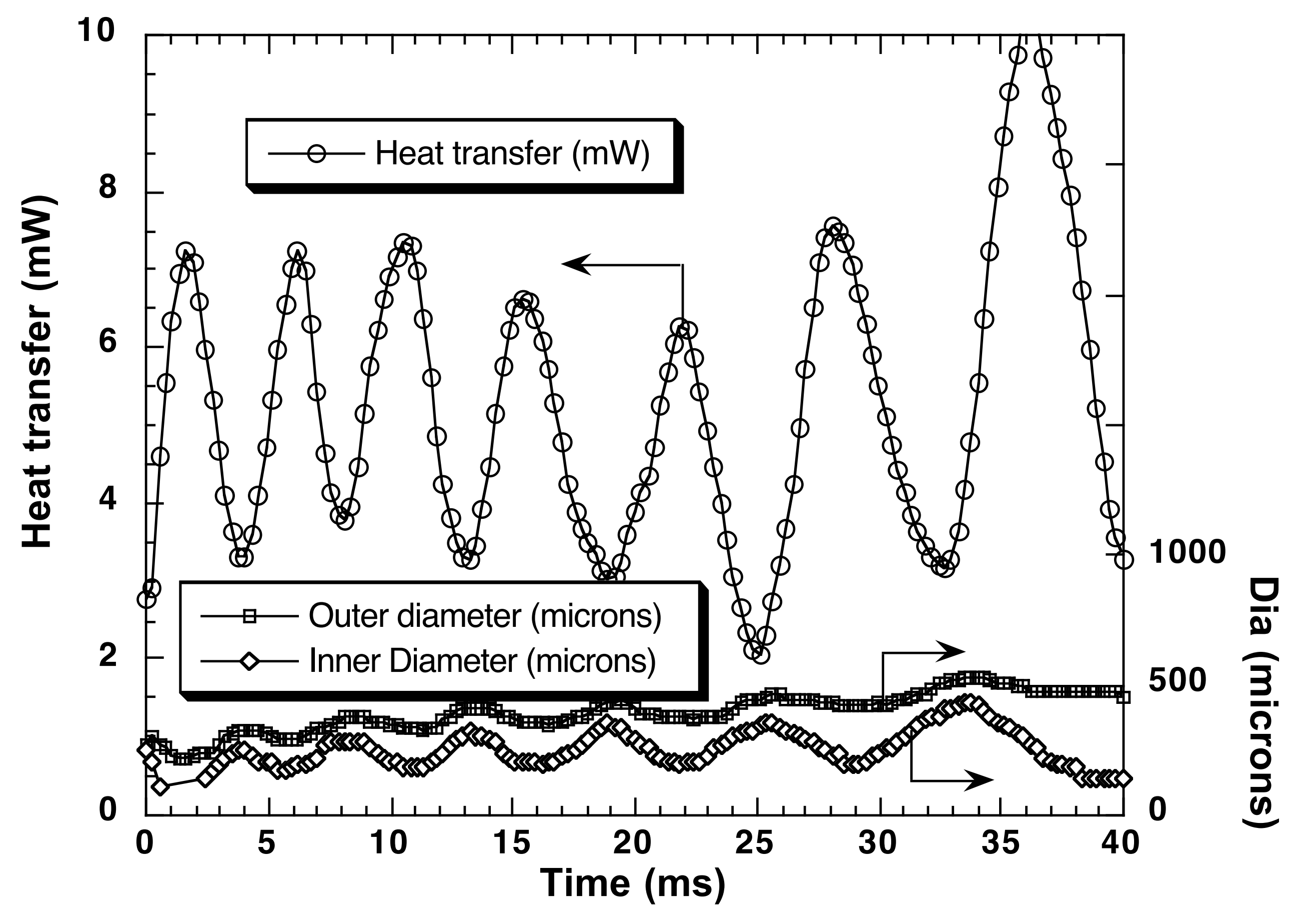
Oscillating Bubble Heat Transfer



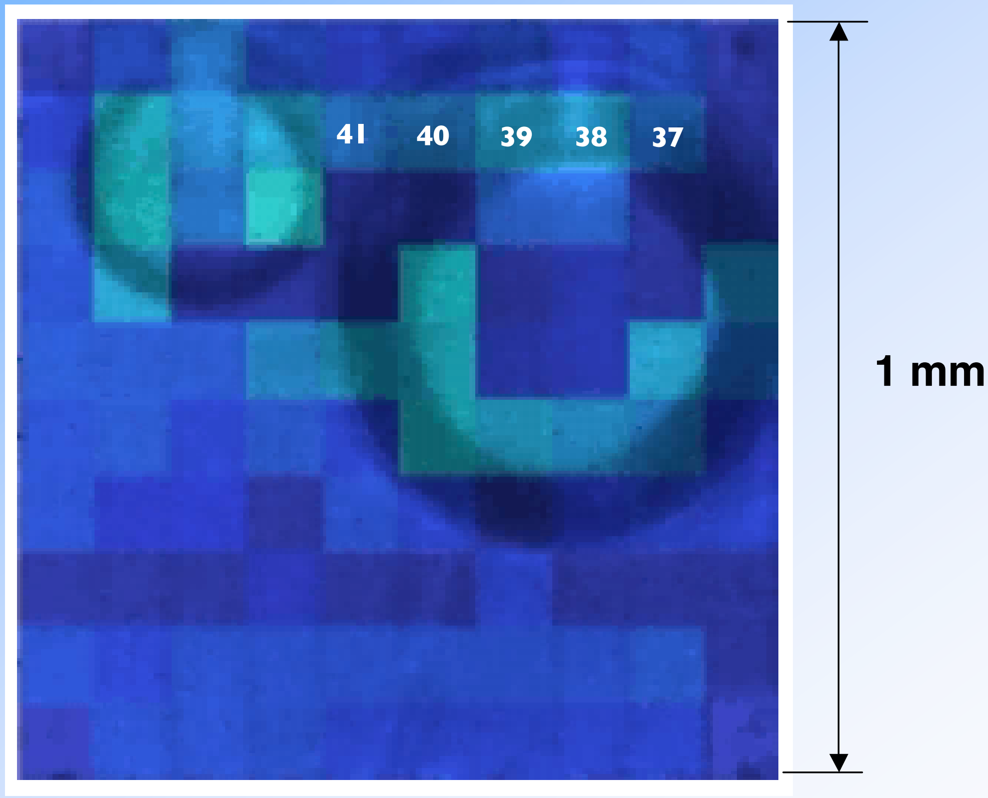


- **Tbulk=41 °C**
- **Bubble oscillates in size due to changing balance between evaporation and condensation**

Oscillating Bubble Heat Transfer

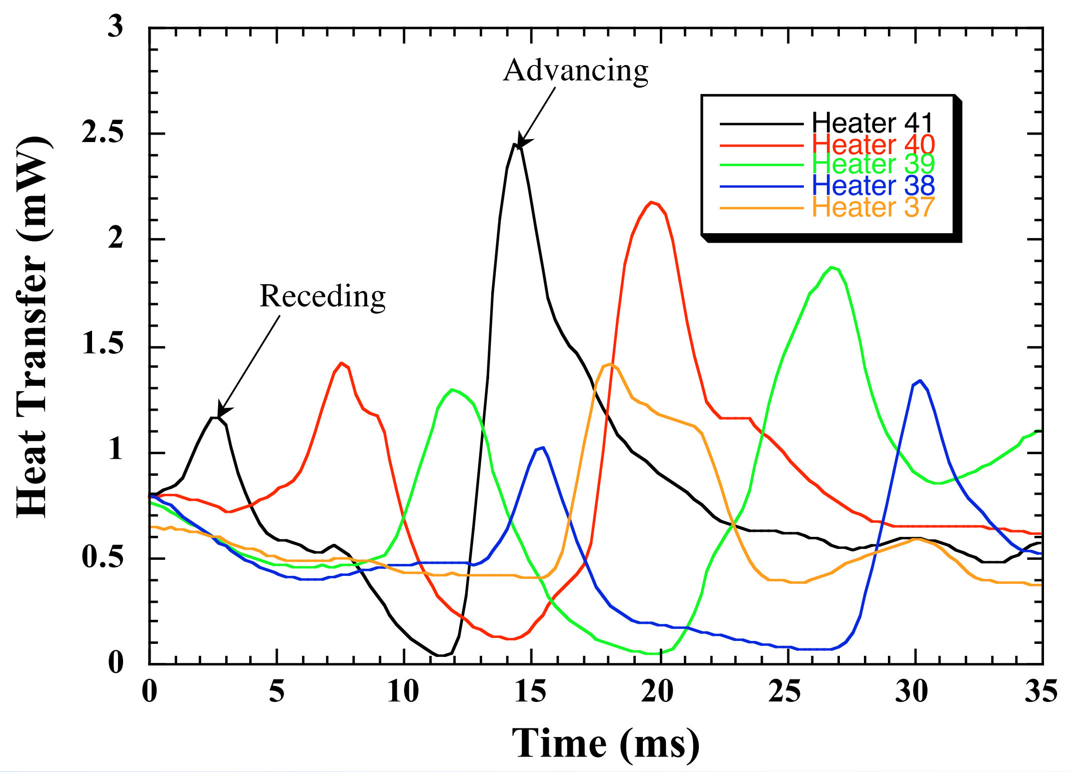


Contact Line Heat Transfer Under Sliding Bubble



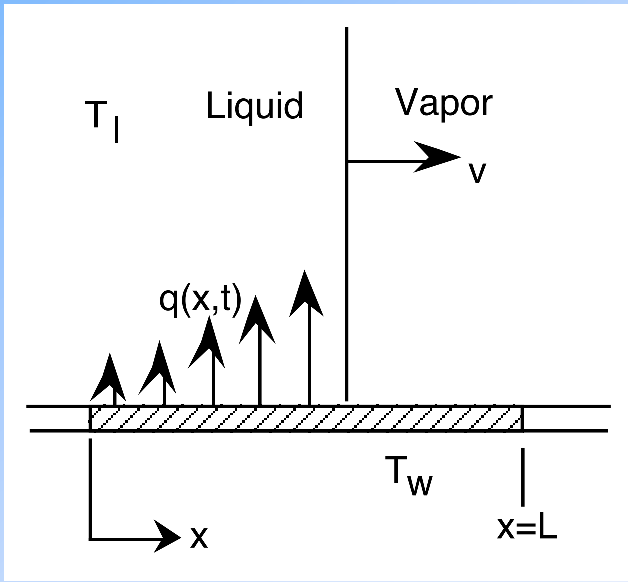
- Tbulk=41 °C
- Bubble velocity~2.2 cm/s

Contact Line Sliding Bubble Heat Transfer



- **Higher heat transfer observed for advancing contact angle**

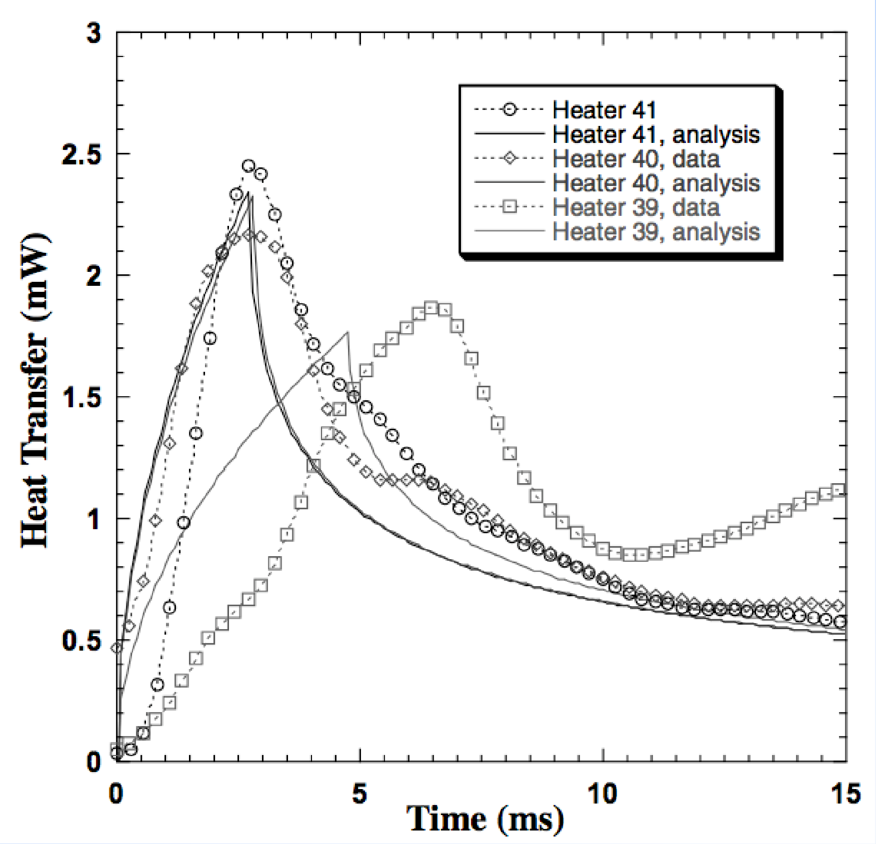
Transient Conduction Rewetting Model



$$\dot{q}'' = \frac{k\left(T_w - T_l\right)}{\sqrt{\pi\alpha_l t}} \Rightarrow \dot{q}\left(t\right) = \frac{2k\left(T_w - T_l\right)}{\sqrt{\pi\alpha_l}} wv\sqrt{t}$$

- **Model given in Demiray and Kim, IJHMT (2004)**
- **Heater heat transfer proportional to wetting velocity v**

Measured vs. Predicted Heat Transfer



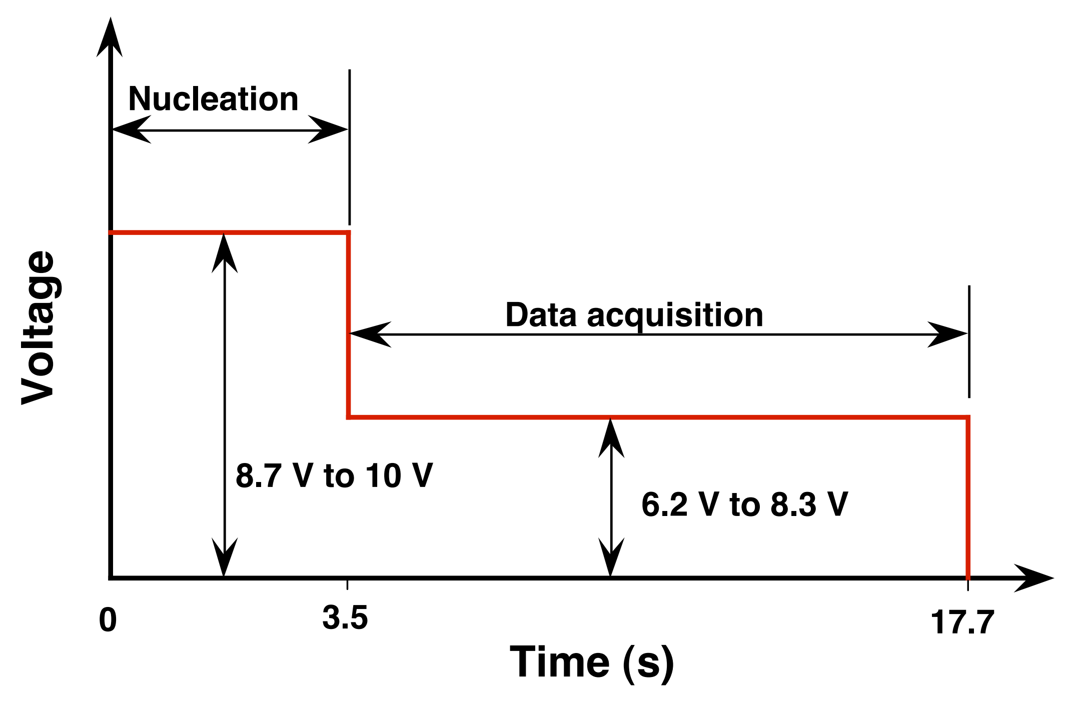
- Good agreement in location and magnitude of peaks in heat transfer.
- Good agreement in shapes of of curves.

Test Conditions for Constant Heat Flux Tests

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

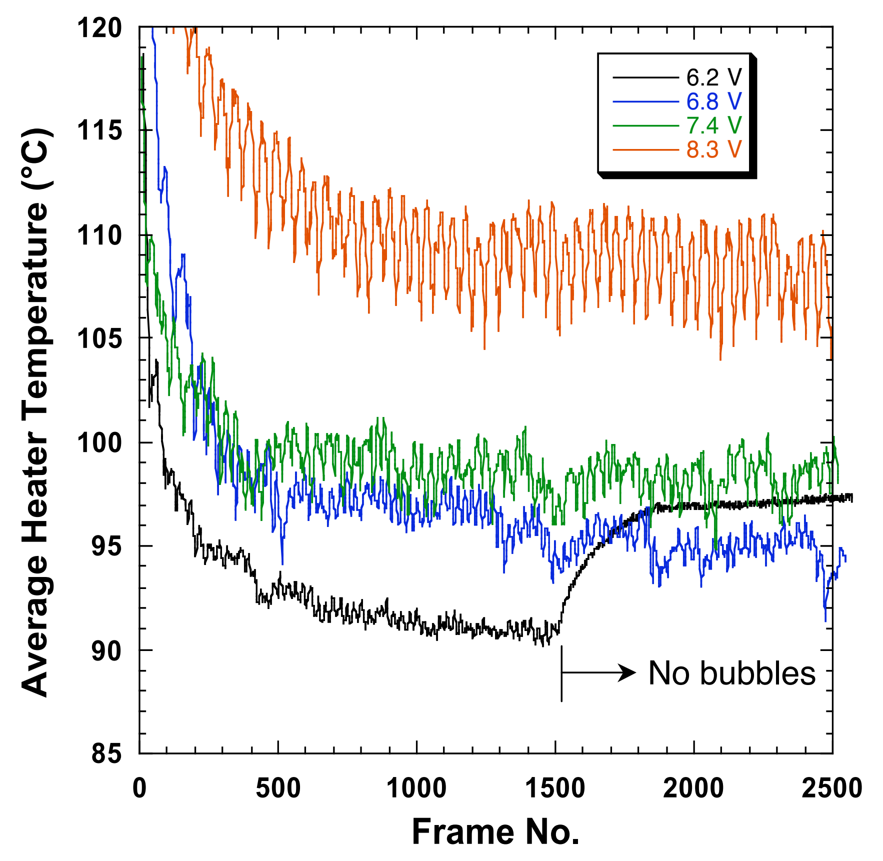
(Single bubbles, coalescing bubbles)

Applied Power Profile



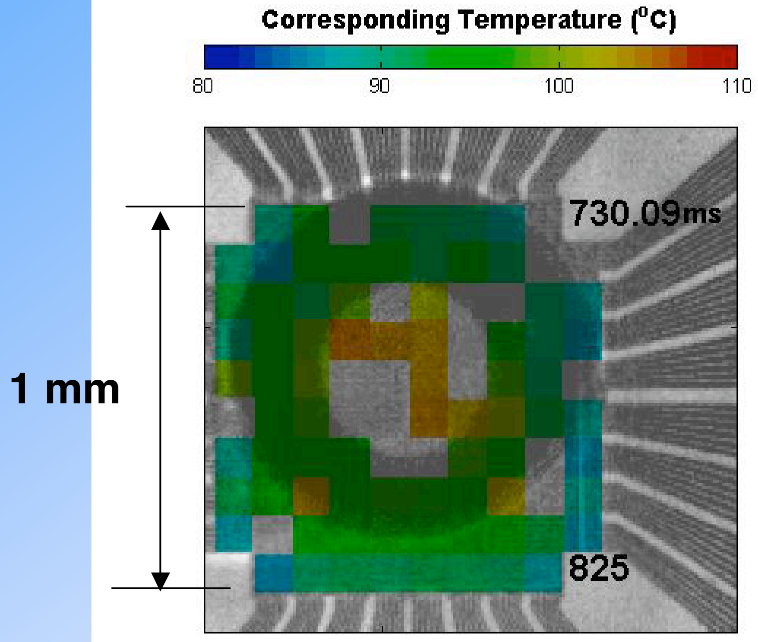
- Initial high voltage (8.7 V–10 V) applies for 3.5 s to initiate nucleation.
- Test voltages between 6.2 V and 8.3 V for 14.2 seconds.

Temperature Measurements



- **Data from each heater acquired at 1130 Hz**

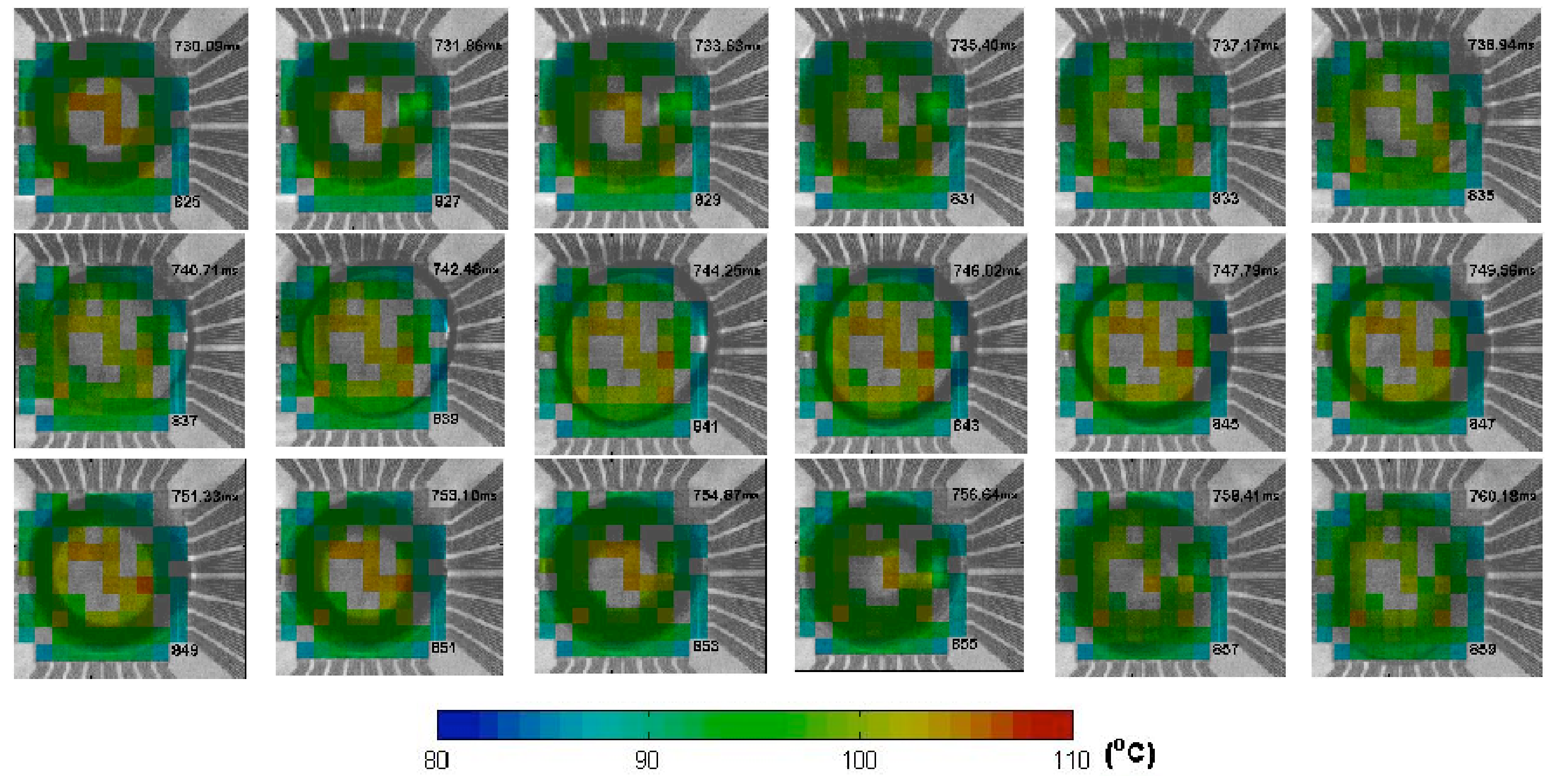
Temperature Distribution Movie (6.8 V case)



Case: pcb5 6p8v pp

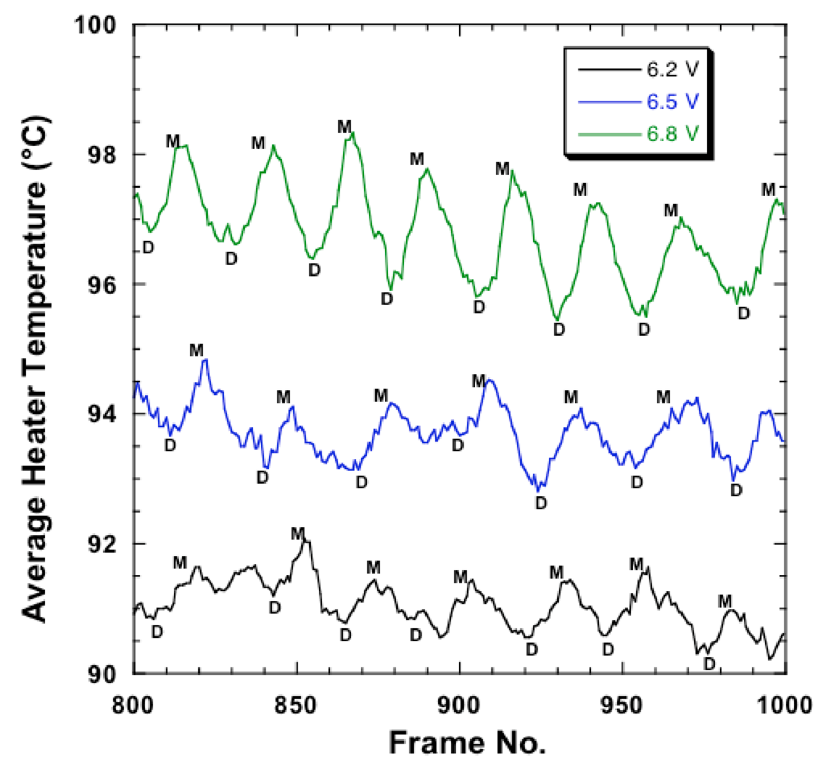
- Video acquired at 1130 Hz.
- Each heater is colored according to heater temperature.

Time Resolved Temperature Distribution During Bubble Nucleation and Departure (6.8 V case)



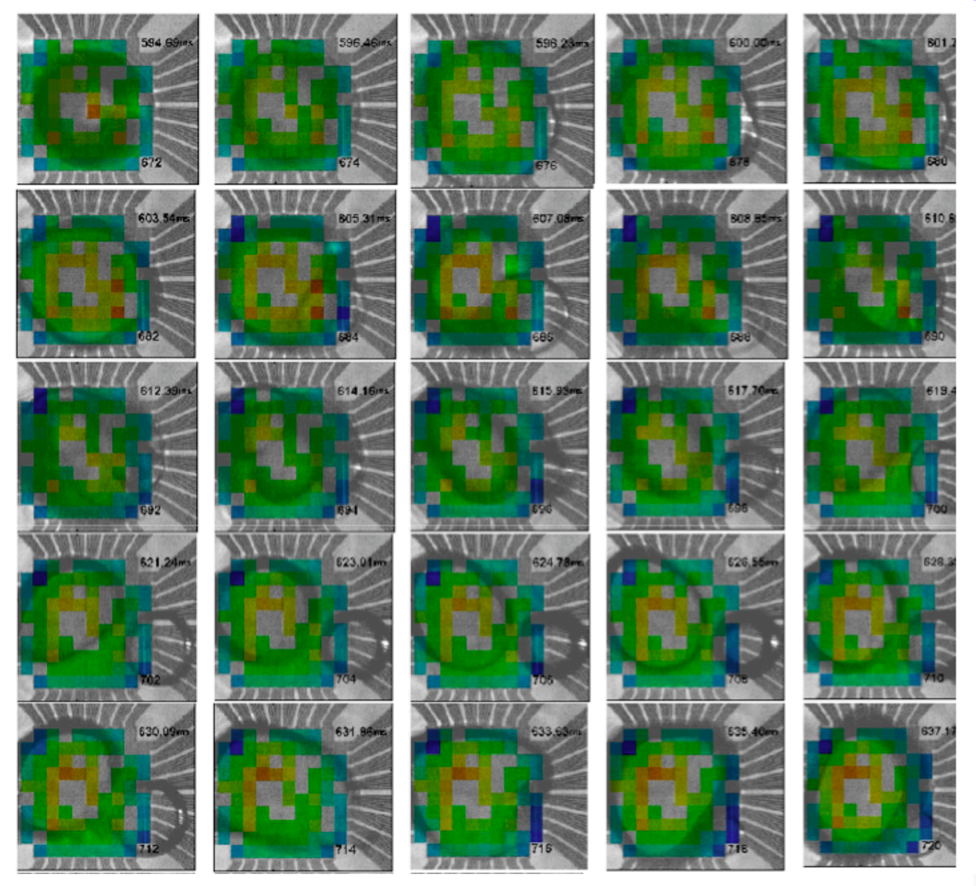
- **Images presented every other frame (565 Hz)**

Average Heater Temperature Variation (Single Bubbles)



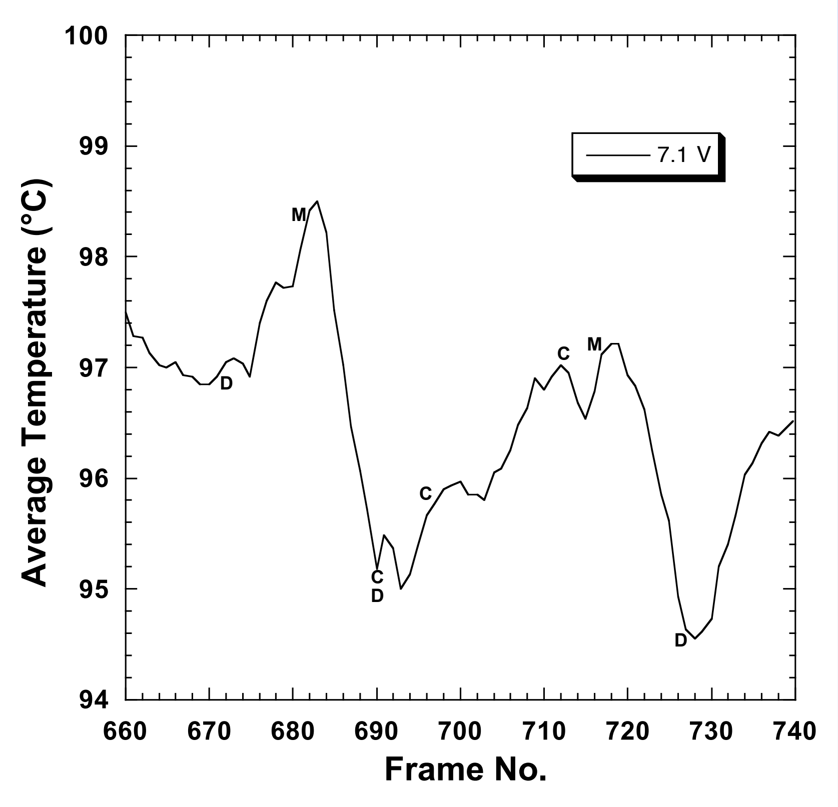
- **Maximum temperature occurs when dry spot size is maximum (M)**
- **Minimum temperature occurs at bubble departure (D).**

Time Resolved Temperature Distribution During Bubble Coalescence and Departure (7.1 V case)



- Images presented every other frame (565 Hz)

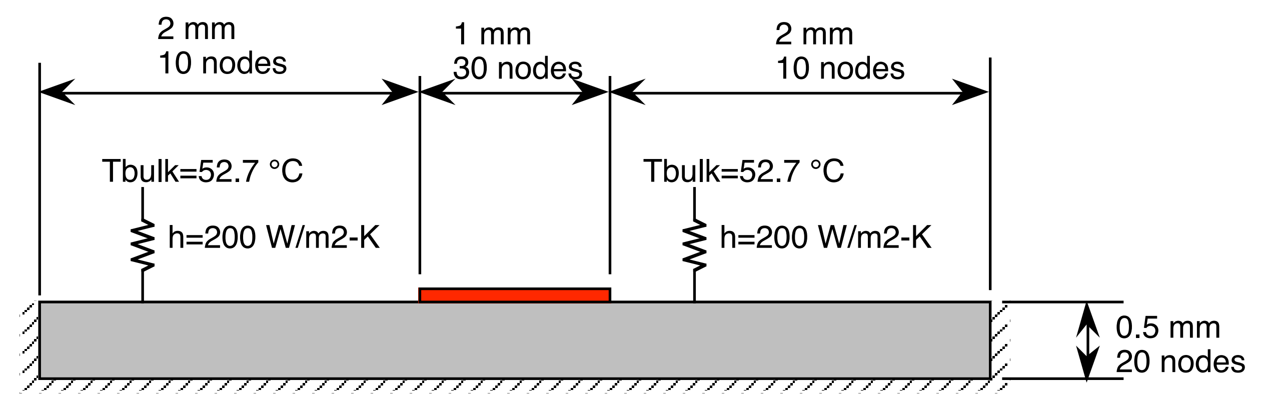
Average Heater Temperature Variation (Bubble Coalescence)



- **Bubble coalescence results in a small drop in wall temperature.**

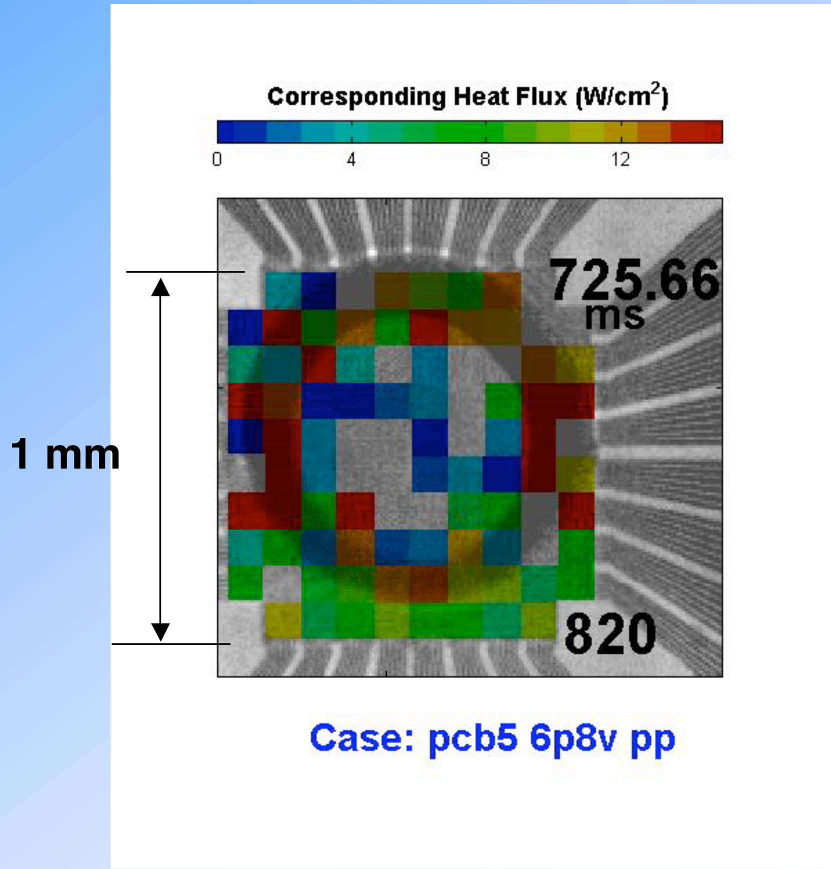
Determination of Wall-to-Liquid Heat Transfer

- **Computational domain:**



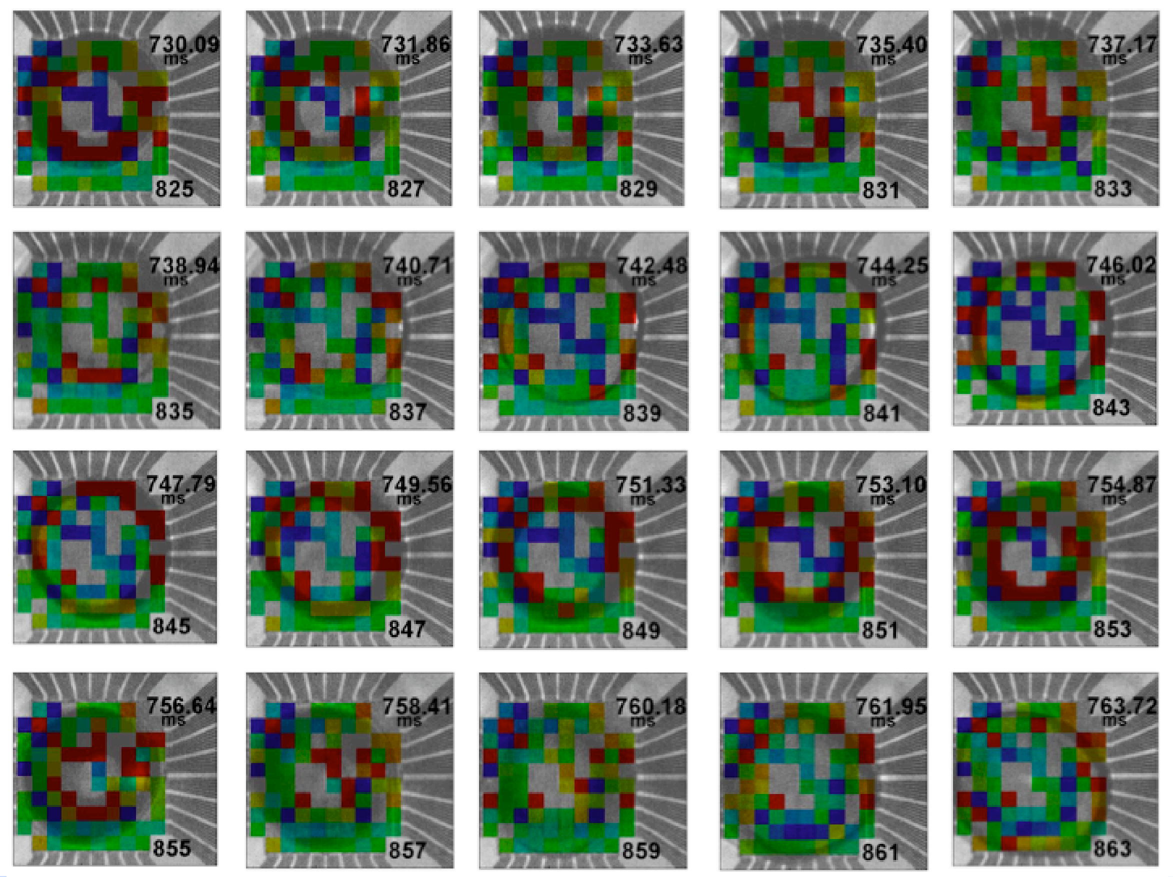
- **Compute temperature distribution within substrate at each time step after imposing heater temperature distribution on surface.**
- **Line-by-line TDMA with Gauss-Seidel iteration applied in all three directions**
- **Heat transfer into substrate was computed at each time step, then subtracted from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

Heat Flux Distribution Movie (6.8 V case)



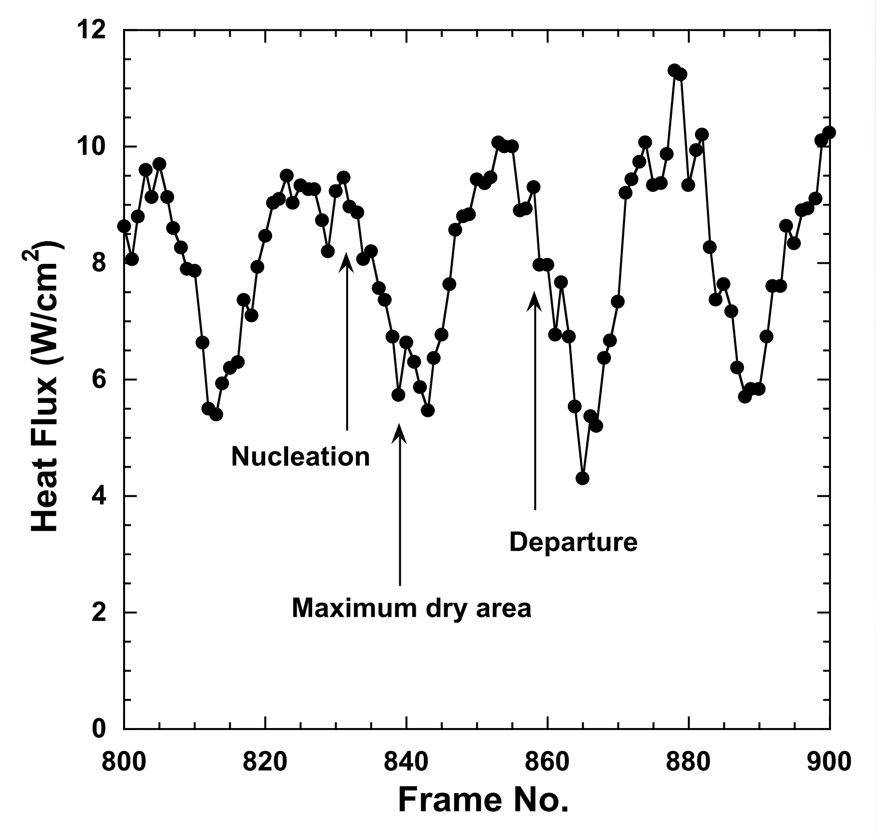
- Video acquired at 1130 Hz.
- Each heater is colored according to heater heat flux.

Time Resolved Heat Flux Distribution During Bubble Nucleation and Departure (6.8 V case)



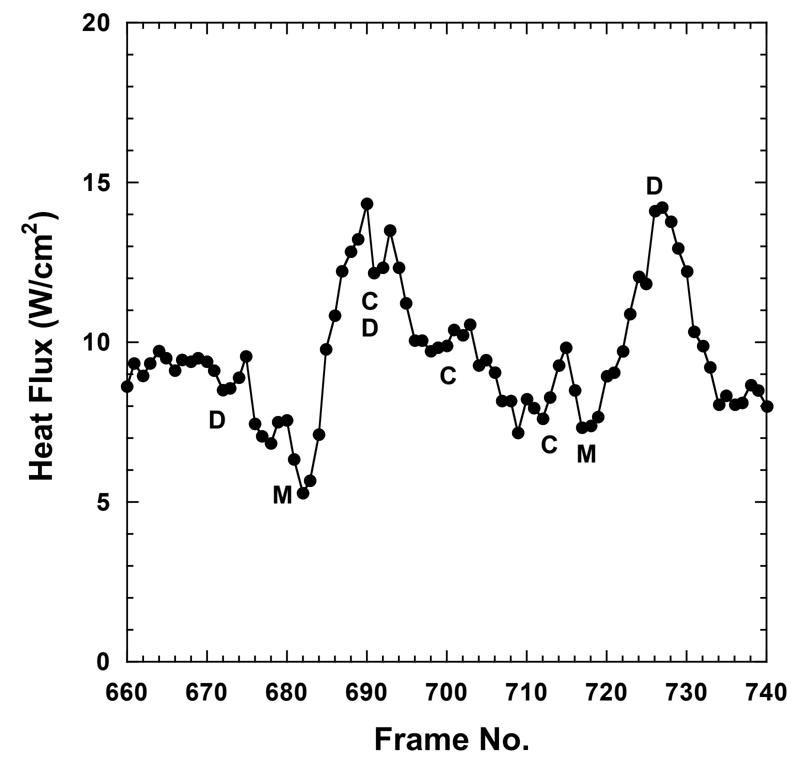
- Images presented every other frame (565 Hz)

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

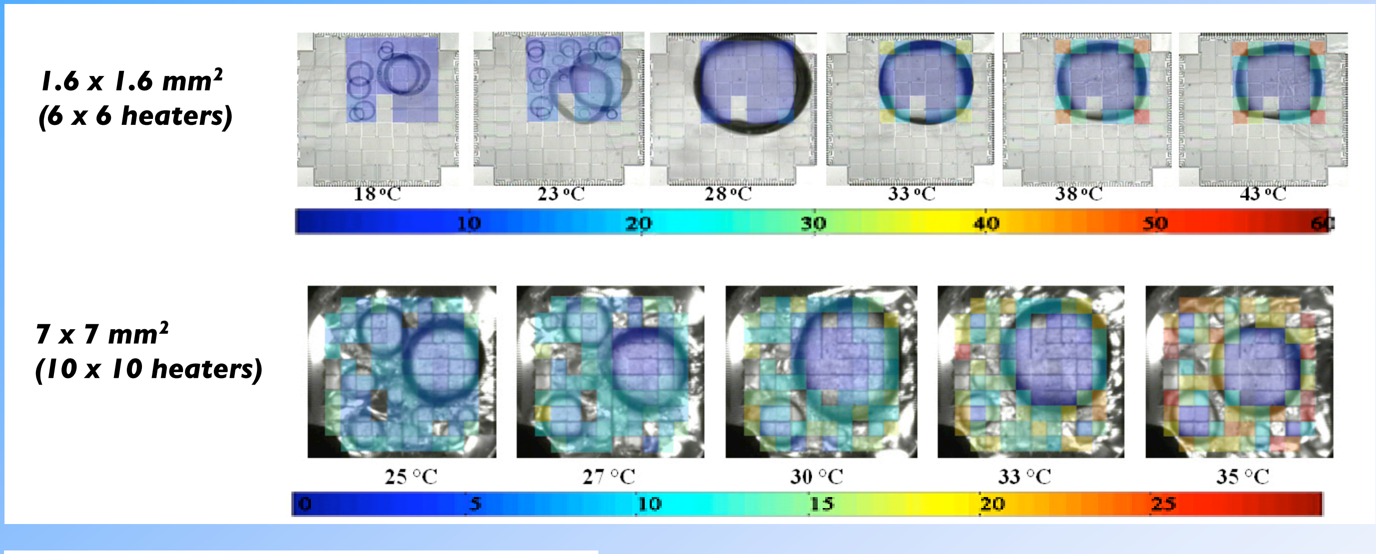
D: Bubble departure

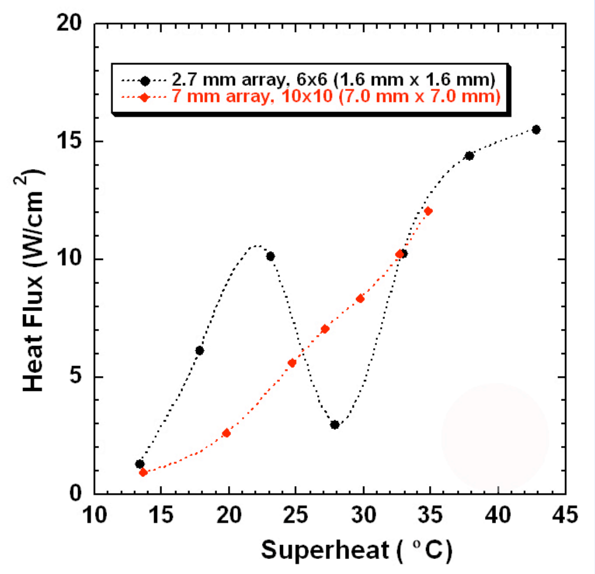
Experimental Results (Low Gravity)

Test Conditions for Low-G Results

- Fluid: FC-72
- Pressure=1 atm (T_{sat}=56.7 °C)
- 7 mm heater array
- Bulk temperatures: 28 °C – 52 °C

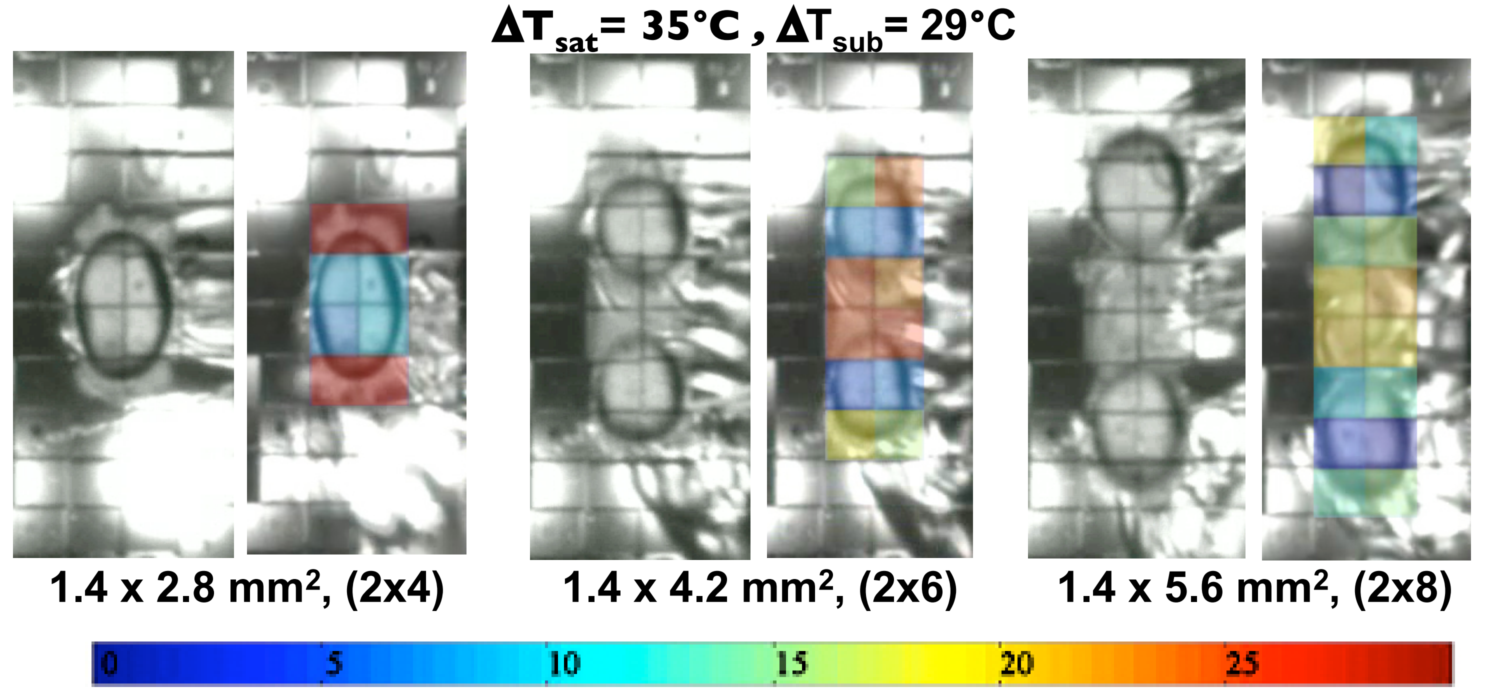
Low-Gravity Boiling Measurements (T_{bulk}= 28°C)





- 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

Aspect Ratio Boiling Observations (7 mm array)


$\Delta T_{sat} = 35°C$, $\Delta T_{sub} = 29°C$

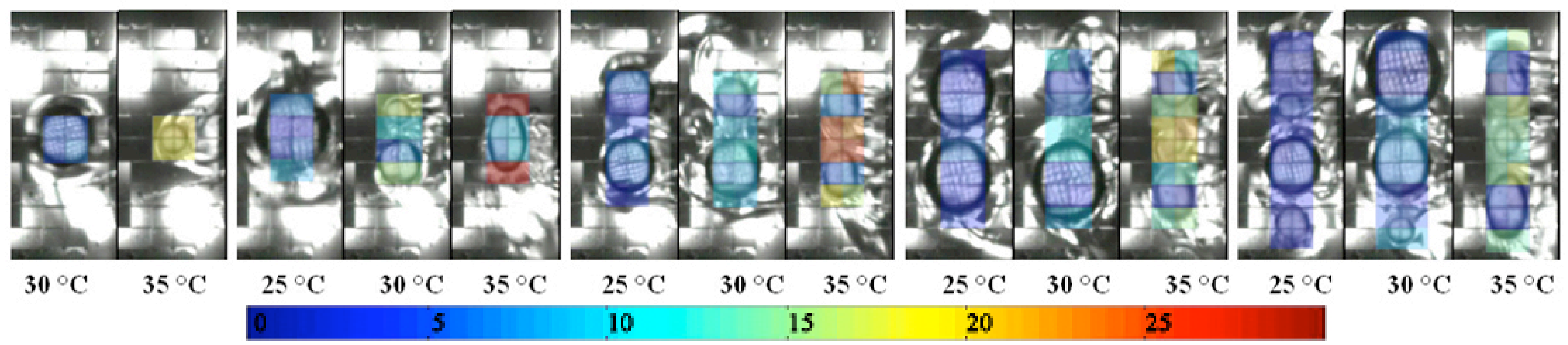
1.4 x 2.8 mm^2, (2x4)

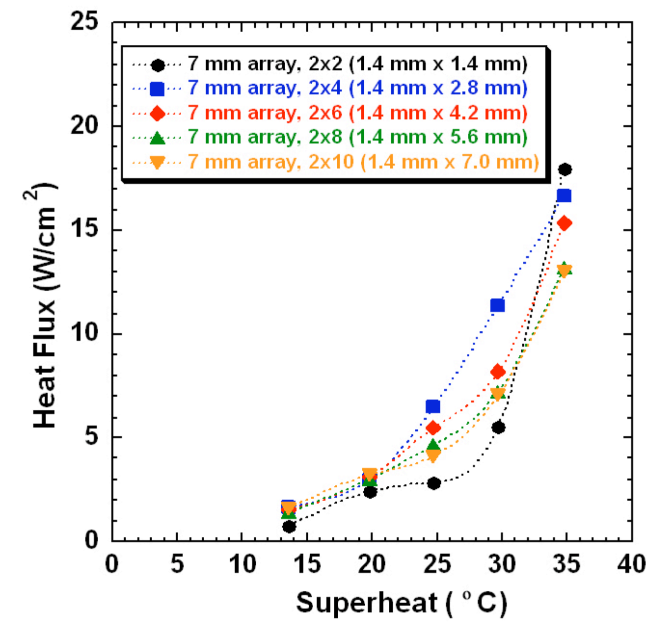
1.4 x 4.2 mm^2, (2x6)

1.4 x 5.6 mm^2, (2x8)

- 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)

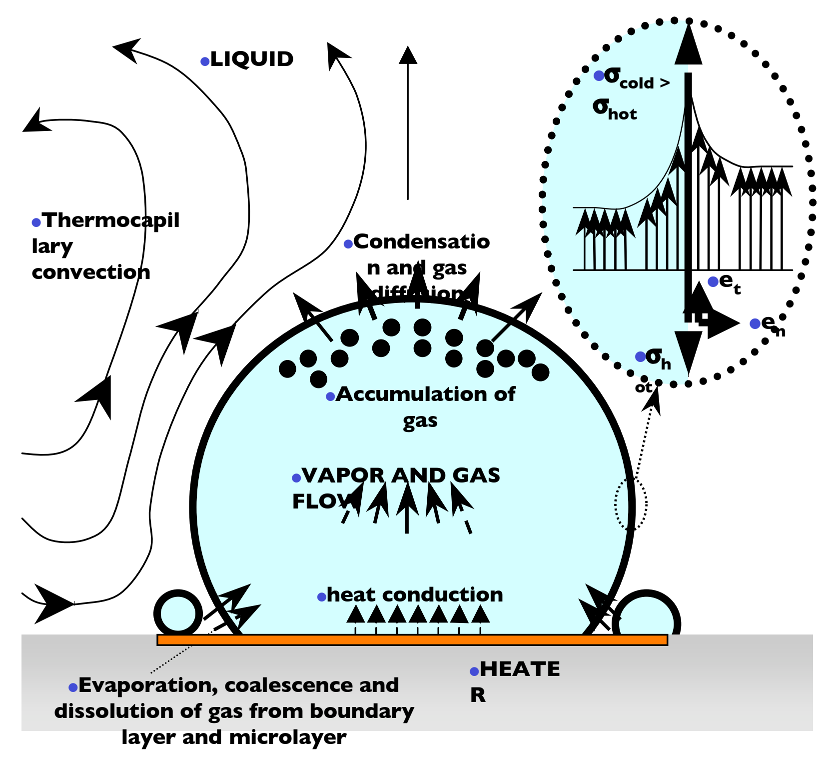
Aspect Ratio (ΔT_{sub} = 28 °C)





- **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**

Origin of Thermocapillary Convection



- Thermocapillary flow results from surface tension gradients along an interface which can form due to:
  - temperature gradients
  - material composition
  - electrical potential

FC-72 Characterization

Substance	M.W.	GC Area %	BP (^{o}C)	
n-perfluorohexane	338	73.2	56	C_6F_{14}
perfluoro-2-methylpentane	338	17.892	57.66	C_6F_{14}
perfluoro-3-methylpentane	338	5.954	58.37	C_6F_{14}
perfluoro-2,3-dimethylbutane + perfluoro-2,2-dimethylbutane	338	1.723		
perfluorocyclohexane	300	1.105	50.61	
perfluoromethylcyclopentane	300	0.126	48	C_6F_{12}

- **Mass spectometry 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

Ulf R. Knothe
Department of Orthopaedic Surgery, Orthopaedic Research Center
The Cleveland Clinic Foundation

Ryan Berglund
Glickman Urological Institute,
The Cleveland Clinic Foundation

Jared O'Leary, Jennifer Ziegler, Melissa L. Knothe Tate
Department of Biomedical Engineering, Orthopaedic Research Center,
The Cleveland Clinic Foundation

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.

Corresponding author and contact information:
Ulf R. Knothe, M.D, Dr. Med.
Department of Orthopaedic Surgery, A41,
9500 Euclid Avenue
Cleveland Clinic Foundation
Cleveland, OH 44195

knotheu@ccf.org
216-445-6513 office
216-445-6255 fax

MOBI: MICROGRAVITY OBSERVATIONS OF BUBBLE INTERACTIONS

Donald L. Koch
Cornell University

Ashok Sangani
Syracuse University

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.

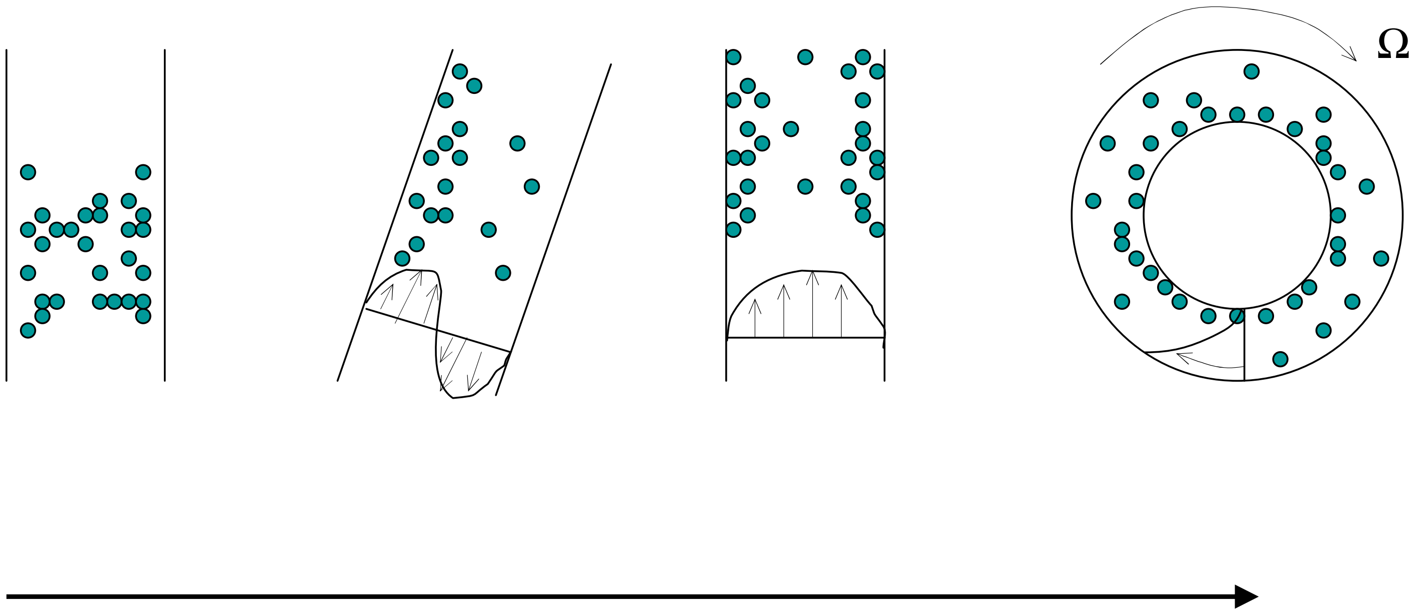
MOBI: Microgravity Observations of Bubble Interactions

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

Donald Koch
Cornell University

Ashok Sangani
Syracuse University

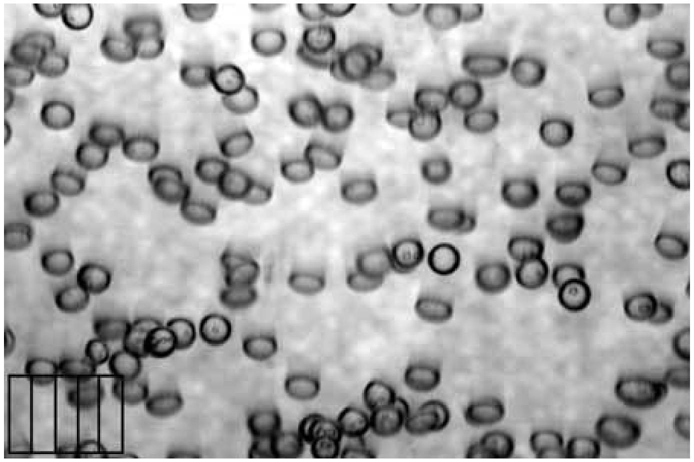
- vertical channel inclined channel vertical pipe flow Couette in μg



Increasing Ratio of Shear to Buoyancy

Monodisperse (Potential-Flow) Bubble Suspension d ≈ 1.4 mm

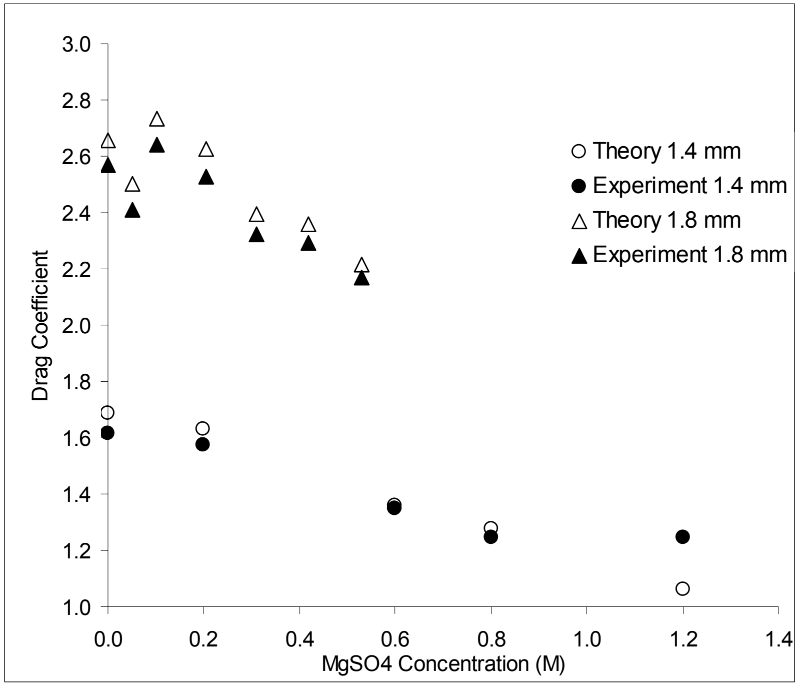
Electrolytes induce hydrophobic bubble-bubble repulsion to prevent coalescence without Marangoni stresses

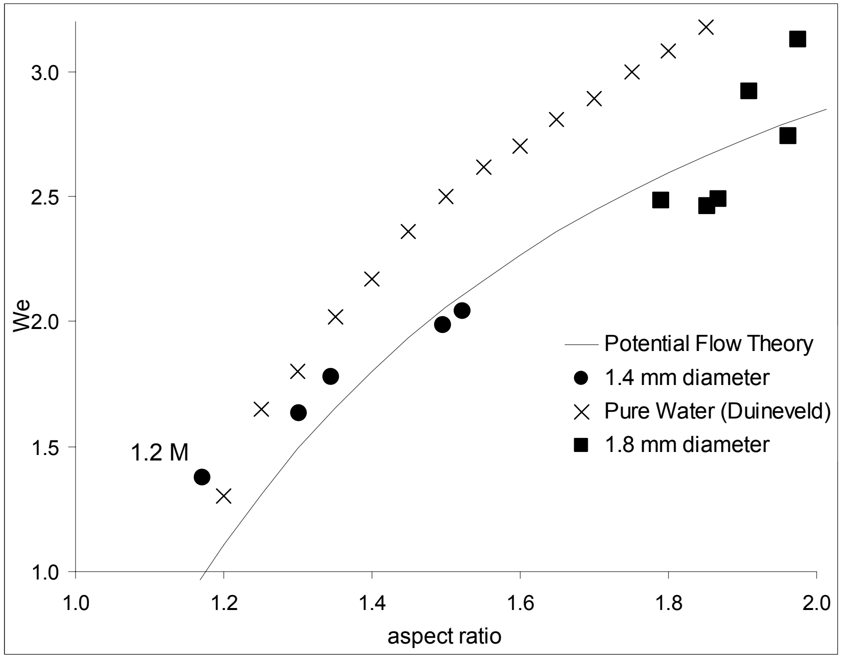


Dual impedance probe: Bubble velocity and volume fraction profiles
Hot film probe: Liquid velocity
Video: Bubble size and aspect ratio

0.8 M $MgSO_4$ 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 :

$$\frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x_j}\left(\phi w_j\right) = 0$$

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

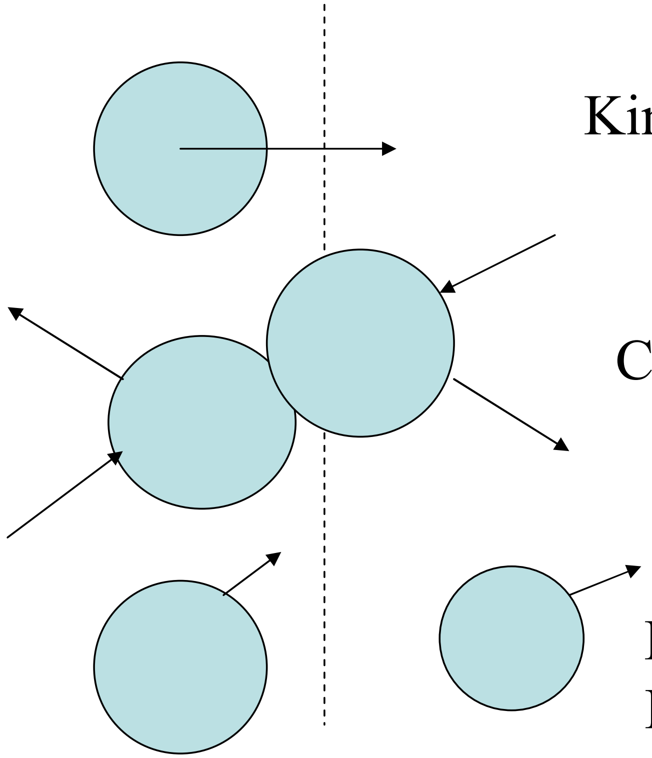
$$n\frac{dT}{dt} = -\frac{\partial Q_j}{\partial x_j} + S$$

- 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



Kinetic (Positive)

Collisional (Positive)

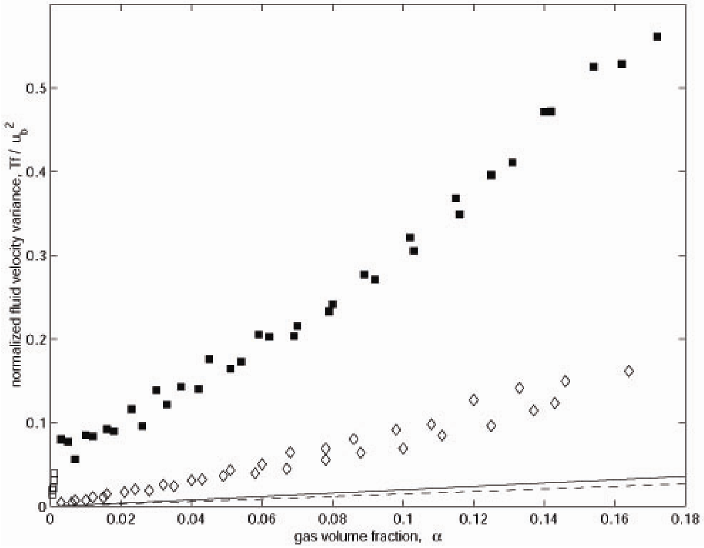
Hydrodynamic
Interactions
(Negative)

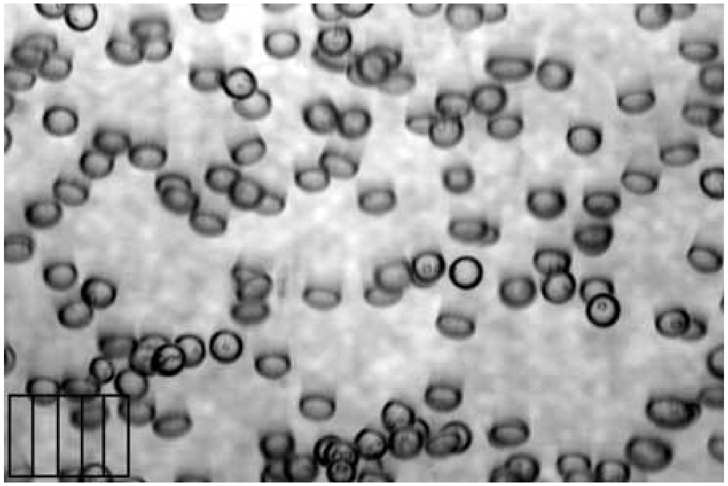
Negative pressure due to hydrodynamic interactions leads to instabilities on Earth that are absent in microgravity

Detection of Instabilities: Vertical Channel Studies

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

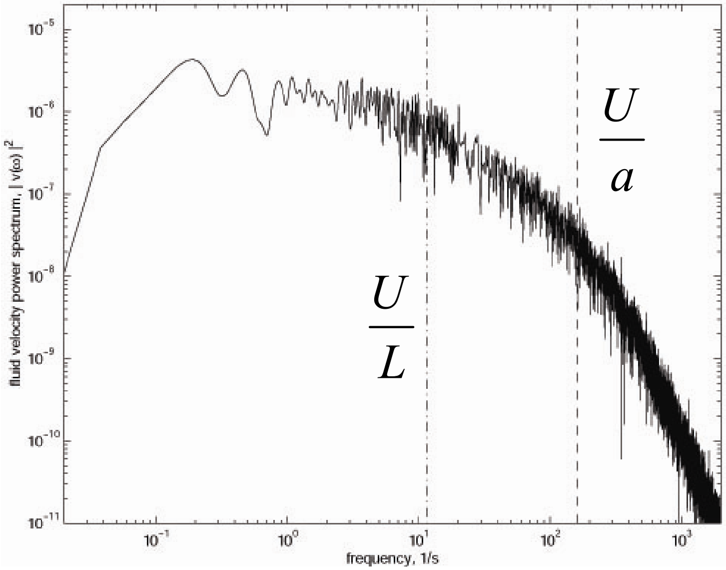
Visual Evidence of Structure:
Some Horizontal Clustering



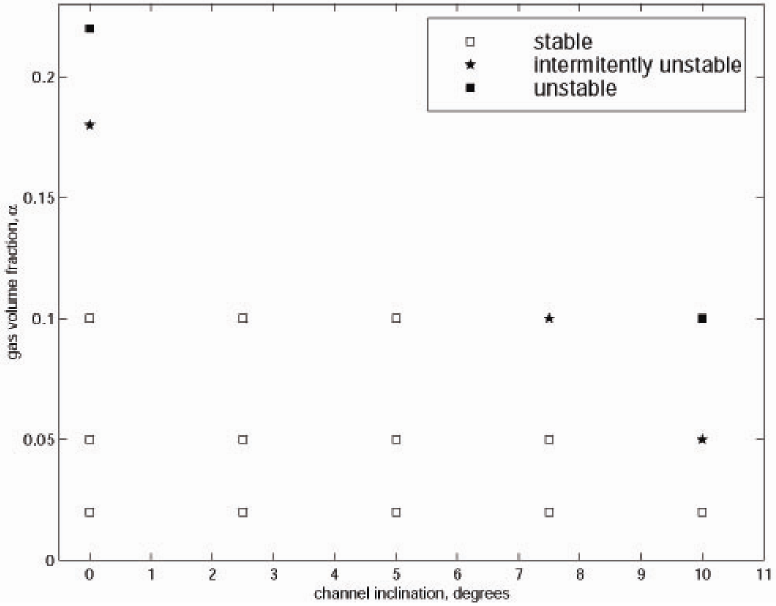


Instability in Vertical and Inclined Channel

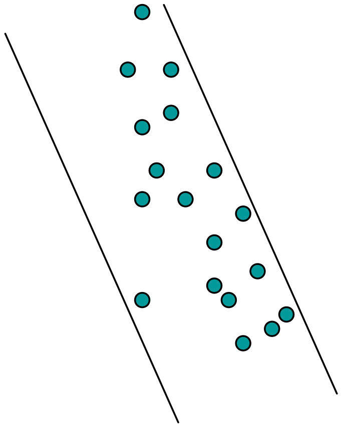
Frequency Spectrum of Liquid Velocity Shows Most of the Energy is at Frequencies Larger than U/a

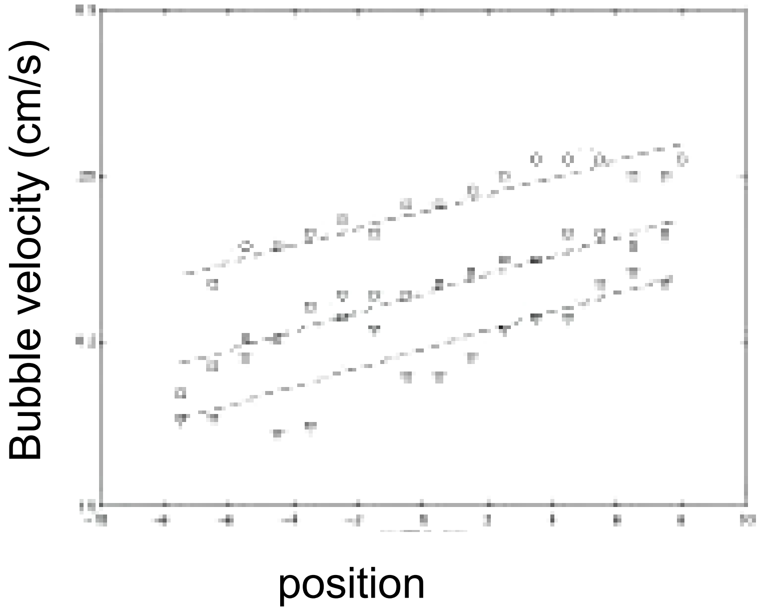


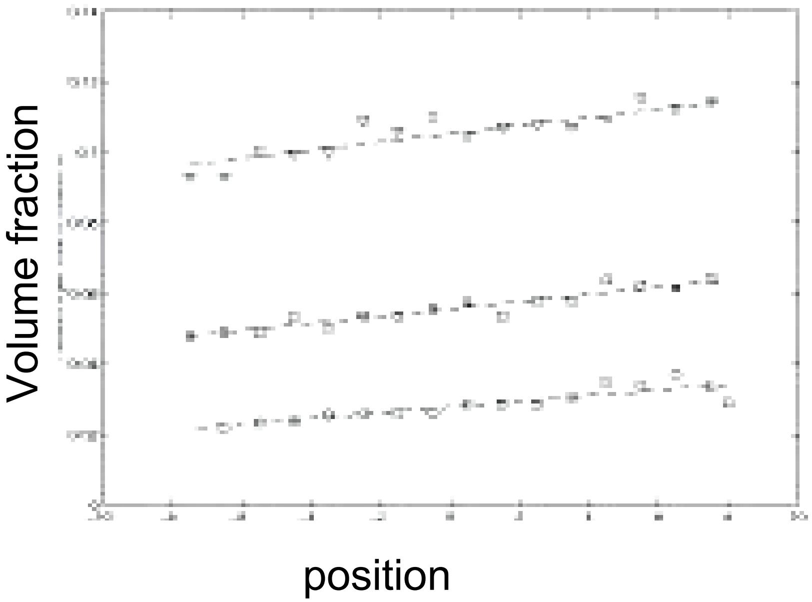
An Instability That is More Apparent to the Naked Eye Arises at Higher Volume Fractions and Inclination Angles



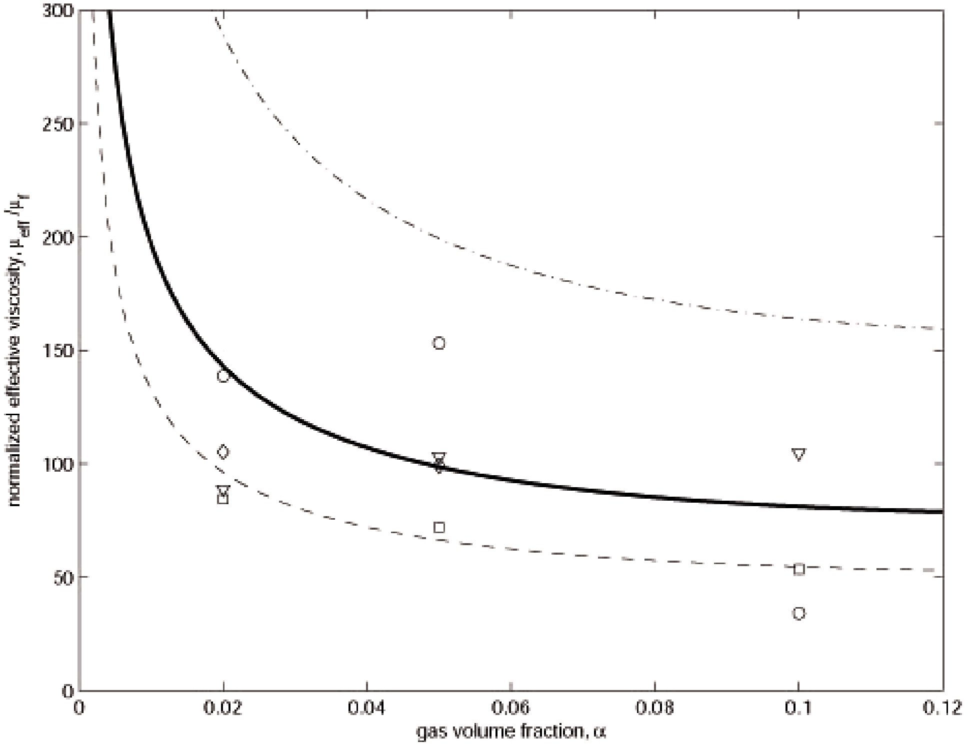
Inclined Channel:
Bubble volume fraction variation drives suspension flow







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

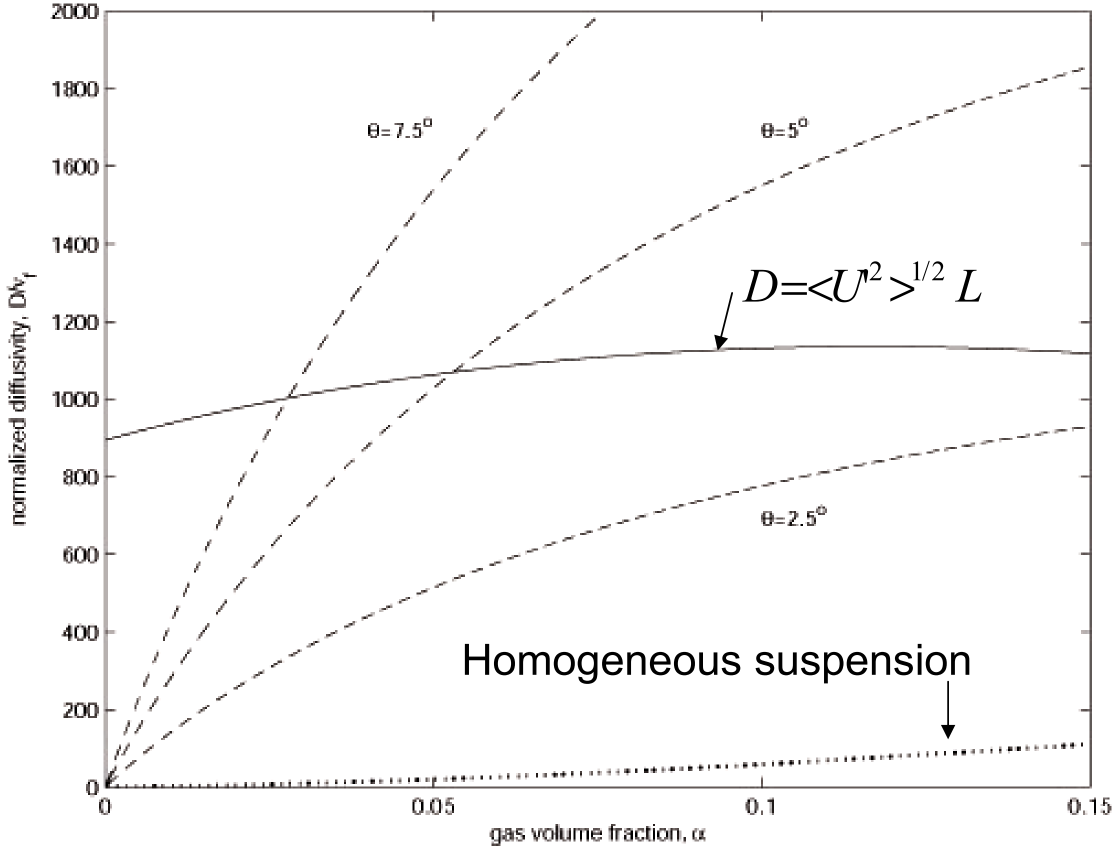


$$\nabla \cdot [\mu_{eff} \nabla \mathbf{U}] = -\rho \mathbf{g} \phi + \nabla p_f$$

Instability induced bubble pressure or diffusivity is also very large

$$n(\mathbf{F_B}+\mathbf{F_L}+\mathbf{F_D}) = \nabla P \longrightarrow \nabla\cdot[(\mathbf{U_B}+\mathbf{U_L})\phi] - \nabla\cdot[D\nabla\phi] = 0$$

$$D = \frac{1}{36\mu_f d R_d}\frac{\partial P}{\partial \phi}$$



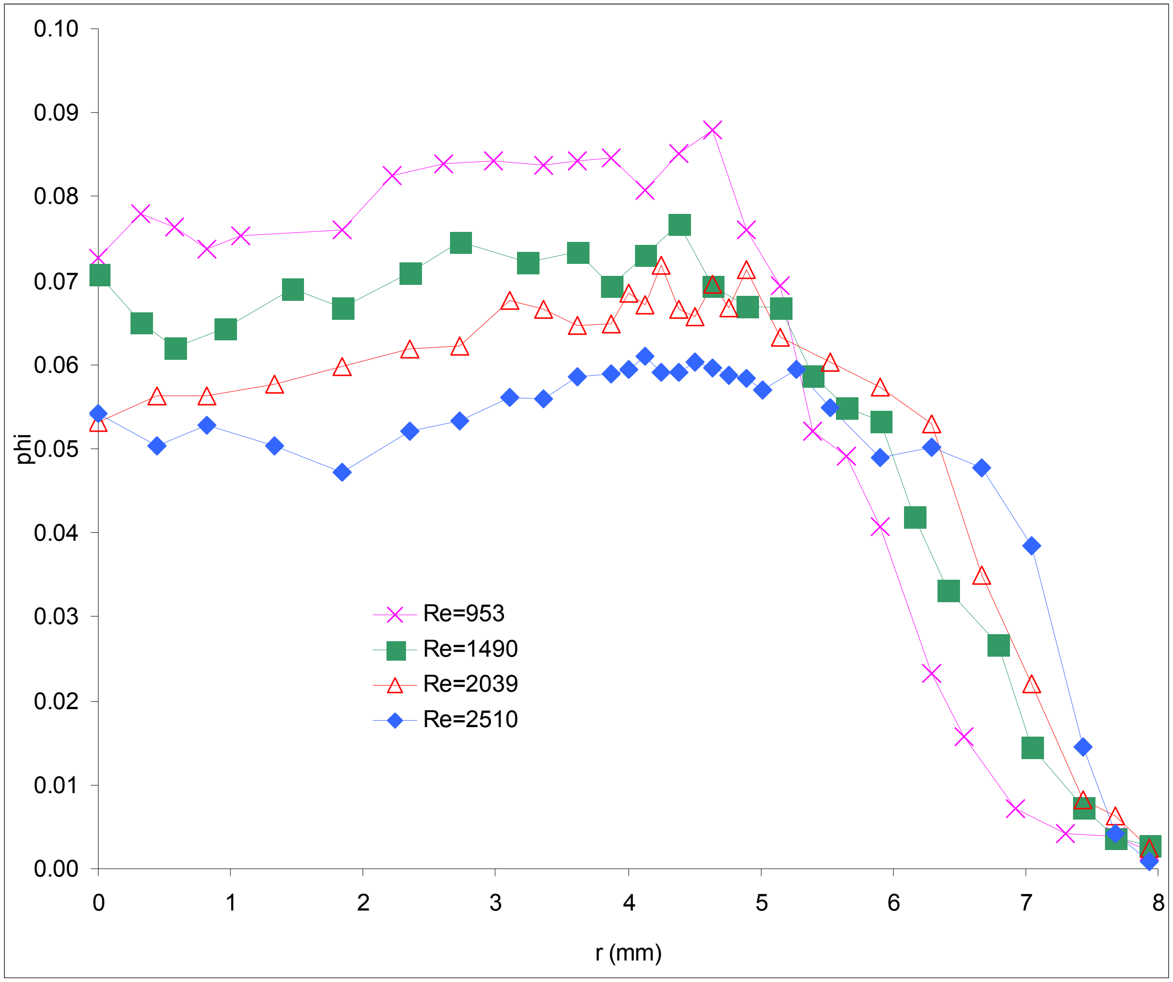
$D = \langle U'^2 \rangle^{1/2} L$

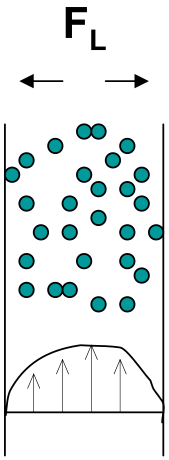
Homogeneous suspension

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

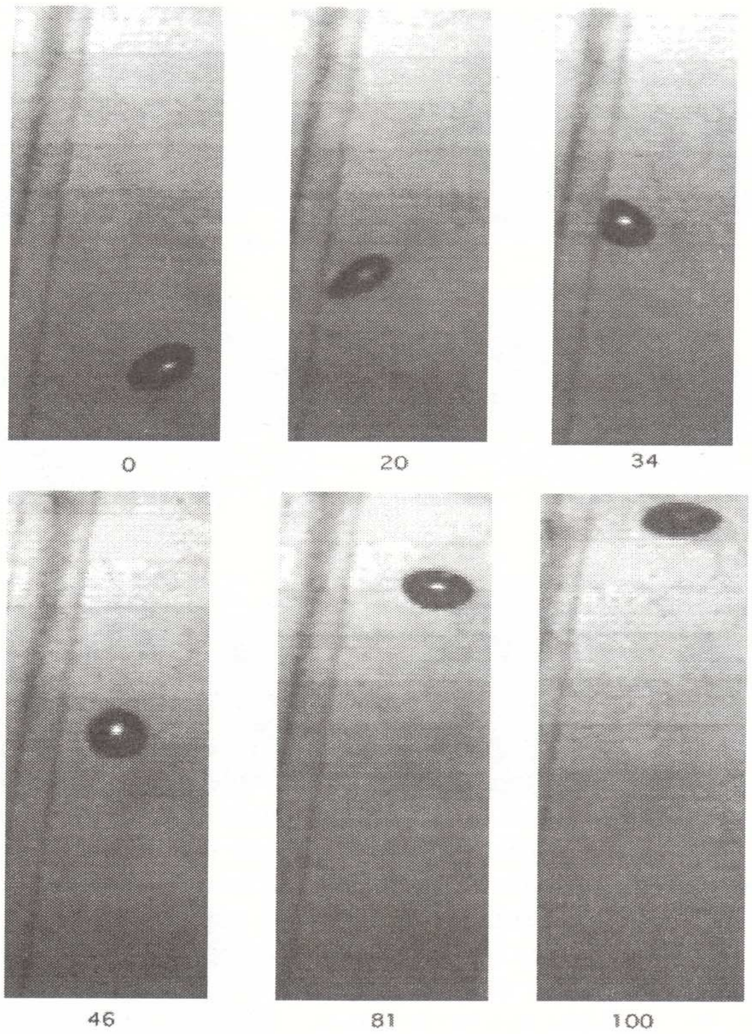


FIG. 12. Sequence of photographs illustrating one cycle of the bubble bouncing motion. The bubble radius is 0.7 mm and the inclination angle is 83°.

Couette Flow of Bubble Suspension at 0g

$U \approx u_L$

Gravity-induced instability absent

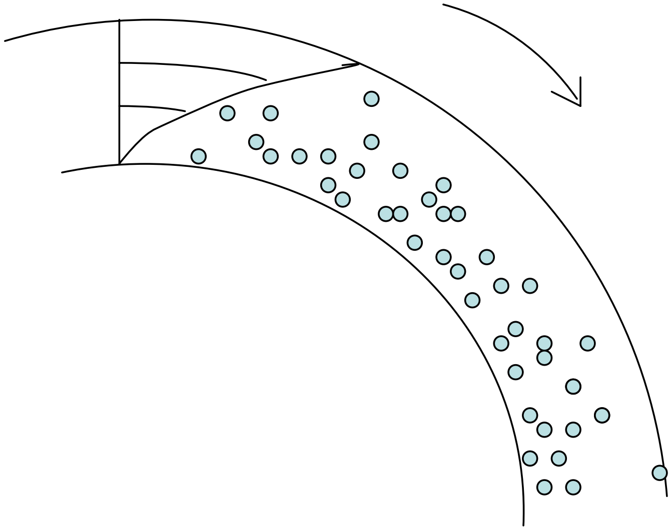
Repeated bouncing from wall absent

Potential flow approximation

    more accurate in high Re

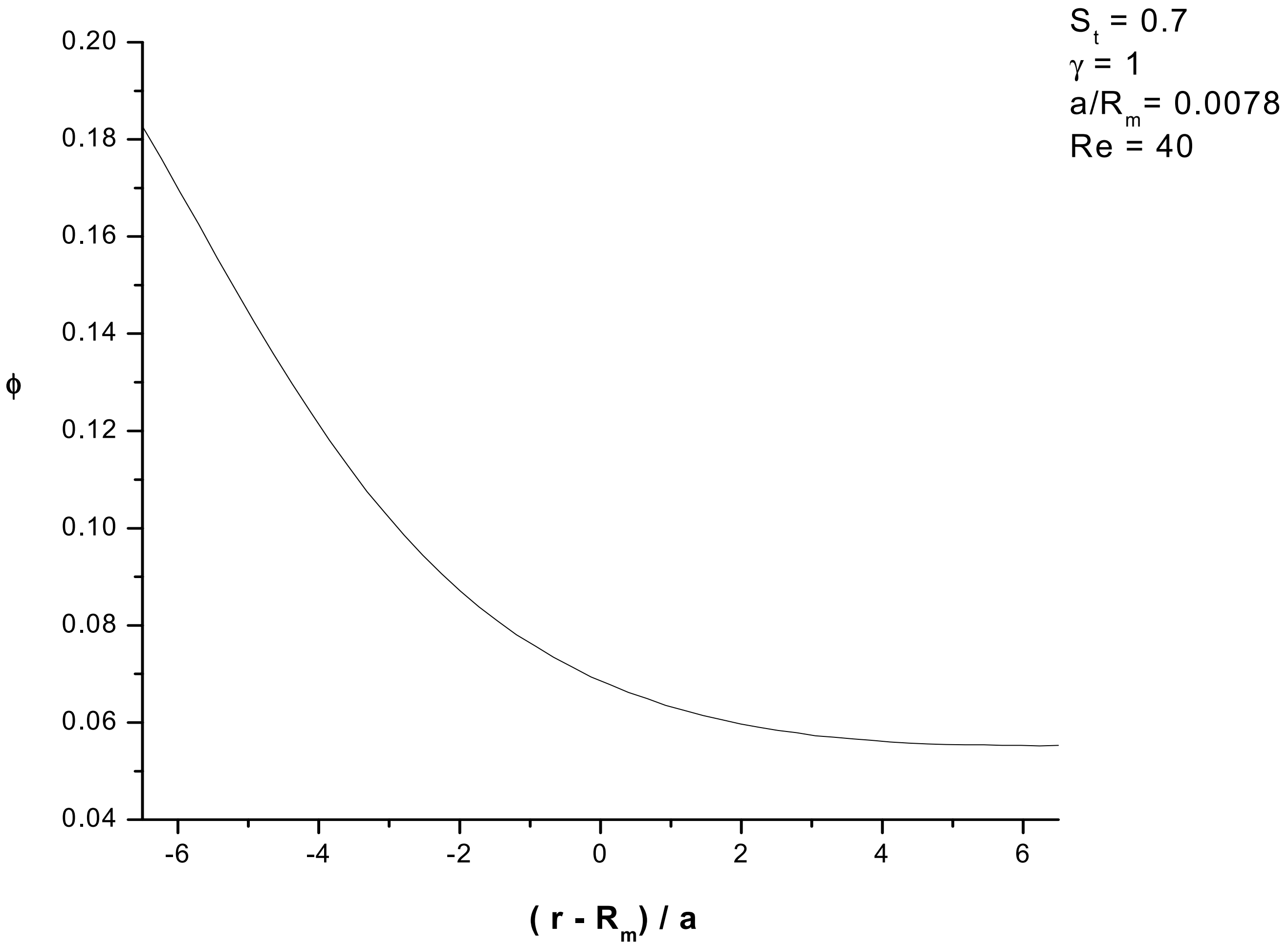
    microgravity shear flow

    than on Earth

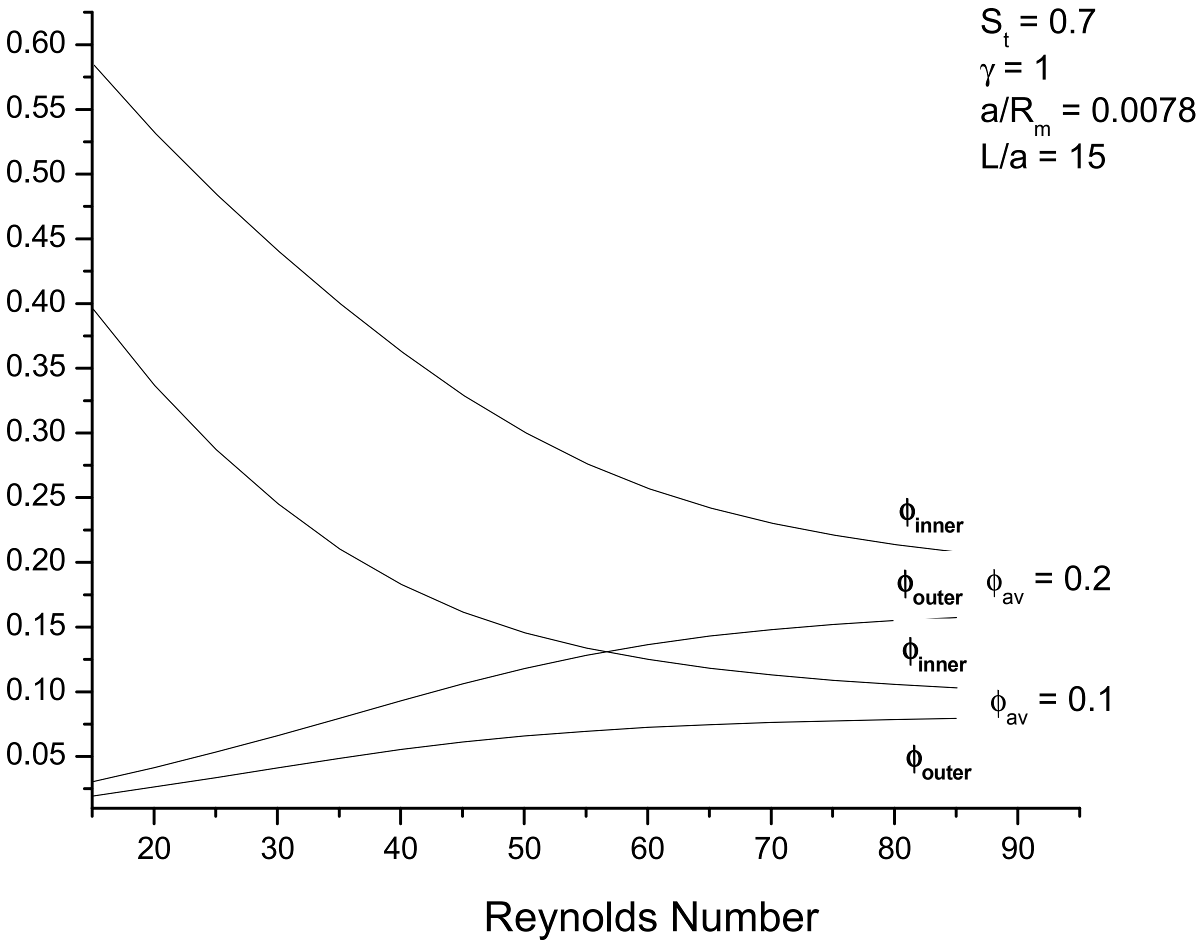


$$\mathrm{Re} = \frac{\rho \Gamma a^2}{\mu_f}$$

Volume fraction Profile by FEM

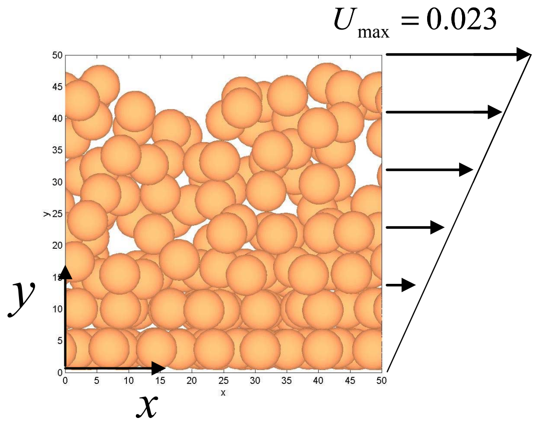


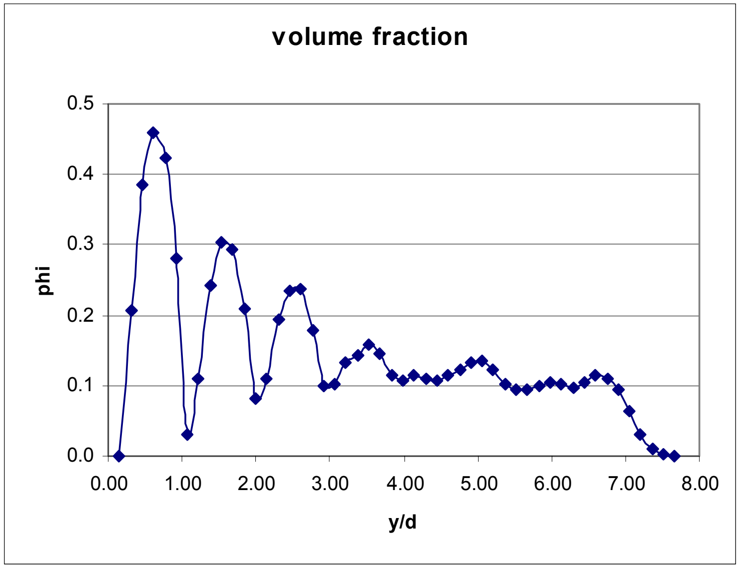
Minimum and maximum volume fractions



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)



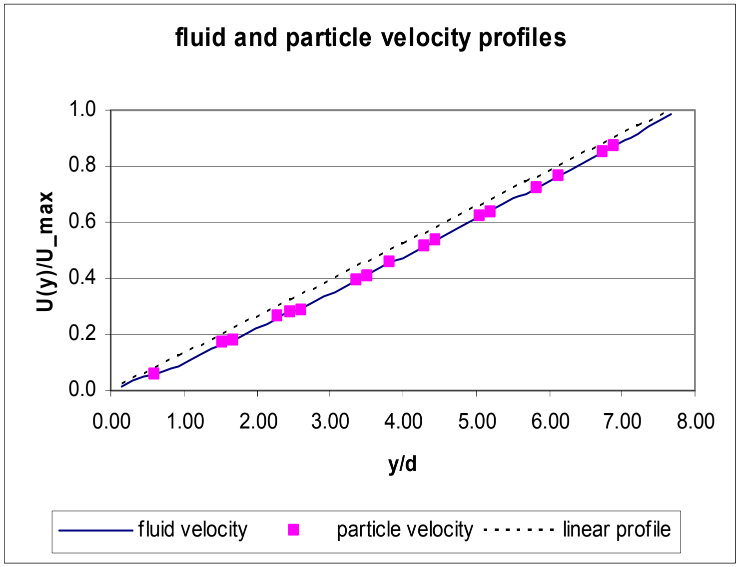


Simulation Parameters:

R/L = 5

L / d = 7.67

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

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Roberto Zenit

NASA grant NAG3-1853

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.

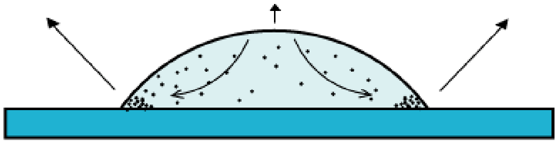

Figure 1. The flow in a drying droplet with pinned contact line.

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).

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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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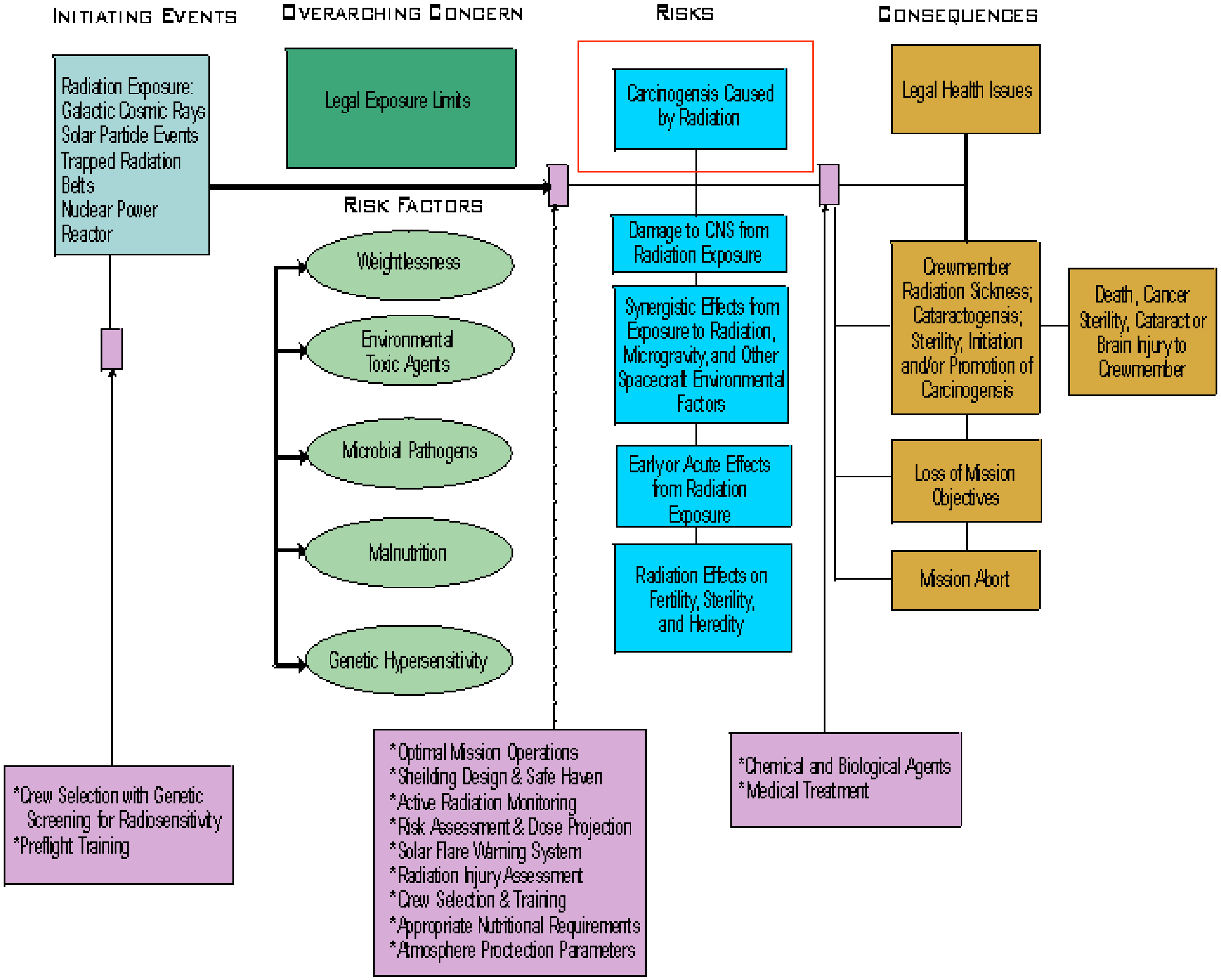
NSF Nano Interdisciplinary Research Team

RADIATION EFFECTS RISK AREA



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

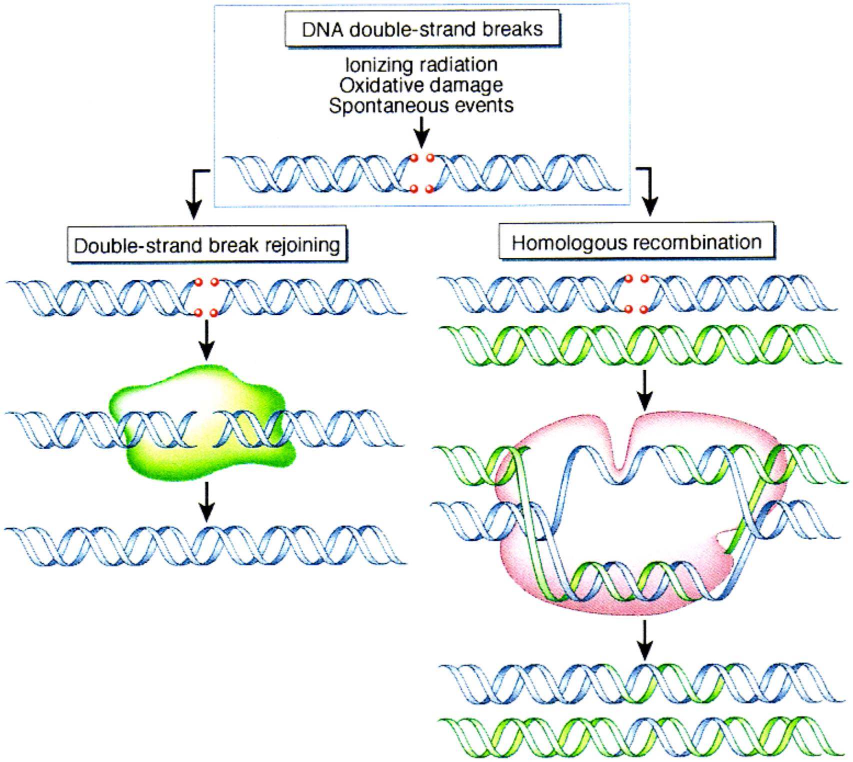


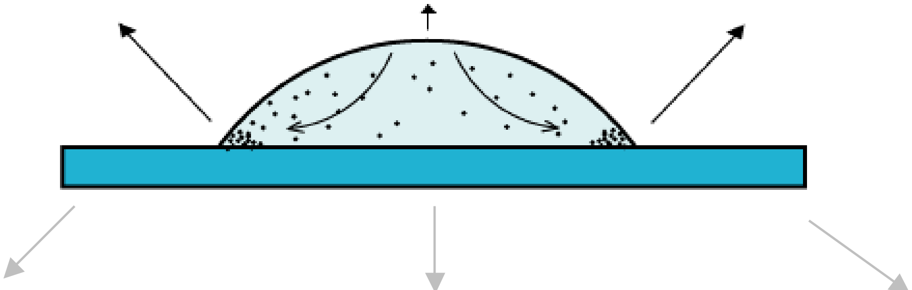
Figure 3 The repair of double-strand breaks in DNA. Double-strand breaks can result from exposure to ionizing radiation, oxidative damage and the spontaneous cleavage of the sugar-phosphate backbone of the DNA molecule. Their repair can be effected by either rejoining the broken ends (left) or by homologous recombination with a sister DNA molecule (right). Both processes involve different multi-protein complexes.

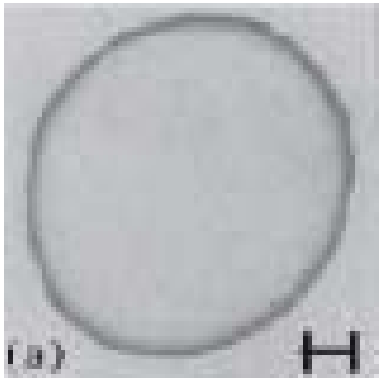
From Friedberg 2003

Surface Fixation of DNA

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

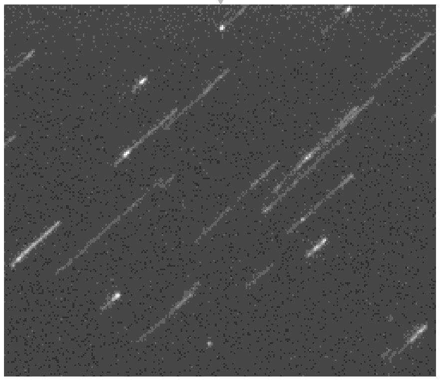
Prototype Microfluidic “Device”





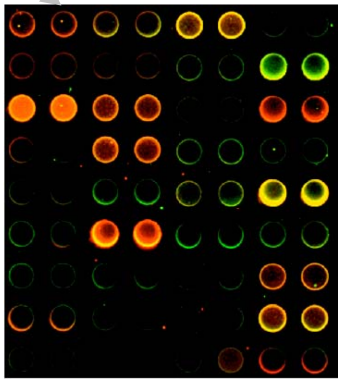
Coffee ring phenomenon

(**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)

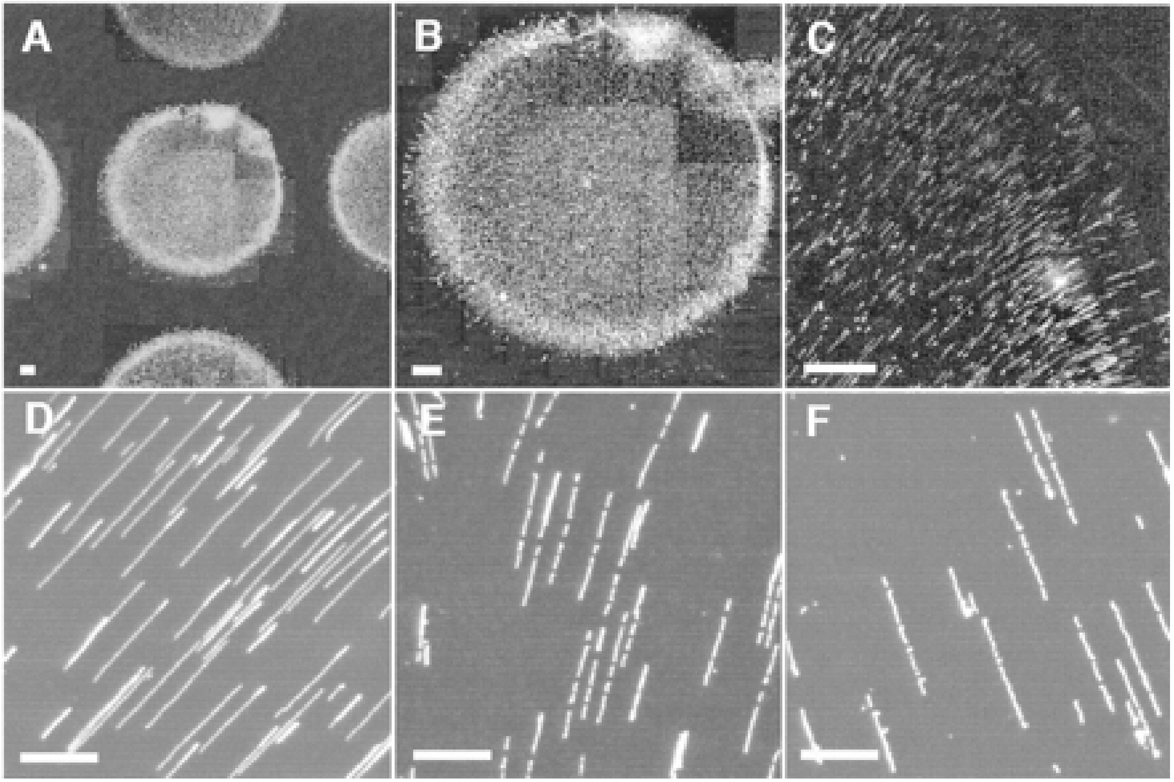


Microarrays for DNA Analysis

(Blossey R. et al, *Langmuir* 2002, *18,* 2952-2954)

DNA Genomics in an Evaporating Droplet

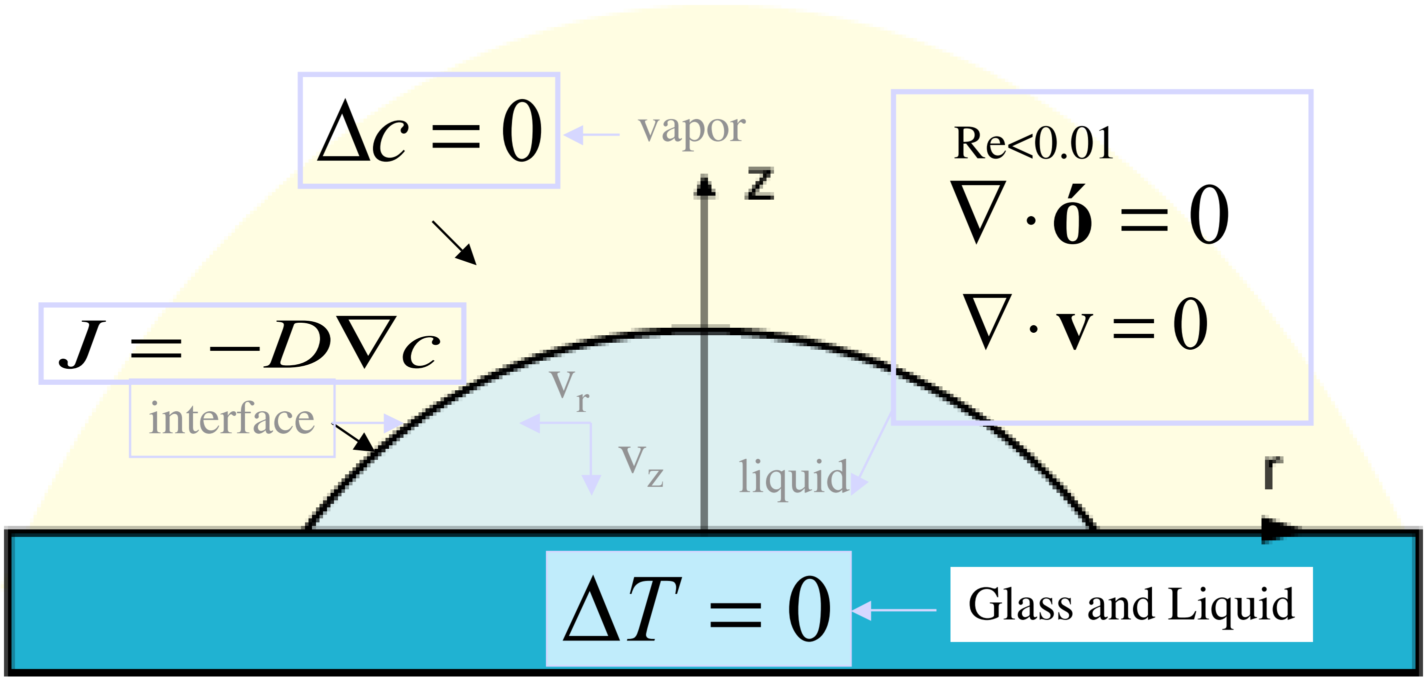
(Schwartz et al.)



Theory: Model

- Mass, momentum and heat balances in three regions:

  1. Vapor 2. Liquid 3.Vapor-liquid interface



$\Delta c = 0$

$J = -D\nabla c$

Re<0.01

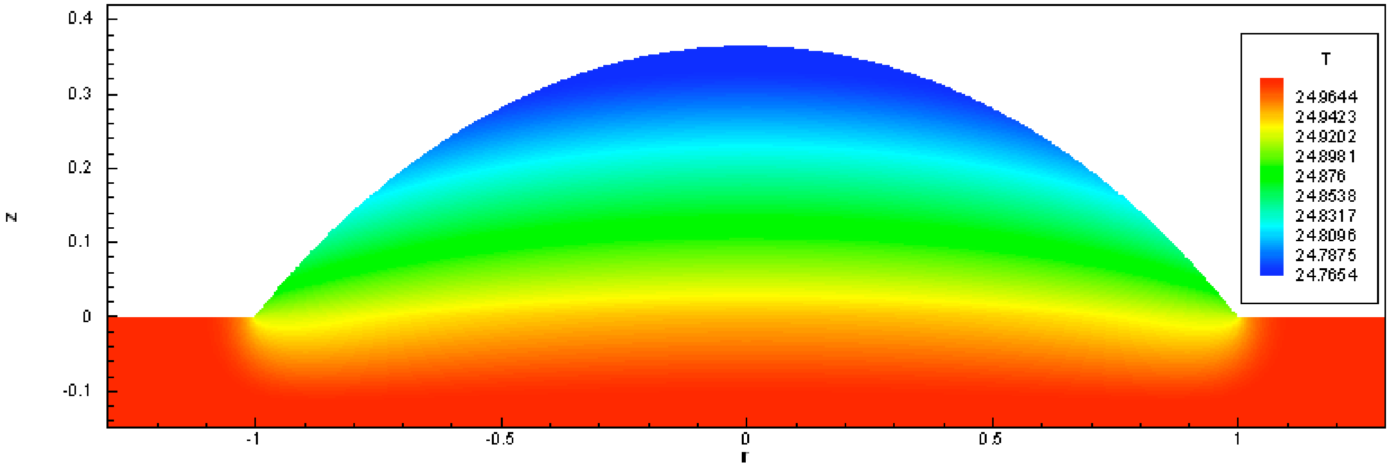
$\nabla \cdot \textbf{ó} = 0$

$\nabla \cdot \mathbf{v} = 0$

$\Delta T = 0$

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

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

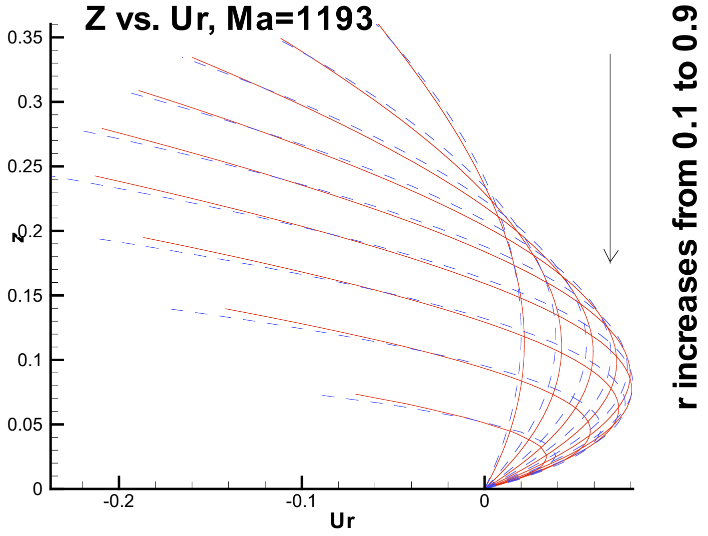
$$\begin{aligned}\tilde{u}_z = {} & \frac{3}{4}\frac{1}{1-\tilde{t}}\left[1 + \lambda(\theta)\left(1-\tilde{r}^2\right)^{-\lambda(\theta)-1}\right]\left(\frac{\tilde{z}^3}{3\tilde{h}^2} - \frac{\tilde{z}^2}{\tilde{h}} \right) + \\ & \frac{3}{2}\frac{1}{1-\tilde{t}}\left[\left(1-\tilde{r}^2\right) - \left(1-\tilde{r}^2\right)^{-\lambda(\theta)}\right]\left(\frac{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

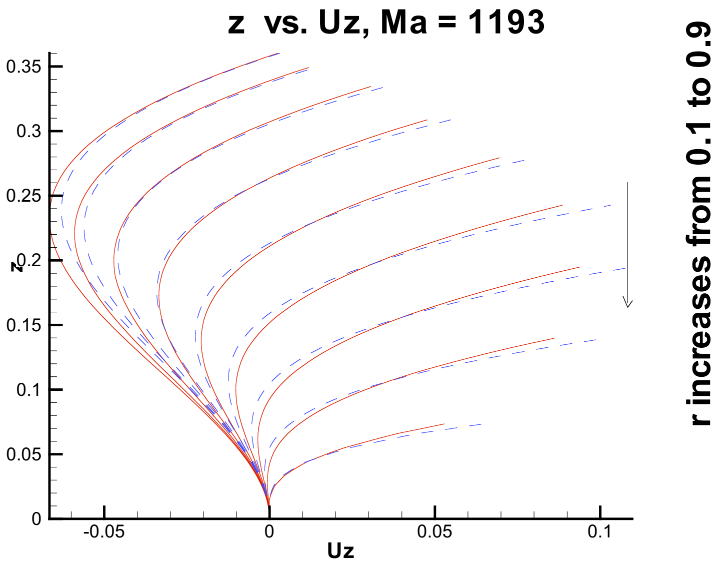
$$Ma = \frac{\beta\, k t_f}{\mu R}$$

$$\lambda(\theta) = \frac{1}{2} - \frac{\theta}{\pi}$$

Results: Comparison Between FEM and Analytical Results, Ma=1193

Comparison of velocity fields with Marangoni stress, Ma = 1193
Contact angle, θ=40^{o}

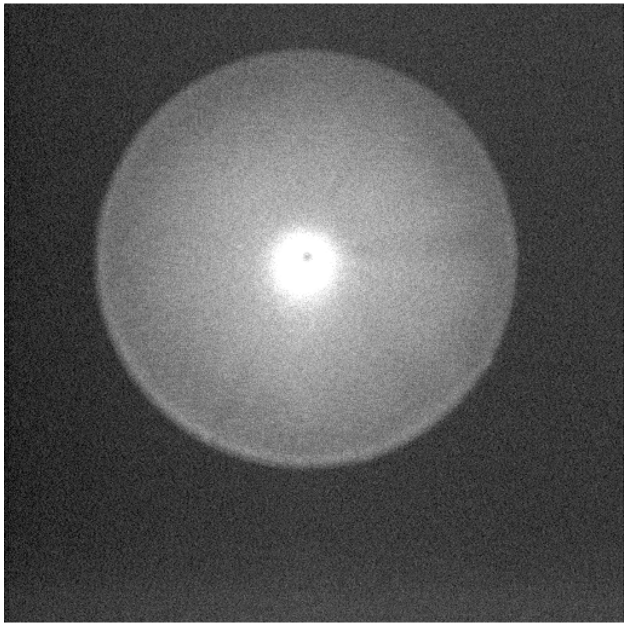


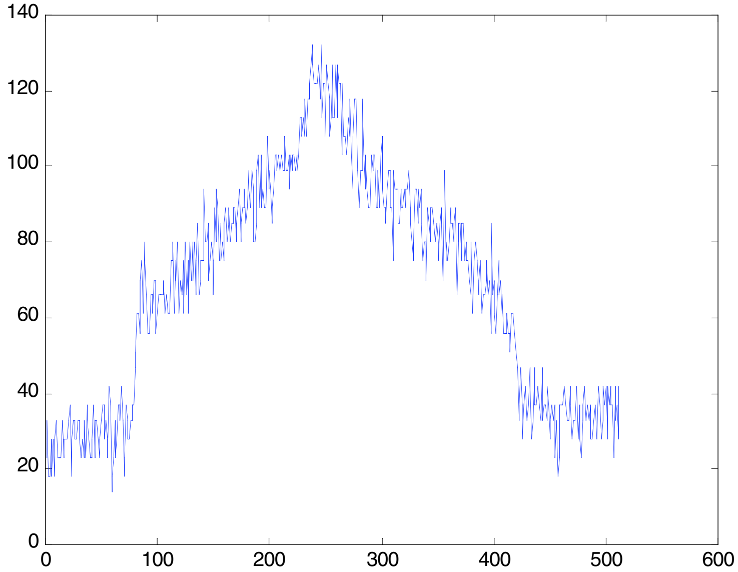


$$\tau_{rz}\Big|_{z=h} = \frac{d\sigma}{dr}$$

Deposition from Octane droplet

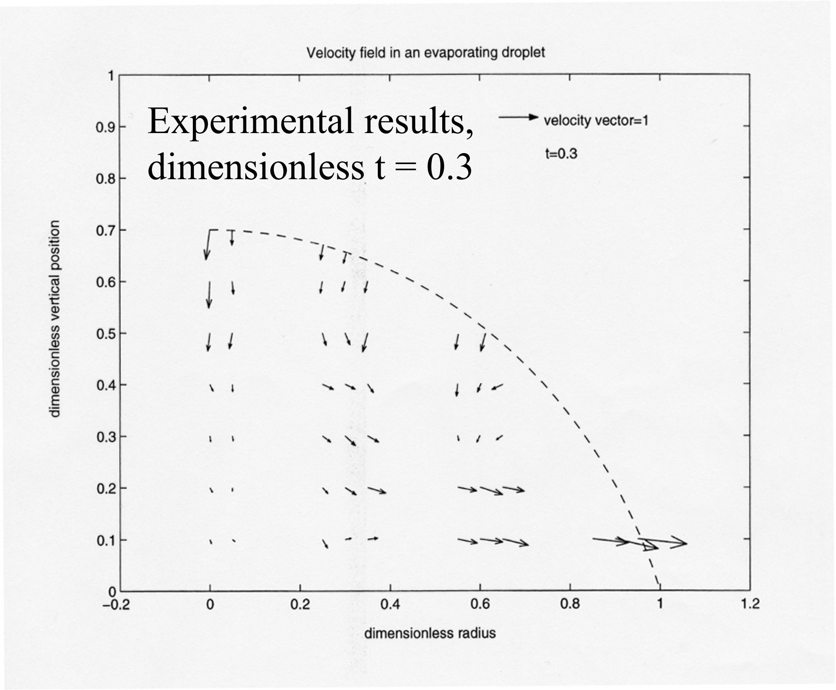
- Particle deposition patterns w/ Marangoni

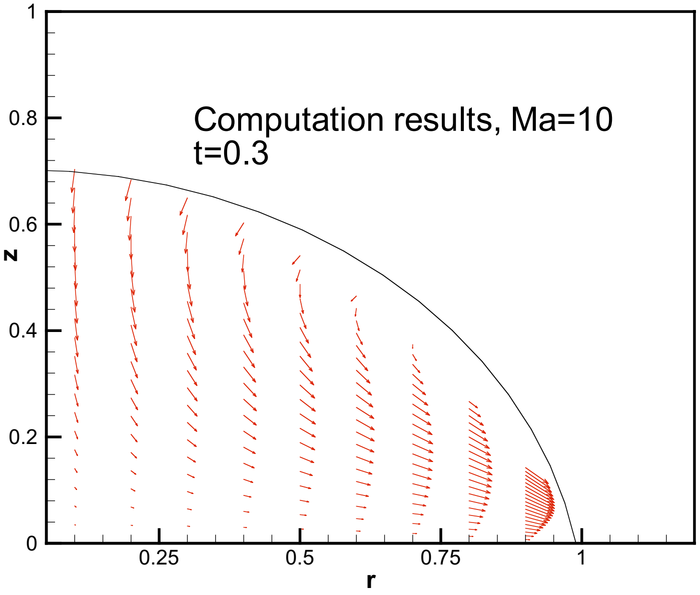




Flowfield in Drying Water Droplet:

Comparison Between Experiments and Computations

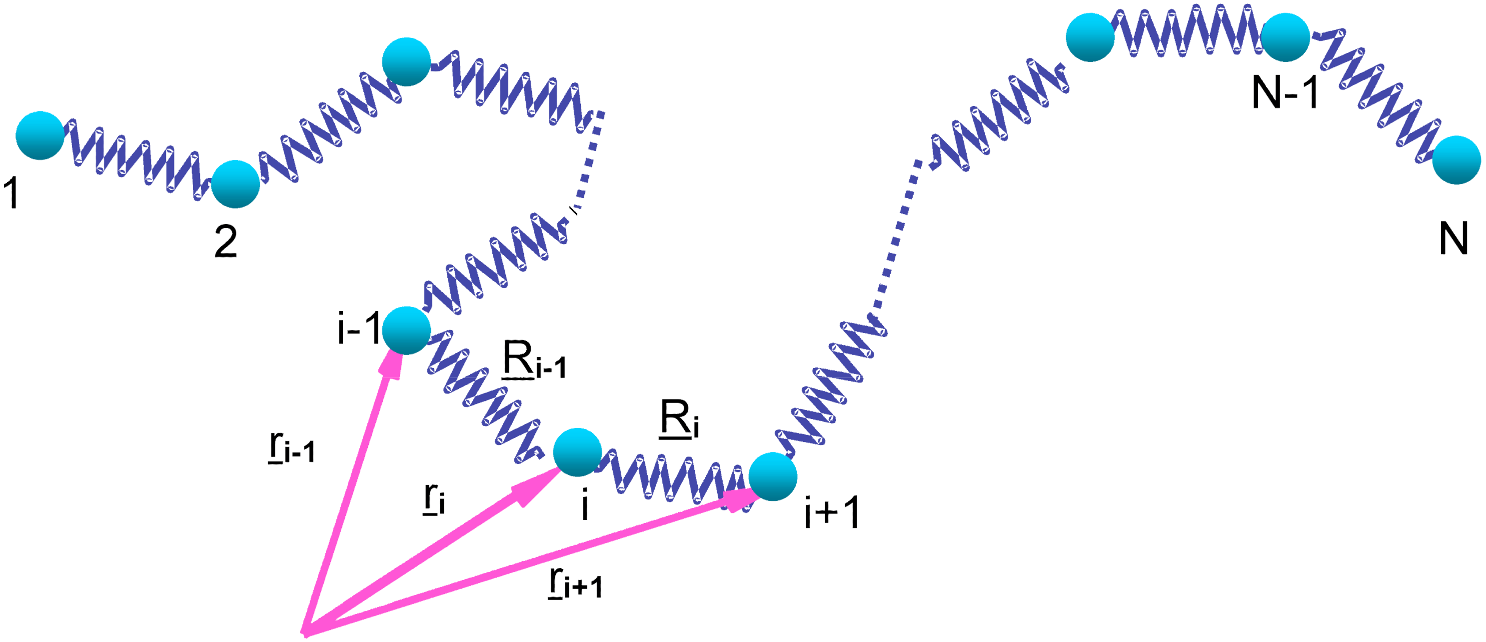




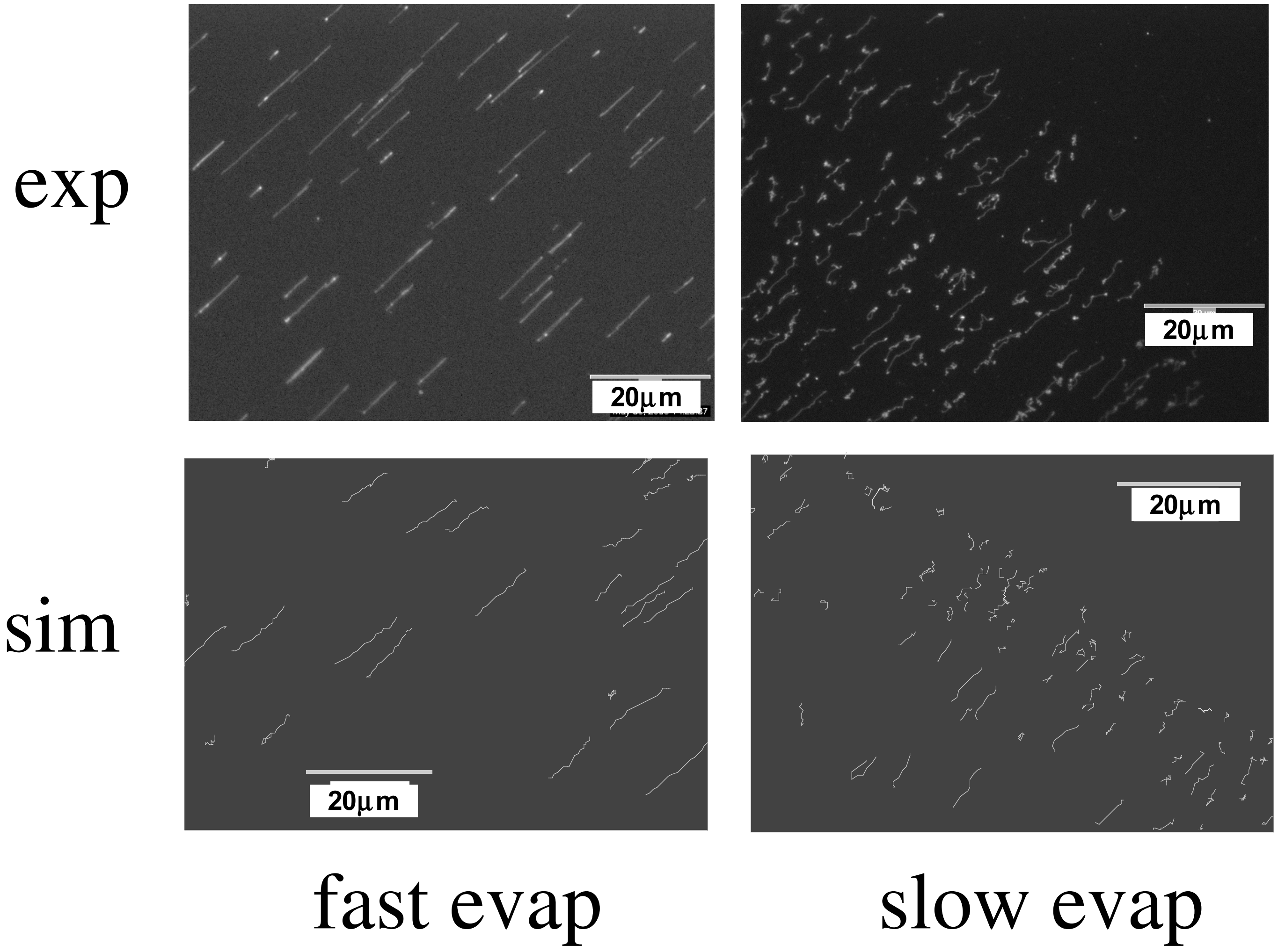
- Velocity field (to reduce the effect of Brownian motion, 250-300 droplets are measured)

Modeling

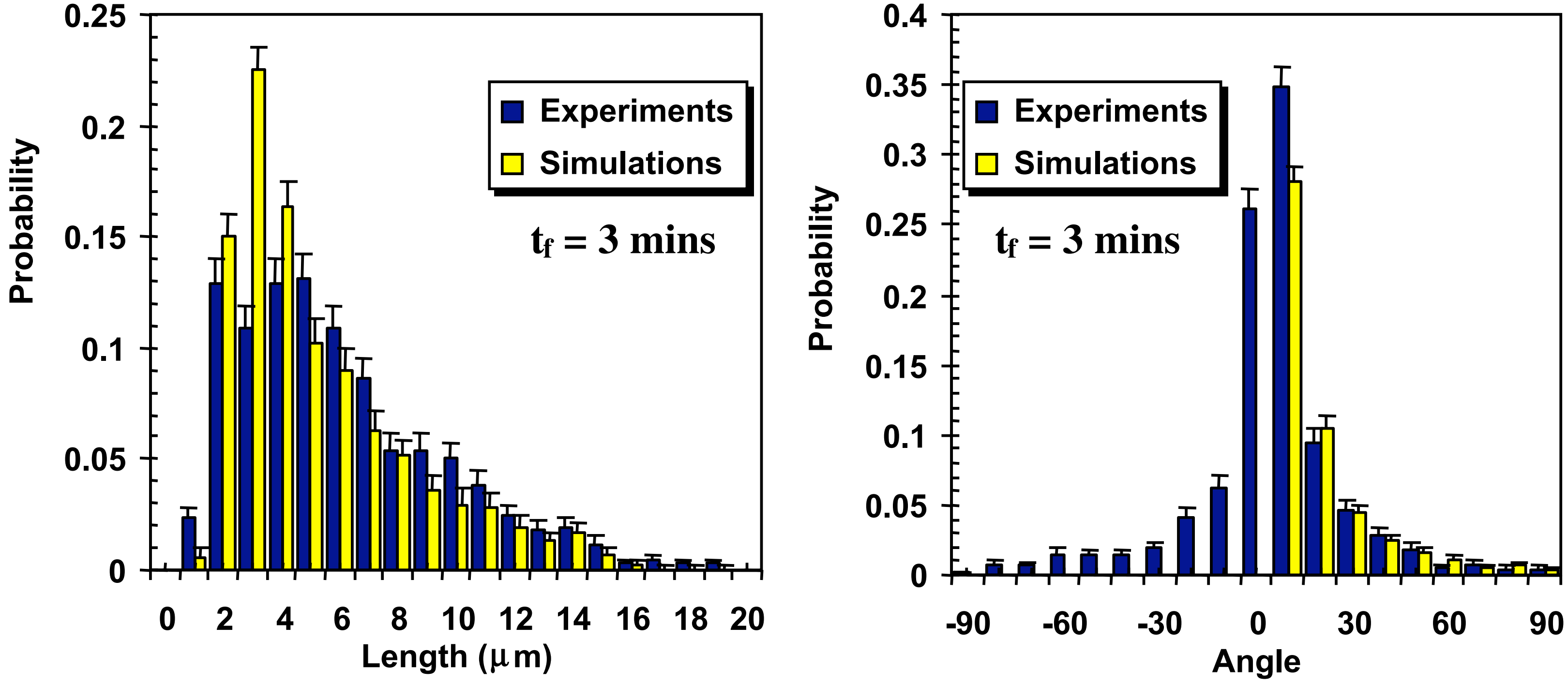
- **Bead-spring model**
- **Solve using Brownian dynamics (BD)**



DNA deposition from an evaporating droplet



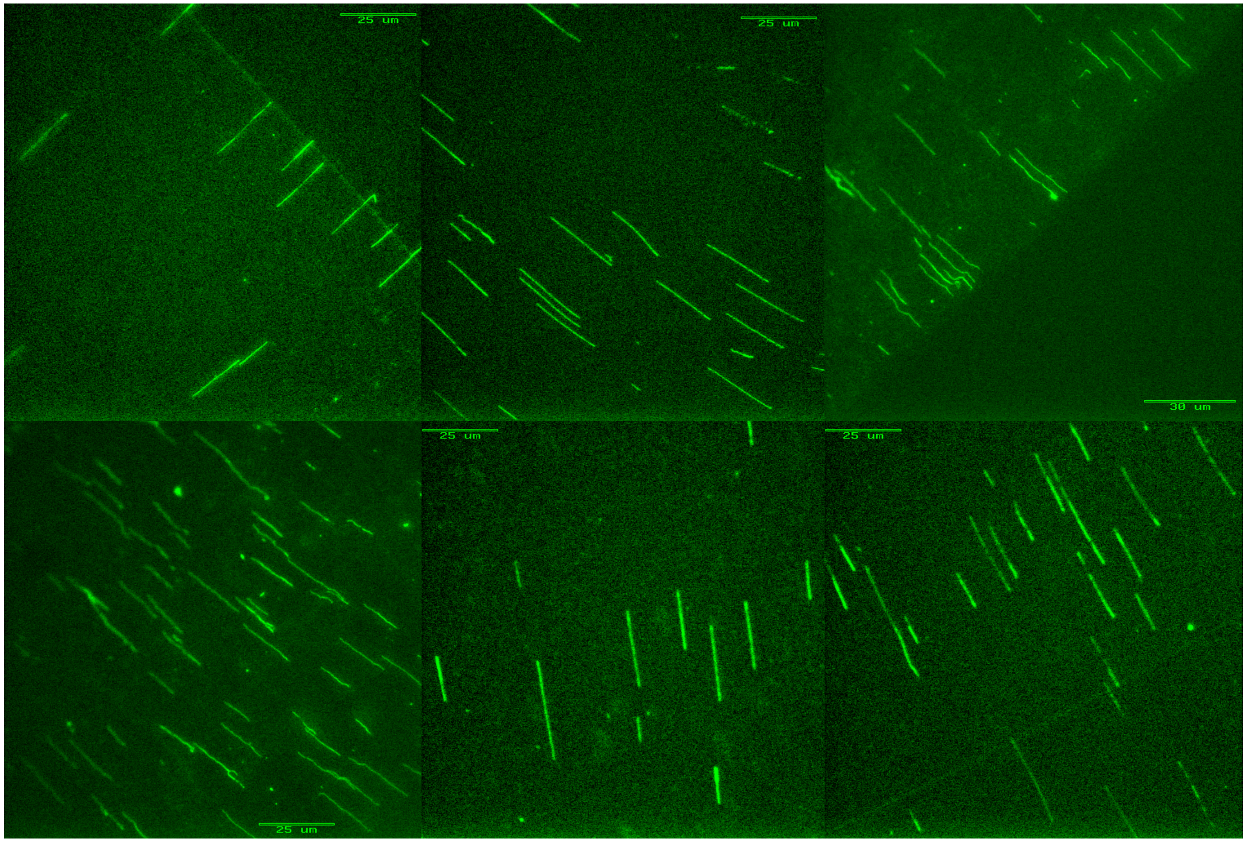
Comparison Between Simulations and Experiments in Drying Droplets



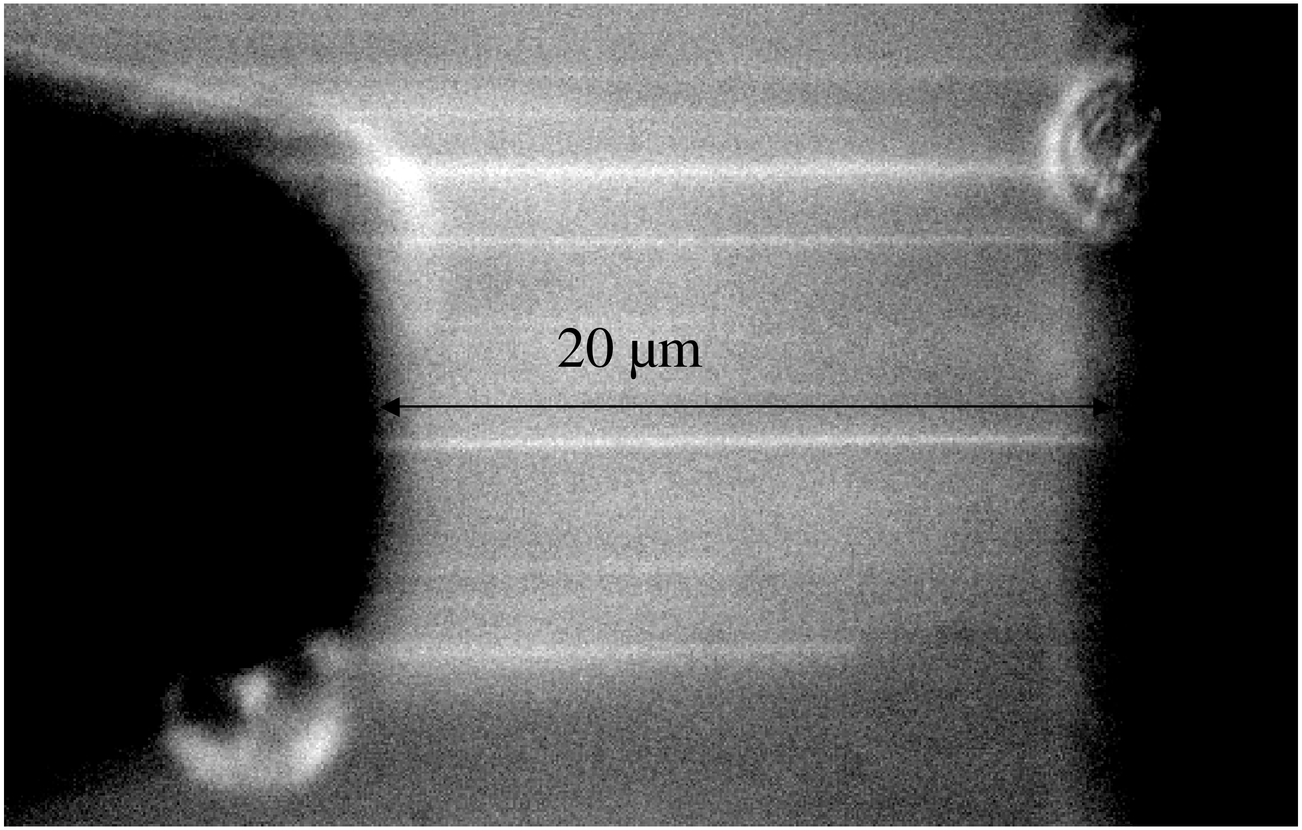
Droplet: simulation and experimental results agree at medium evaporation rate

Molecular Combing

adapted from Bensimon and coworkers



DNA Electro-Stretching



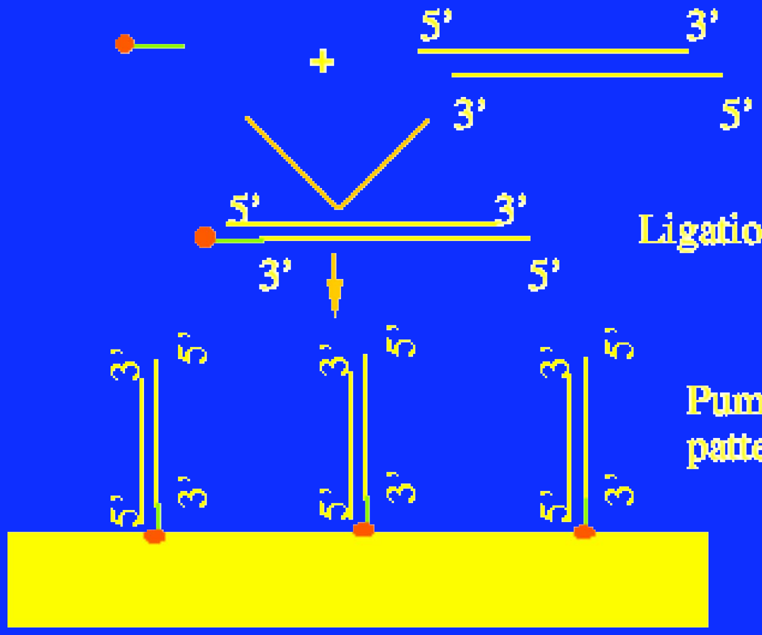
DNA Stretching

Immobilization

Thiol-On -Gold

Thiol labeled 12-mer
(Sigma Genosys)

Lambda DNA
(Gibco BRL)

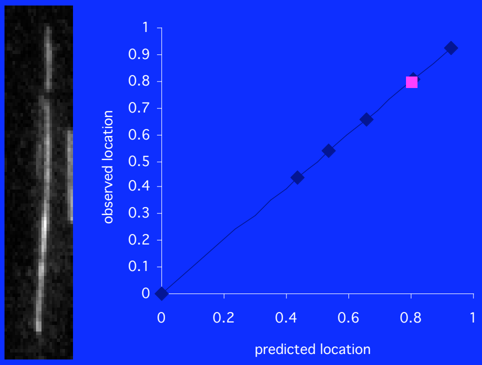


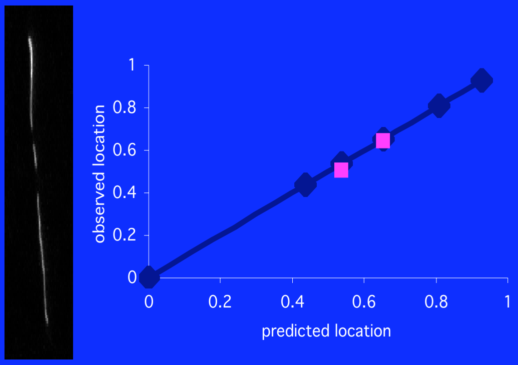
Ligation Reaction

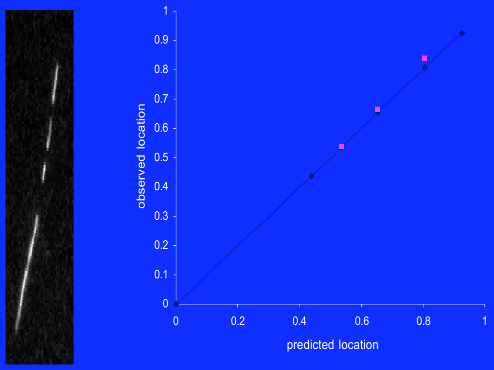
Pump through channels
patterned with gold electrodes

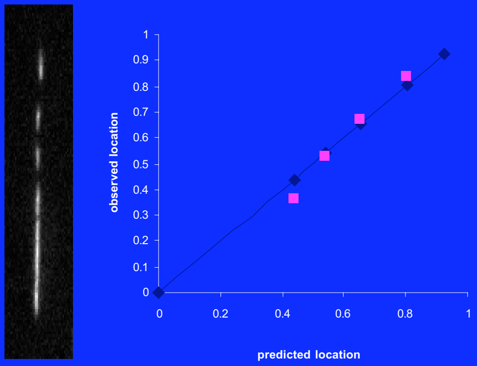
DNA Immobilized on Gold Electrode

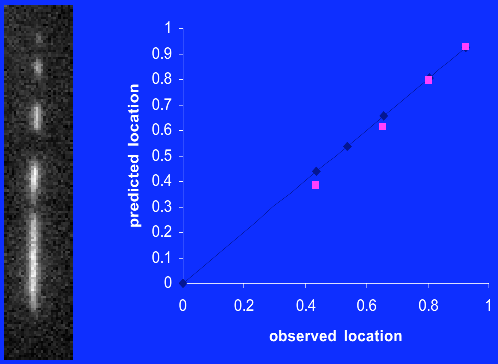
Enzymatic Cleavage of DNA

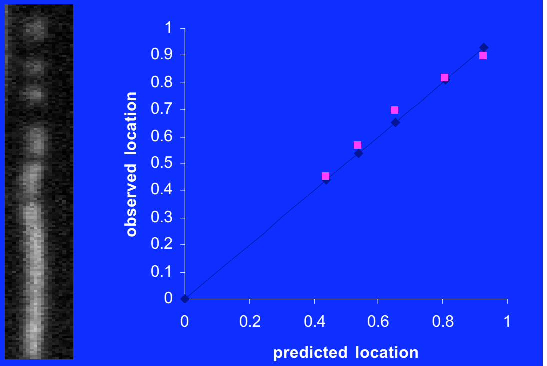




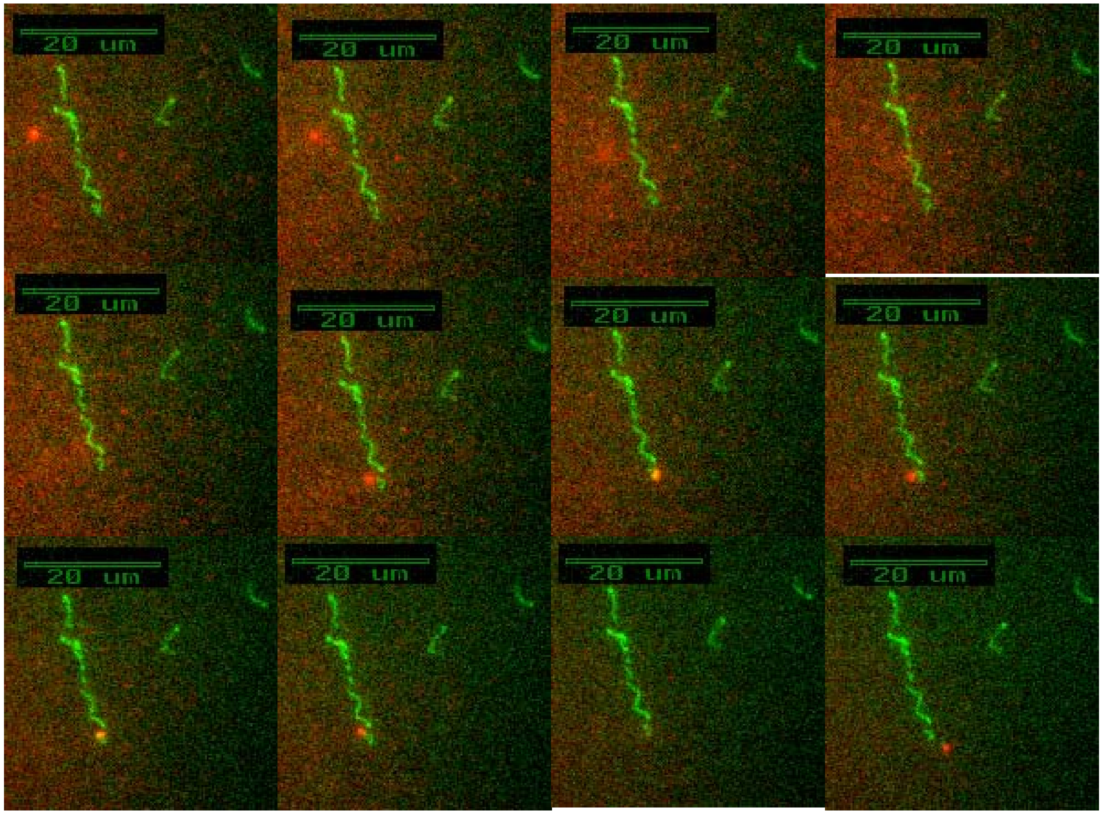




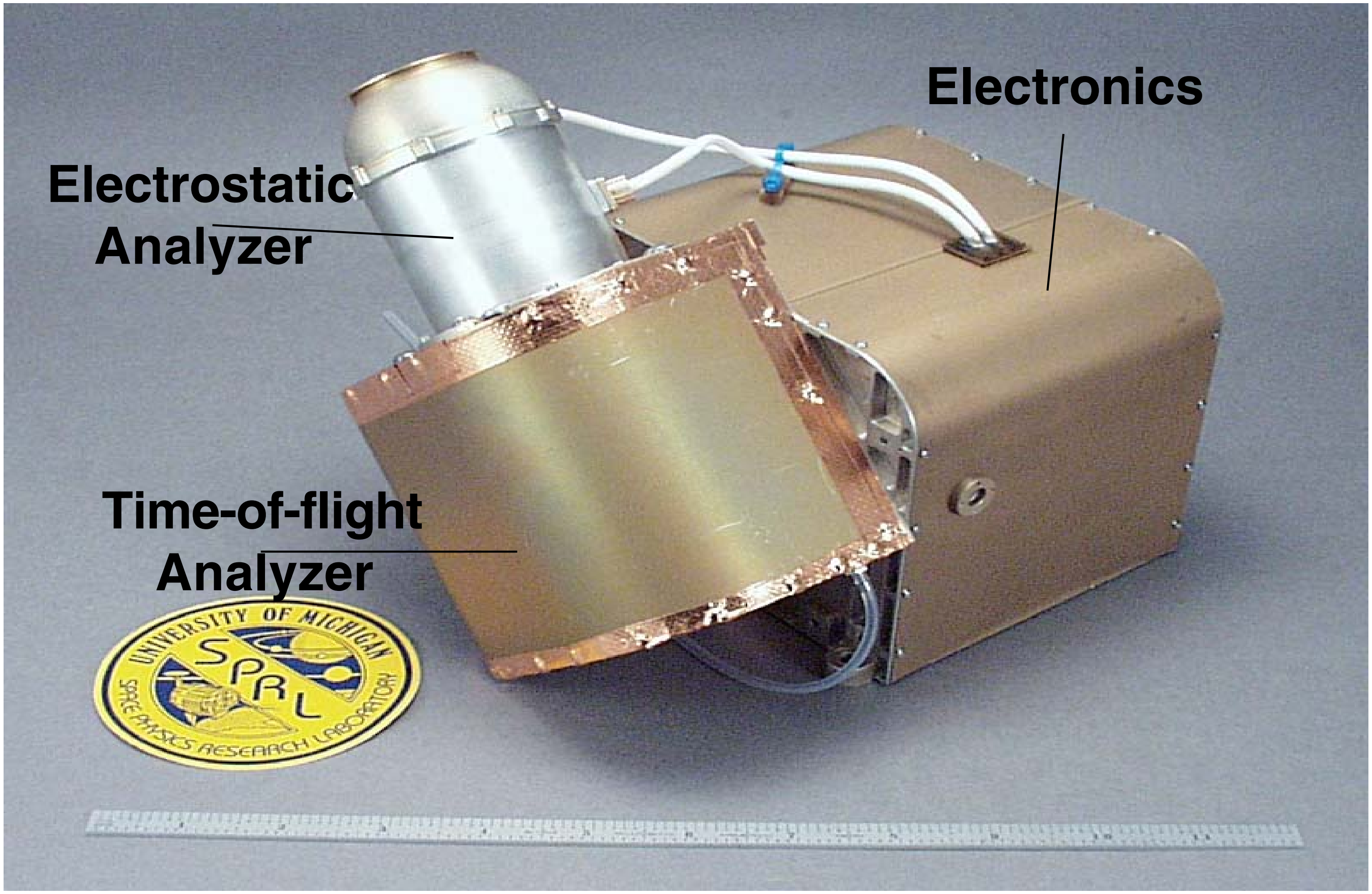




Interaction of Dnase I (red) with lambda DNA (green)

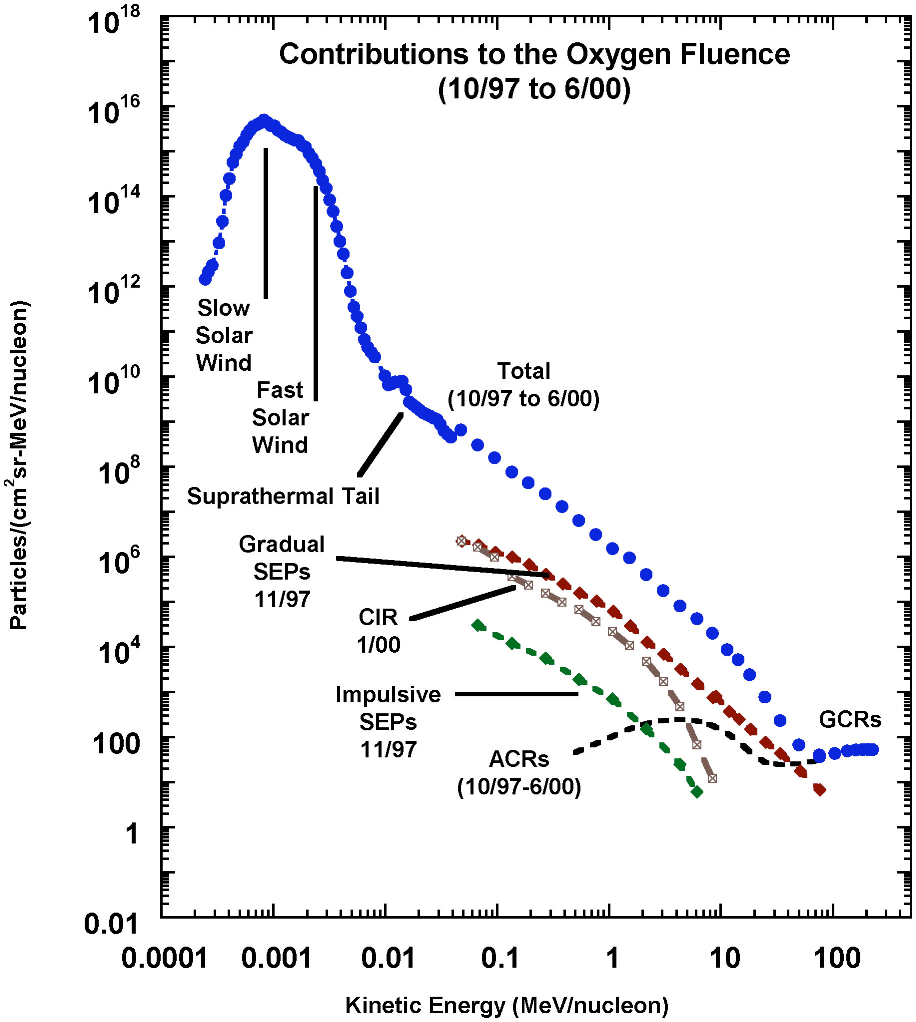


Radiation sensor for space environment (from Thomas Zurbuchen, Umich)

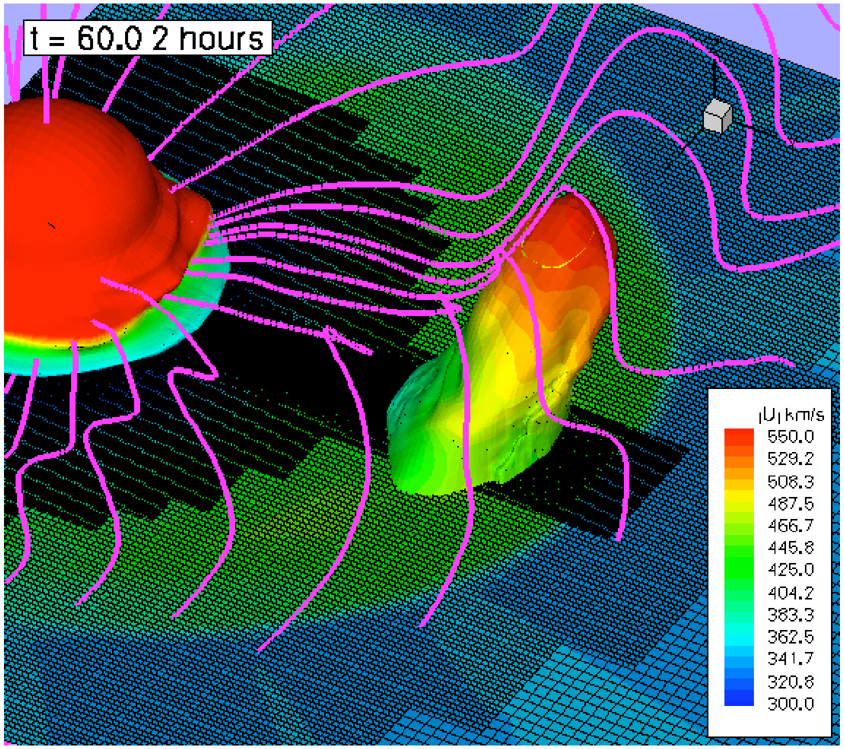


Average space radiation

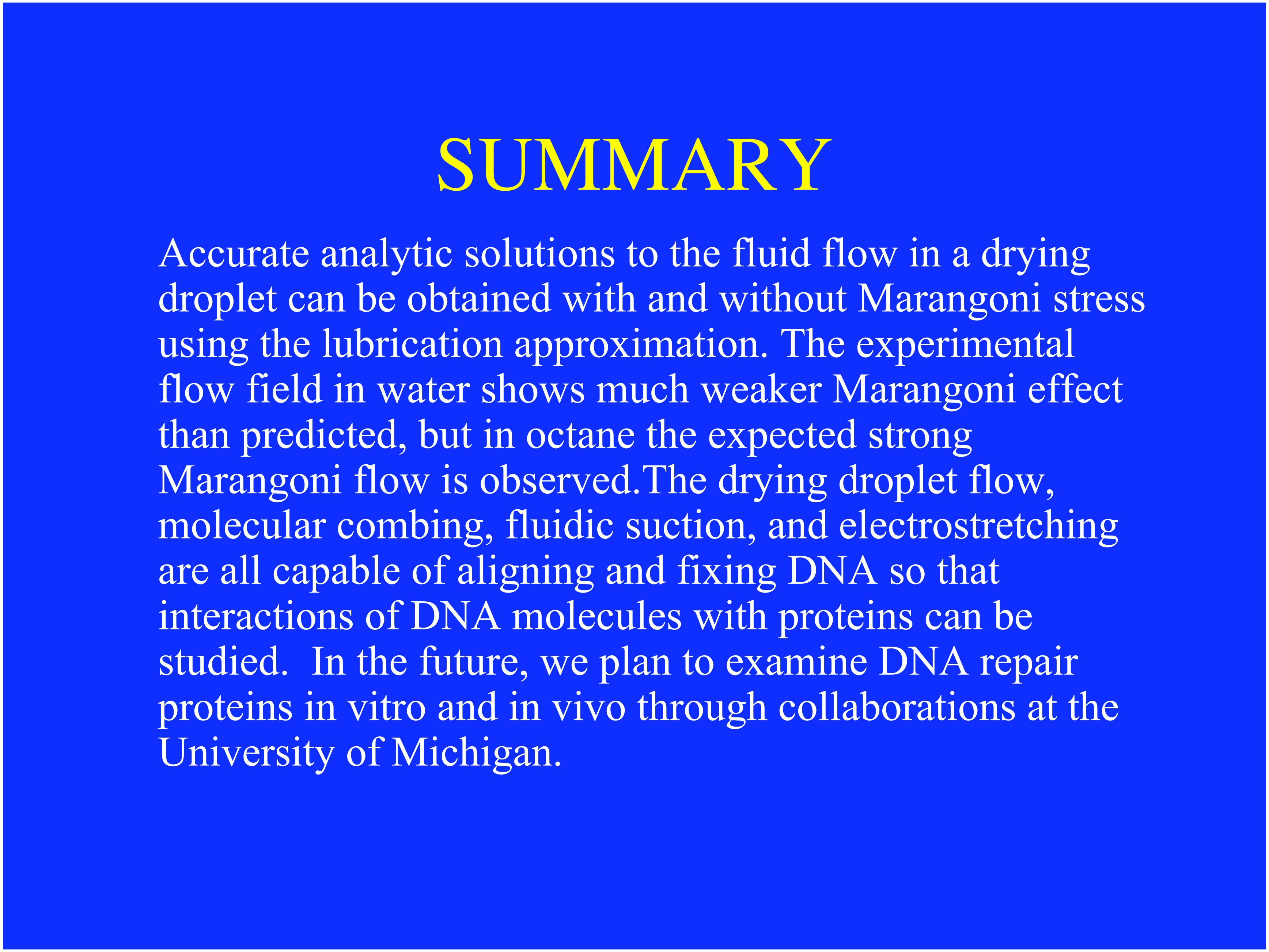
- Space radiation and its components observed at 1 AU.
- UM operates the instruments that measure particles up to 0.1 MeV/nuc.



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

Michel Y. Louge, PI
Sibley School of Mechanical and Aerospace Engineering
Cornell University, Ithaca, NY 14853

James T. Jenkins, CoI
Department of Theoretical and Applied Mechanics
Cornell University, Ithaca, NY 14853

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

CORNELL
UNIVERSITY

Conference-Workshop on
Strategic Research to Enable NASA's Exploration Missions

Cleveland, Ohio
June 22 - 23, 2004

Activities
Significance
Applications

IFPRI
International Fine Particle Research Institute

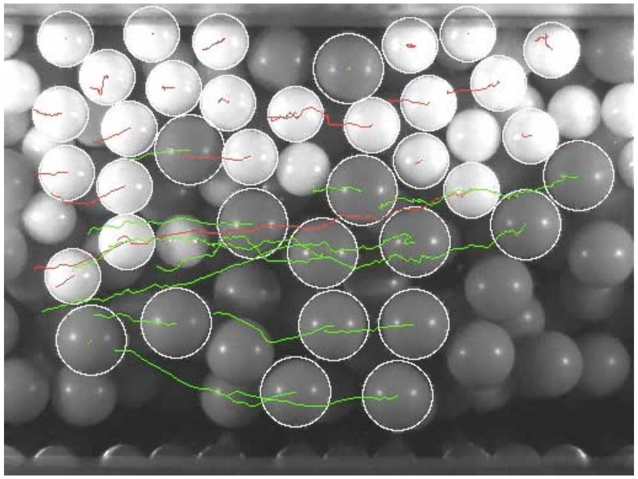
with Enrique Ramé, John Caruso and the NASA-Glenn Engineering Team

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)



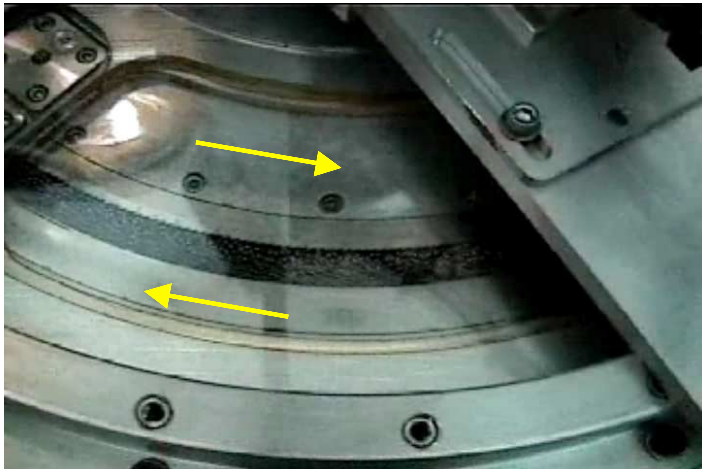
Gullies in the northern wall of a crater at 39.1°S, 166.1°W
Subframe of MOC image E11-04033

NASA/JPL/Malin Space Science Systems

Granular Flow Module

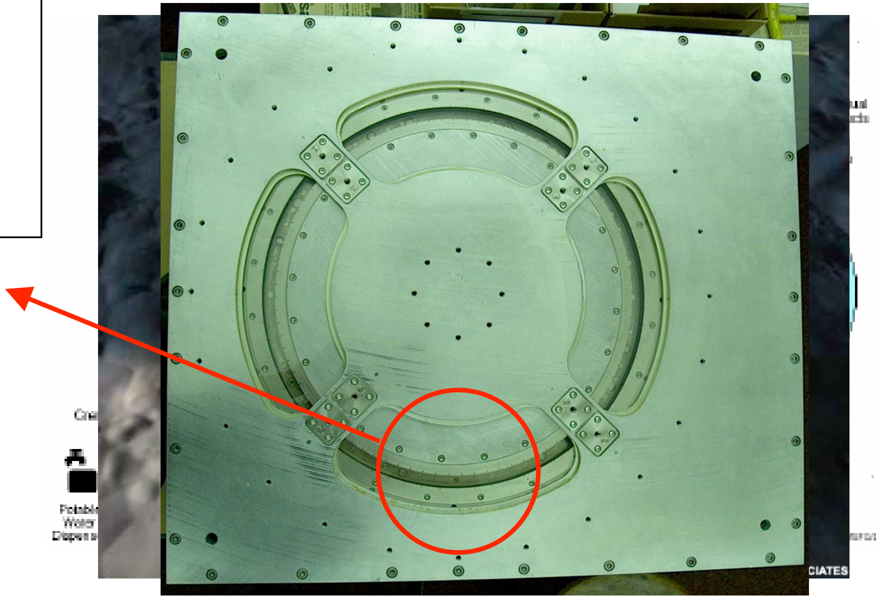
Solids interacting with a Gas

in a Microgravity Apparatus (SiGMA)

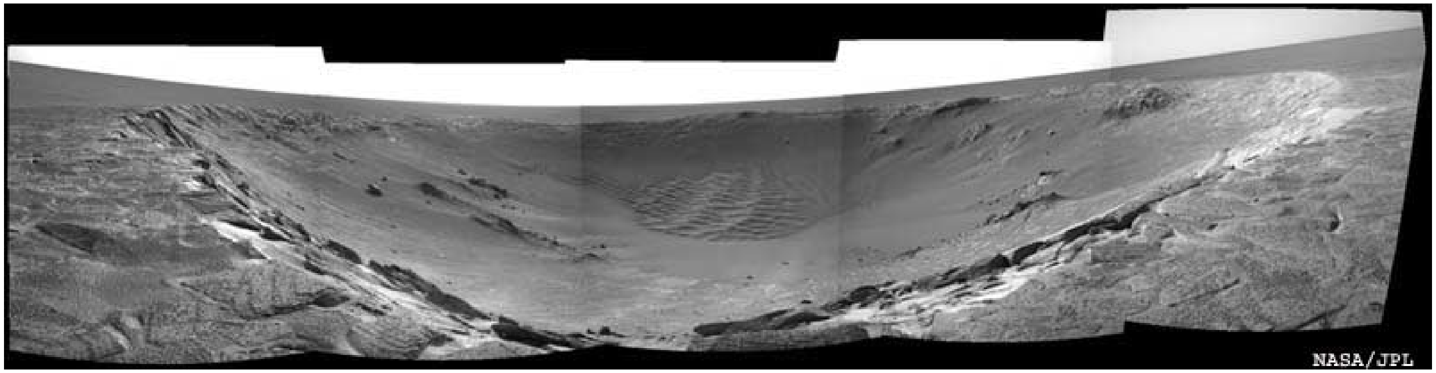


Agitated solids interacting with a gas

Chemical, oil and energy industries;
solid transport & drying,
waste management & water recovery,
thermal systems, ISRU.

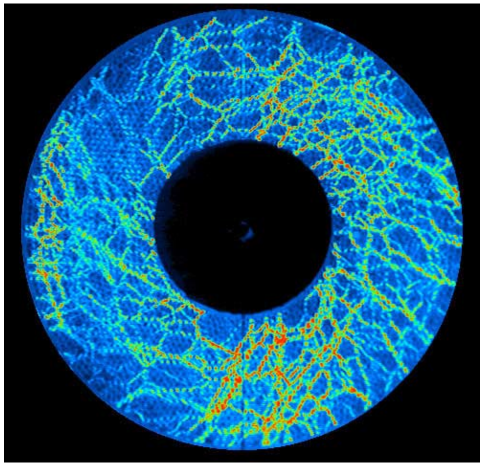


Granular Flow Module



Robert Behringer

Force networks



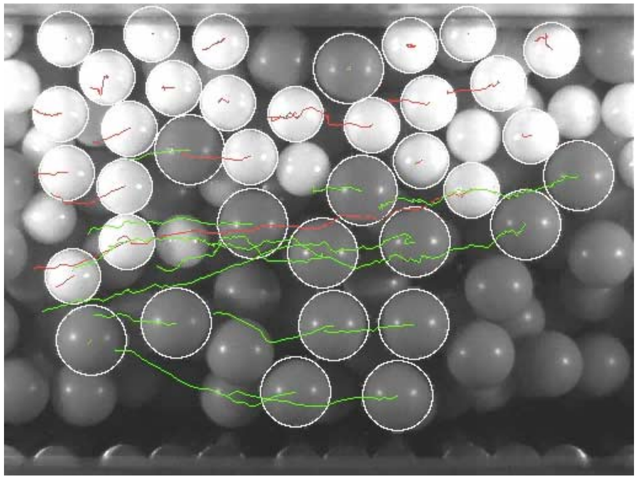
Dense, quasi-static particle assemblies

Solid transport and storage,
soil mechanics, ISRU.

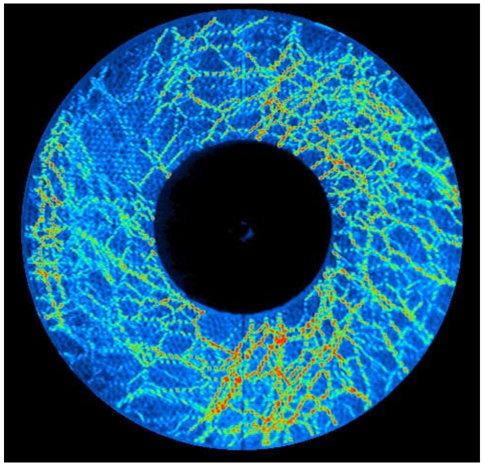
Activities

Solids interacting with a Gas in a Microgravity Apparatus (SiGMA)

Microgravity Segregation of Energetic Grains (μgSEG)



Force networks



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

$$T = \frac{1}{3} m \overline{u_i u_i}$$

fluctuation kinetic energy of the grains

"granular temperature" → viscosity $\boxed{\mu_s \propto \rho_s d \sqrt{T/m}\, f_\mu(\nu)}$

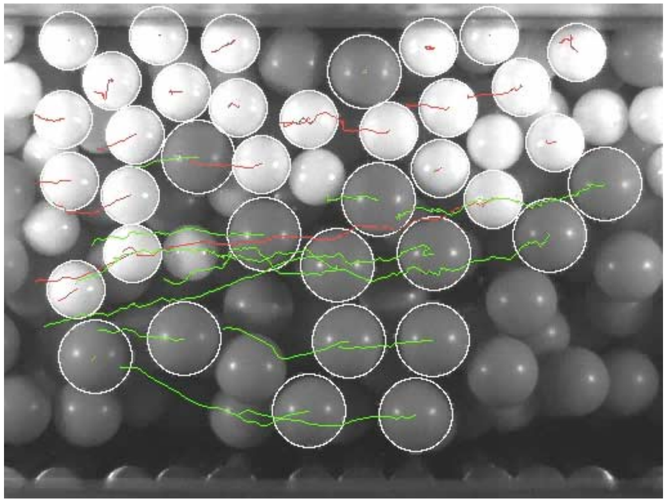
→ conductivity $\boxed{k_s \propto \rho_s d \sqrt{T/m}\, f_k(\nu)}$

Collisional granular segregation

In a fully-developed, steady, rectilinear flow:

$$0 = (\ldots)\nabla \ln T + \frac{n_A}{nT}\left(\frac{\partial \mu_A}{\partial n_A}\nabla n_A + \frac{\partial \mu_A}{\partial n_B}\nabla n_B\right)$$

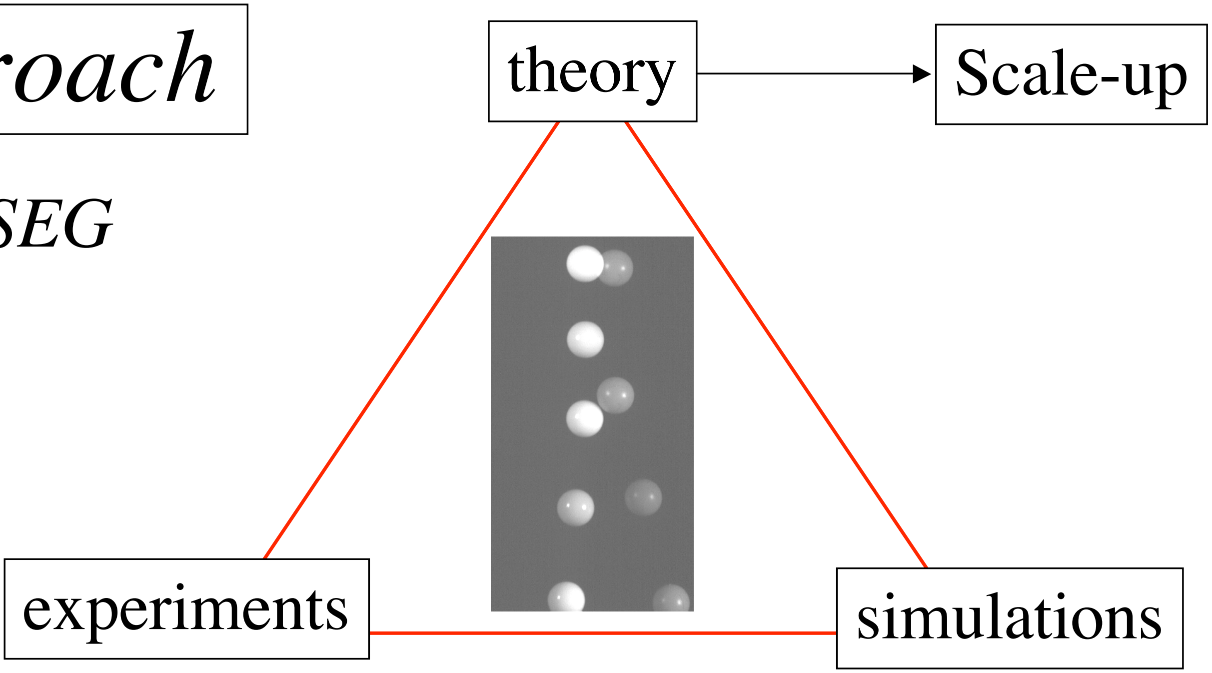
μgSEG



Dominant segregation mechanism in reduced gravity;
granular flows on moons and planets;
solid waste management, ISRU.

Approach

μgSEG

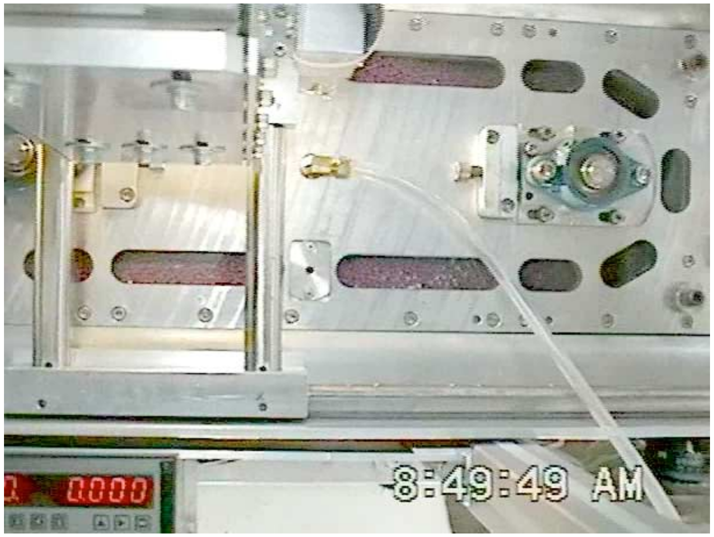


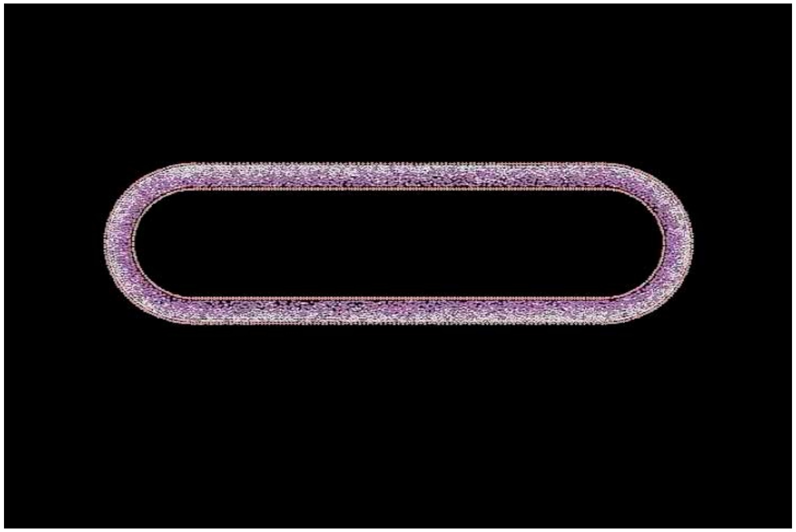
theory

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

MERCK

Unilever

P&G

ExxonMobil

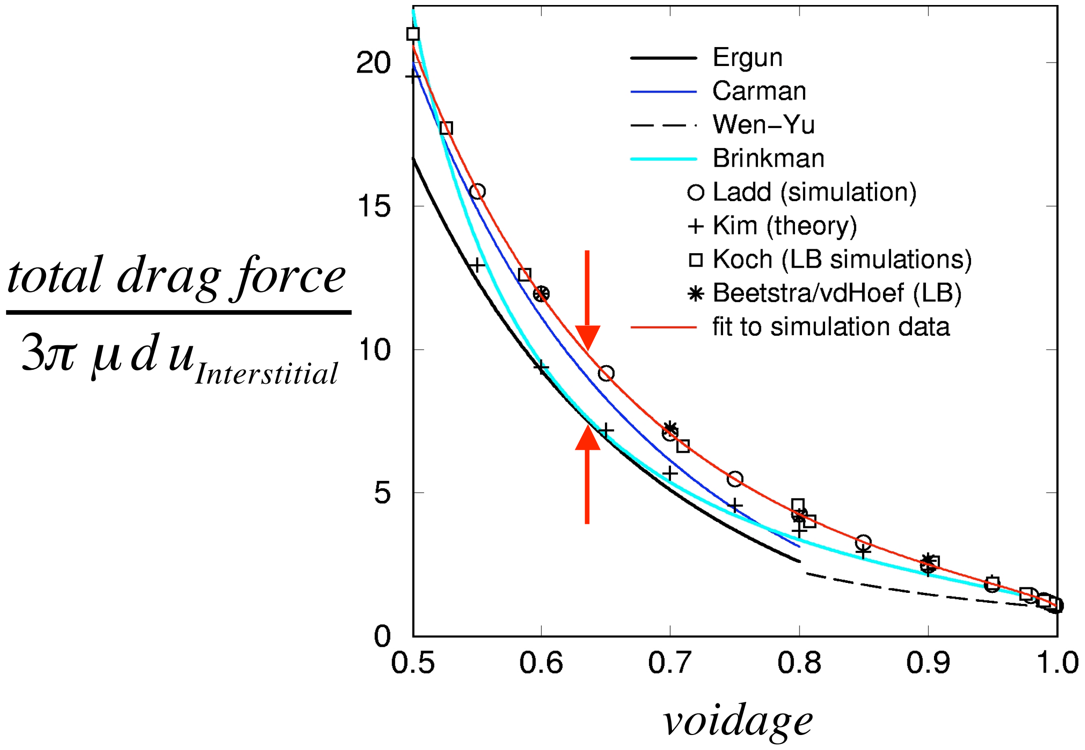
IFPRI
International Fine Particle Research Institute

DUPONT The miracles of science

DOW
Living.
Improved daily.

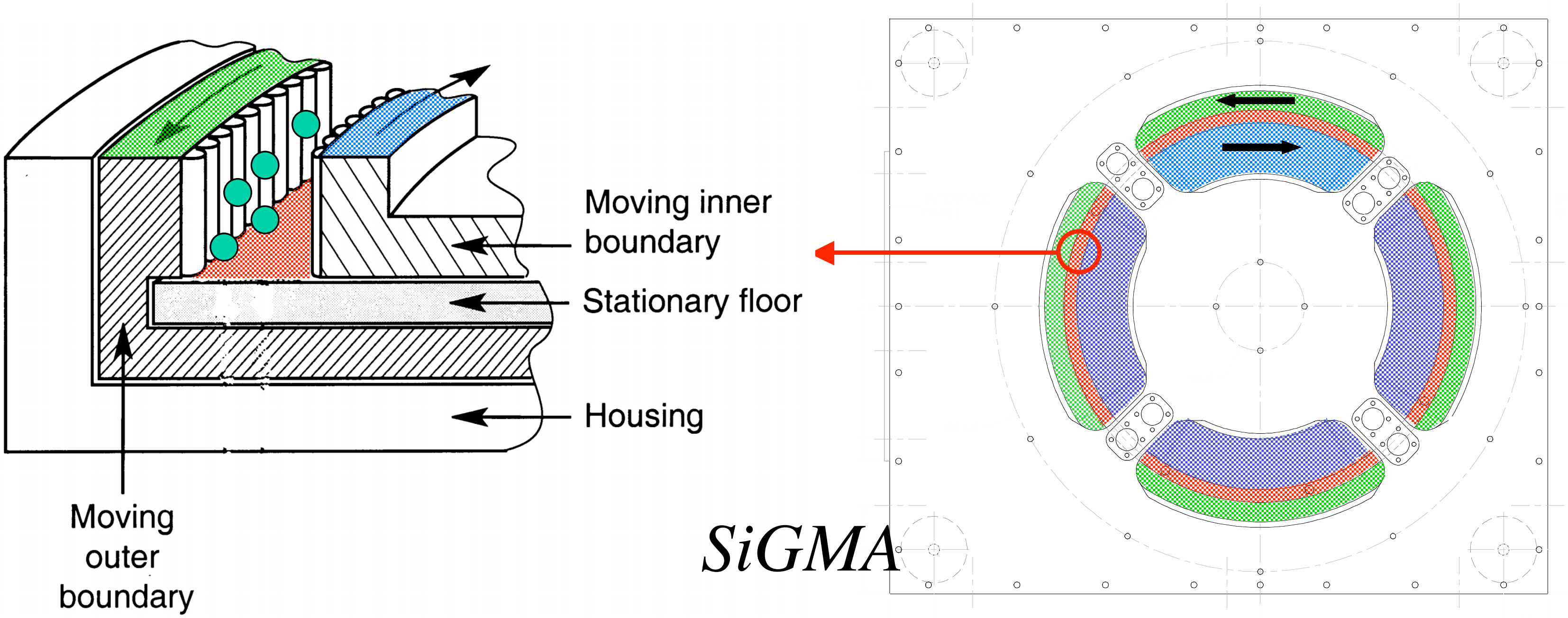
Drag force in the limit Re = 0

Random array of static spheres
Predictions from theory, experiment and simulation



courtesy of Martin van der Hoef

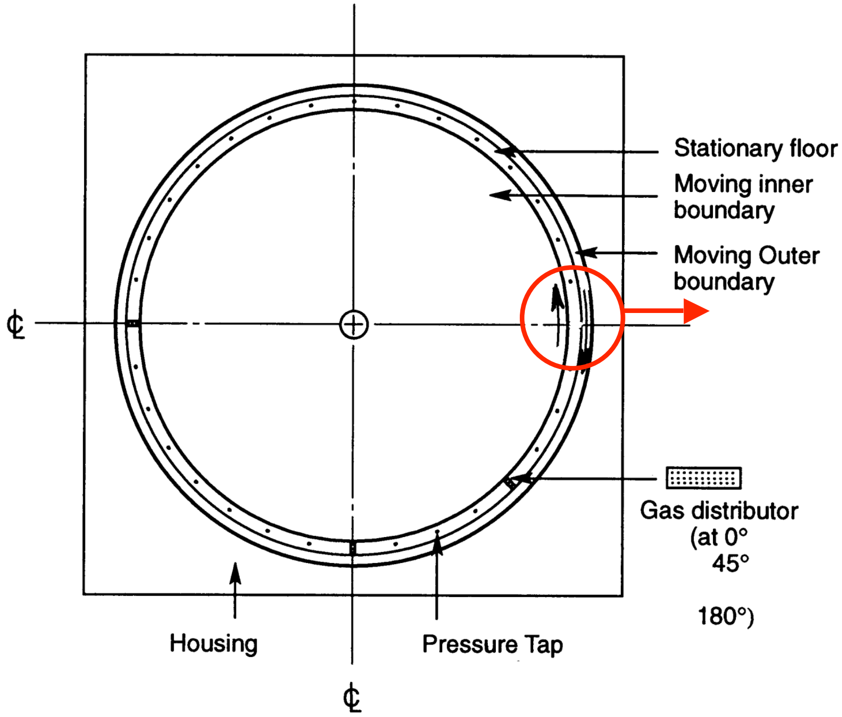
Viscous dissipation experiments

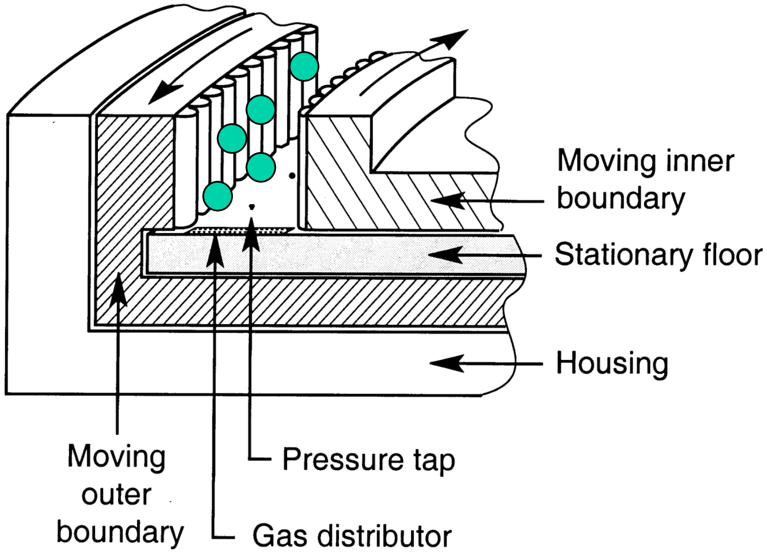


Reduce boundary speeds until the viscous dissipation of fluctuation energy dominates its collisional counterpart.

Test duration requires long-lasting microgravity.

Gas drag on agitated solids





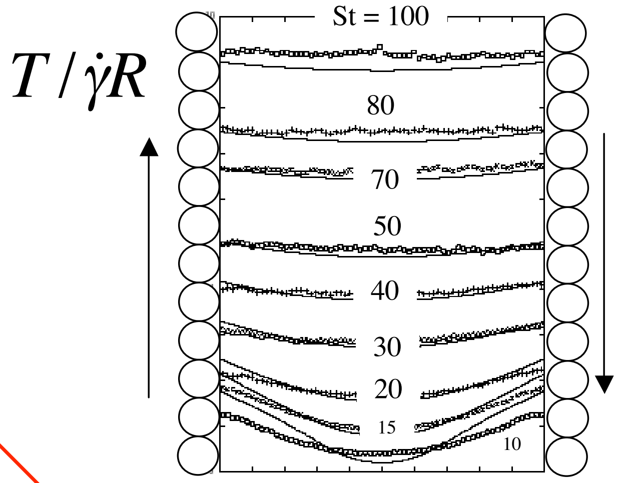
Impose a gas pressure gradient on the agitated, sheared granular material.

SiGMA

Approach

SiGMA

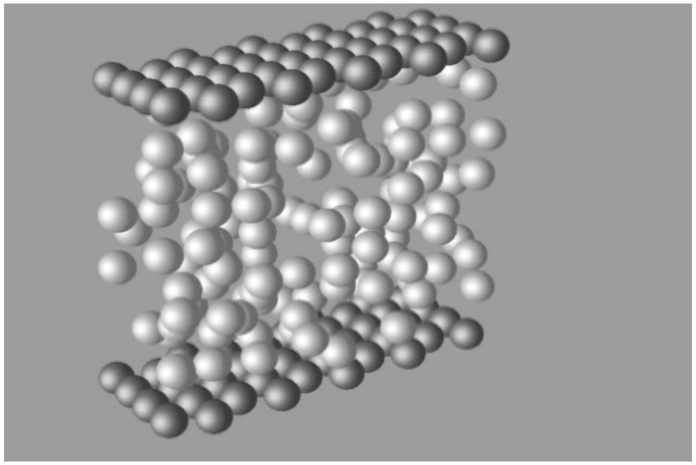
Scale-up ← theory



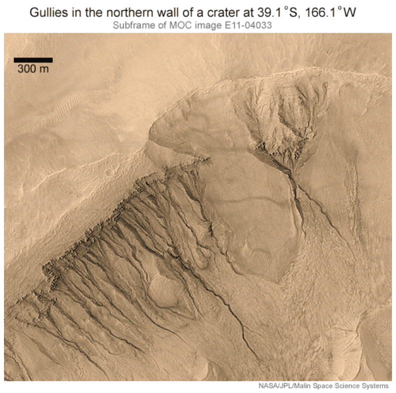
Haitao Xu, Michel Louge

experiments

Lattice-Boltzmann simulations



Rolf Verberg, Donald Koch, Chris Pelkie

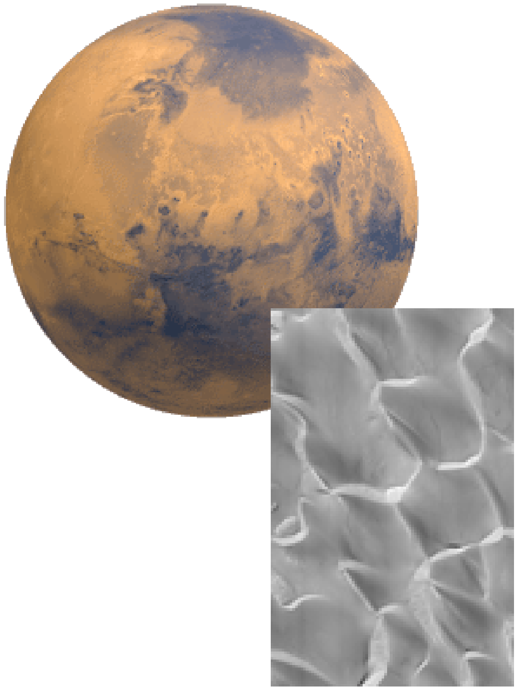


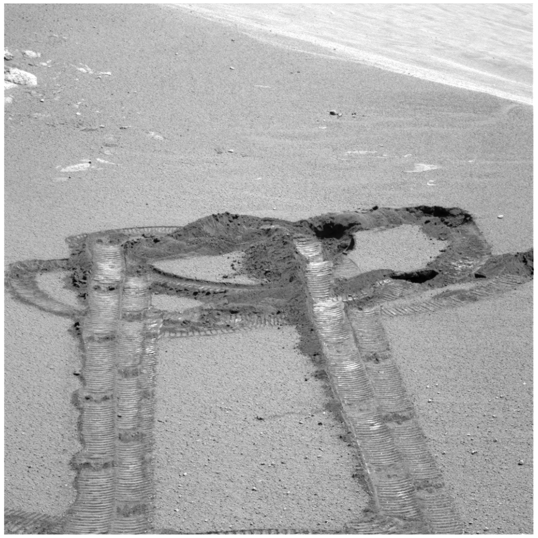
Benefits

Use extended microgravity platform to

Obtain practical information for multiphase flows.

Inform technologies for human exploration of space and for Earth-based industries.

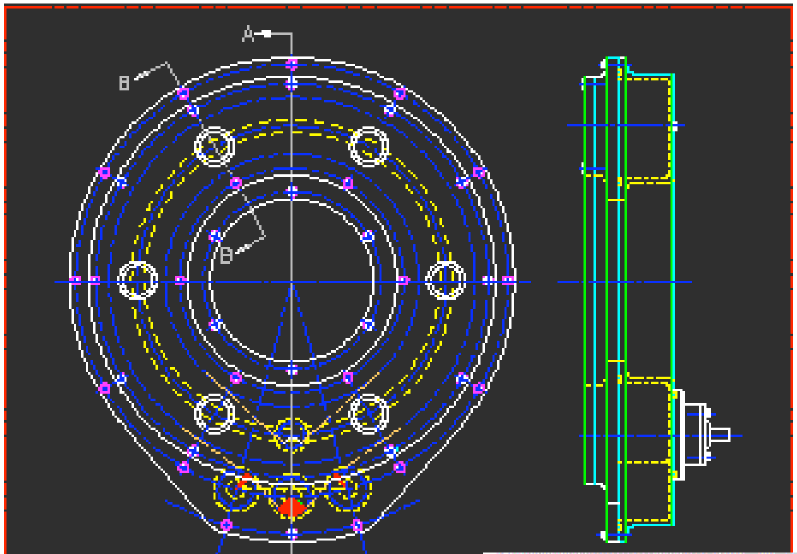


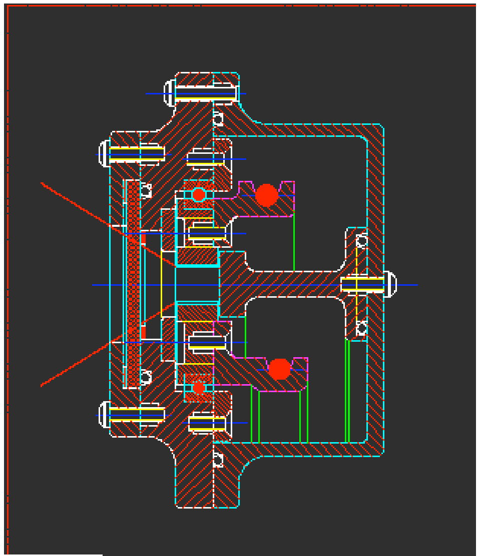


Space Program at Glenn Research Center

IFPRI

International Fine Particle Research Institute





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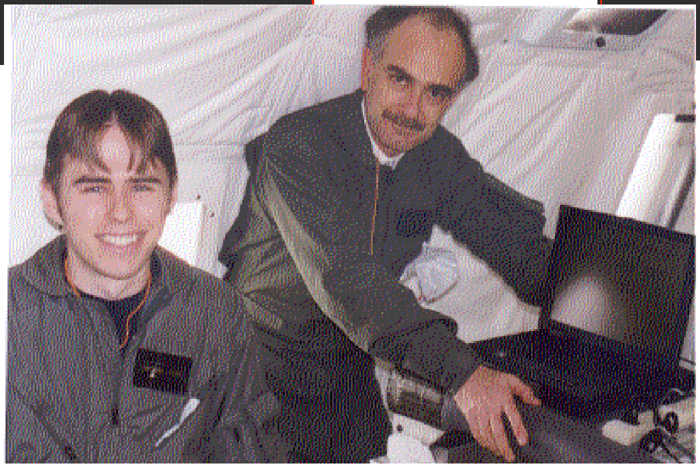


NASA

Rotating Reverse Osmosis for Wastewater Reuse

Richard M. Lueptow[*], Yeomin Yoon, Cynthia Pederson

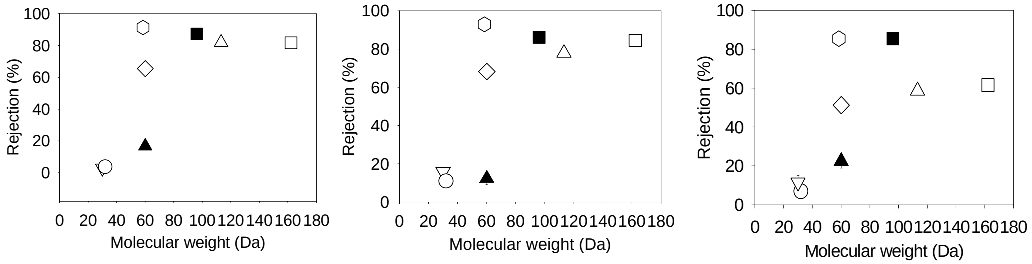
Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road,
Evanston, IL, 60208, USA

*Email: r-lueptow@northwestern.edu, Telephone: 1-847-491-4265, Fax: 1-847-491-3915

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).



(a) RO (b) LPRO (c) NF

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 $(NH_4)_2CO_3$, 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.

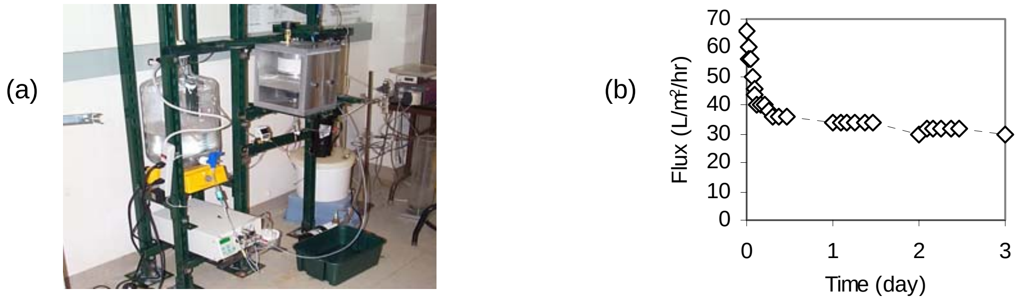


Figure 2. (a) Photograph of second generation rotating reverse osmosis filter and fluid circuit and (b) Flux as a function of time for a 3 day experiment. Operating conditions: LPRO (ESPA); ΔP=500 psi; rotation rate=90 rpm; recovery=75 to 90 %; wastewater composed of NaCl (1,000 mg/L), $(NH_4)_2CO_3$ (3,429 mg/L), and detergent (2,000 mg/L).

Funded by NASA.

NASA/CP—2004-213205/VOL1

NASA-NCMR 2004

Rotating Reverse Osmosis for Wastewater Reuse

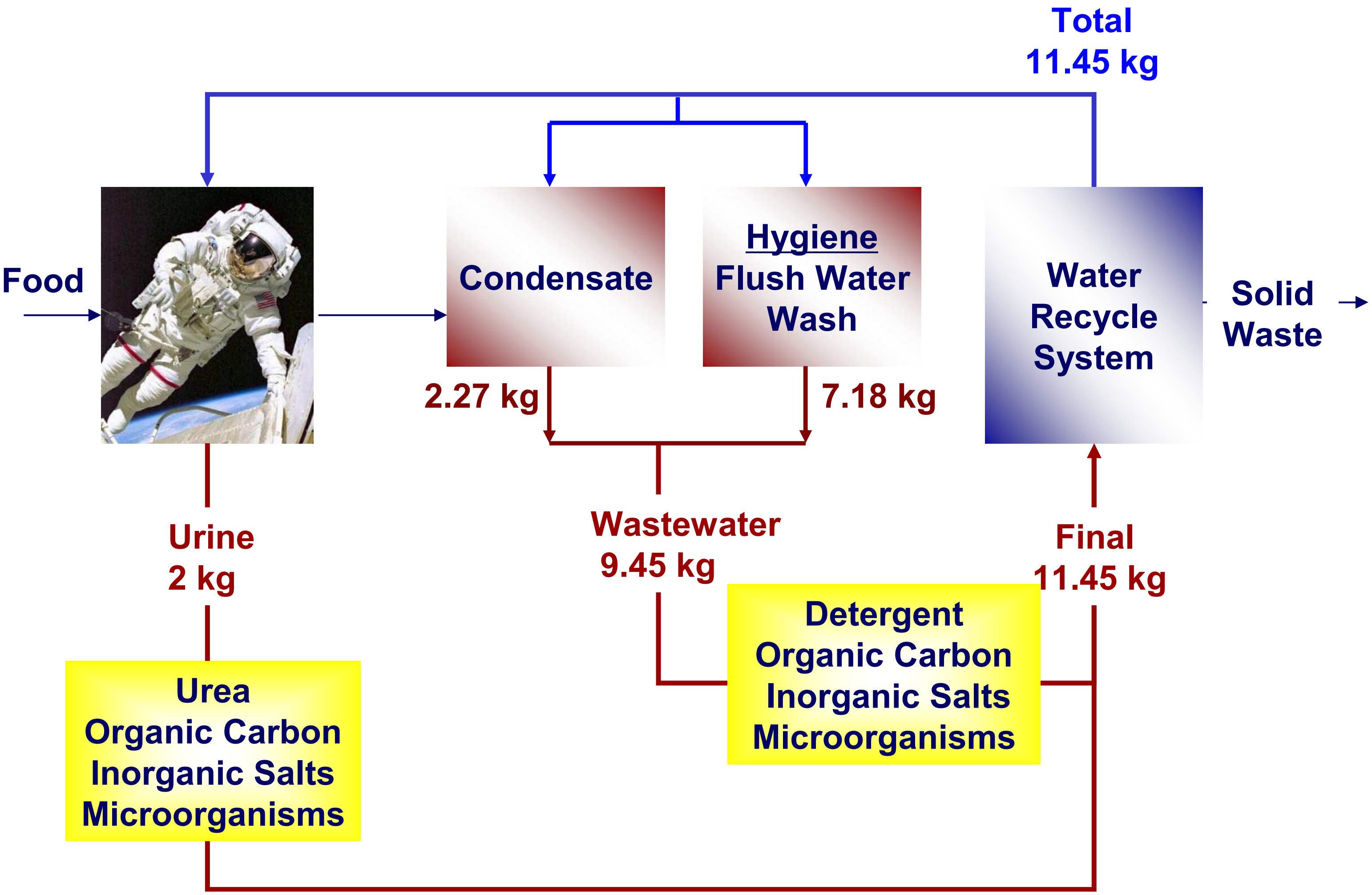
(http://quest.arc.nasa.gov/space/)

Northwestern University
Mechanical Engineering
Richard M. Lueptow

Contributors:
Sangho Lee
Richard Neal
Cynthia Pederson
Yeomin Yoon

Funded by NASA

Laboratory for Applied Fluid Dynamics
Filtration Team



Total
11.45 kg

Food

Condensate

Hygiene
Flush Water
Wash

Water
Recycle
System

Solid
Waste

2.27 kg

7.18 kg

Urine
2 kg

Wastewater
9.45 kg

Final
11.45 kg

Urea
Organic Carbon
Inorganic Salts
Microorganisms

Detergent
Organic Carbon
Inorganic Salts
Microorganisms

Total Water Requirement for Several Human Space Missions

ID	Crew Size	Transit Duration, Days	Surface Stay Duration, Days	Total Number of Duration Days	Water Requirement per Person (kg)	**Total Water Requirements (kg)**
Lunar Human-Mission	3	7	1	8	233	**698**
Space Station	3	171	0	171	4,976	**14,928**
Mars Short Visit	4	1,100	7	1,107	32,214	**128,854**
Mars Long-Term Mission	6	1,100	90	1,190	34,629	**207,774**
Evolutionary Space Station	10	3,650	0	3,650	106,215	**1,062,150**

Removal of Molecules and Ions by Reverse Osmosis

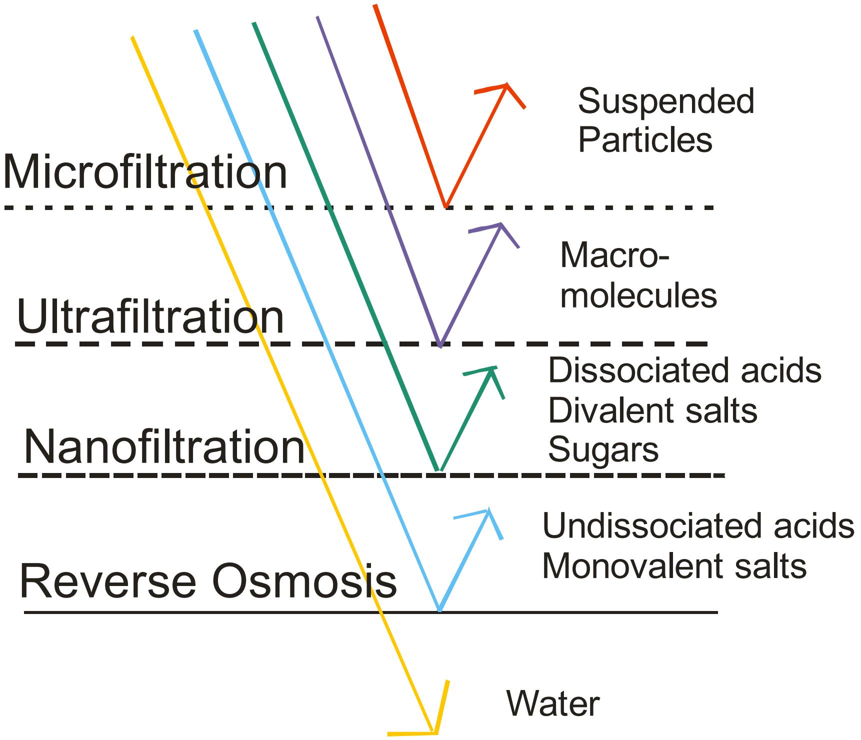
Compact

Easy to control

Small energy consumption compared to evaporation (and fewer contaminants)

Independent of gravity

Concentration polarization and membrane fouling are issues



Microfiltration

Suspended Particles

Ultrafiltration

Macro-molecules

Nanofiltration

Dissociated acids
Divalent salts
Sugars

Reverse Osmosis

Undissociated acids
Monovalent salts

Water

Key Contaminants

Urine and Flush:

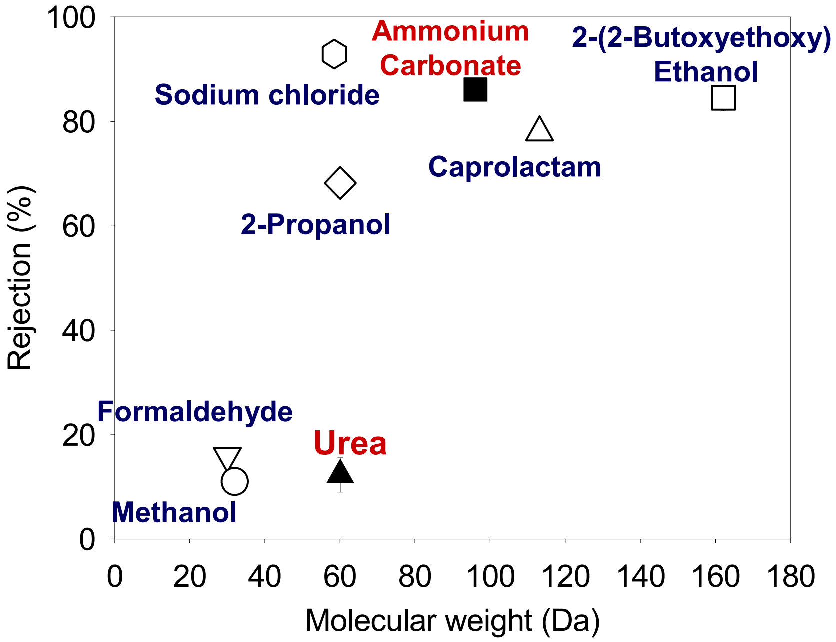
Compound	MW (g/mol)	Radius (nm)
Urea	60.1	0.18
Ammonium carbonate	96.1	Cation: 0.125 Anion: 0.133
Sodium chloride	58.5	Cation: 0.184 Anion: 0.121

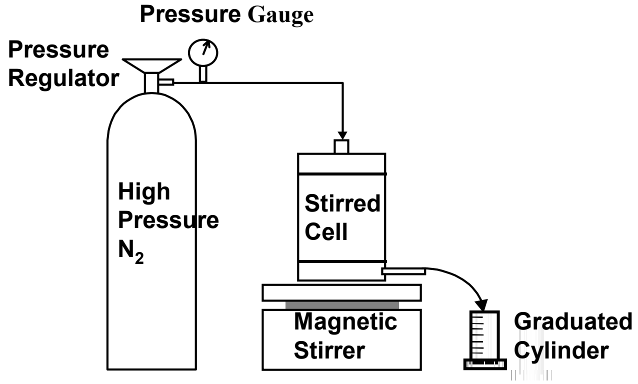
Condensate:

Compound	MW (g/mol)	Radius (nm)
2-(2-Butoxyethoxy) ethanol	162.2	0.32
Caprolactam	113.2	0.28
2-Propanol	60.1	0.26
Formaldehyde	30.0	0.22
Methanol	32.0	0.19

From Stirred-Cell Test

Rejection Test: Organic and Inorganic Contaminants





LPRO (ESPA); C_o=1 mM; ΔP= 800 kPa (116 psi); stirring speed=400 rpm; pH=7; recovery=60 %

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Pore Size Calculation

$$J_v = \frac{r_p^2 \Delta P}{8\mu\left(\Delta x / A_k\right)}$$

Solvent Flux

$$C_p = \frac{C_m K_c \phi}{1 - \exp\left(-\frac{K_c}{K_d}\frac{J_v \Delta x}{A_k}\right)\left(1 - \phi K_c\right)}$$

Solute Conc.

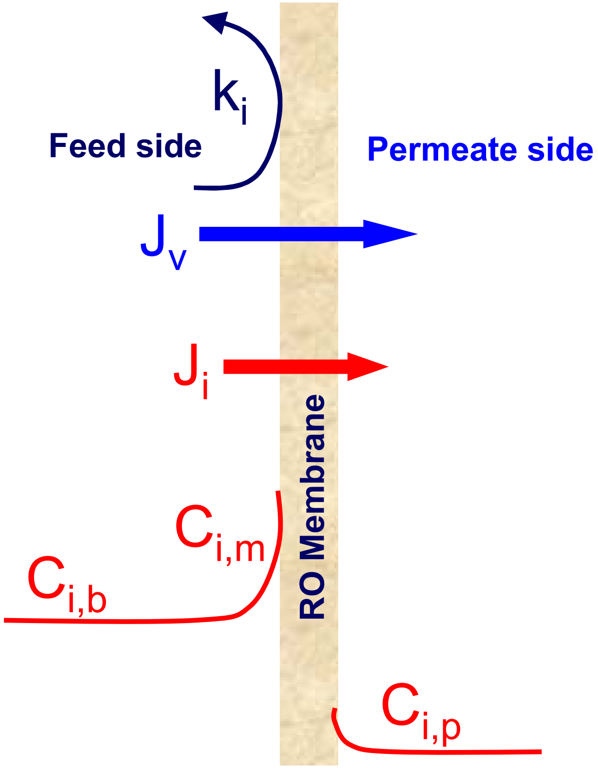
$$\frac{C_{i,m} - C_{i,p}}{C_{i,b} - C_{i,p}} = e^{\frac{J_v}{k_i}}$$

Concentration Polarization

$$K_{i,d} = 1.0 - 2.30\lambda_i + 1.154\lambda_i^{\ 2} + 0.224\lambda_i^{\ 3}$$

$$K_{i,c} = 1.0 + 0.054\lambda_i - 0.988\lambda_i^{\ 2} + 0.441\lambda_i^{\ 3}$$

Steric Factors



Key Parameters Measured:
J_i; J_v; $C_{i,p}$; $C_{i,b}$; ΔP

Key Parameters Calculated:
$C_{i,m}$;k_i

(Lee and Lueptow, 2001 ES&T)

Pore Size Calculation

$$J_v = \frac{r_p^2 \Delta P}{8\mu\left(\Delta x / A_k\right)}$$

Solvent Flux

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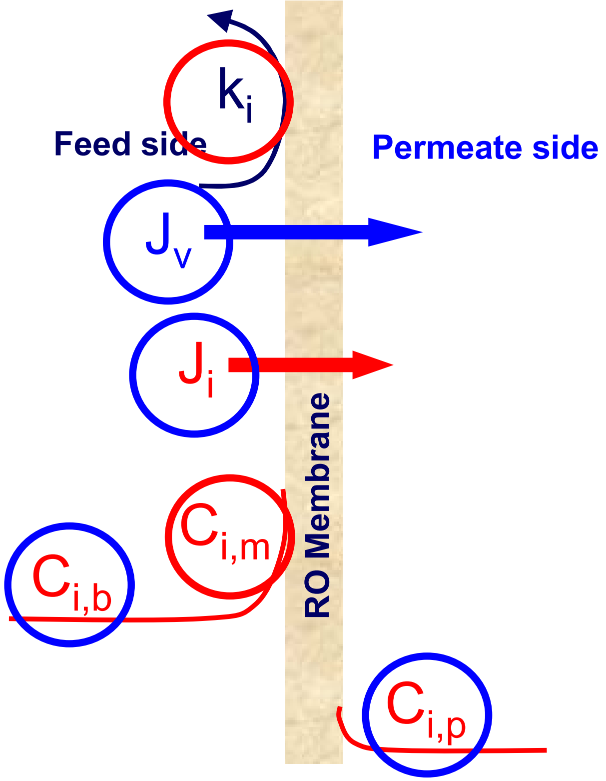
Steric Factors



Key Parameters Measured:
J_i; J_v; $C_{i,p}$; $C_{i,b}$; ΔP

Key Parameters Calculated:
$C_{i,m}$;k_i

(Lee and Lueptow, 2001 ES&T)

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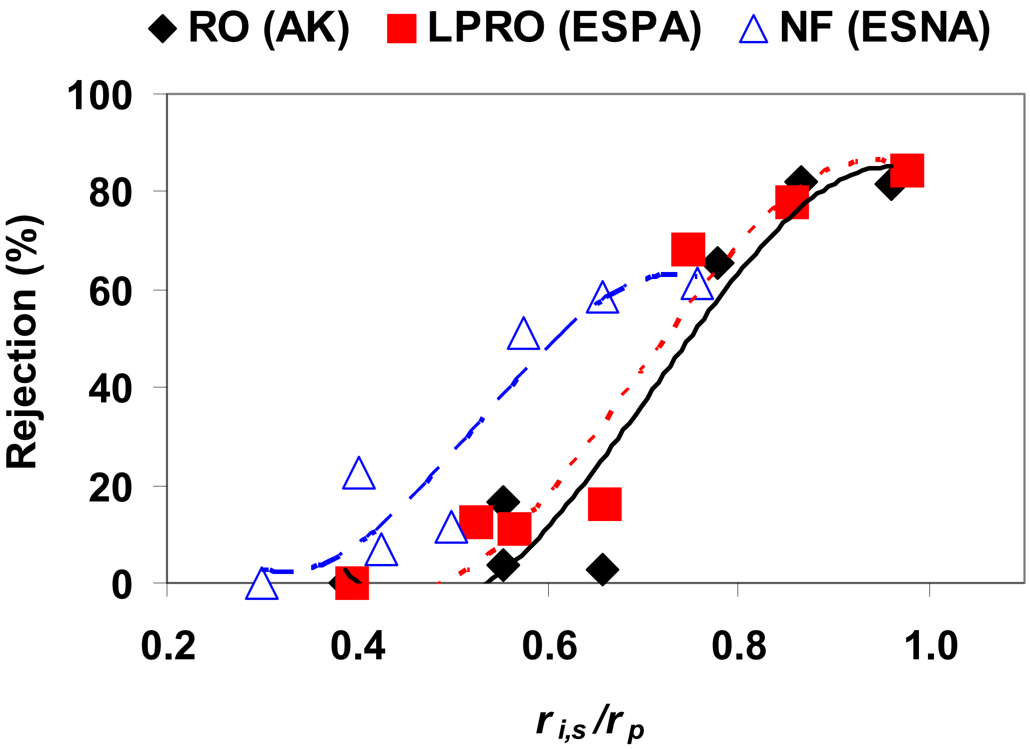
From Stirred-Cell Test

Membrane Properties Obtained from Experiments and Model Calculation

		Effective Membrane Pore Size r_p, (nm)		
Compound	**Molecular Radius (nm)**	**RO (AK)**	**LPRO (ESPA)**	**NF (ESNA)**
2-(2-Butoxyethoxy) Ethanol	**0.32**	**0.333**	**0.327**	**0.423**
Caprolactam	**0.28**	**0.324**	**0.327**	**0.427**
2-Propanol	**0.26**	**0.334**	**0.349**	**0.452**
Formaldehyde	**0.22**	**0.335**	**0.334**	**0.440**
Methanol	**0.19**	**0.344**	**0.336**	**0.448**
Urea	**0.18**	**0.326**	**0.343**	**0.448**
Average		**0.333**	**0.336**	**0.440**

From Stirred-Cell Test

Dependence of Rejection on Solute Radius



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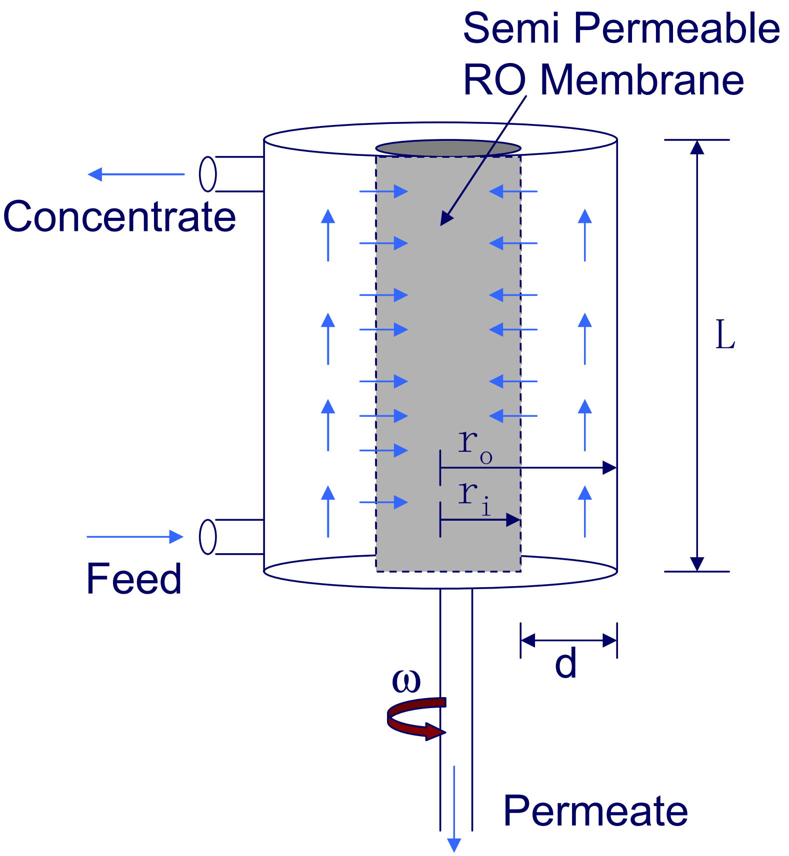
Rotating Reverse Osmosis

Taylor-Couette Flow
+
Reverse Osmosis

Reduces
Concentration Polarization
and Fouling



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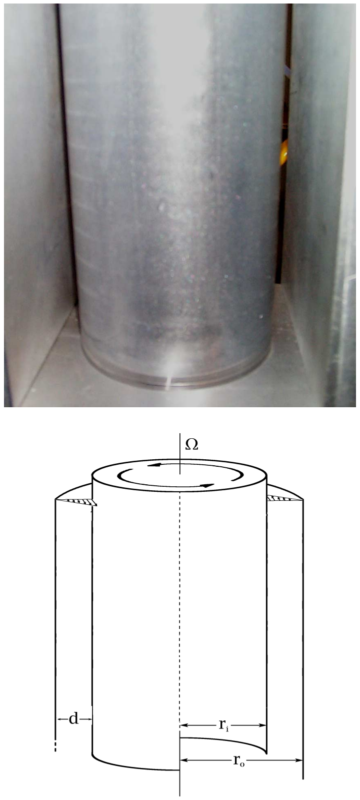
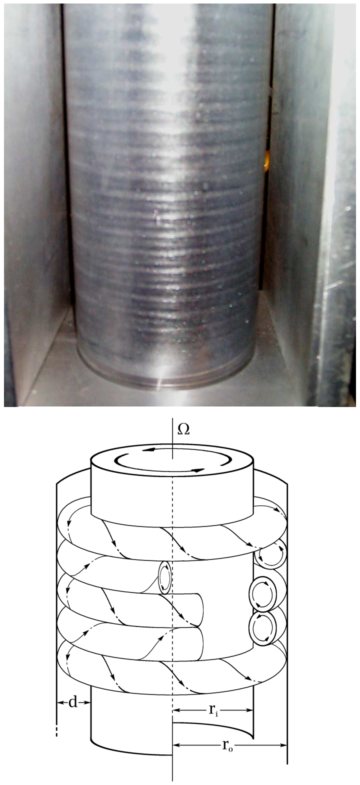
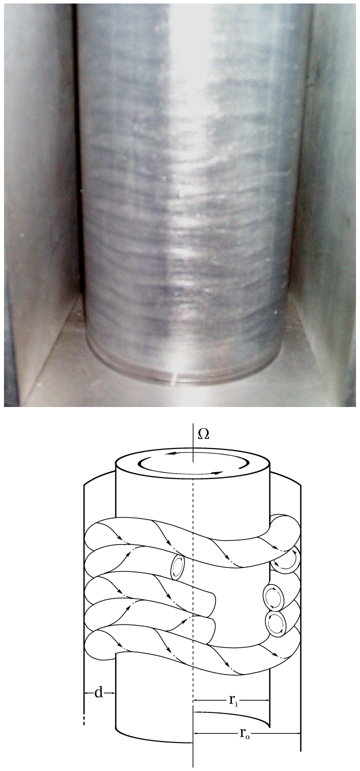
Taylor-Couette Flow

$$Ta = \frac{r_i \Omega d}{\nu}$$

Laminar Couette flow → Taylor vortices → Wavy vortices

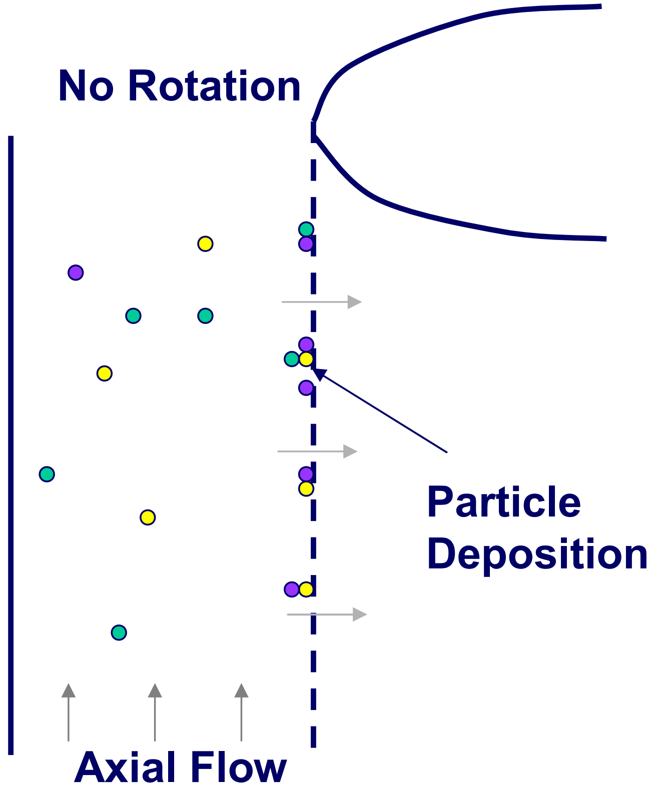






Fouling

Deposition of Particles or Solutes on the Membrane Surface



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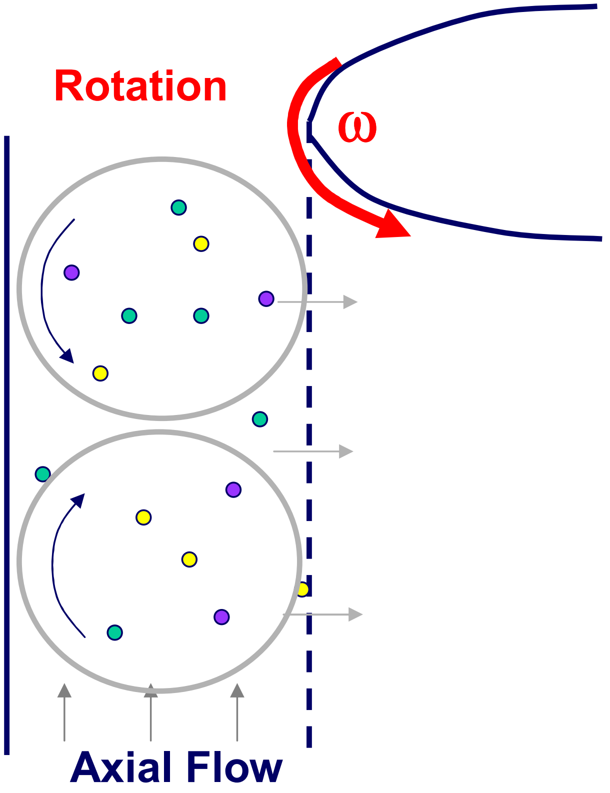
Fouling



Rotation Decreases Fouling

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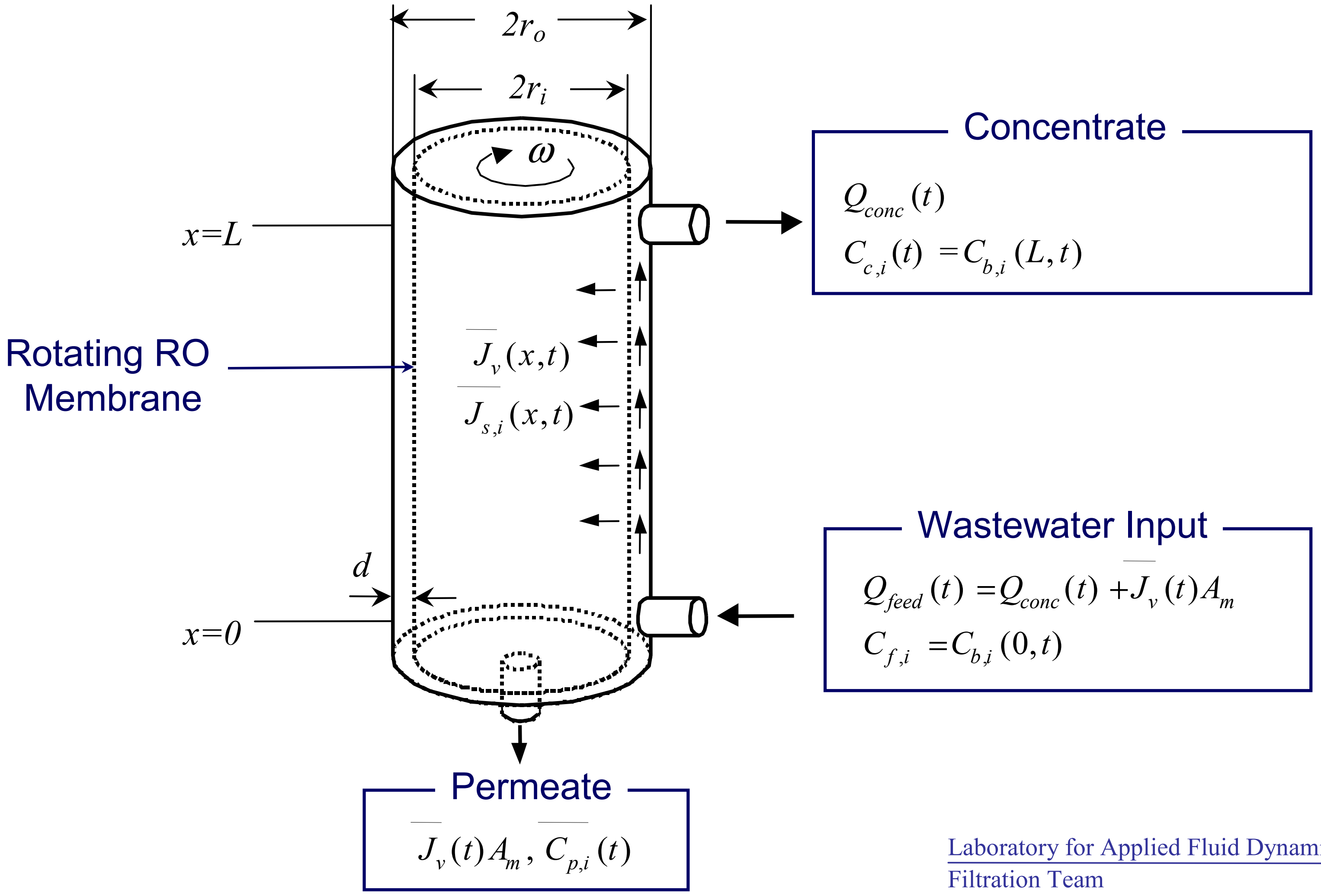
Geometry for Rotating RO



Concentrate

$Q_{conc}(t)$

$C_{c,i}(t) = C_{b,i}(L,t)$

Wastewater Input

$Q_{feed}(t) = Q_{conc}(t) + \overline{J}_v(t) A_m$

$C_{f,i} = C_{b,i}(0,t)$

Permeate

$\overline{J}_v(t) A_m, \overline{C}_{p,i}(t)$

Mass Transfer Model

$$\underbrace{\frac{\partial C_{b,i}(x,t)}{\partial t}}_{\textbf{Unsteady Term}} = -\underbrace{\frac{1}{S_a}\left(Q_{conc}(t)+2\pi r_i\int_x^L J_v(x,t)\,dx\right)\frac{\partial C_{b,i}(x,t)}{\partial x}}_{\textbf{Concentrate Flow}} + \underbrace{\frac{2\pi r_i\cdot J_v(x,t)}{S_a}C_{b,i}(x,t)}_{\textbf{Input Flow}} - \underbrace{\frac{2\pi r_i\cdot J_{s,i}(x,t)}{S_a}}_{\textbf{Permeate Flow}}$$

$$J_v = L_v\left(\Delta P - P_{loss}\right)$$

Water Transport

$$J_{s,i} = J_v C_{p,i} = L_{s,i}(C_{m,i} - C_{p,i})$$

Solute Transport

Solution-Diffusion Model

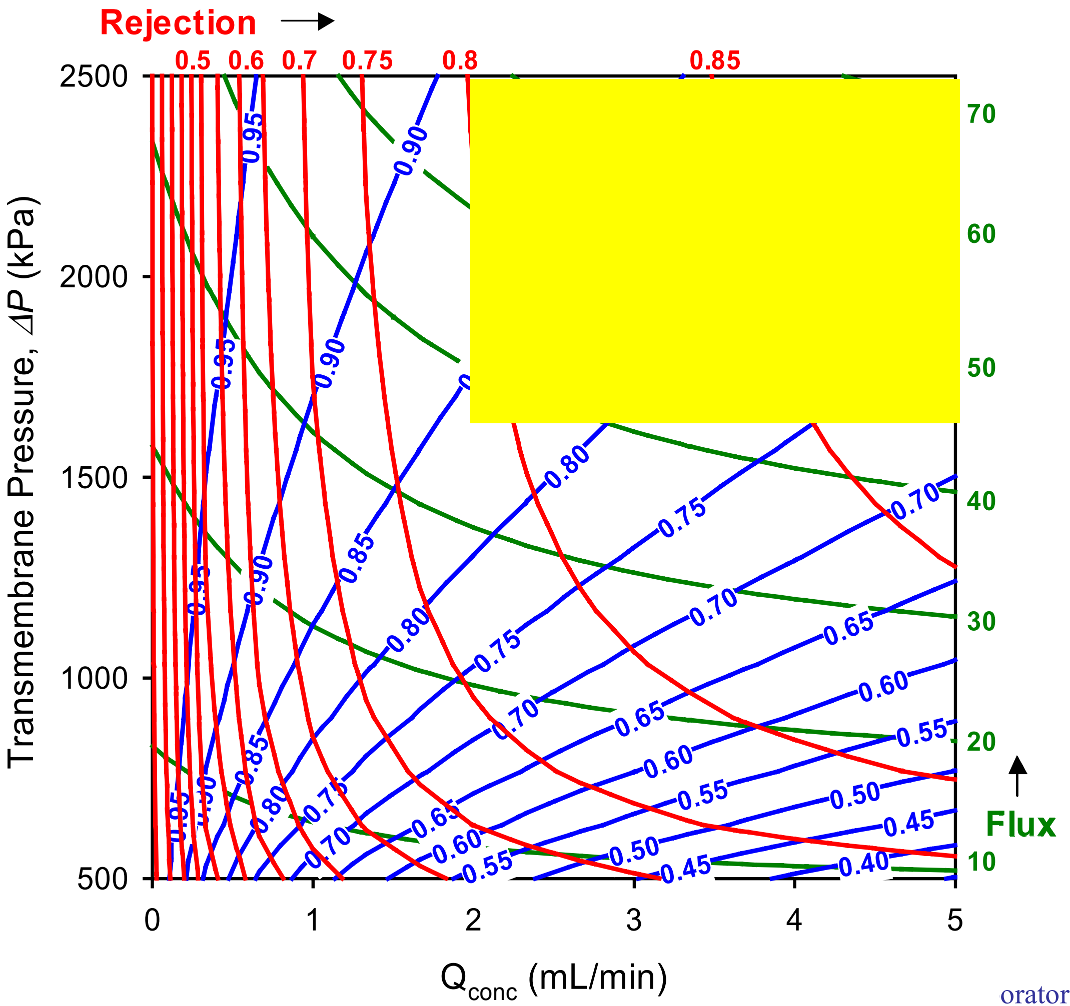
$$\frac{C_{m,i} - C_{p,i}}{C_{b,i} - C_{p,i}} = e^{\frac{J_v}{k_i}}$$

Concentration Polarization

$$P_{loss} = \sum_i^n \Delta\Pi_i + \Delta P_{rot} + \Delta P_{axis} + \rho g x$$

Pressure Drop

Modeling Operating Conditions



> 40 L/m^2-hr Flux

> 80% Rejection

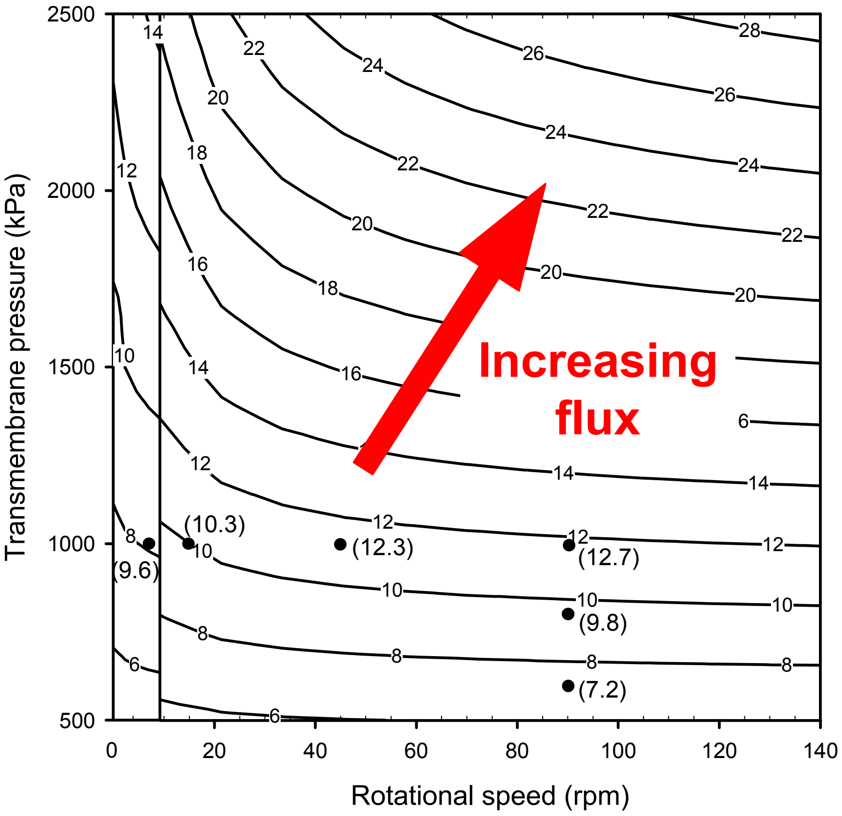
> 80% Recovery

ω = 100 rpm

Increasing the Flux

Curves of Constant Flux
(L/m²/hr)

To Increase Flux:
Increase Pressure



***(Lee and Lueptow, 2001 JMS)**

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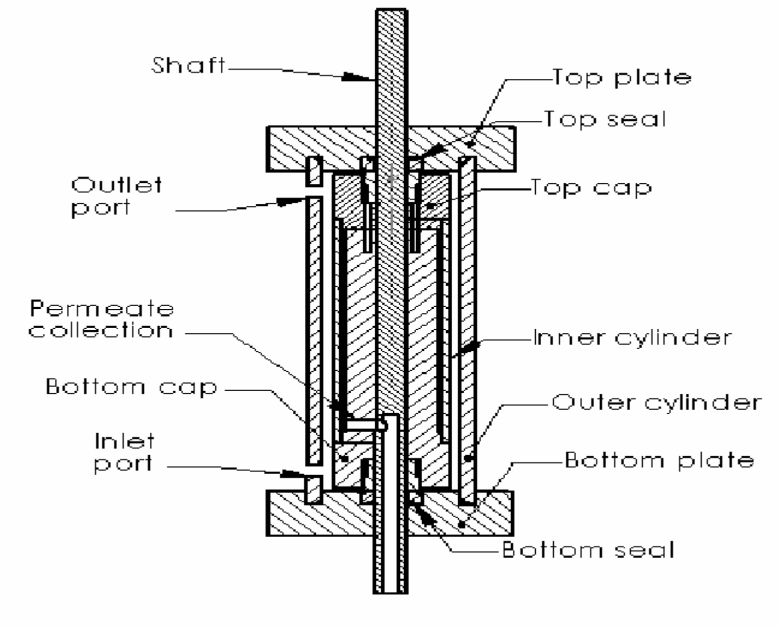
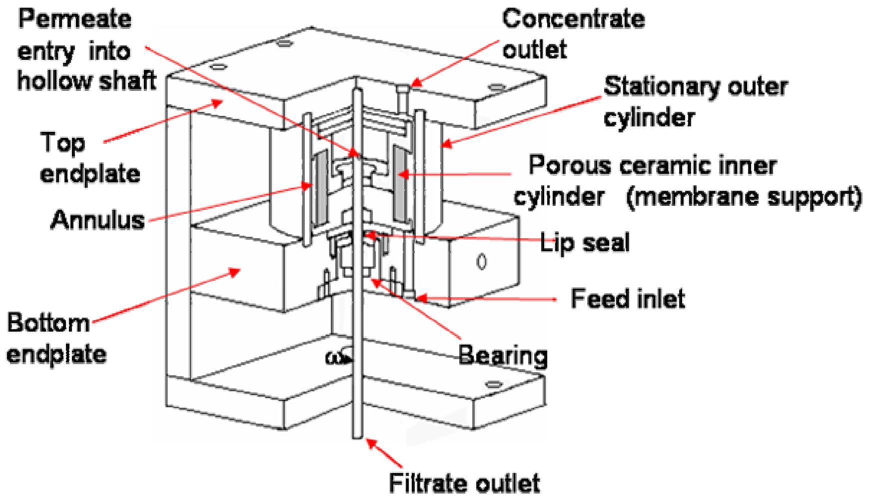
First vs. Second Generation Design

First:
150 psi and 4 to 6 hr tests

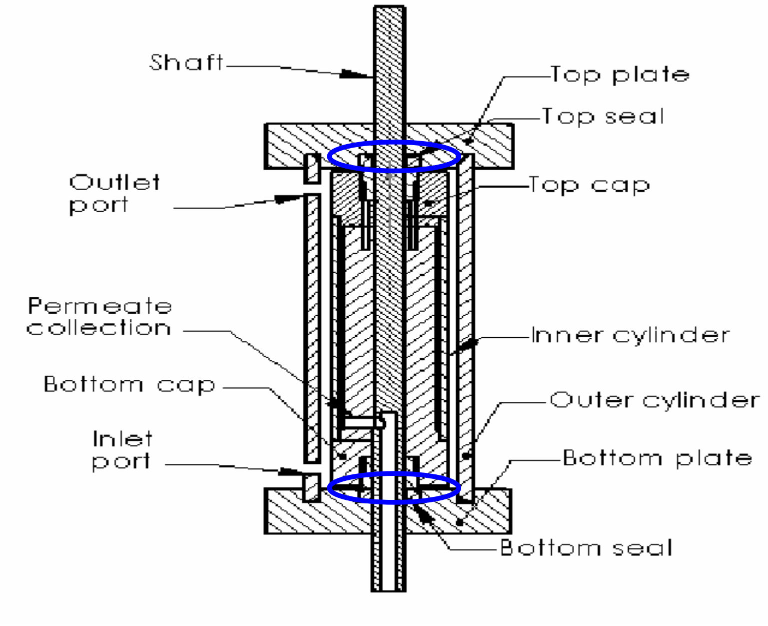


Second:
> 500 psi and 24 hr to 3+ month tests

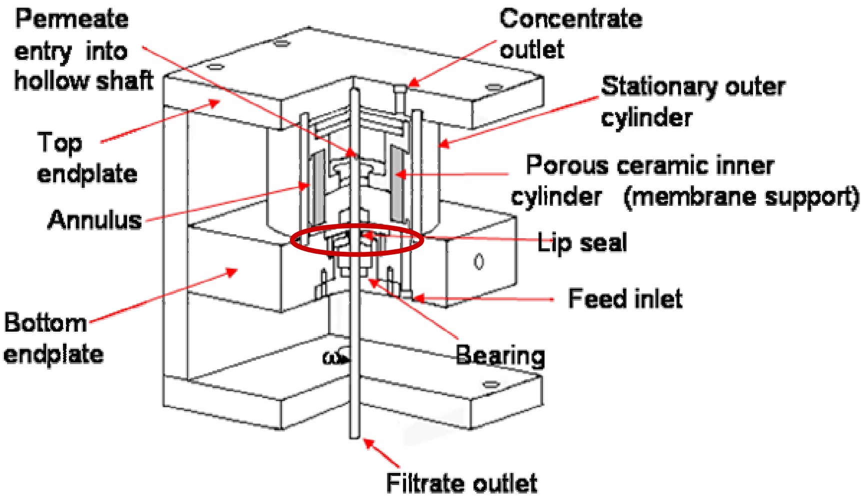


First vs. Second Generation Design

First:
150 psi and 4 to 6 hr tests



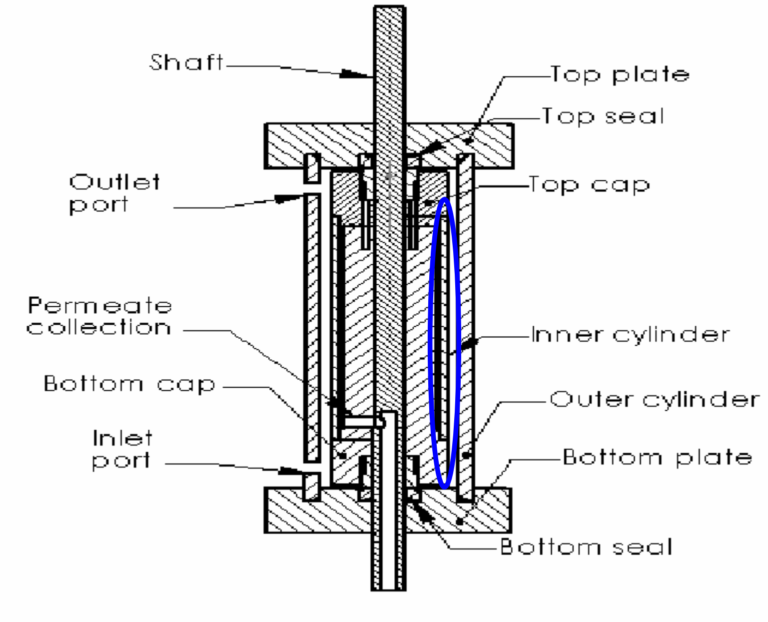
Second:
> 500 psi and 24 hr to 3+ month tests

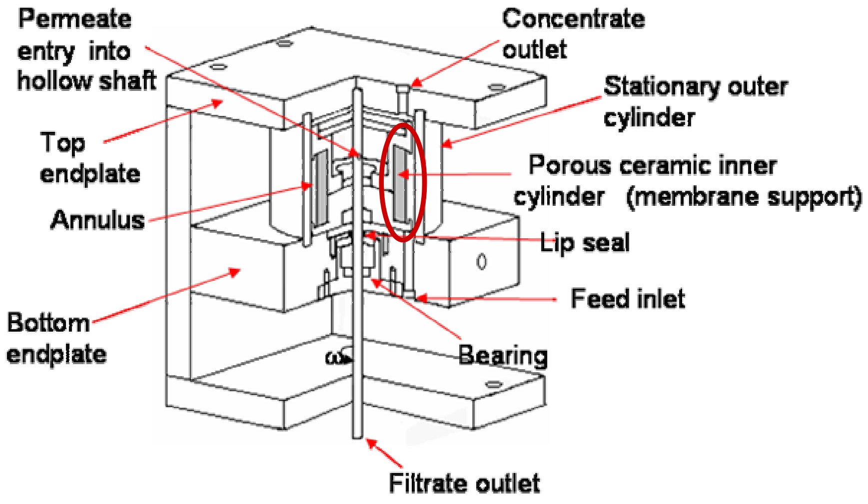


First vs. Second Generation Design

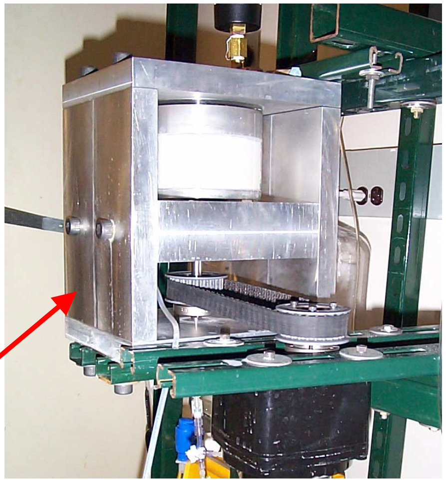
First:
150 psi and 4 to 6 hr tests

Second:
> 500 psi and 24 hr to 3+ month tests

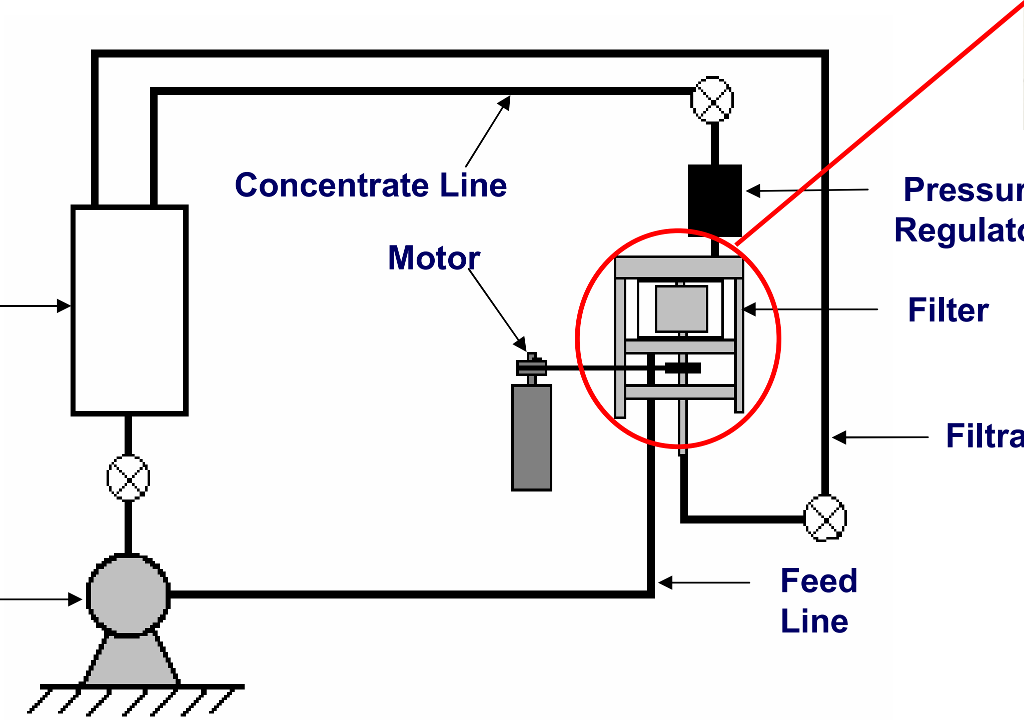




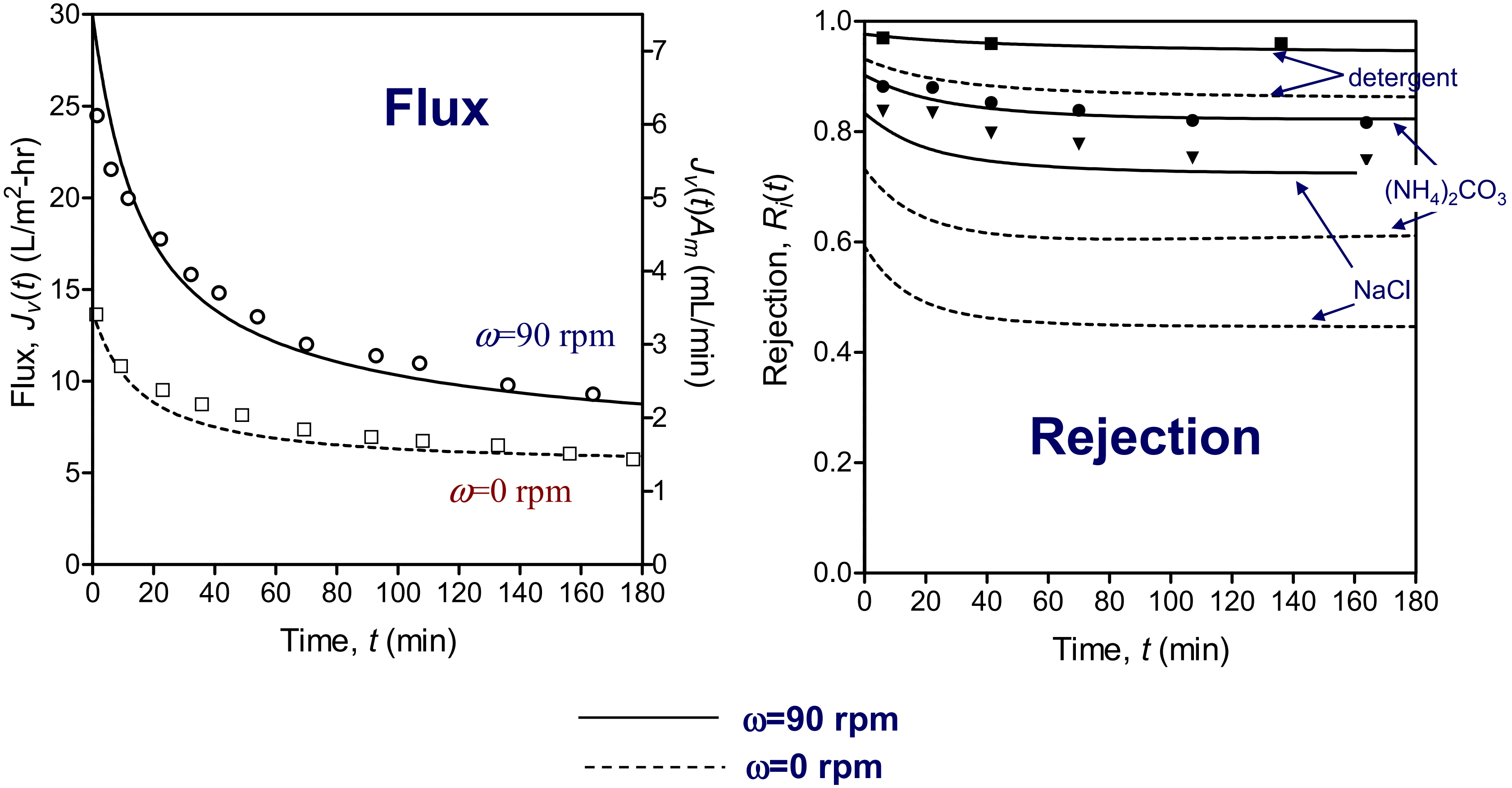
Long Term Testing



Fluid Circuit Diagram



Comparison of Rotating RO with Non-Rotating RO



ΔP= 1000 kPa, Q_{conc}= 0 ml/min

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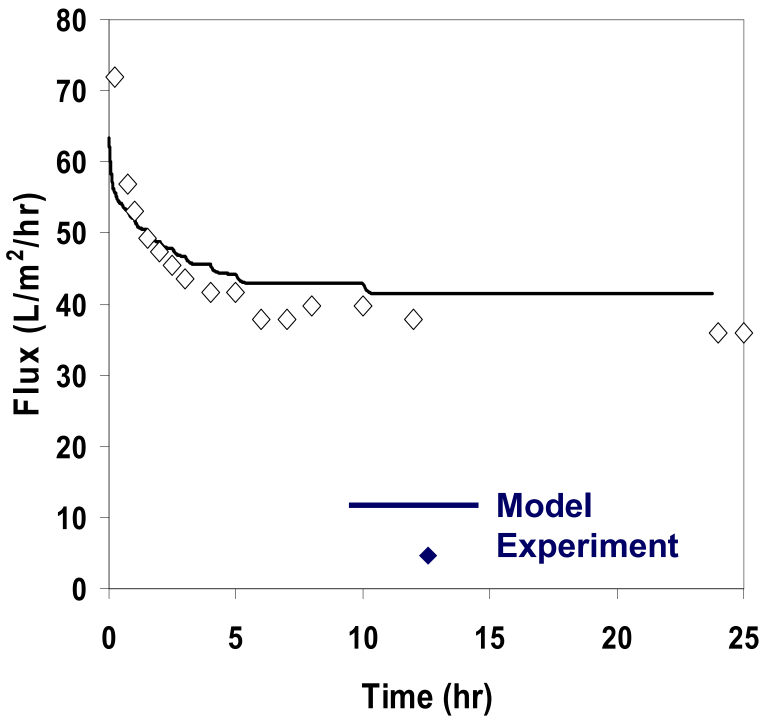
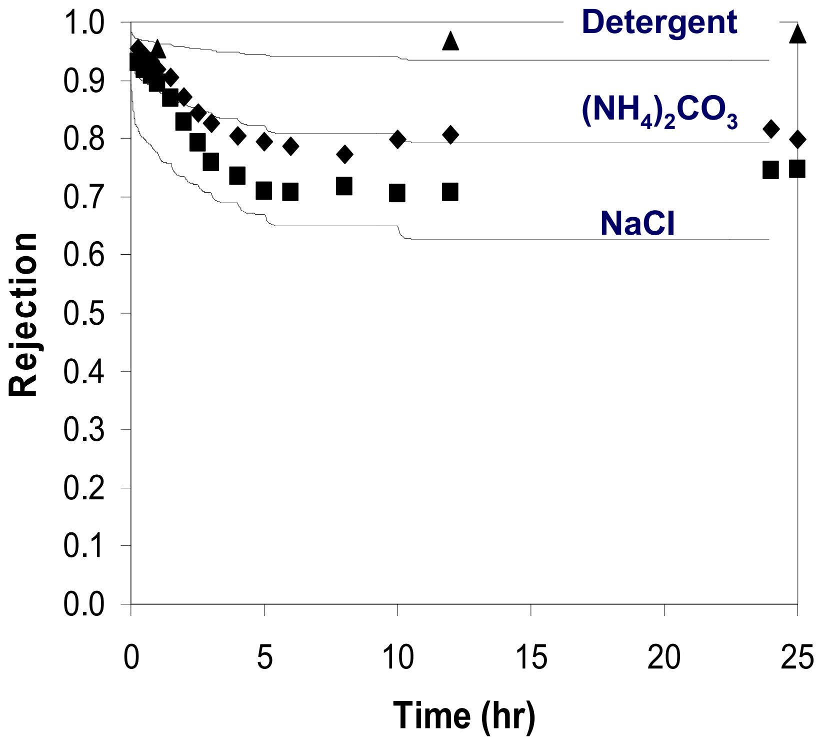
Preliminary Results: 24 Hour Test

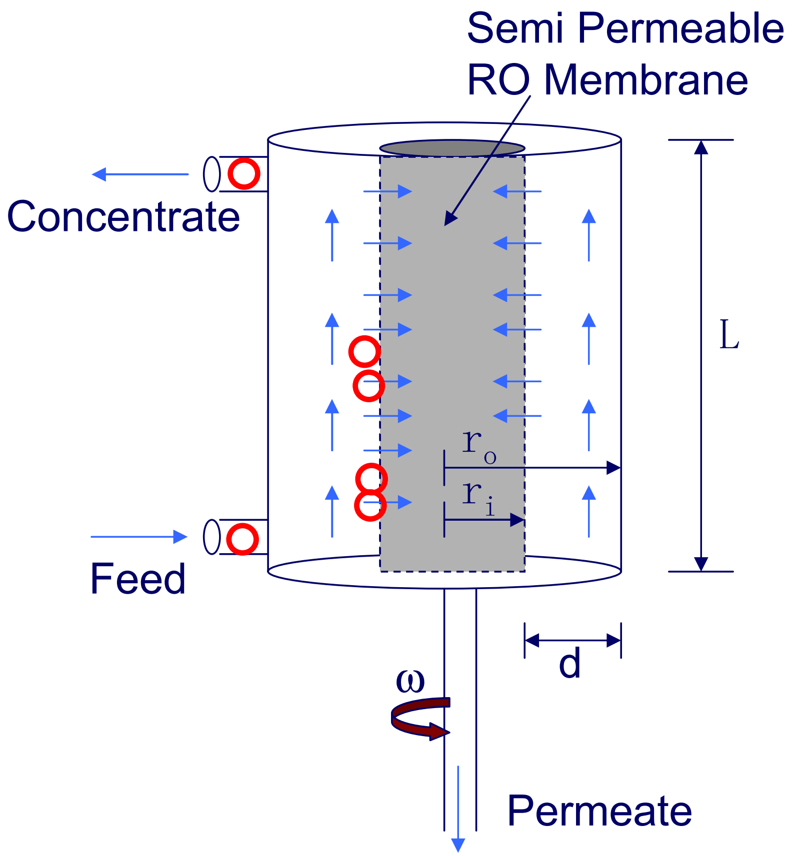




LPRO (ESPA); ΔP= 3450 kPa (500 psi);
rotation speed=90 rpm; recovery=83 %

Microgravity Issue: Bubbles

- Blocking inlet or outlet conduits
- Blocking membrane at inflow regions between vortices



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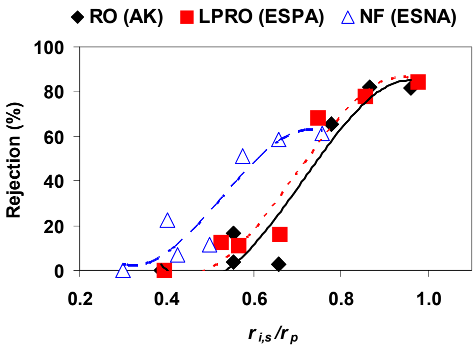
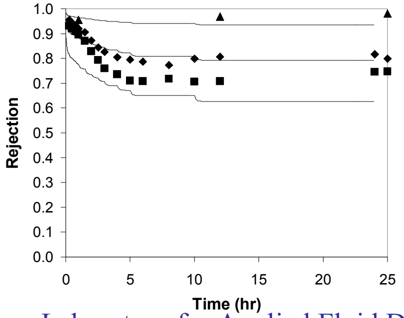
Summary

- 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



$$J_v = L_v(\Delta P - P_{loss})$$

$$J_{s,i} = J_v C_{p,i} = L_{s,i}(C_{m,i} - C_{p,i})$$



NASA-NCMR 2004

Rotating Reverse Osmosis for Wastewater Reuse

(http://quest.arc.nasa.gov/space/)

Northwestern University
Mechanical Engineering
Richard M. Lueptow

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Funded by NASA

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Filtration Team

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

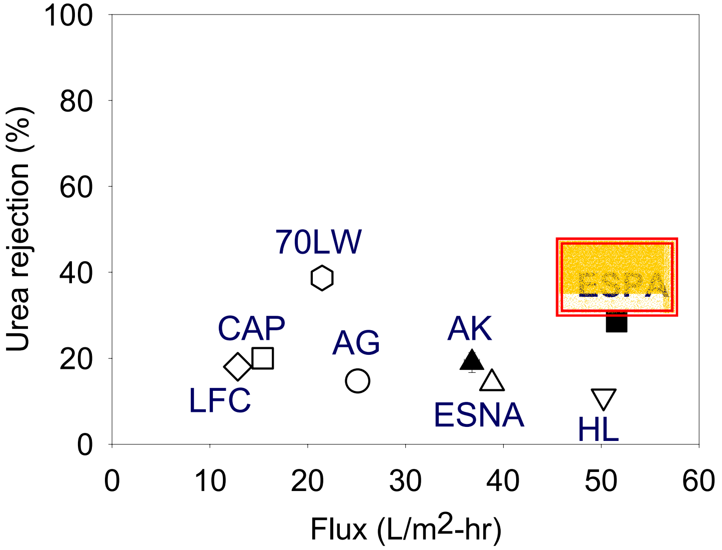
From Stirred-Cell Test

Rejection Test: Urea and Ammonium Carbonate

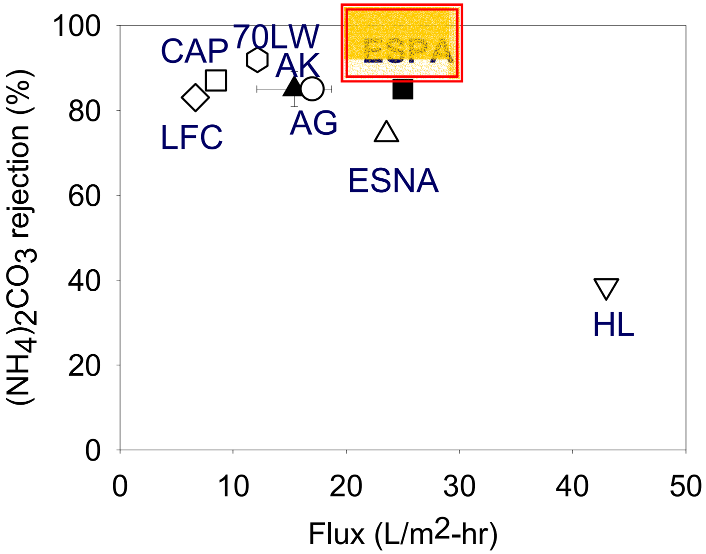
Urea Hydrolysis

$$CO(NH_2)_2 + 3H_2O \xrightarrow{Urease} 2NH_4^+ + HCO_3^- + OH^-$$

Before Urea Hydrolysis



After Urea Hydrolysis



ΔP= 800 kPa (116 psi); stirring speed=400 rpm; pH=7; recovery=60 %; urea=2,000 mg/L, ammonium carbonate=3,429 mg/L

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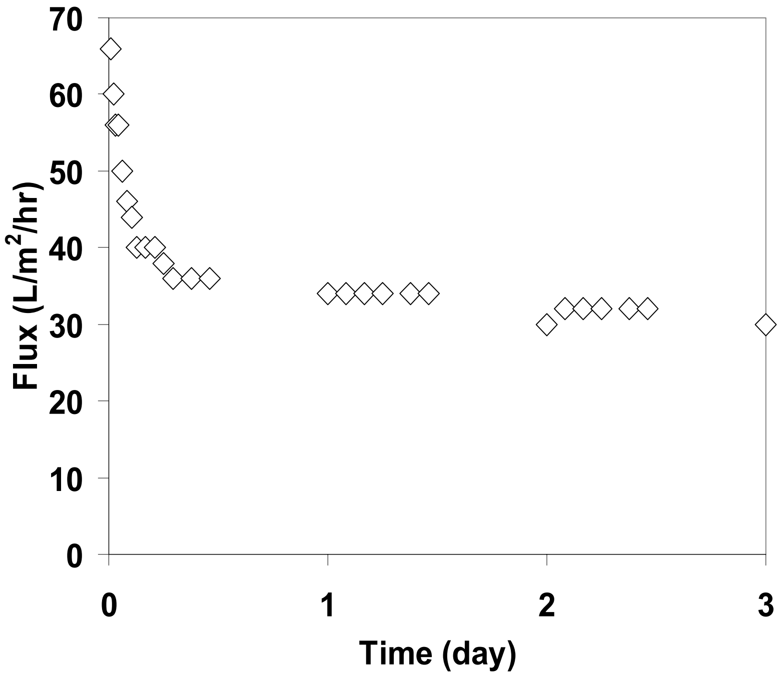
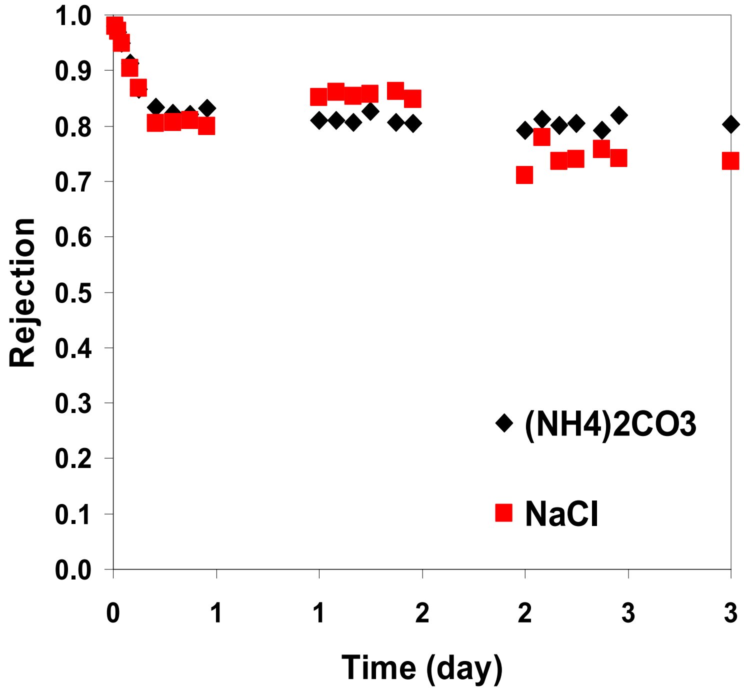
Filtration Team

Preliminary Results: 3 Day Test





LPRO (ESPA); ΔP= 3450 kPa (500 psi);
rotation speed=90 rpm; recovery=75-90 %

Laboratory for Applied Fluid Dynamics
Filtration Team

Gas-Liquid Flows and Phase Separation

by

John McQuillen

Strategic Research to Enable NASA's Exploration Missions

June 22 - 23, 2004
Cleveland, Ohio

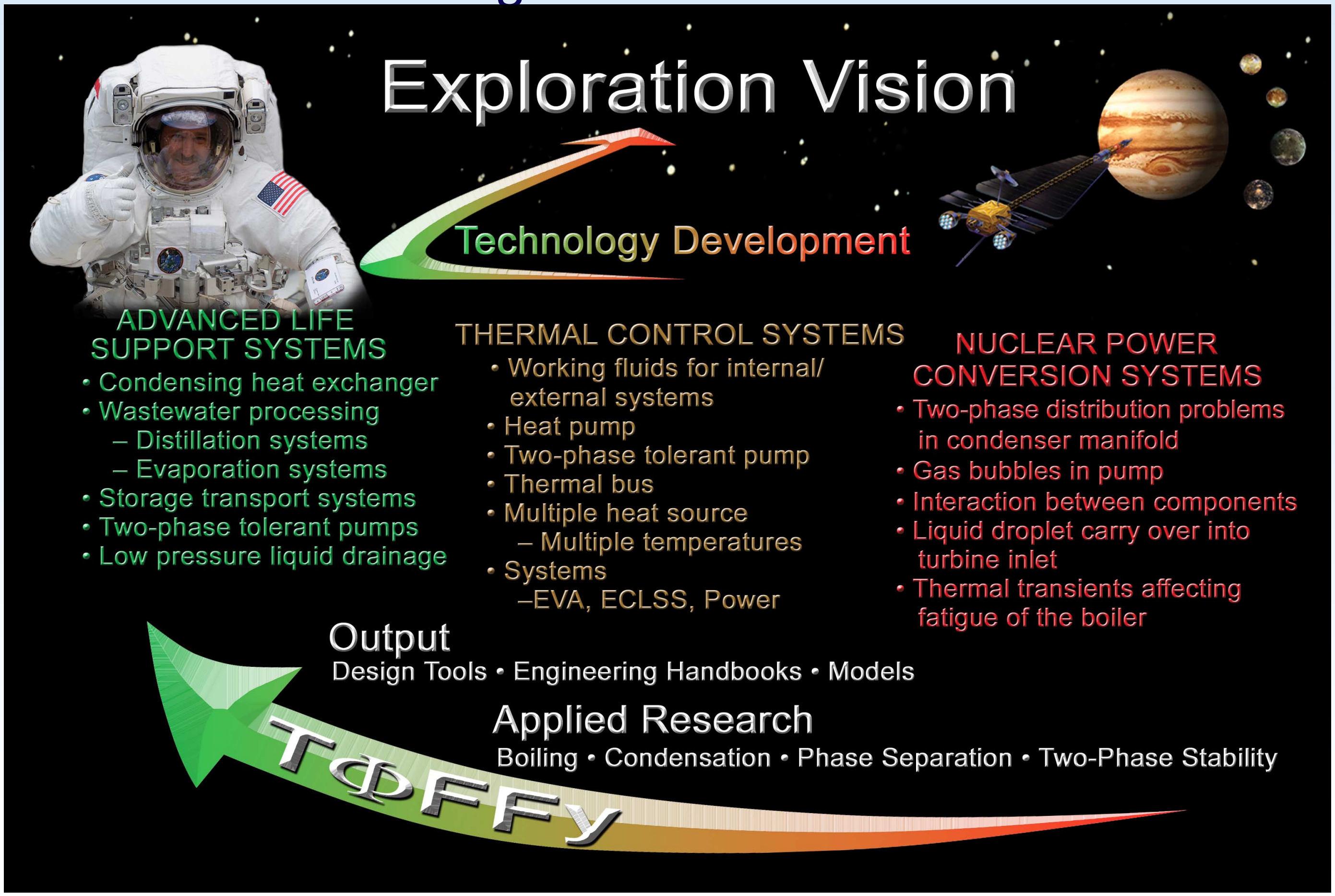
Microgravity Fluid Physics Branch
Glenn Research Center at Lewis Field

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

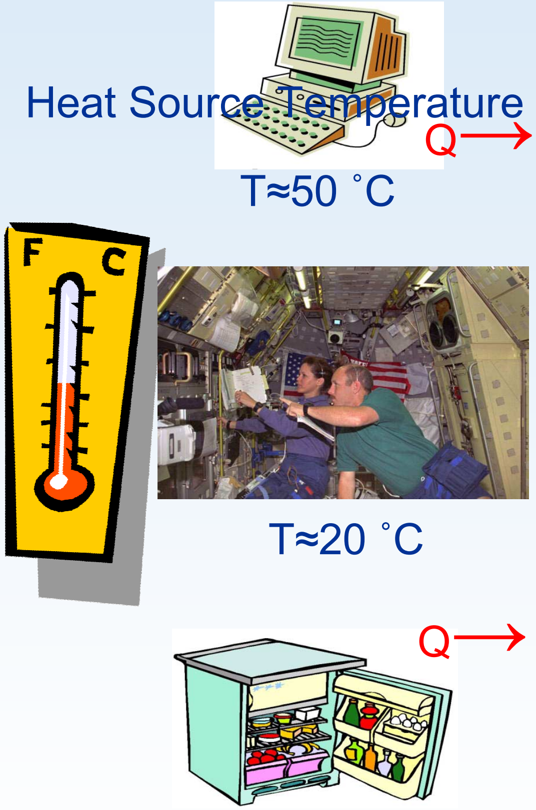
Stream Type	Air Revitalization	Water Reclamation	Thermal Management	Solid Waste Management
Cabin Humidity Condensate	√		√	
Urine		√		
Spills		√		√
Dish Washing		√		
Laundry		√		
Sabatier CO_2 Reaction	√			
Waste Solids Drying				√
Food Processing		√		√

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

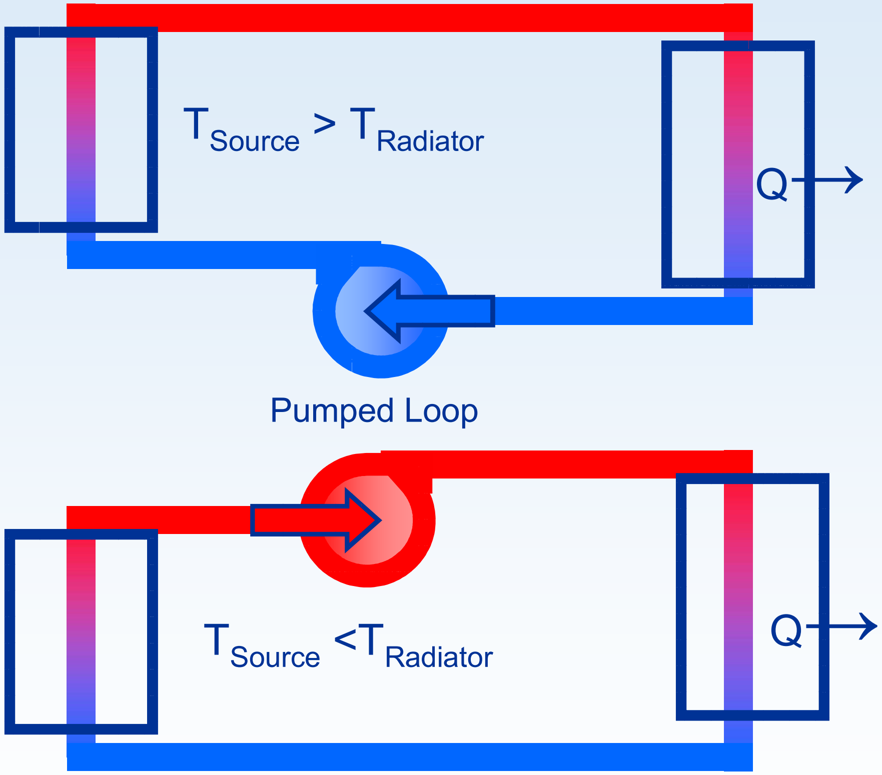
Heat Source Temperature



T≈50 ˚C

T≈20 ˚C

T≈2 ˚C



$T_{Source} > T_{Radiator}$

Pumped Loop

$T_{Source} < T_{Radiator}$

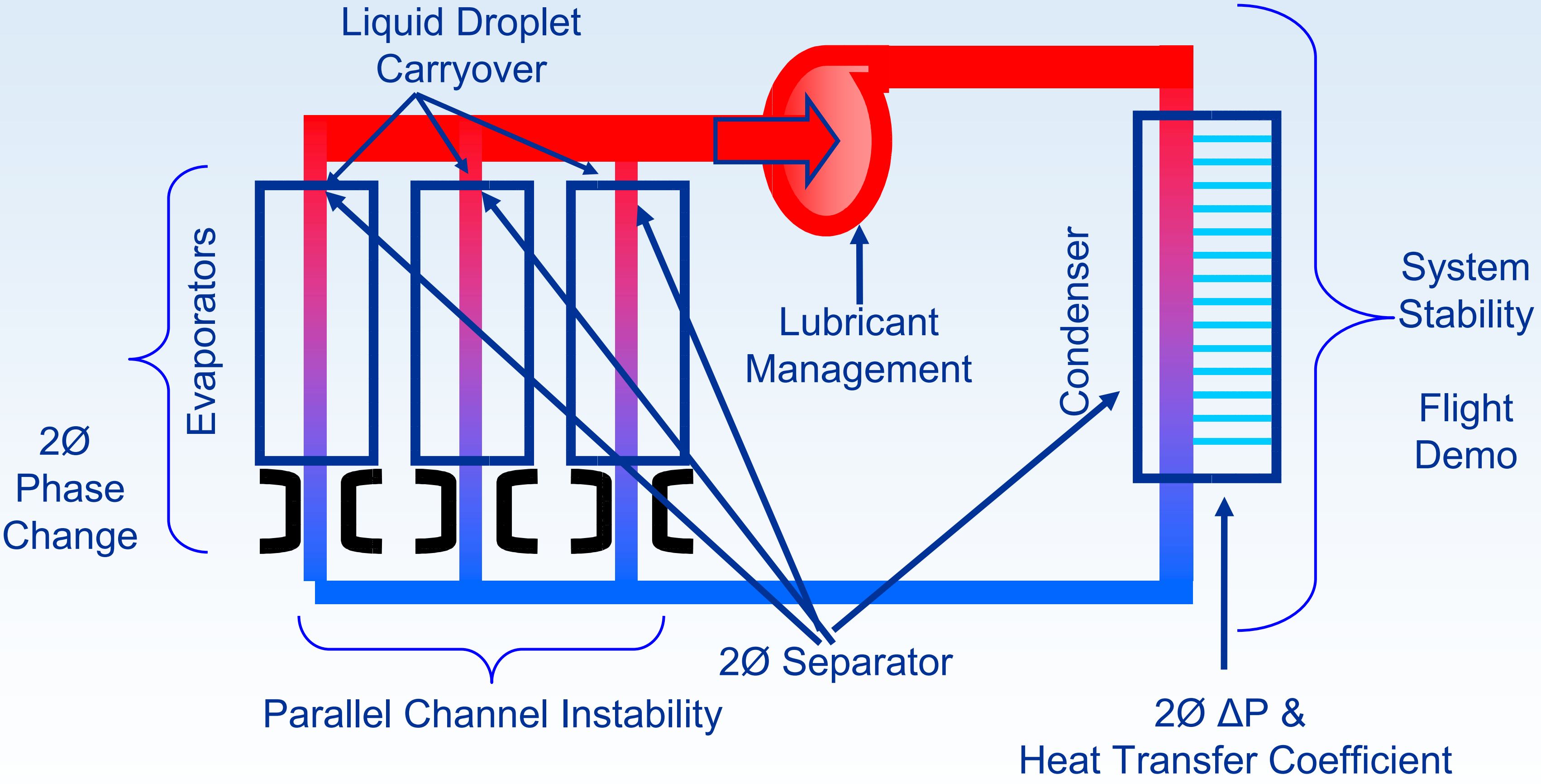
Vapor Compression

Microgravity Fluid Physics Branch

Glenn Research Center at Lewis Field

Vapor Compression Cycle

Two Phase Issues



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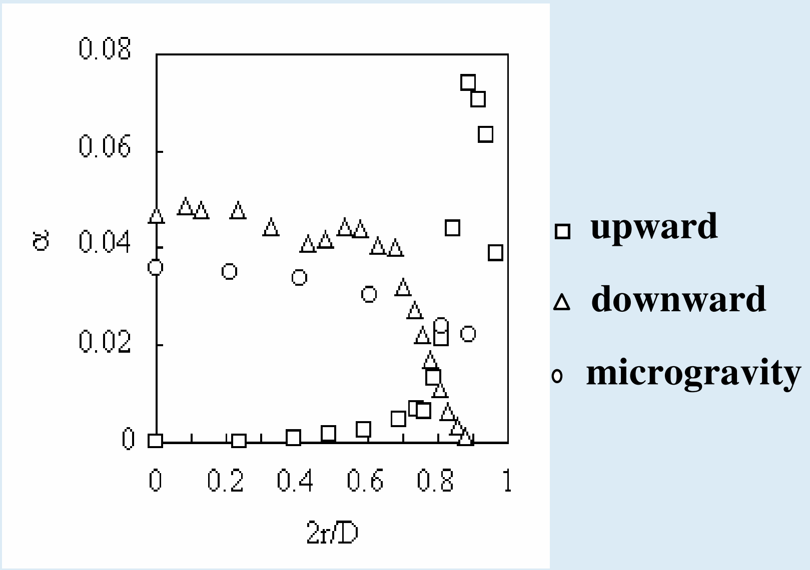
The Effect of Reduced Gravity on Gas-Liquid Flows

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



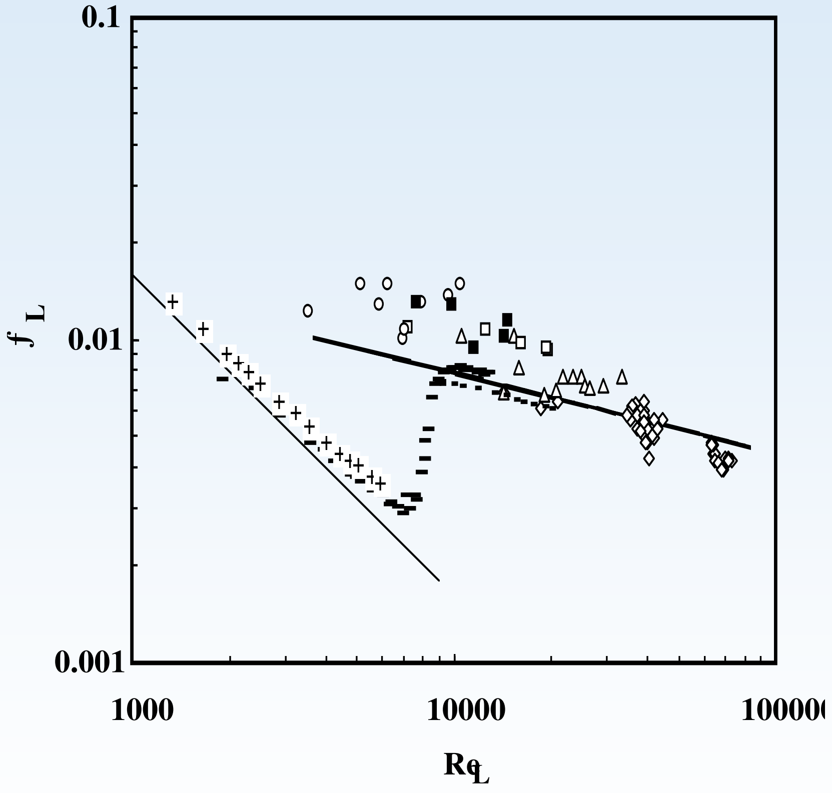
What Do We Know? Flow Regimes

- 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

Click here to play movie

Click here to play movie

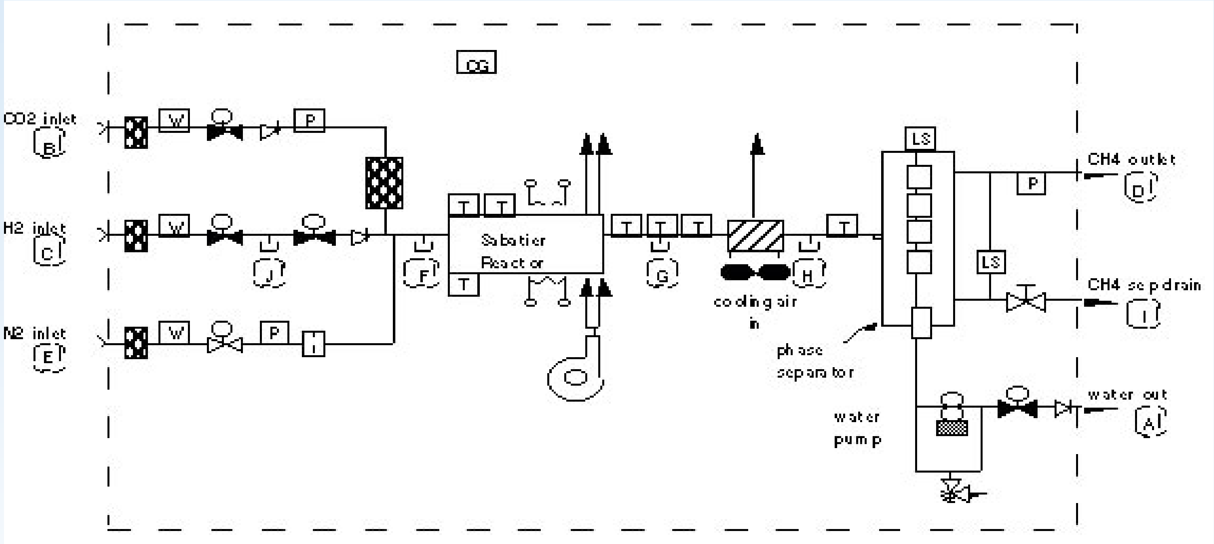
- Liquid Film Rupture and Dryout

Click here to play movie

Click here to play movie

Example: Sabatier Reactor

$CO_2 + 4H_2\ 4 \rightarrow CH_4 + 2(H_2O) + heat$

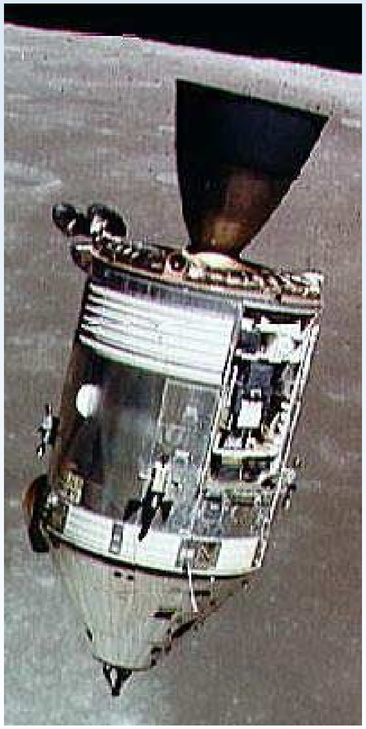


<u>2Ø Issues</u>

- 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 ft^2
- 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

Stream Type	Near Continous or Batch	Inlet Void Fraction
Cabin Humidity Condensate	Continuous	?
Urine	Batch	Low
Dish Washing	Batch	Low- Initially
Laundry	Batch	Low - Initially
Sabatier CO_2 Reaction	Continuous	High
Waste Solids Drying	Continuous	High
Food Processing	Batch	High
Bioreactor	Continuous	Low

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

Click here to play movie

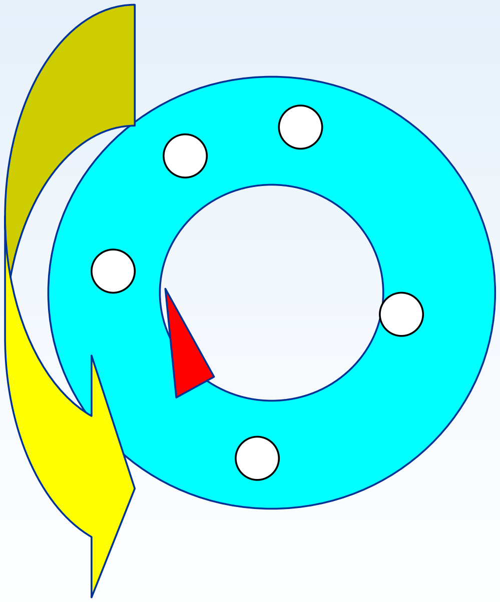
Bubble Flow through Tee

Click here to play movie

Gas Accumulation in Vena Contracta

Passive Separation: Inertial

- Phase Separation achieved due to inertial differences in liquid and gas phase inertia



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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

Click here to play movie

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.

[1] Graf, J., Finger, B., Daues, K., "**Life Support Systems for the Space Environment: Basic Tenets for Designers Rev. A,** " http://advlifesupport.jsc.nasa.gov/documents/lsstenets.doc, 2003.

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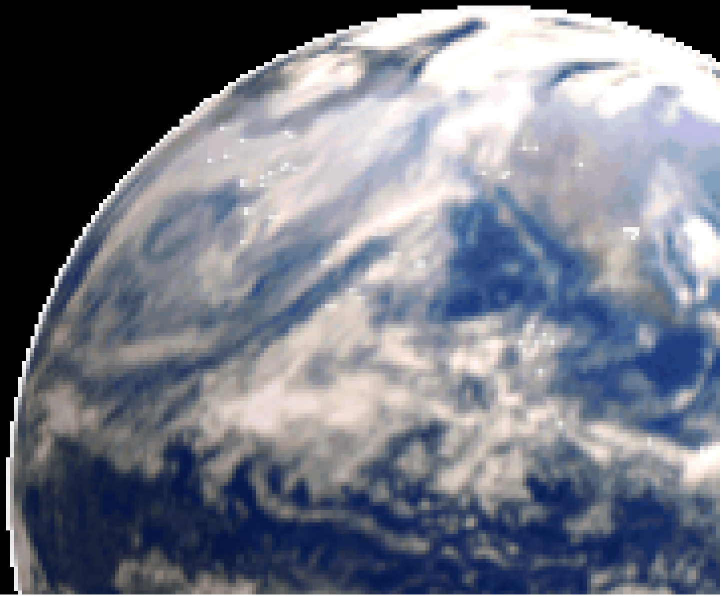
- Lahey, R. T. Jr. and Dhir, V. "Research In Support Of The Use Of Rankine Cycle Energy Conversion Systems For Space Power And Propulsion," NASA SWG Report 2004
- Low Gravity Two Phase Flow Movies

  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



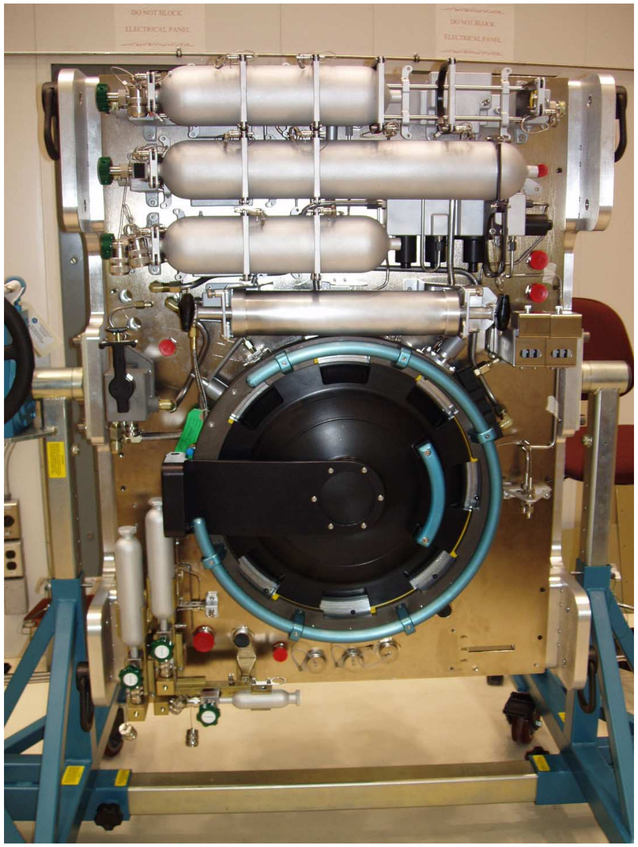
Strategic Research to Enable NASA's Exploration Missions
Cleveland, OH June22-23, 2004

National Aeronautics and
Space Administration
John H. Glenn Research Center

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



Combustion Integrated Rack (CIR)

Background

- A team consisting of 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?

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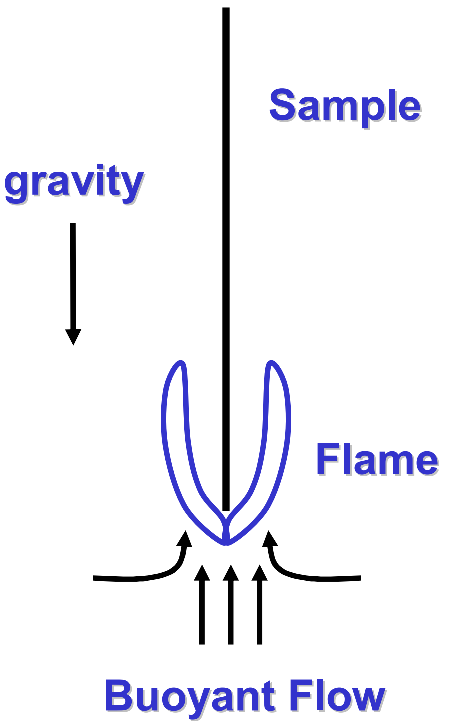
Microgravity Material Flammability Acceptance Criteria

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.**

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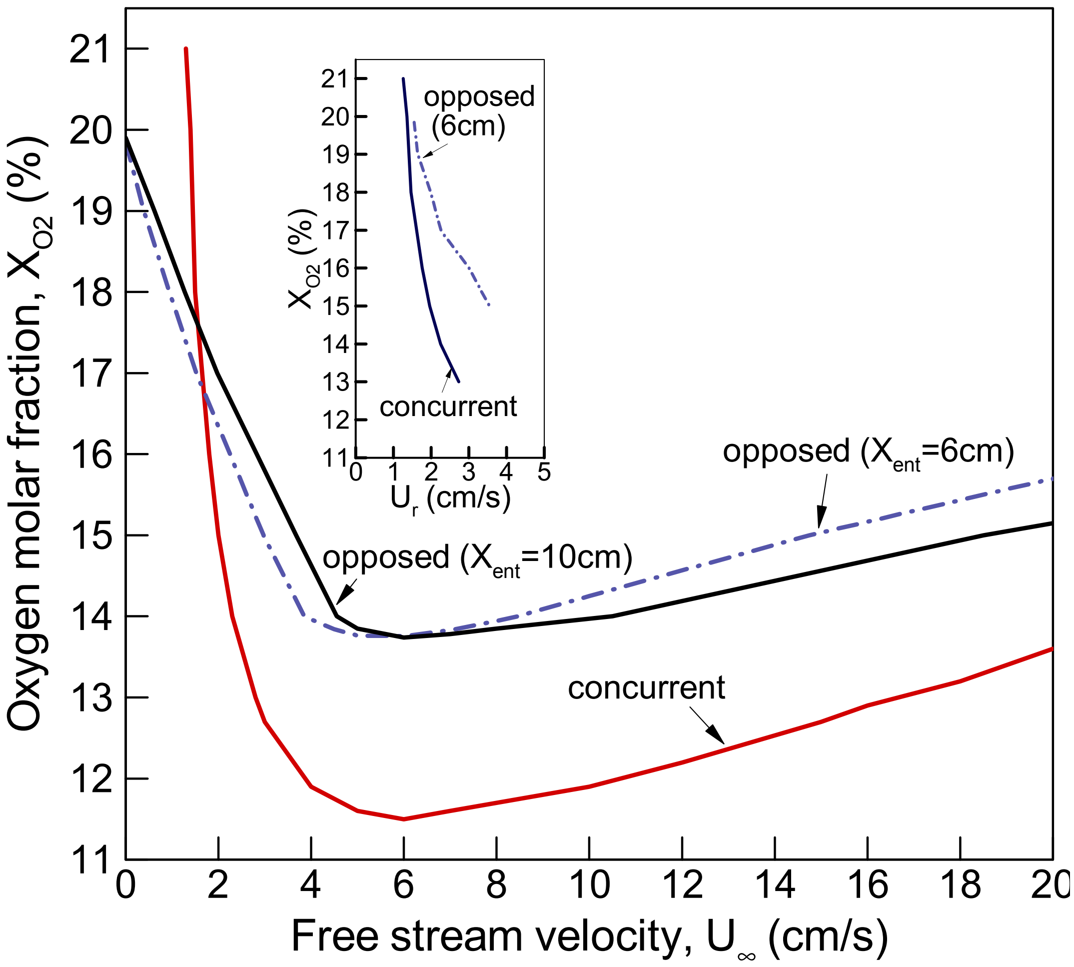
Calculated Concurrent vs. Opposed Extinction Limits

(Kumar, Shih, & T'ien, *Combustion and Flame*, 2003)



Thermally thin solid (paper)

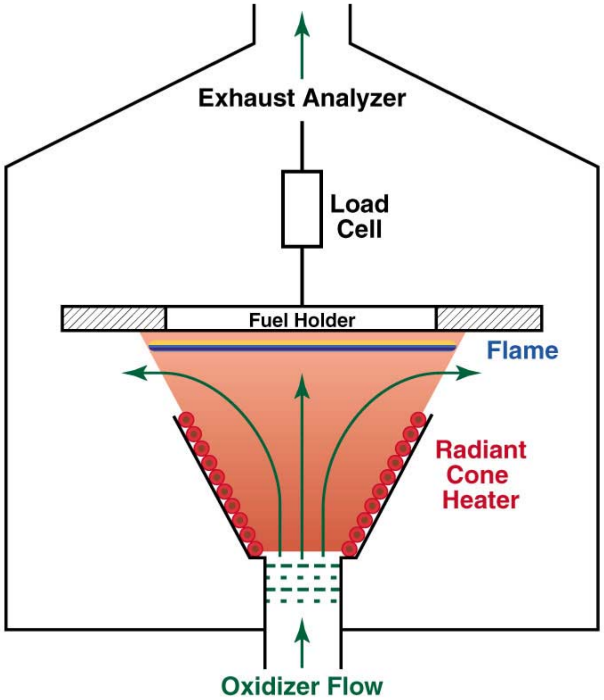
Two-dimensional model with radiation

Two entrance lengths considered for opposed flow

Microgravity Material Flammability Acceptance Criteria

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.

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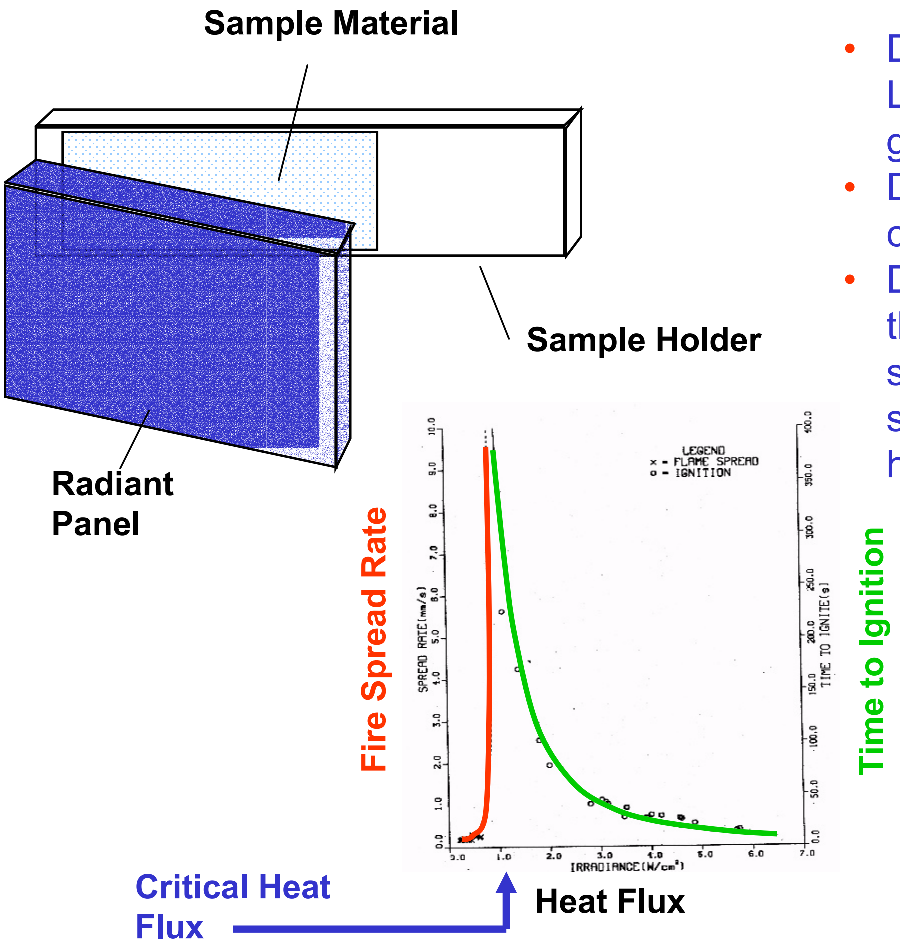
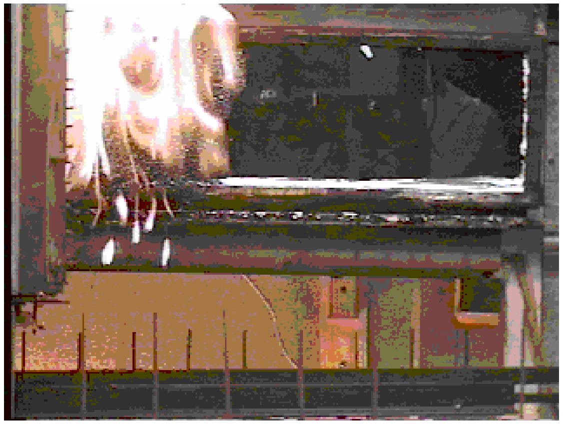
Forced Ignition and Spread Test (FIST)

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



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Microgravity Material Flammability Acceptance Criteria

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

Microgravity flame
with low flow velocity

Upward Flame Spread Test

The laminar nature of both flames makes it possible to use a simple formulation to correlate normal and microgravity results.

$$B = \frac{\textit{net heat liberated by combustion}}{\textit{heat input to fuel + heat loss}}$$

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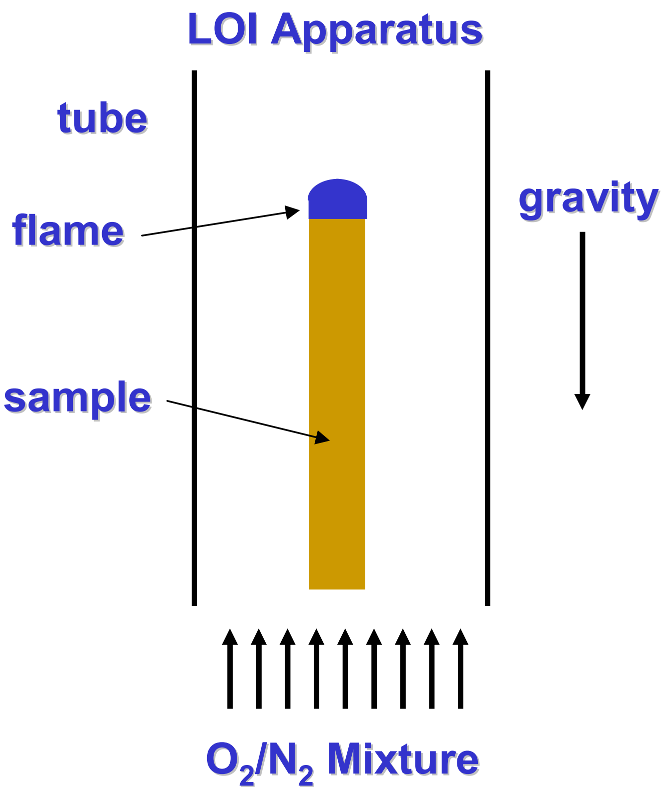
Material Flammability and Ignitability in Reduced gravity

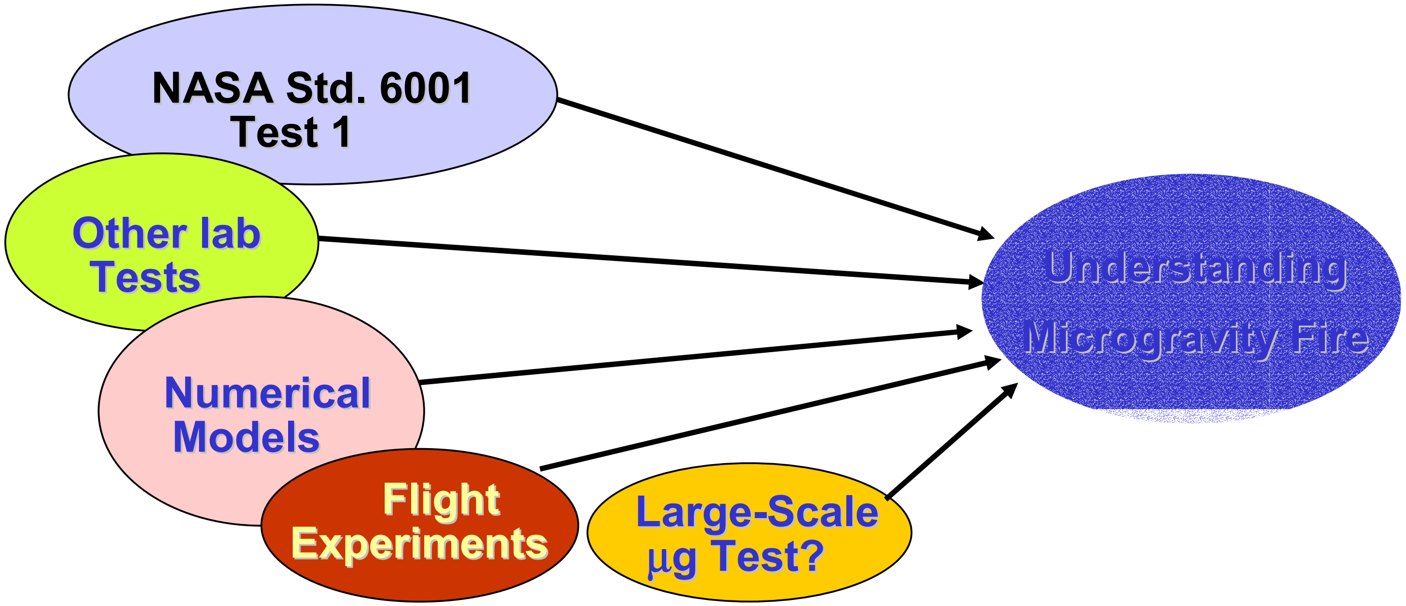
4. How does the flammability, ignitability and Limiting Oxygen Index (LOI) of a material change with gravitational level?



Some Typical values	LOI
Polyurethane foam	16.5
PMMA (Perspex)	17.3
Poly(ethylene)	17.4
Poly(propylene)	17.4
Poly(styrene)	17.8
Plywood	23.0
Nylon 6.6	24-29
Nomex	28.5
PVC (unplasticised)	45-49
PTFE (Teflon)	95

Fire in Microgravity

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?



Exploration Environments

6. How do the flammability and ignitability of materials change in high-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.

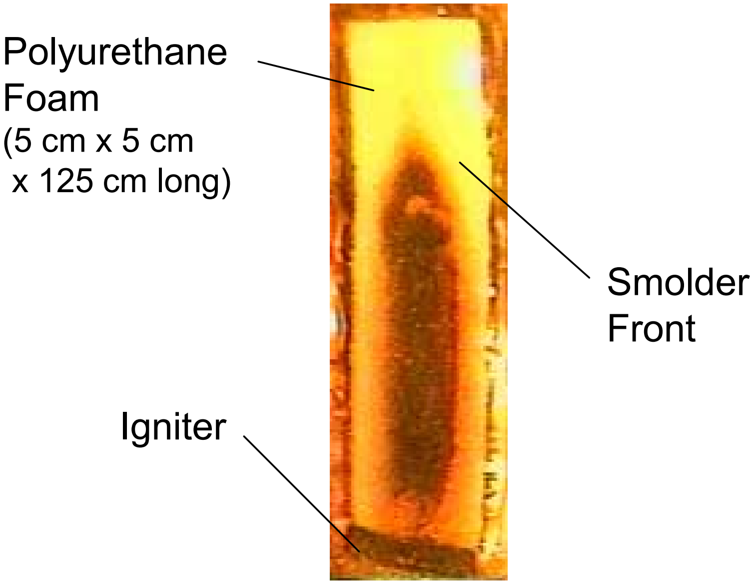
Smoldering

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



Ignition & Products

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?

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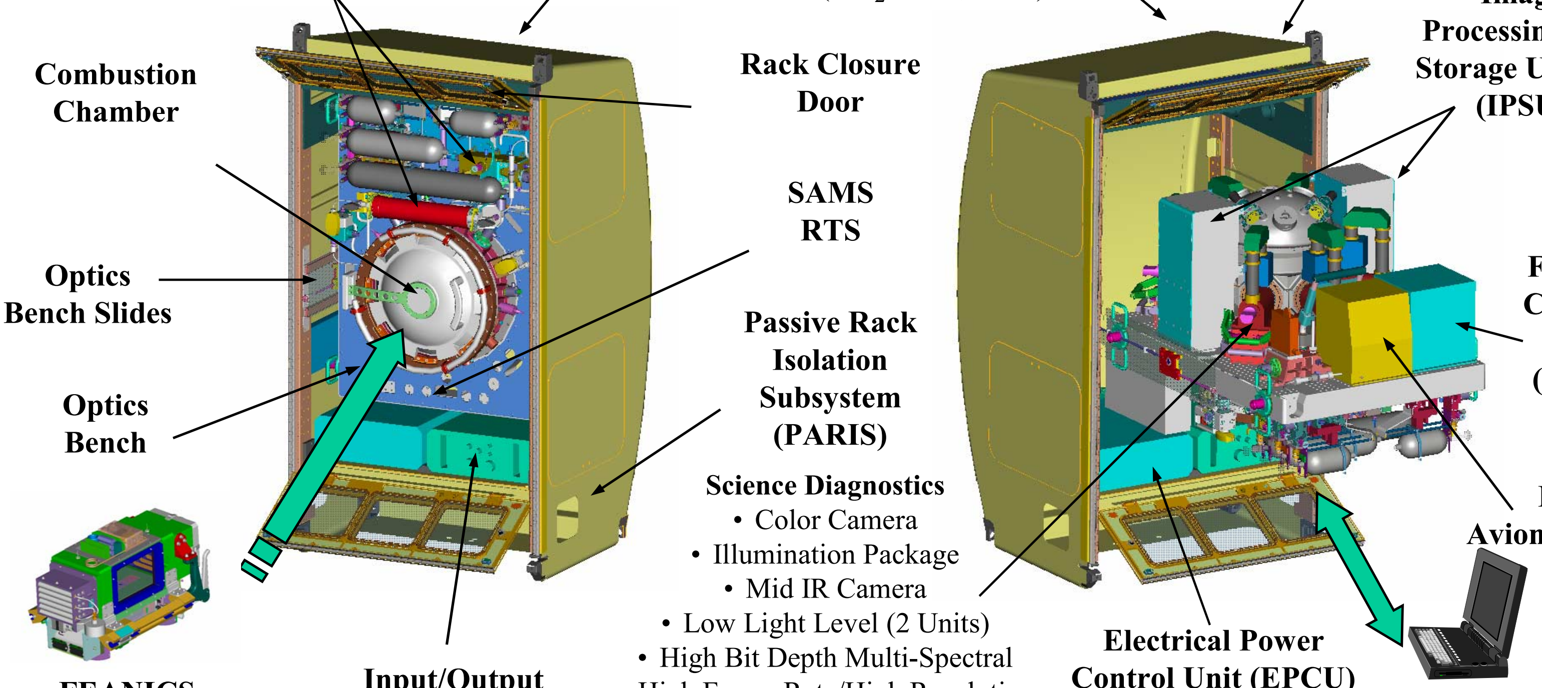
Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS)

June 23, 2004

Combustion Integrated Rack Overview



Environmental Control (ECS)
- Air Thermal Control
- Fire Detection & Suppression
- Water Thermal Control
- Gas Interfaces (GN_2, VES, VRS)

Fuel/Oxidizer Management Assembly (FOMA)

International Standard Payload Rack (ISPR)

Image Processing and Storage Unit (2) (IPSU)

Combustion Chamber

Rack Closure Door

SAMS RTS

Optics Bench Slides

FOMA Control Unit (FCU)

Passive Rack Isolation Subsystem (PARIS)

Optics Bench

Science Diagnostics
- Color Camera
- Illumination Package
- Mid IR Camera
- Low Light Level (2 Units)
- High Bit Depth Multi-Spectral
- High Frame Rate/High Resolution

<u>OR</u>

Experiment Specific Diagnostics

PI Avionics Box

Electrical Power Control Unit (EPCU)

FEANICS Chamber Insert Assembly

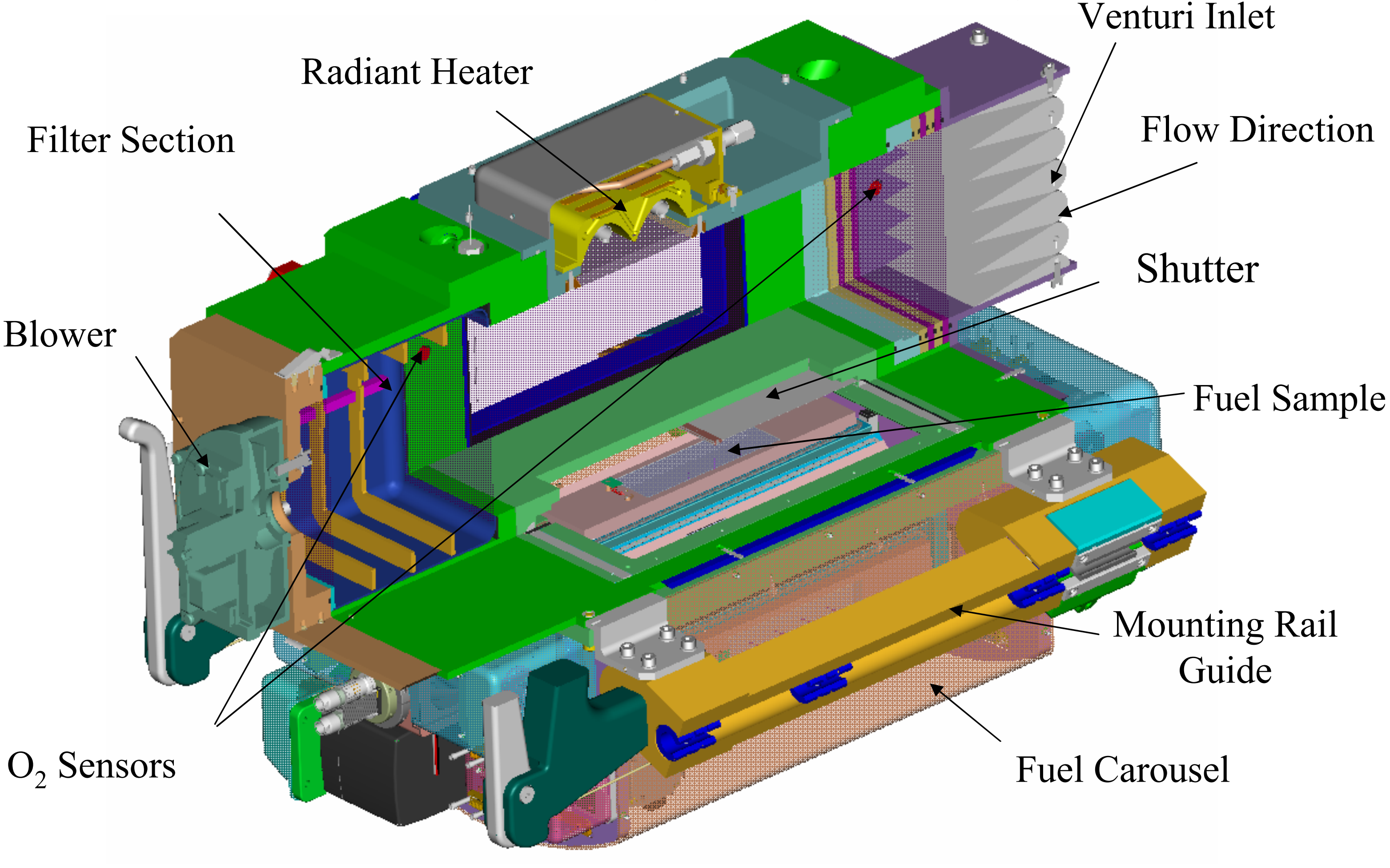
Input/Output Processor (IOP)

Laptop Computer

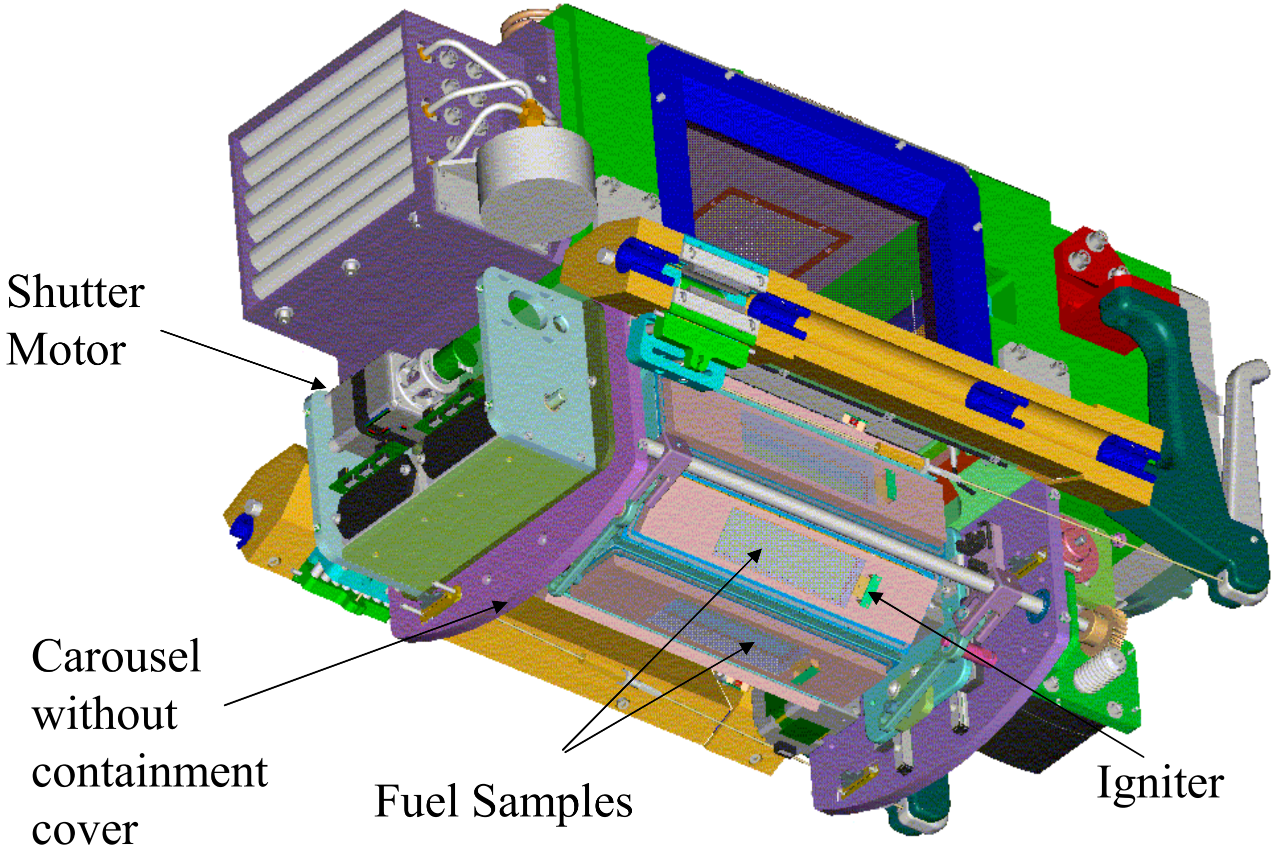
FEANICS-1 Capabilities

- **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

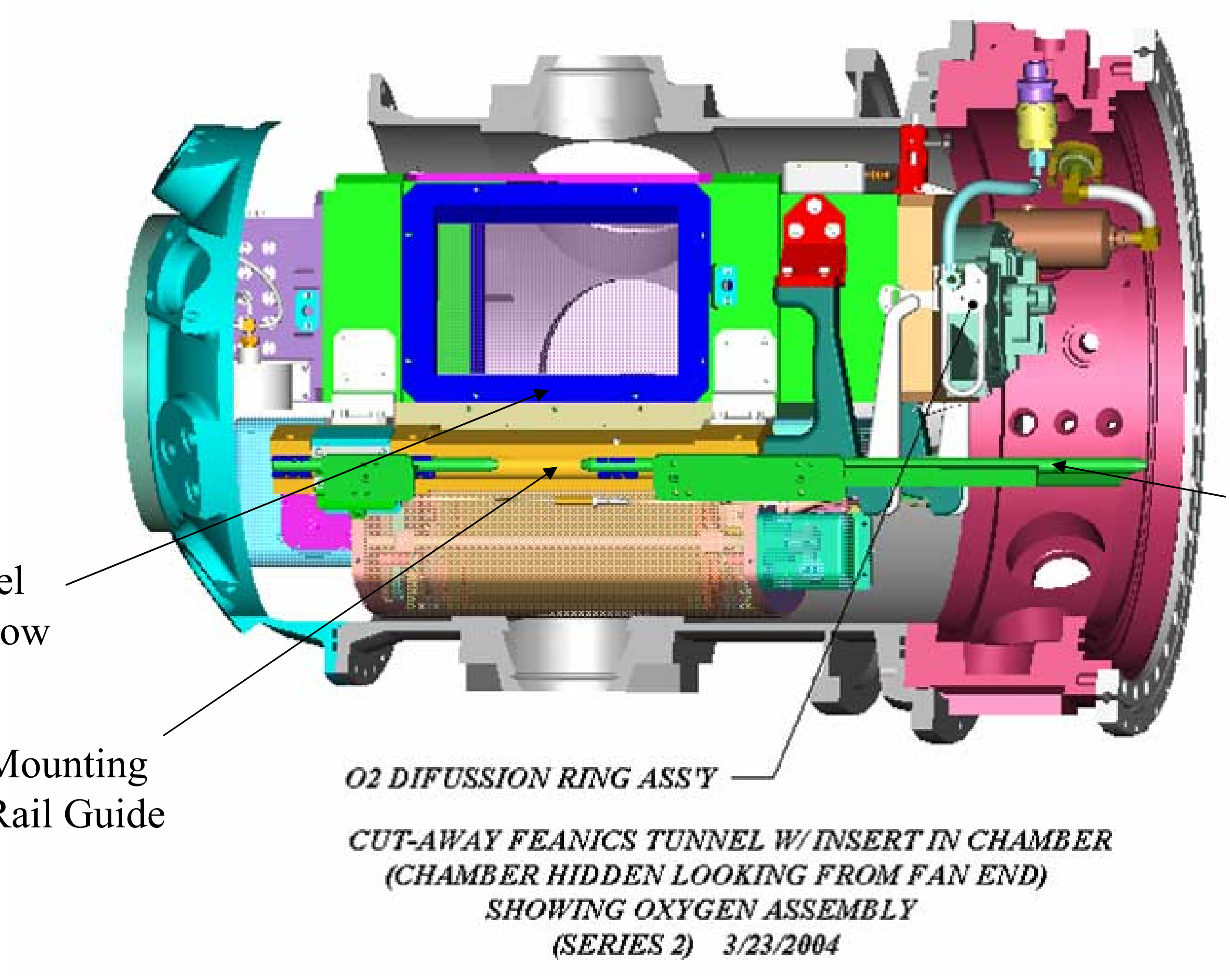
FEANICS-1 Insert (w/Radiant Heater)



FEANICS-1 Insert with 8-Sided Carousel



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

Tunnel
Window

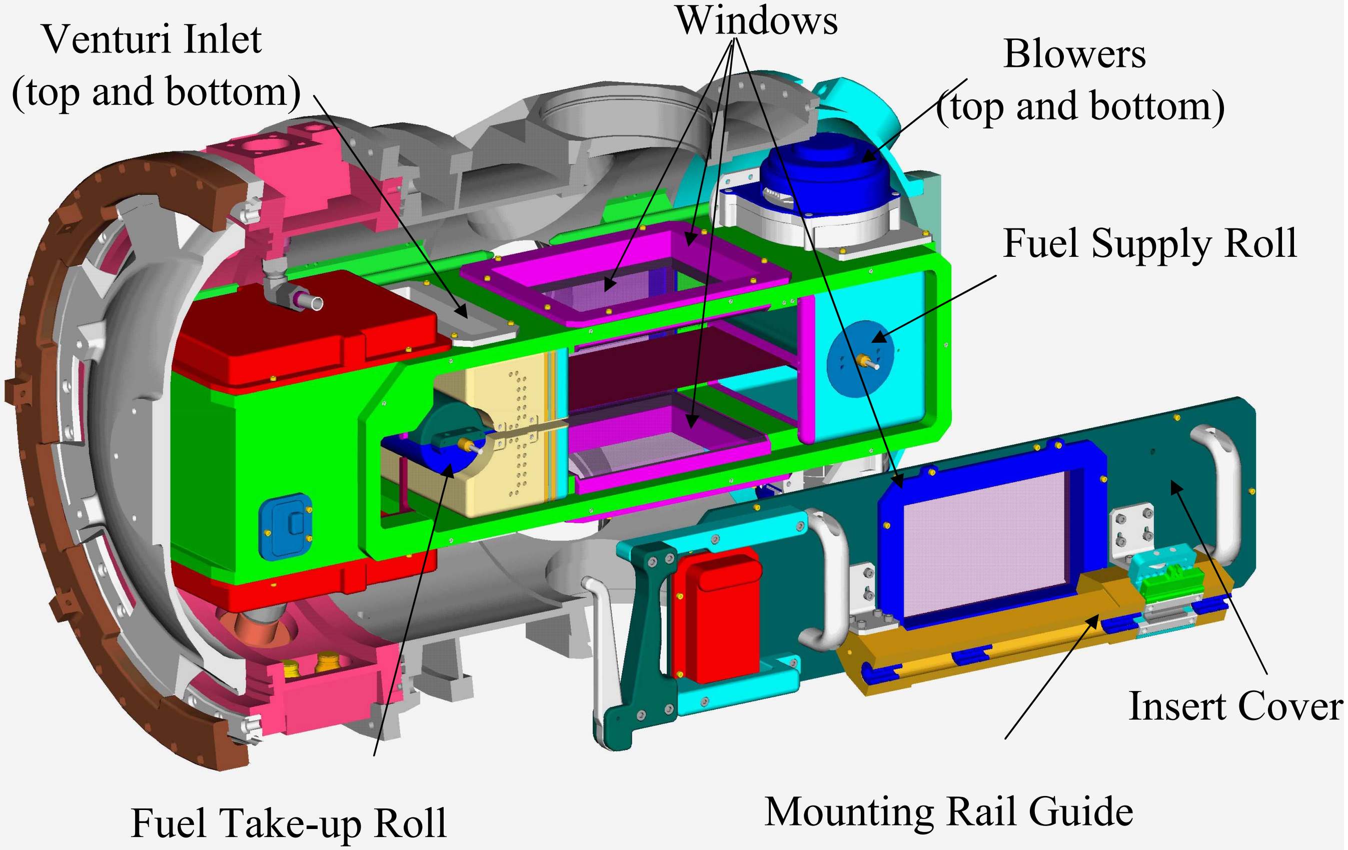
Mounting
Rail Guide

CIR
Chamber
Rail

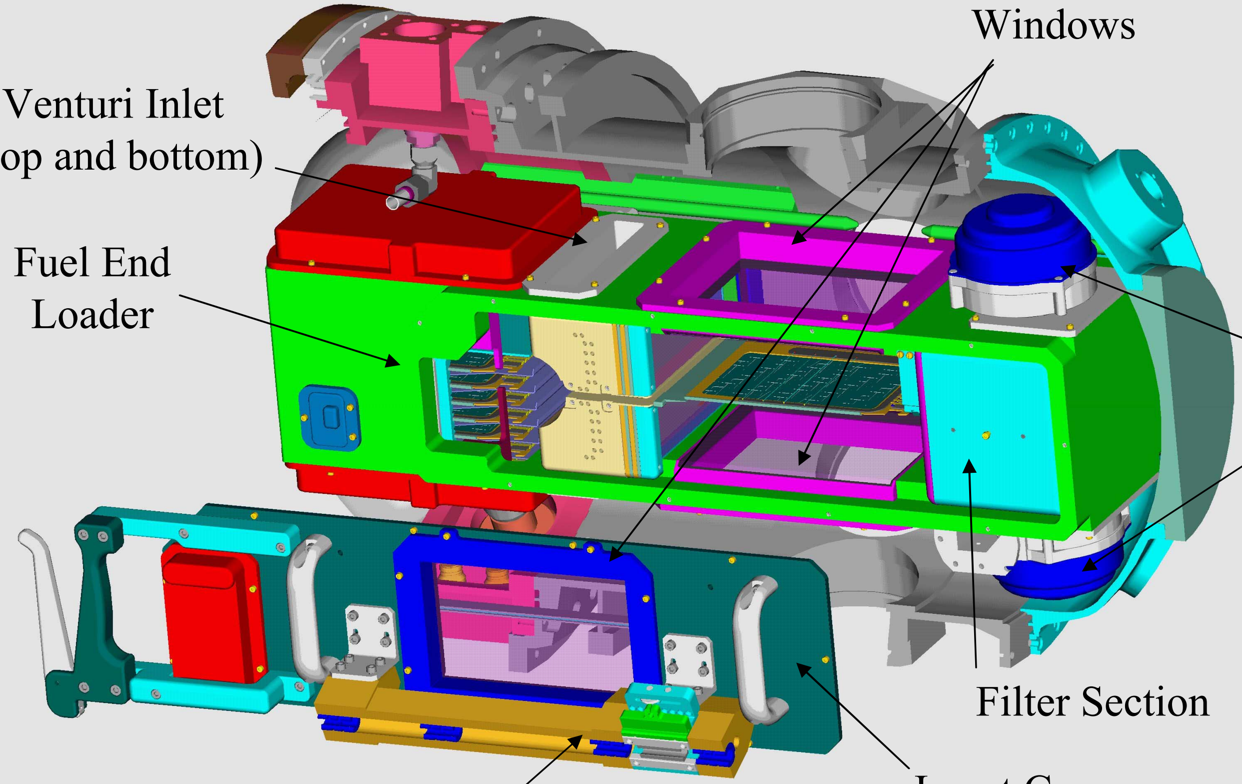
FEANICS-2 Capabilities

- **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



FEANICS-2 Insert with End Loader



Windows

Venturi Inlet
(top and bottom)

Fuel End
Loader

Blowers

Filter Section

Insert Cover

Mounting Rail Guide

Diagnostics Capabilities

Camera System	Pixels Array	Bit Depth (bits)	Frames Per Second	Spectrum (nm)
Low Light Level-IR	512x 512	12	30	400-900
Low Light Level-UV	512x 512	12	30	250-700
High Bit Multispectral	512x 512	12	15	650-950
Color	640x 480	8	30	400-700
Mid-IR	256x 256	12	120	3000-5000

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

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

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

Past, Present and Future Advanced ECLSS

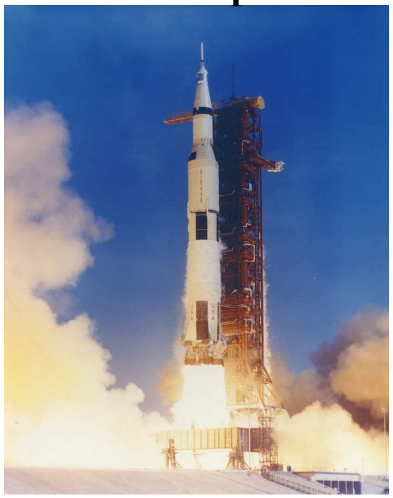
(Strategic Planning for Participation in New Initiatives of NASA HQ/Code T and Code U)

Taking the Journey Together

Prepared by
Kenny Mitchell/FD20
256-544-9259
kenny.mitchell@nasa.gov

NASA has Vast Experience in Human Space Exploration Programs

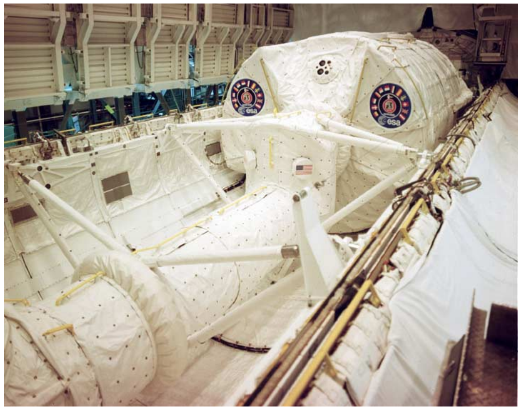
Saturn/Apollo



Skylab

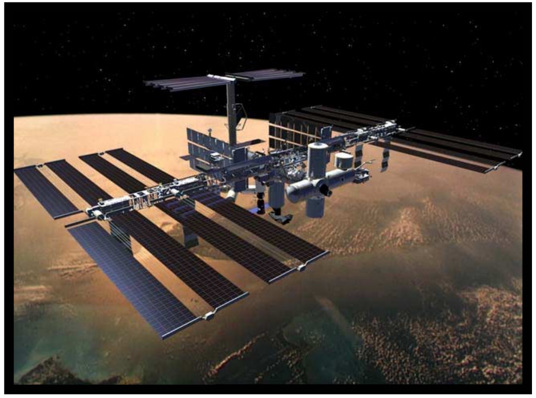
Space Shuttle

Spacelab



Shuttle/Mir

International Space Station



Historical Driving Mission Requirements for Human Exploration

	Mission Length	Crew Size	Habitat Atmosphere
Saturn/Apollo	< 14 days	3	5 Pisa (pure oxygen)
Skylab*	28 – 84 days	3	5 Pisa (N2/02, 70%/30%)
Space Shuttle	< 14 days	2 - 7	14.7 Pisa (N2/02, 79%, 21%)
Spacelab	< 14 days	3 - 4	14.7 Pisa (N2/02, 79%, 21%)
Mir*	~ 15 years	2 - 6	14.7 Pisa (N2/02, 79%, 21%)
International Space Station*	15 -20 years Planned	2 - 6	14.7 Pisa (N2/02, 79%, 21%)

*Regenerative life support systems on-board

Basic ECLSS Functions for Human Support

Atmosphere Revitalization

- CO2 Removal
- CO2 Reduction
- Oxygen Generation
- Trace Contaminant Control
- Trace Contaminant Monitoring
- Atmosphere Composition Monitoring

Atmosphere Control & Supply

- O2 Storage Systems
- N2 Storage Systems
- 02/N2 Atmosphere Pressure Control
- Negative & Positive Pressure Relief of Habitat
- Purge and pressurant supply gases
- EVA Support
- O2/N2 Distribution

Water Management Systems

- Potable H20 Storage
- Waste H20 Processing
- Urine Processing
- Water Distribution
- Hygiene H20 Supply
- Water Quality Monitoring
- Biocide and Sterilization

Fire Detection & Suppression

- Smoke Detection
- Fire Detection
- Fire Suppression
- Emergency Breathing Support

Temperature & Humidity Control

- Cabin Air Temperature Control
- Habitable Volume Air Ventilation
- Air Filtration
- Air Circulation
- Humidity Control
- Temperature & Humidity Monitoring

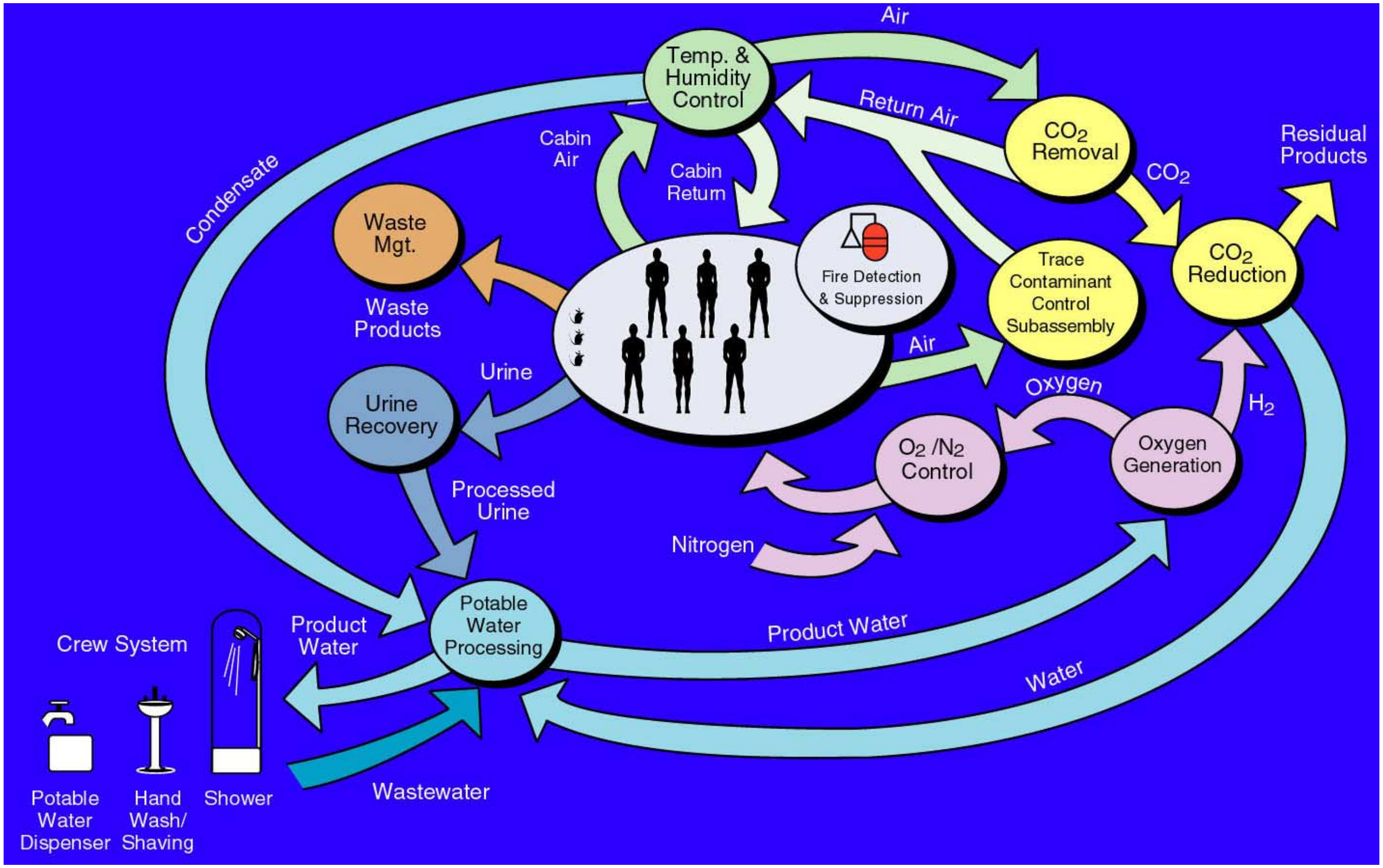
Waste Management Systems

- Urine Collection and Pre-treatment
- Fecal Collection & Processing

Human Friendly ECLSS Features

- Habitable noise level satisfies NC-50 Criteria *(MPLM and Node 2 met on ISS)*
- Low maintenance requirements (planned or unplanned)
- Personal hygiene support is simple and effective
- Comfortable environmental control (temperature/humidity/ventilation)
- Water management is “earth-like”.
- Fire and smoke detection is reliable
- Robust (handles anomalies with minimal crew attention)
- Significant safety features for crew life support

Typical ECLSS Functions Including Regenerative



Environmental Control and Life Support Systems

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

Needs

Oxygen = 0.84 kg (1.84 lb)

Food Solids = 0.62 kg (1.36 lb)

Water in Food = 1.15 kg (2.54 lb)

Food Prep Water = 0.76 kg (1.67 lb)

Drink = 1.62 kg (3.56 lb)

Metabolized Water = 0.35 kg (0.76 lb)

Hand/Face Wash Water = 4.09 kg (9.00 lb)

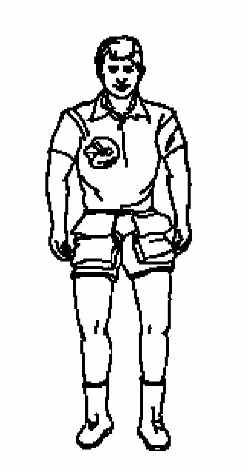
Shower Water = 2.73 kg (6.00 lb)

Urinal Flush = 0.49 kg (1.09 lb)

Clothes Wash Water = 12.50 kg (27.50 lb)

Dish Wash Water = 5.45 kg (12.00 lb)

Total = 30.60 kg (67.32 lb)



Effluents

Carbon Dioxide = 1.00 kg (2.20 lb)

Respiration & Perspiration
Water = 2.28 kg (5.02 lb)

Food Preparation,
Latent Water = 0.036 kg (0.08 lb)

Urine = 1.50 kg (3.31 lb)

Urine Flush Water = 0.50 kg (1.09 lb)

Feces Water = 0.091 kg (0.20 lb)

Sweat Solids = 0.018 kg (0.04 lb)

Urine Solids = 0.059 kg (0.13 lb)

Feces Solids = 0.032 kg (0.07 lb)

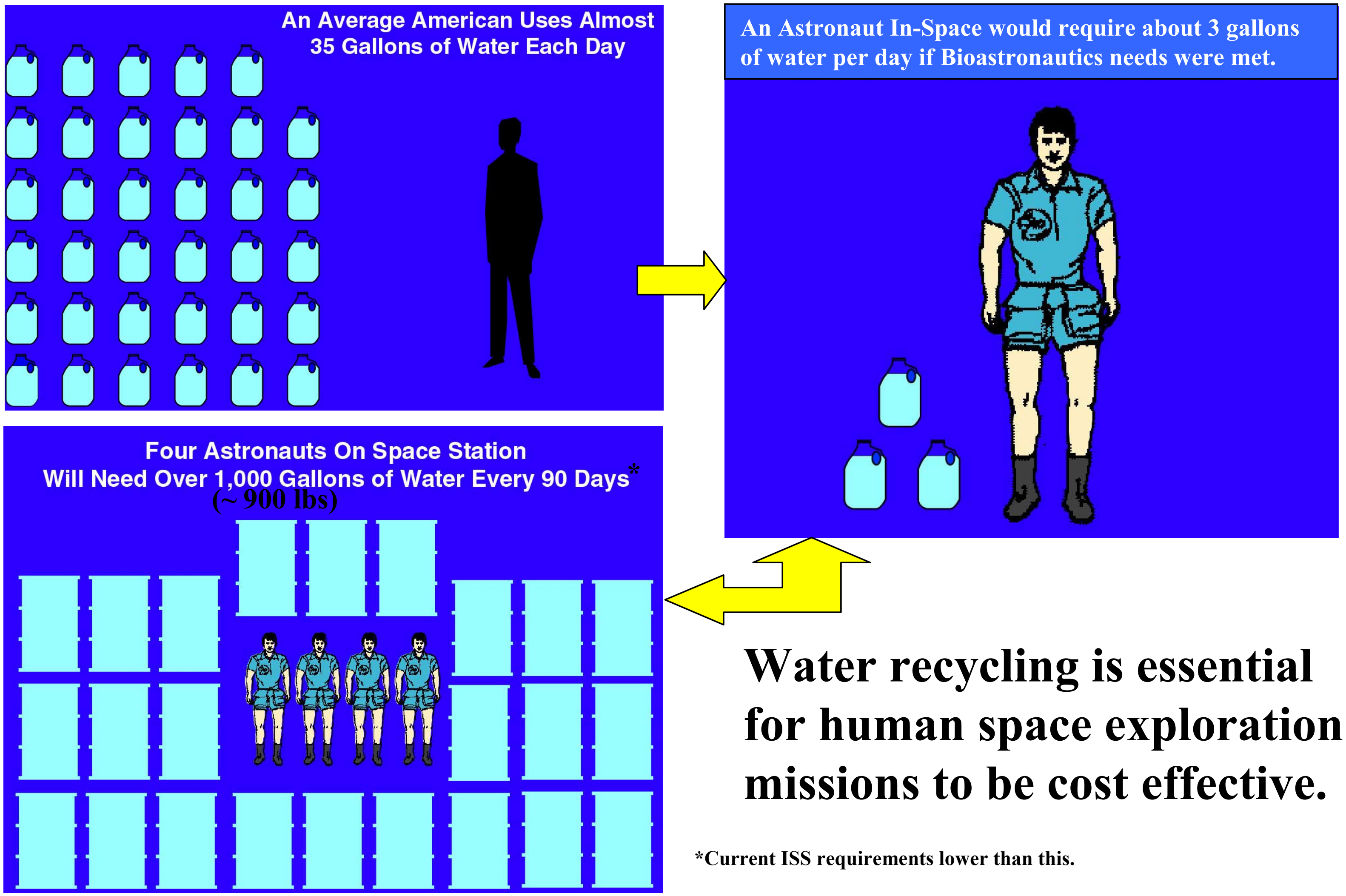
Hygiene Water = 12.58 kg (27.68 lb)

Clothes Wash Water
Liquid = 11.90 kg (26.17 lb)
Latent = 0.60 kg (1.33 lb)
Total = 30.60 kg (67.32 lb)

Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 BTU/person/day) and a respiration quotient of 0.87.
The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO_2 generated to O_2 consumed.

Regenerative Life Support Systems Required

(Example is reclamation of waste water)



An Average American Uses Almost 35 Gallons of Water Each Day

An Astronaut In-Space would require about 3 gallons of water per day if Bioastronautics needs were met.

Four Astronauts On Space Station Will Need Over 1,000 Gallons of Water Every 90 Days* (~ 900 lbs)

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

International Space Station

Space operations
to the Moon

u-g CEV

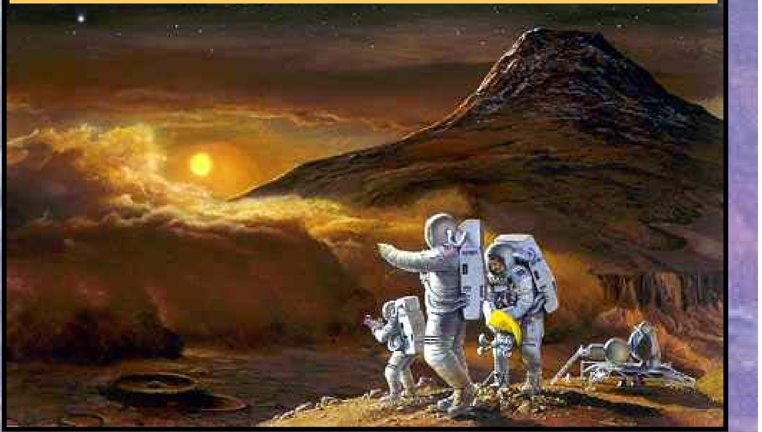
Space operations
to another planet

CEV u-g

Lunar Outpost

Partial-g

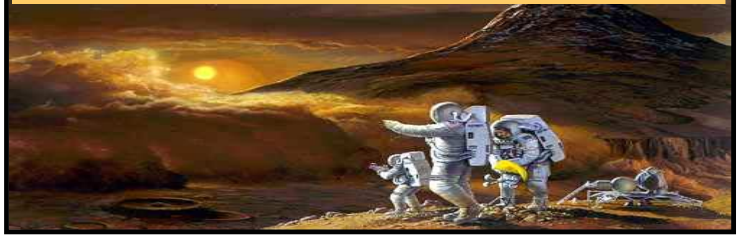
Humans on Another Planet



Partial-Gravity Environments Benefit ECLSS Design/Operations

Lunar Outpost

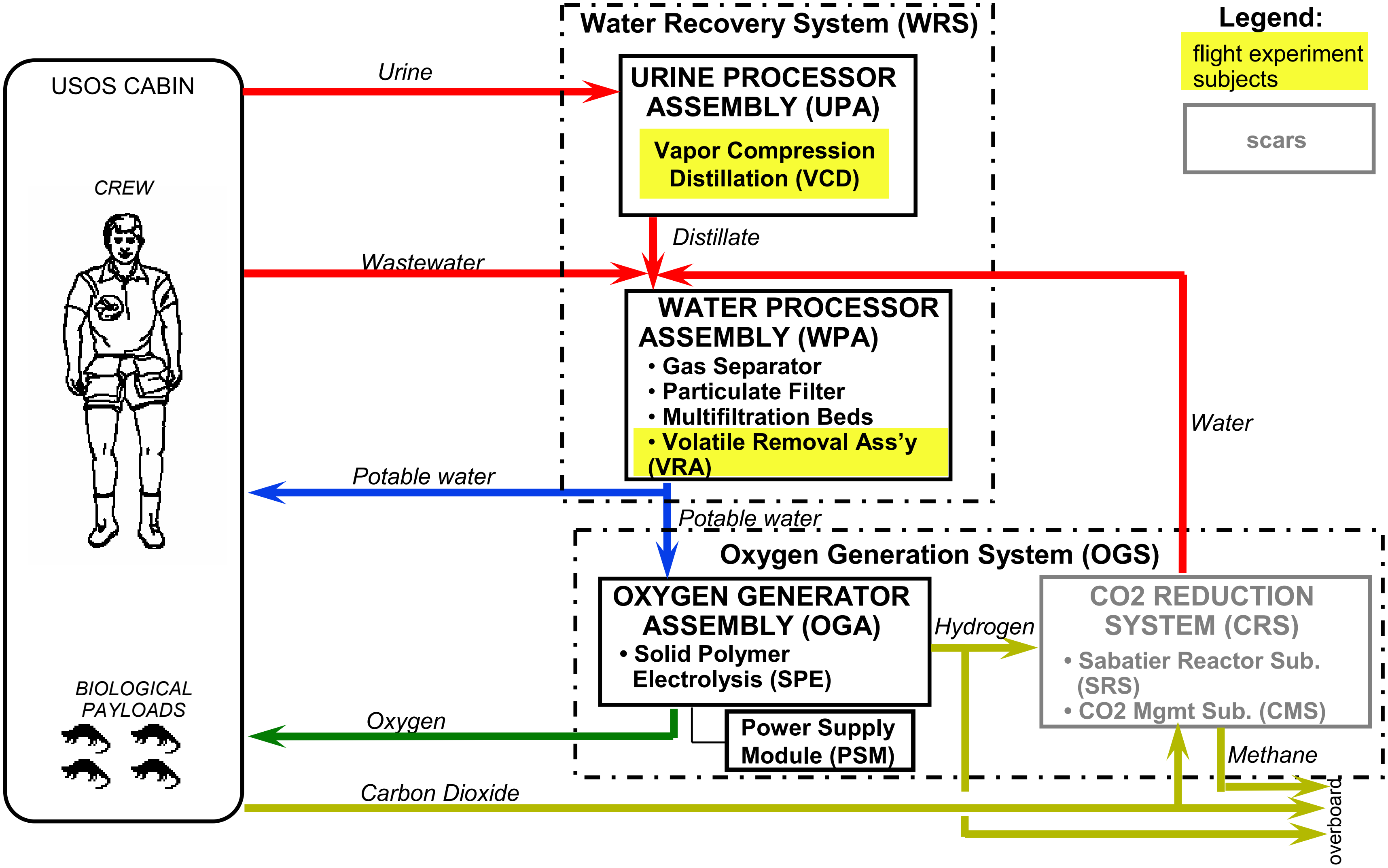
Humans on Another Planet



Design Simplications	Benefits
- Eliminates need for liquid/gas phase separation	Saves development costs, power, mass, volume, and reduces contribution to noise.
- Fire suppression easier	Suppressant "falls" on fire
- Smoke detection easier	Integrate detectors for natural convection
- Ventilation systems more "Earth-like"	Easier to design/integrate air flow for thermal comfort, CO2 removal, etc. and reduces noise production associated with fans.
- Water distribution systems utilize gravity	Simplifies water management hardware.
- Human hygiene functions more "Earth-like"	Urine/fecal collections systems lower weight, volume, power. Easier to recycle waste.

Regenerative ISS ECLSS Architecture Overview

(Complete Atmosphere Revitalization System not shown)



Legend:

flight experiment subjects

scars

USOS CABIN

CREW

BIOLOGICAL PAYLOADS

Urine

Wastewater

Potable water

Oxygen

Carbon Dioxide

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

Water

Oxygen Generation System (OGS)

OXYGEN GENERATOR ASSEMBLY (OGA)

- **Solid Polymer Electrolysis (SPE)**

Power Supply Module (PSM)

Hydrogen

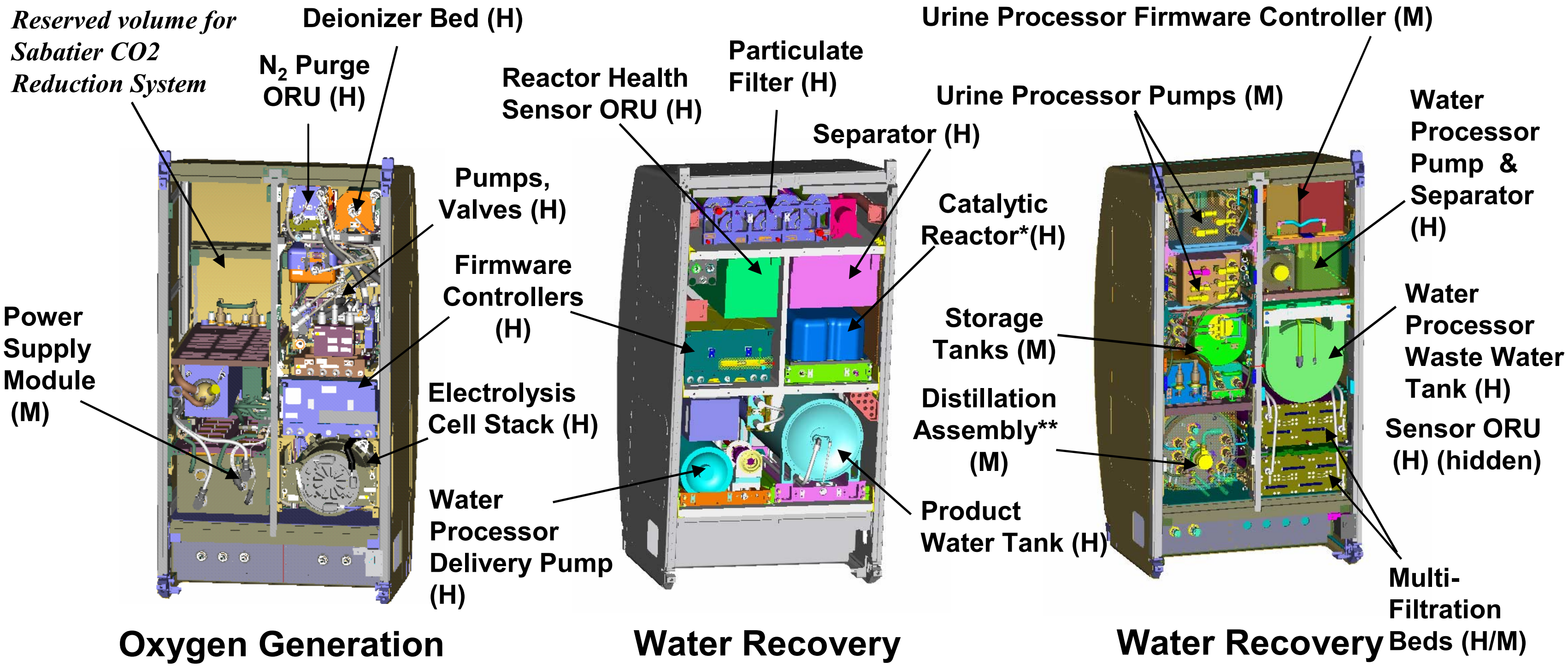
CO2 REDUCTION SYSTEM (CRS)

- **Sabatier Reactor Sub. (SRS)**
- **CO2 Mgmt Sub. (CMS)**

Methane

overboard

ISS Node 3
Regenerative ECLSS Racks



Reserved volume for Sabatier CO2 Reduction System

Deionizer Bed (H)

N_2 Purge ORU (H)

Pumps, Valves (H)

Firmware Controllers (H)

Power Supply Module (M)

Electrolysis Cell Stack (H)

Water Processor Delivery Pump (H)

Reactor Health Sensor ORU (H)

Particulate Filter (H)

Separator (H)

Catalytic Reactor*(H)

Product Water Tank (H)

Urine Processor Firmware Controller (M)

Urine Processor Pumps (M)

Storage Tanks (M)

Distillation Assembly** (M)

Water Processor Pump & Separator (H)

Water Processor Waste Water Tank (H)

Sensor ORU (H) (hidden)

Multi-Filtration Beds (H/M)

Oxygen Generation System Rack (Rack #3)

Water Recovery System Rack #1

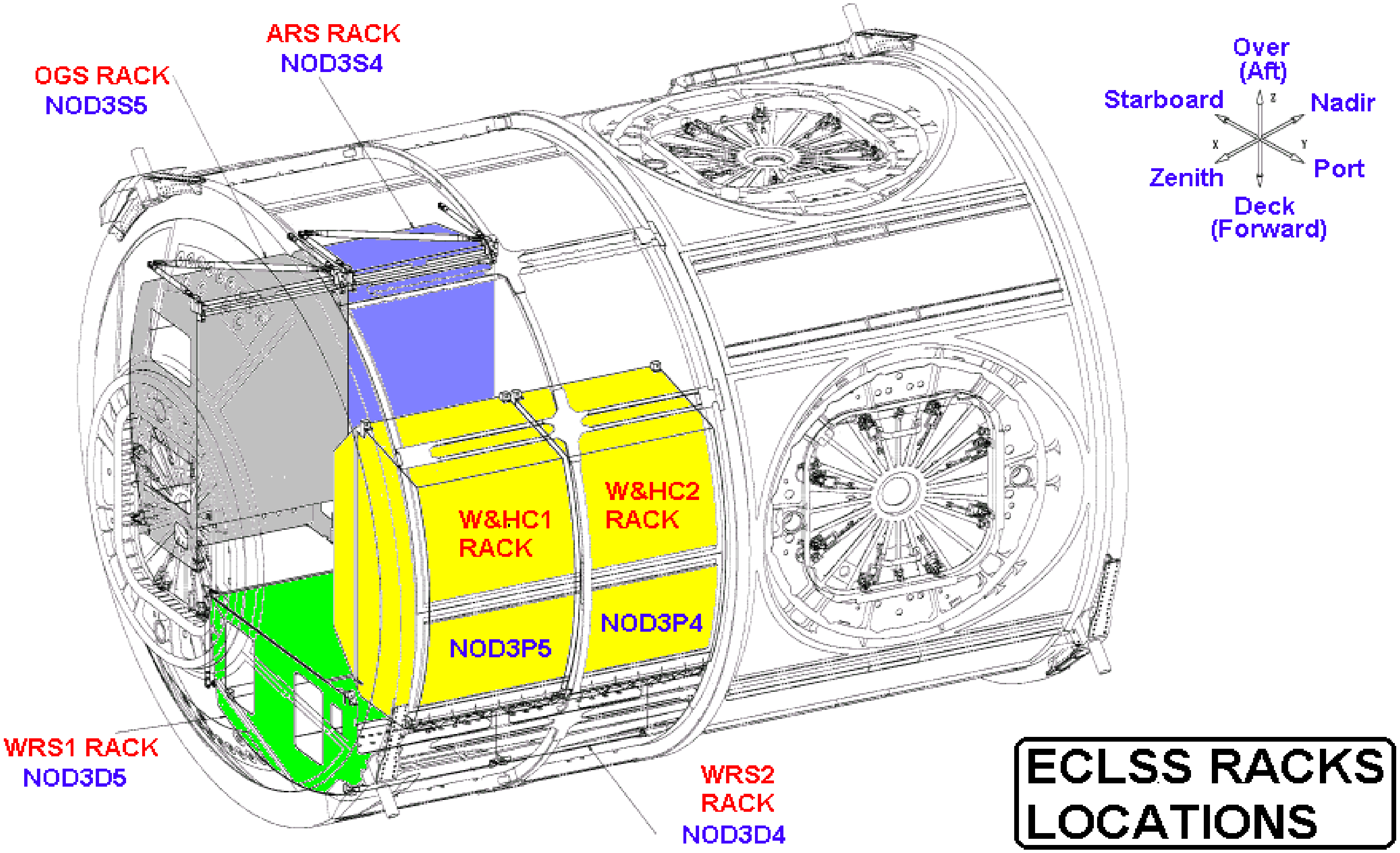
Water Recovery System Rack #2

* Volatile Removal Assy Flight Experiment successfully flown on Flight 2A.1, May 1999.
** 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.

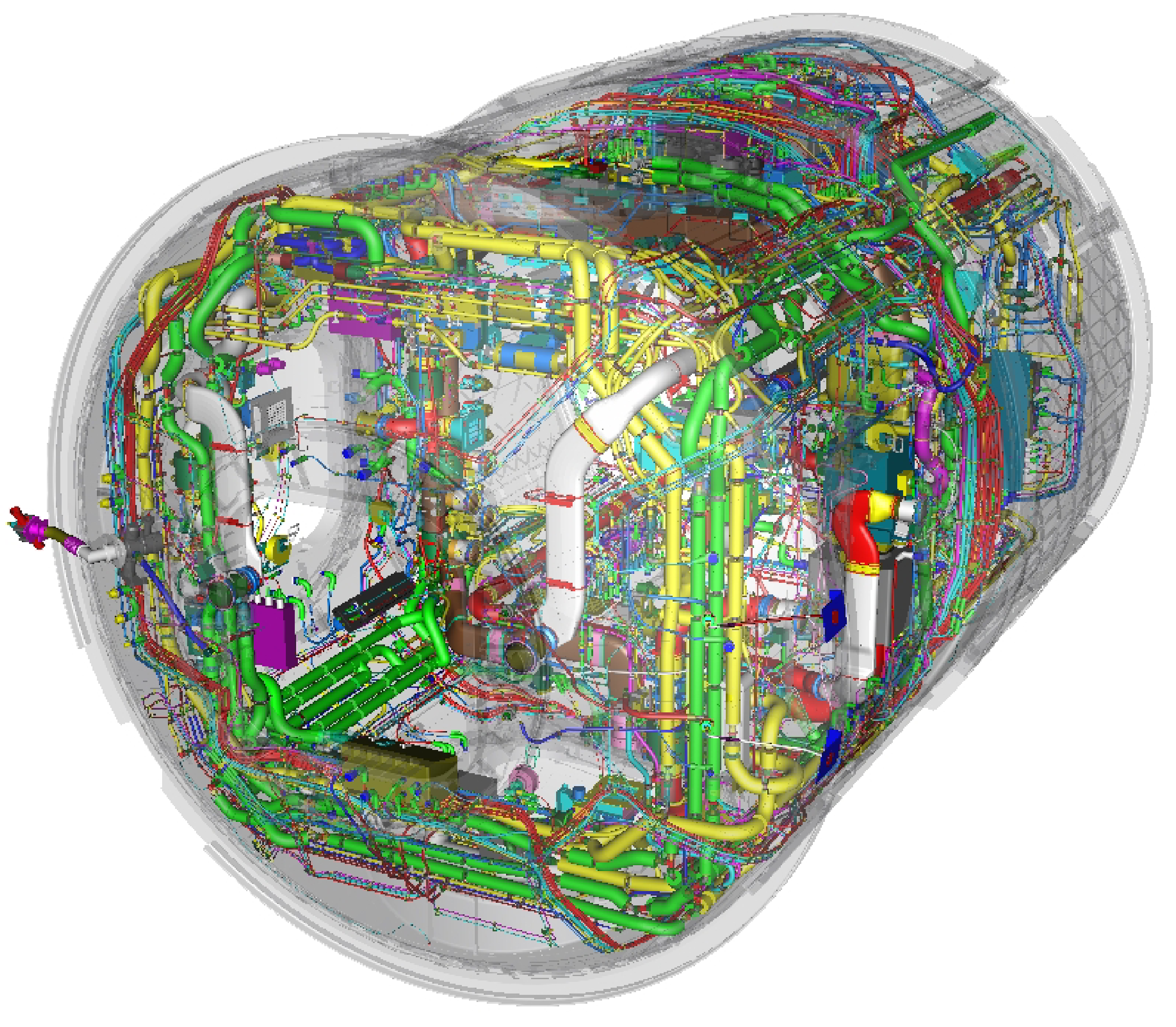
ISS Node 3 Architecture

(MSFC Manages Node 3 DDT&E)



ECLSS RACKS LOCATIONS

Node 3 Plumbing/Harnesses/Ducting Integrated with Primary/Secondary Structure

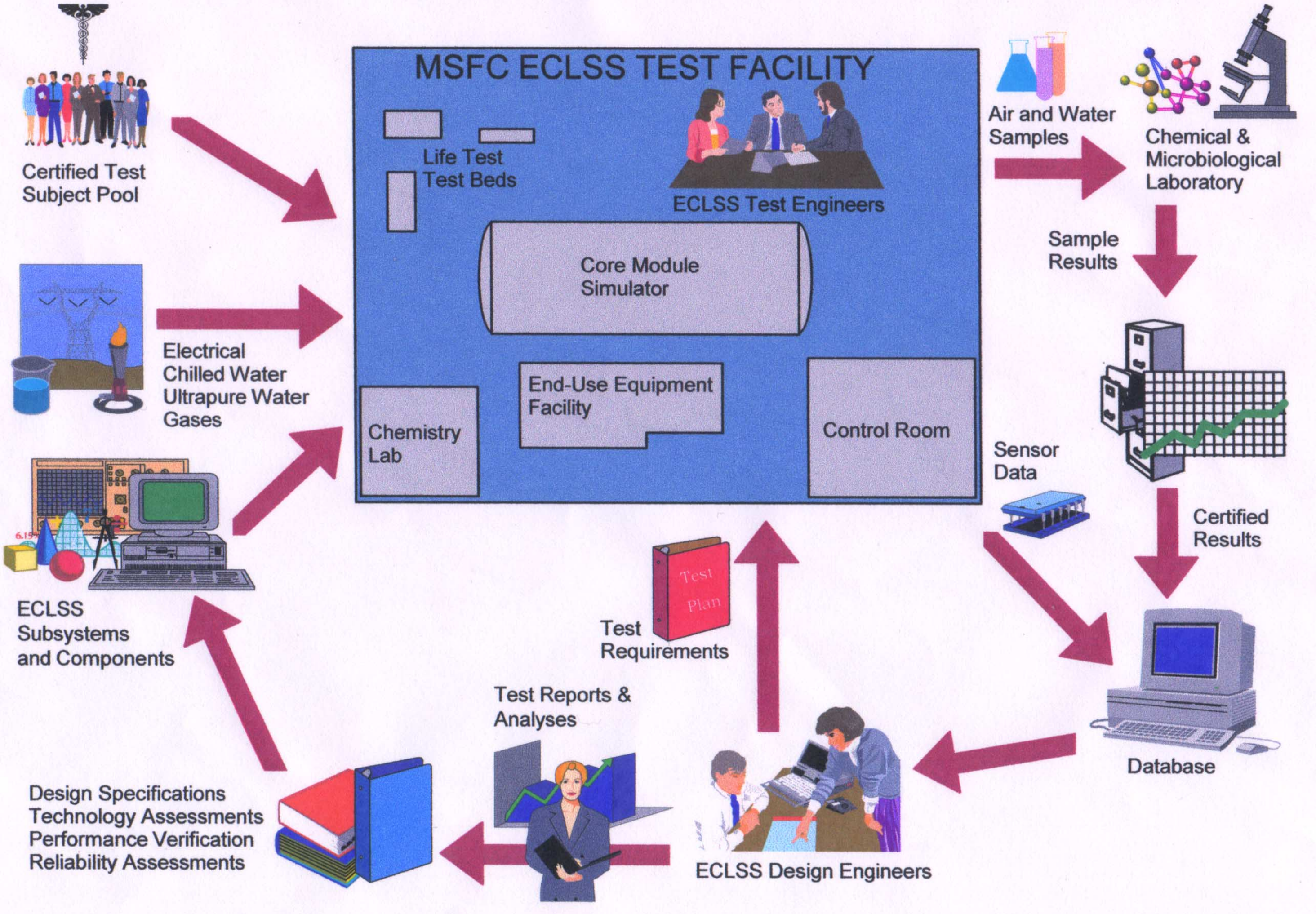


How Did ISS ECLSS Get To Where It Is?

- **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

ECLSS DEVELOPMENT TESTBED RESOURCES



MSFC ECLSS TEST FACILITY

Life Test Test Beds

ECLSS Test Engineers

Core Module Simulator

End-Use Equipment Facility

Chemistry Lab

Control Room

Certified Test Subject Pool

Electrical
Chilled Water
Ultrapure Water
Gases

ECLSS Subsystems and Components

Air and Water Samples

Chemical & Microbiological Laboratory

Sample Results

Sensor Data

Certified Results

Database

ECLSS Design Engineers

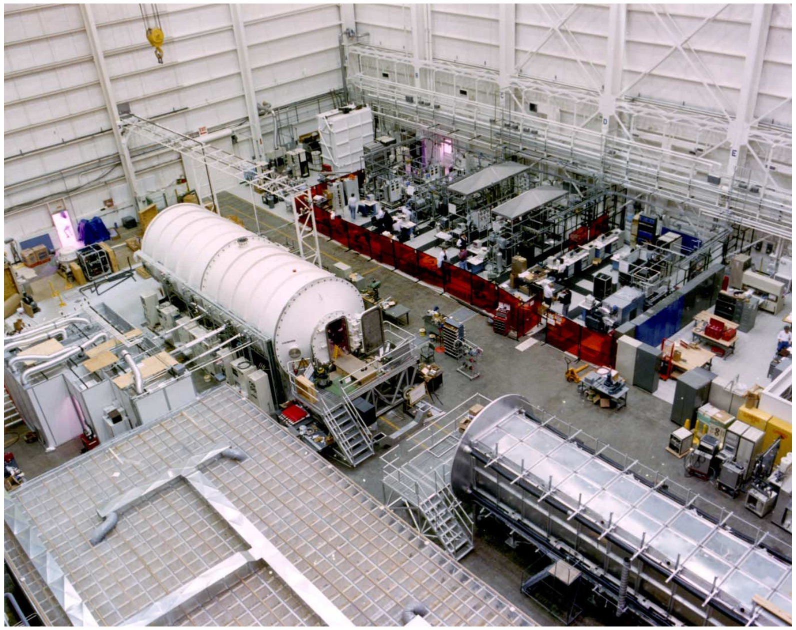
Test Requirements

Test Reports & Analyses

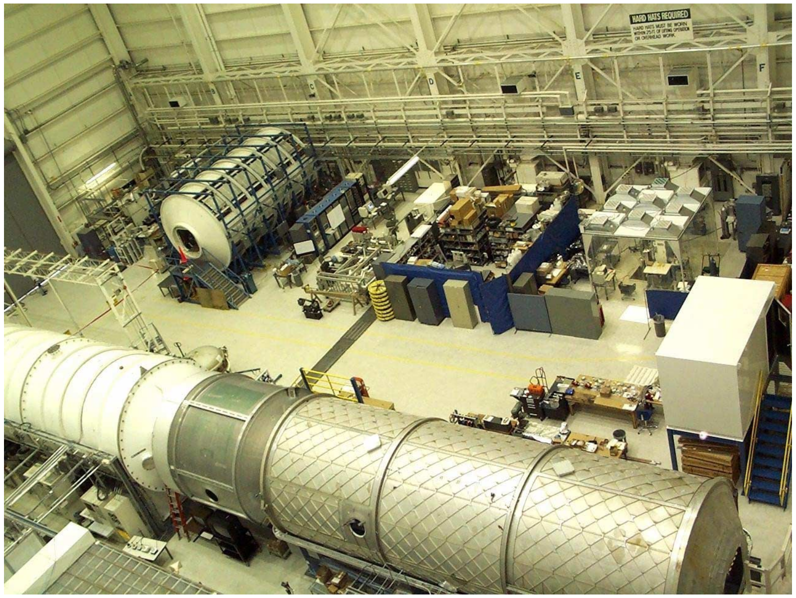
Design Specifications
Technology Assessments
Performance Verification
Reliability Assessments

History of MSFC ECLSS Test Beds

MSFC Building 4755 in 1989-1992 for Comparative Testing of ECLSS Technologies for Space Station Freedom Program

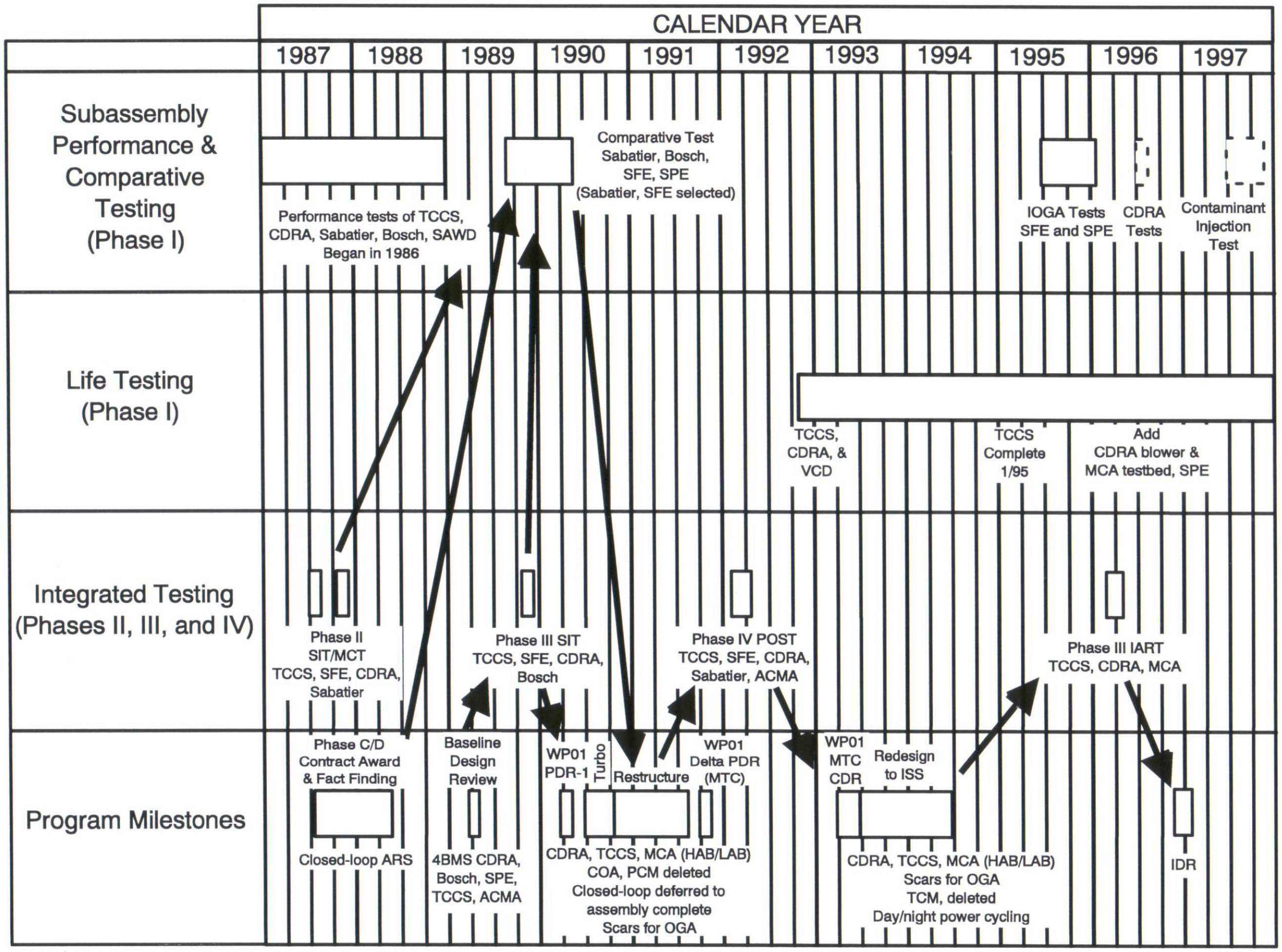


MSFC Building 4755 in 2004 for International Space Station ECLSS/Thermal Test Beds



Focused Technology Testing for C/D Milestones

(Illustrates Technology Development Supporting Program Needs)



CALENDAR YEAR
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997

Subassembly Performance & Comparative Testing (Phase I)

Performance tests of TCCS, CDRA, Sabatier, Bosch, SAWD Began in 1986

Comparative Test Sabatier, Bosch, SFE, SPE (Sabatier, SFE selected)

IOGA Tests SFE and SPE

CDRA Tests

Contaminant Injection Test

Life Testing (Phase I)

TCCS, CDRA, & VCD

TCCS Complete 1/95

Add CDRA blower & MCA testbed, SPE

Integrated Testing (Phases II, III, and IV)

Phase II SIT/MCT TCCS, SFE, CDRA, Sabatier

Phase III SIT TCCS, SFE, CDRA, Bosch

Phase IV POST TCCS, SFE, CDRA, Sabatier, ACMA

Phase III IART TCCS, CDRA, MCA

Program Milestones

Phase C/D Contract Award & Fact Finding

Closed-loop ARS

Baseline Design Review

4BMS CDRA, Bosch, SPE, TCCS, ACMA

WP01 PDR-1

Turbo

Restructure

WP01 Delta PDR (MTC)

CDRA, TCCS, MCA (HAB/LAB) COA, PCM deleted Closed-loop deferred to assembly complete Scars for OGA

WP01 MTC CDR

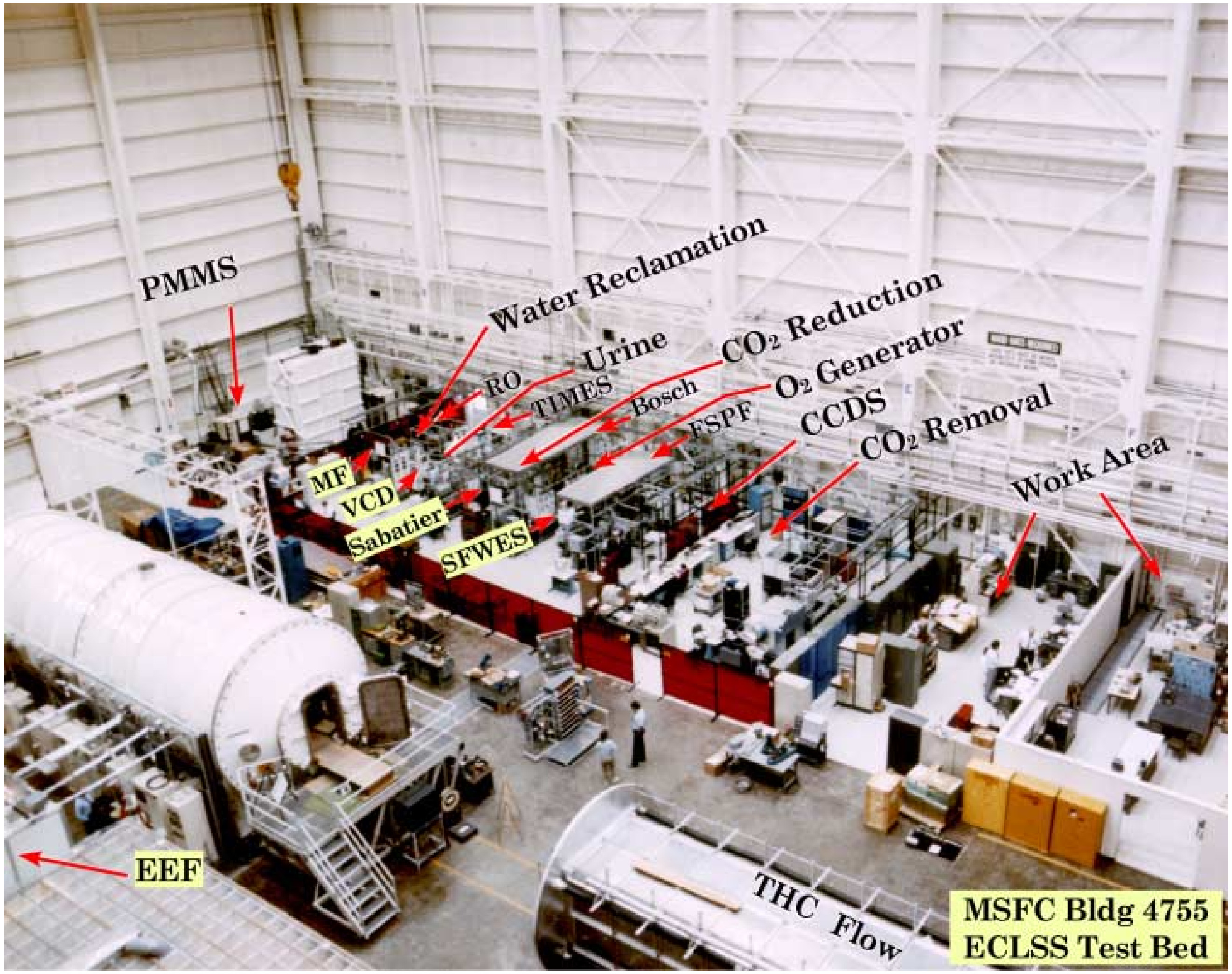
Redesign to ISS

CDRA, TCCS, MCA (HAB/LAB) Scars for OGA TCM, deleted Day/night power cycling

IDR

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

C02 Reduction

- Sabatier
- Bosch

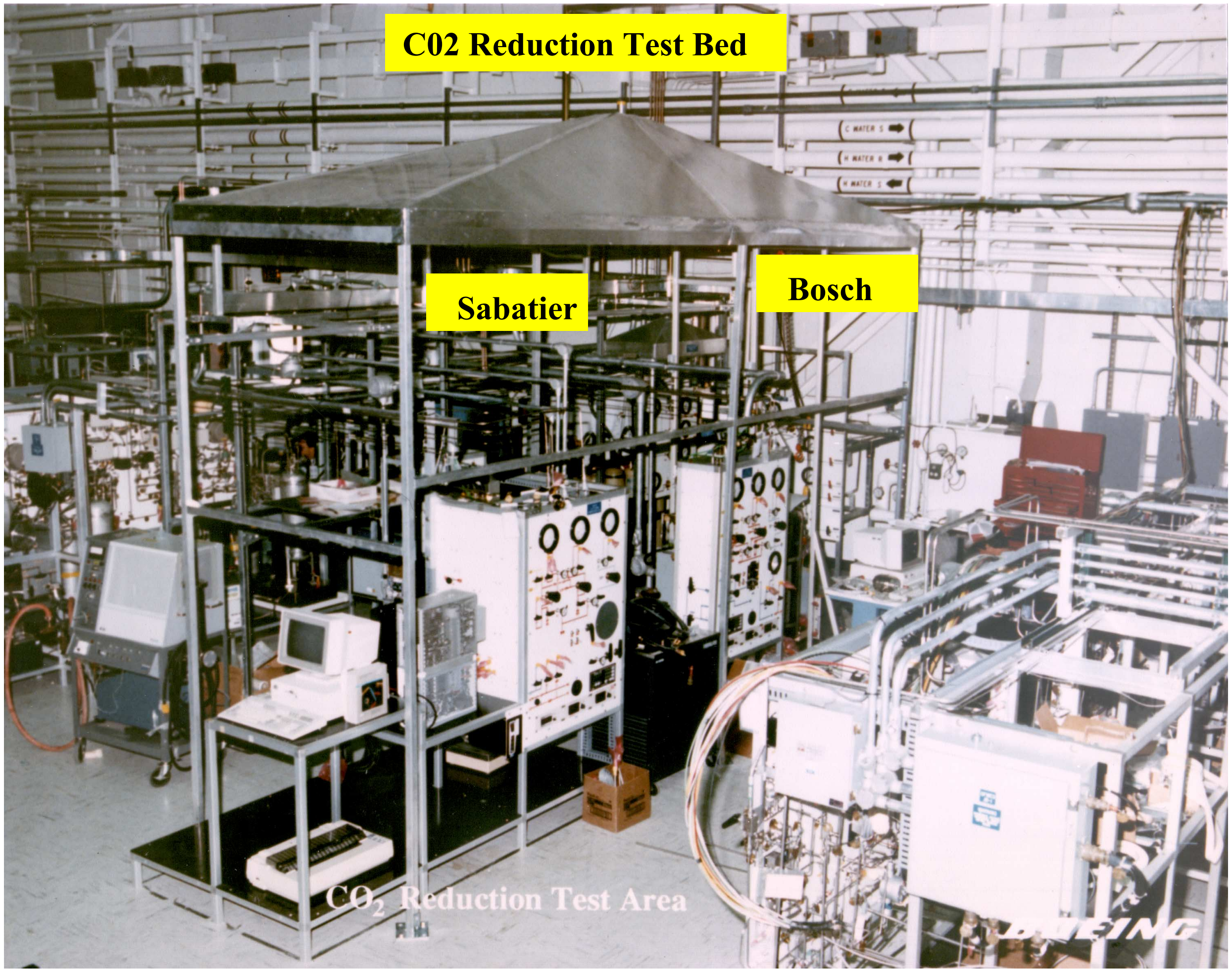
C02 Removal

- Molecular Sieve

Trace Contaminant Cont.

ECLSS Comparative Technology Test Bed

(MSFC testing for Space Station application)



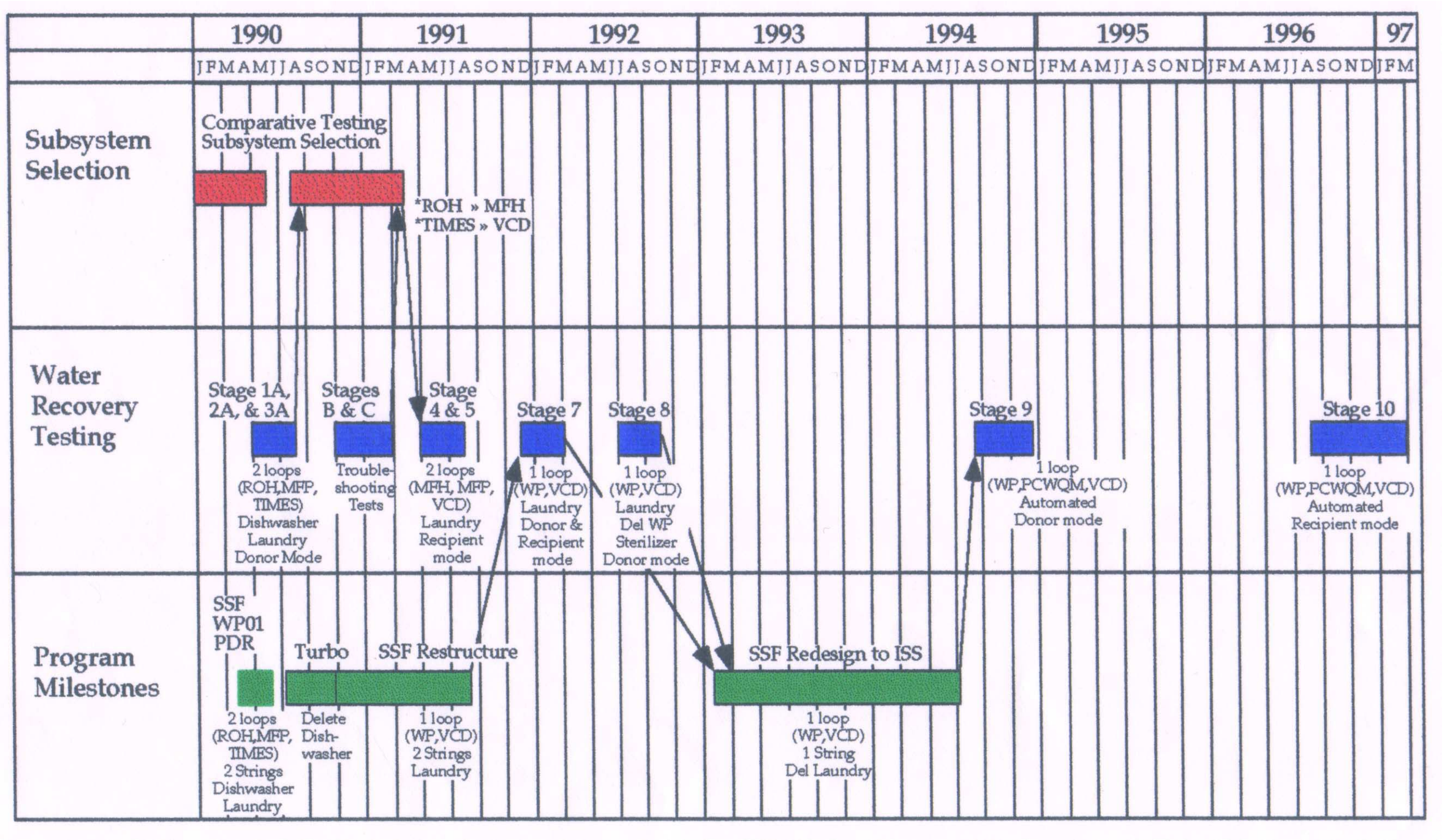
C02 Reduction Test Bed

Sabatier

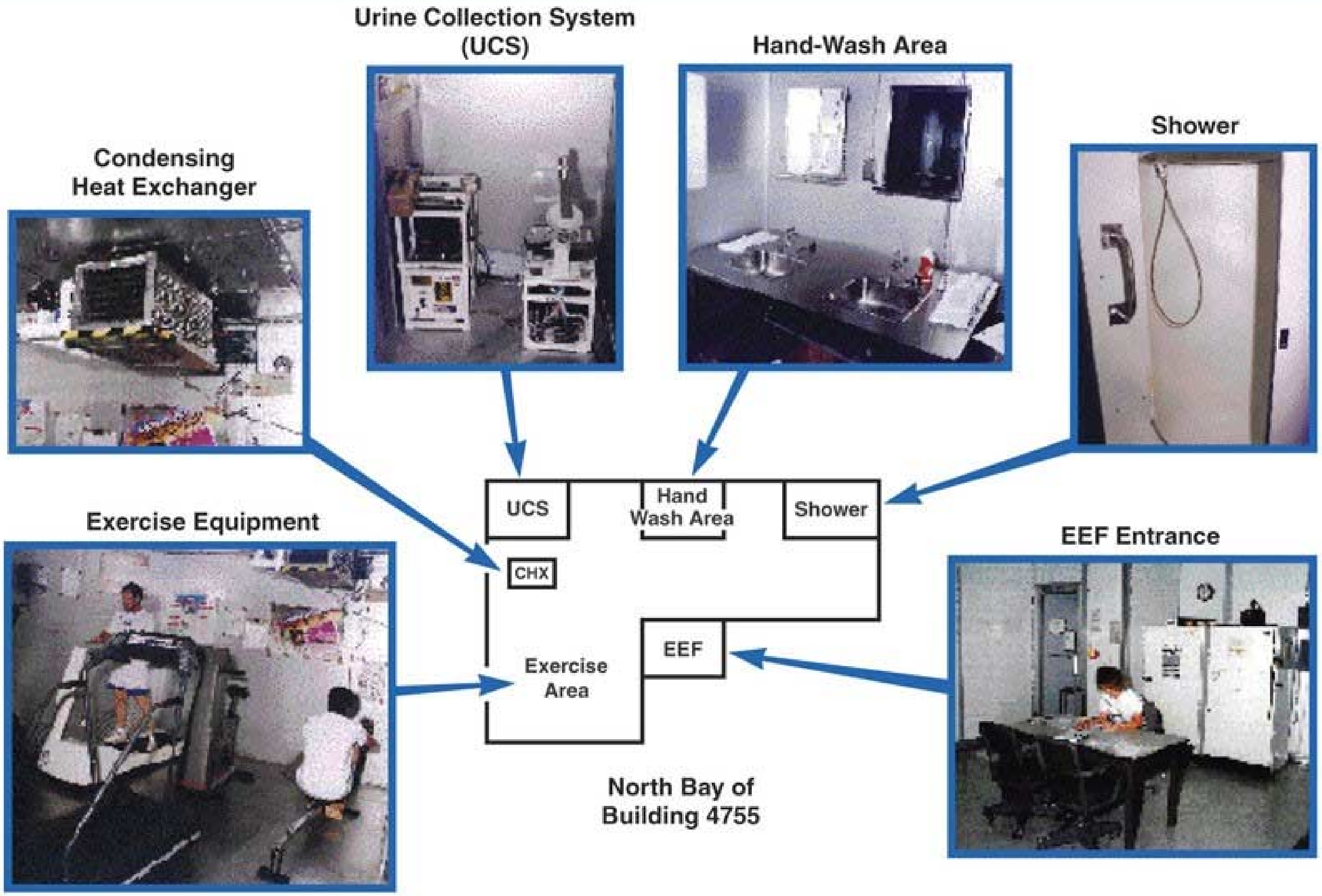
Bosch

WATER RECOVERY TEST HISTORY

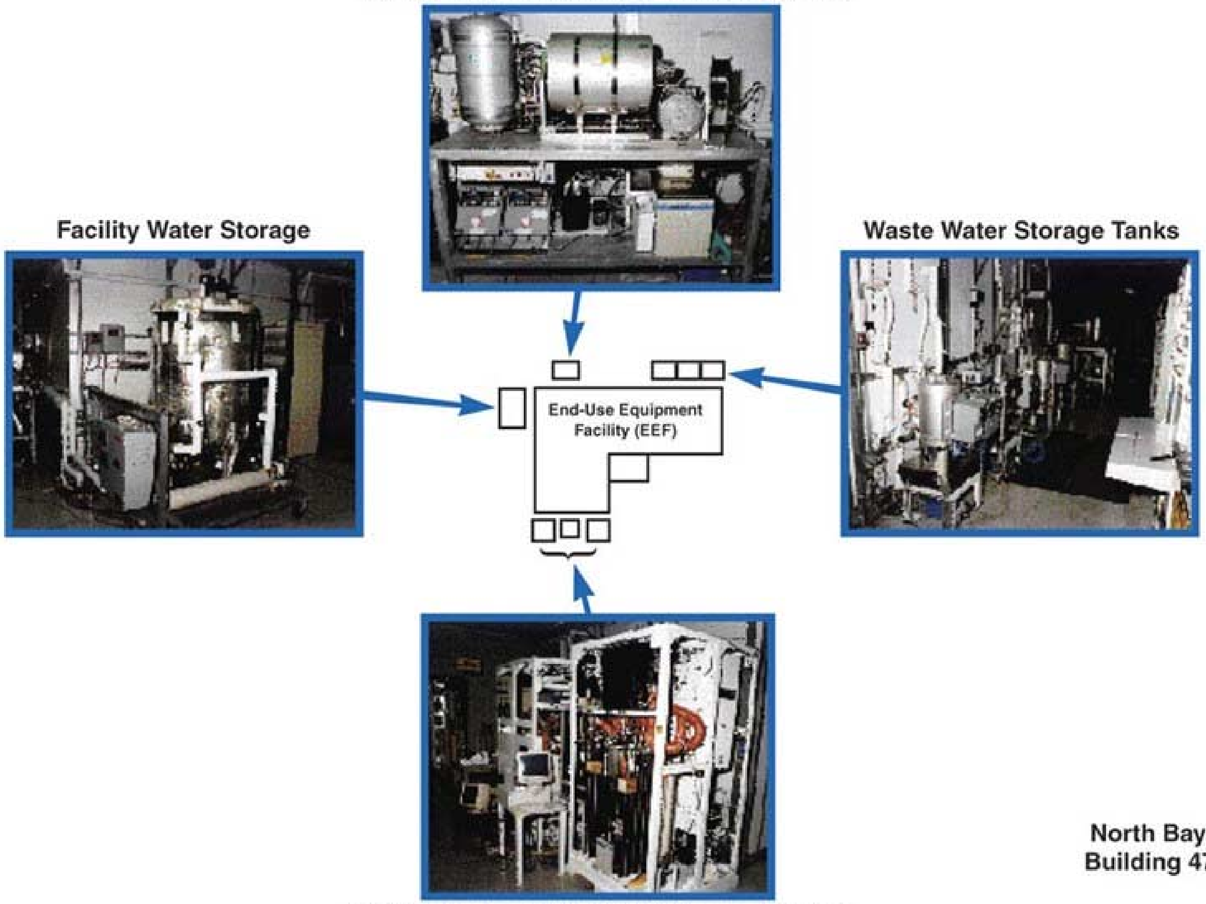
(Illustrates Technology Development Supporting Program Needs)



End-Use Equipment Facility (EEF)



Space Station ECLSS Water Recovery Testing Area



Vapor Compression Distillation (VCD) Unit

Facility Water Storage

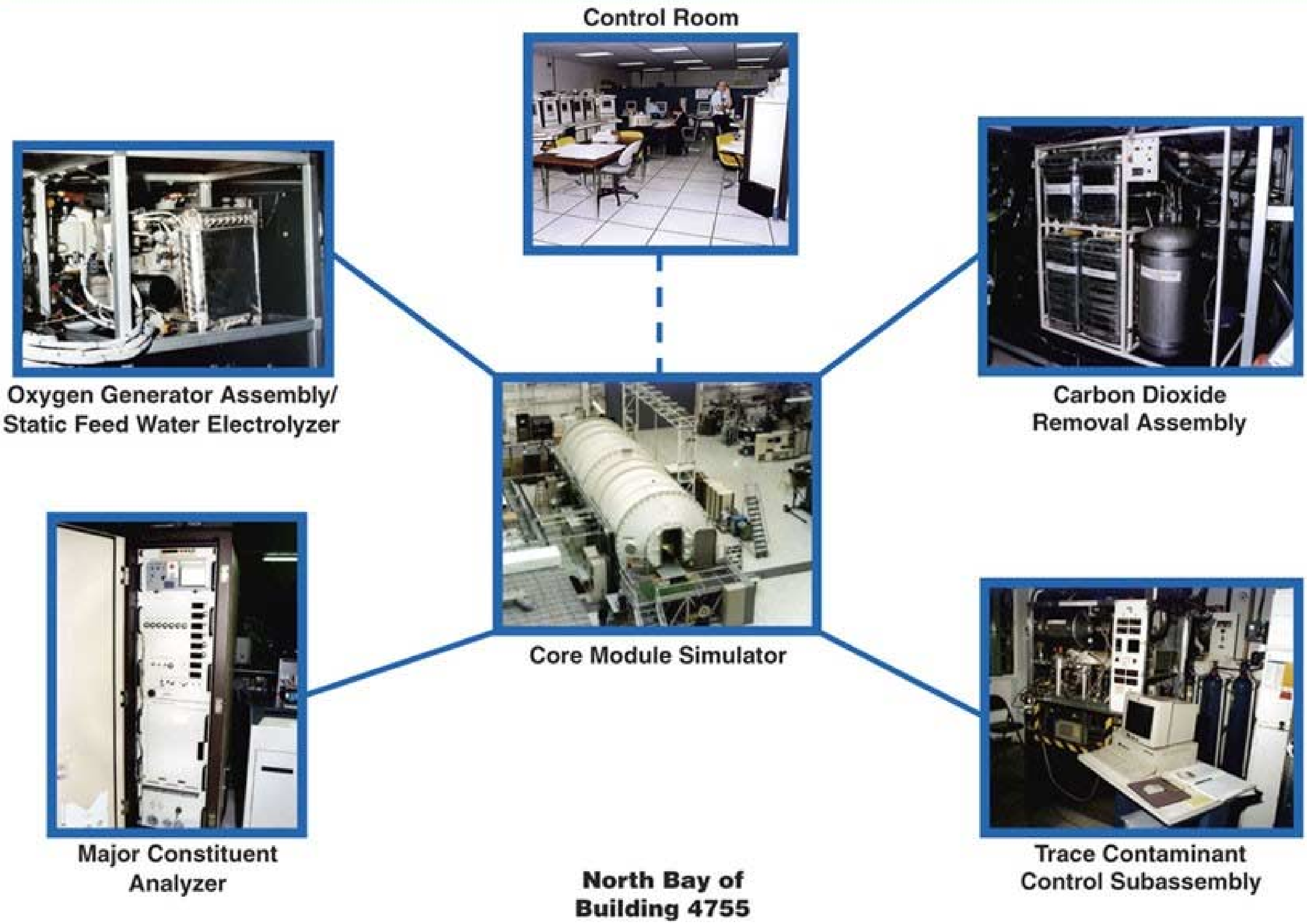
Waste Water Storage Tanks

End-Use Equipment Facility (EEF)

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

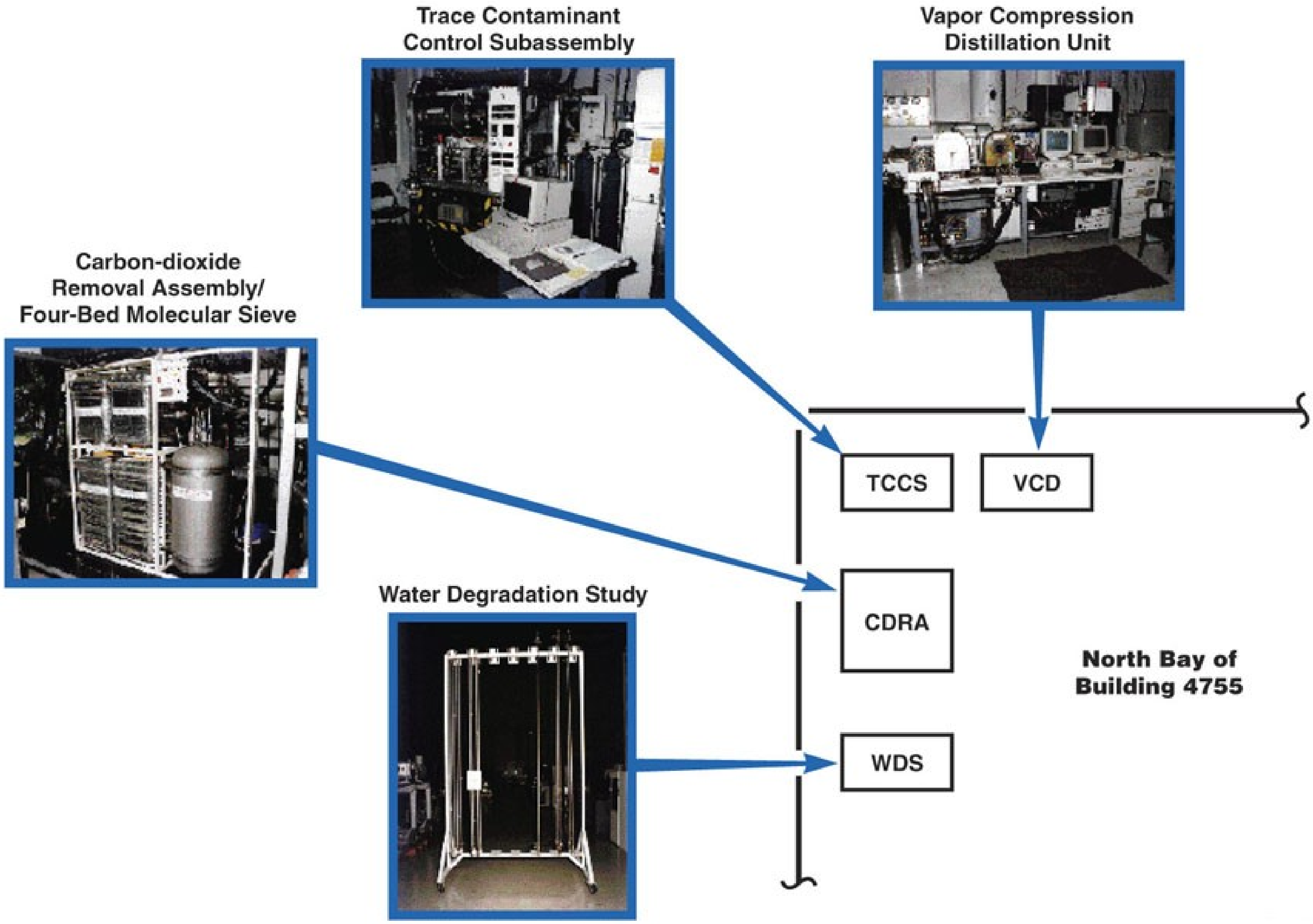
Core Module Simulator

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

Status of ISS Regenerative ECLSS Development

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

- **<u>Technology Selection</u>: based on comparative testing & analysis conducted during Space Station Freedom program**
  - **Selection methodology and rationale documented in “Space Station Freedom Environmental Control and Life Support System Regenerative Subsystem Selection”, NASA TM 4340, February 1992.**
- **<u>Process Demonstration</u>: thousands of hours of ground testing (bench & integrated system).**
- **<u>Flight Demonstration</u>: full size unit delivered for micro-gravity demonstration on STS-107**
- **<u>Life Demonstration</u>: Distillation Assembly compressor, Purge Pump, Fluids Pump life demonstrated during 3,000-17,000 hr life-test programs during SSF.**
- **<u>ISS Development Testing</u>:**
  - **<u>DA Stationary Bowl condensate control</u>: developed & demonstrated heater-based controls**
  - **<u>Materials compatibility</u>: bearings & seals with pretreated urine**
  - **<u>Acoustic Testing</u>: analytical flight predictions based on ORU-level test data show that planned attenuation measures will meet rack acoustic requirements**
  - **<u>Micro-gravity Disturbance</u>: 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**
  - **<u>Hose Gas Permeation</u>: characterize gas introduction through flex hoses & impacts on UPA pressure control/operability**

Urine Processor Assembly Technology Development Status

Flight Projects Directorate

Development Concerns Legend:

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

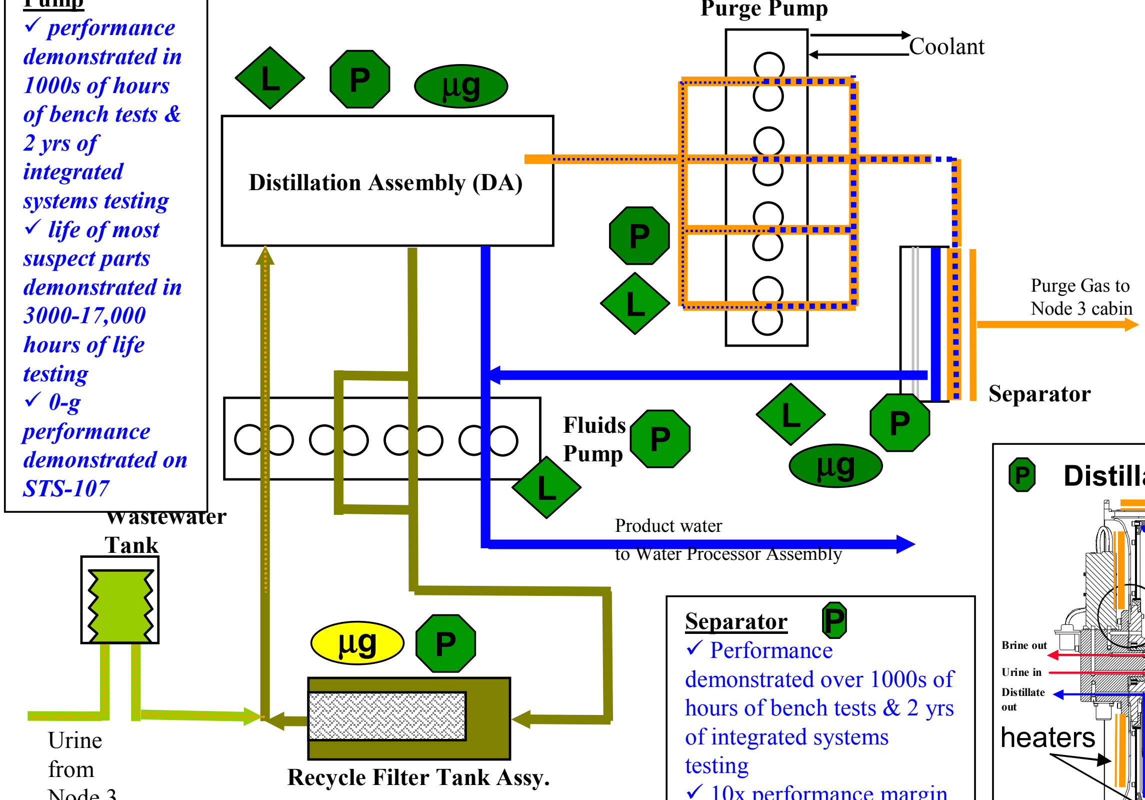
µg Microgravity Sensitivities
L Life
P Performance

Distillation Assy, Purge Pump, Fluids Pump P L

✓ 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 µg

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

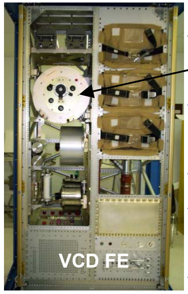
Separator P

✓ Performance demonstrated over 1000s of hours of bench tests & 2 yrs of integrated systems testing

✓ 10x performance margin demonstrated in bench tests

✓ system schematic modified to mitigate impact of failure

µg DA & Separator Micro-g Risk Mitigation



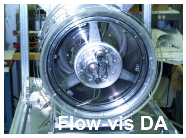
✓ VCD Flight Exp't

✓ Full-scale DA

✓ steady state & transient ops

✓ STS-107

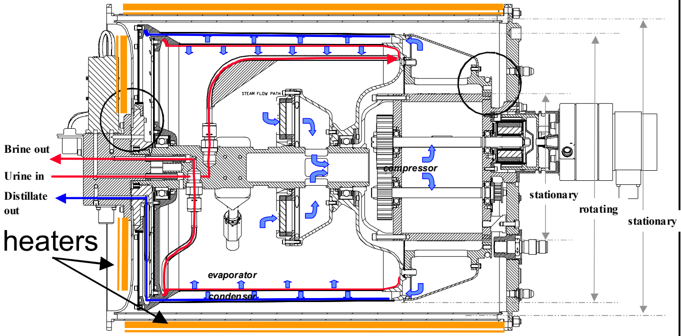
✓ functionality confirmed



✓ KC-135 "flow visualization" testing Feb '02

✓ observed flow patterns & fluid distrib'n

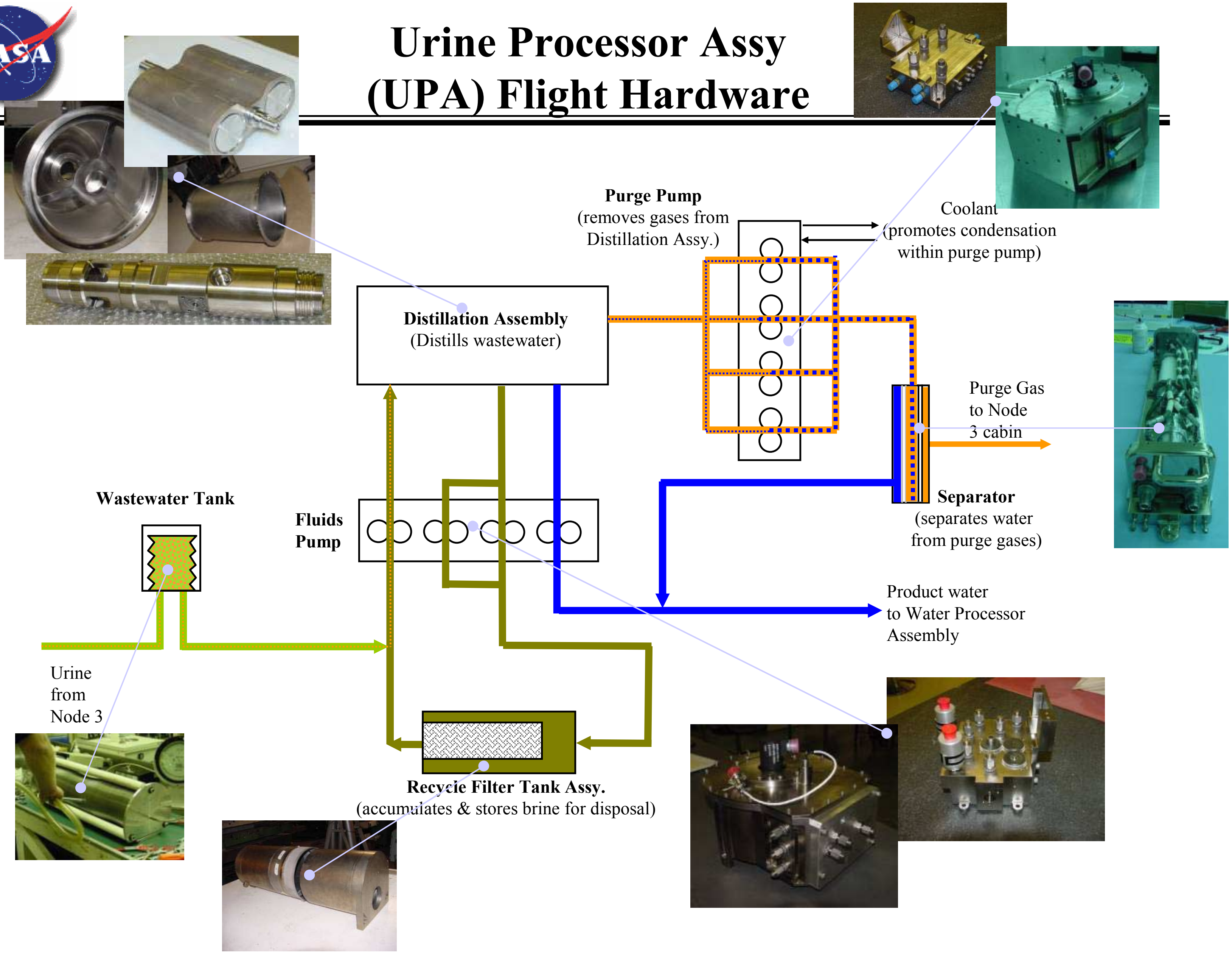
P Distillation Assembly Condensate Control



✓ external heaters added to prevent condensation in stationary bowl

✓ design finalized; release complete 8/02

Urine Processor Assy (UPA) Flight Hardware



Purge Pump
(removes gases from Distillation Assy.)

Coolant
(promotes condensation within purge pump)

Distillation Assembly
(Distills wastewater)

Purge Gas to Node 3 cabin

Separator
(separates water from purge gases)

Wastewater Tank

Fluids Pump

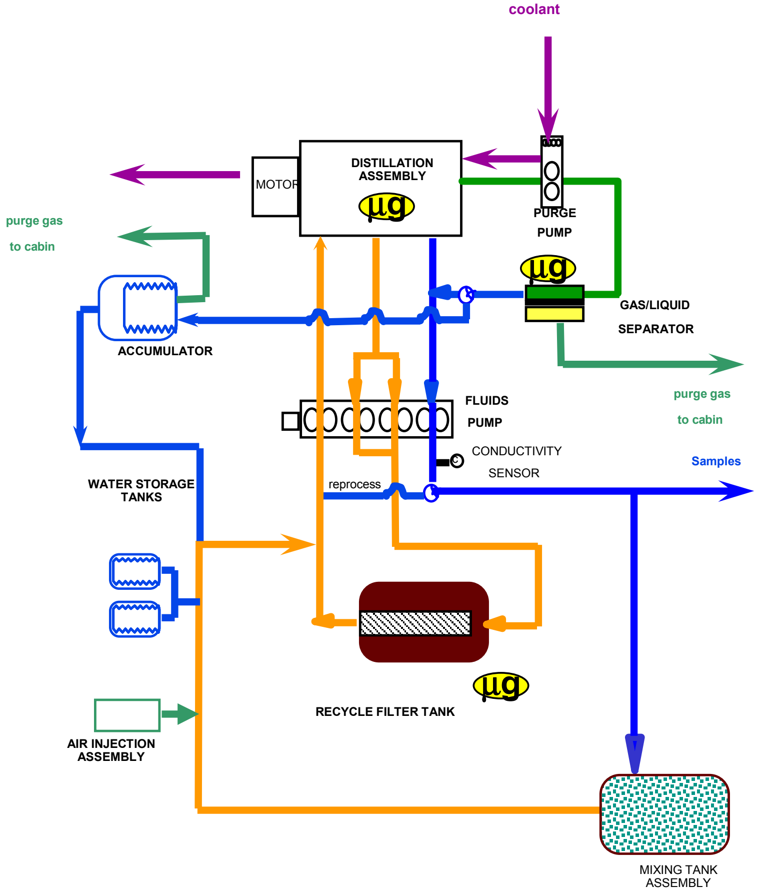
Product water to Water Processor Assembly

Urine from Node 3

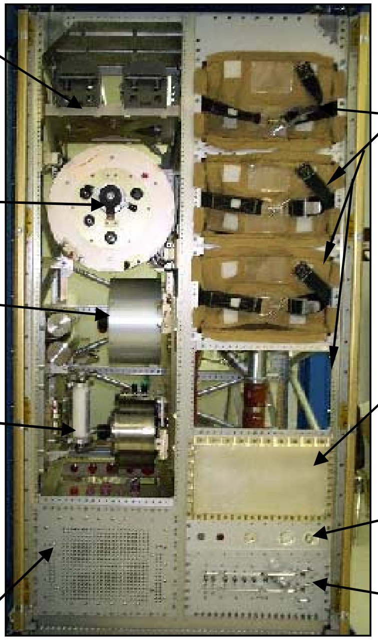
Recycle Filter Tank Assy.
(accumulates & stores brine for disposal)

VCD Flight Experiment
STS-107

VCD FE Schematic



Flight Experiment in Spacehab Rack (prior to acoustic treatment)



RFTA/MTA

Distillation Assy (DA)

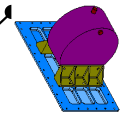
Pressure Control & Pump Assy (PCPA)

Fluids Control & Pump Assy (FCPA)

Control Monitor Instrumentati on

Soft Stowage Assemblies (not associated w/ VCD FE)

Accumulator (hidden)



EPDP

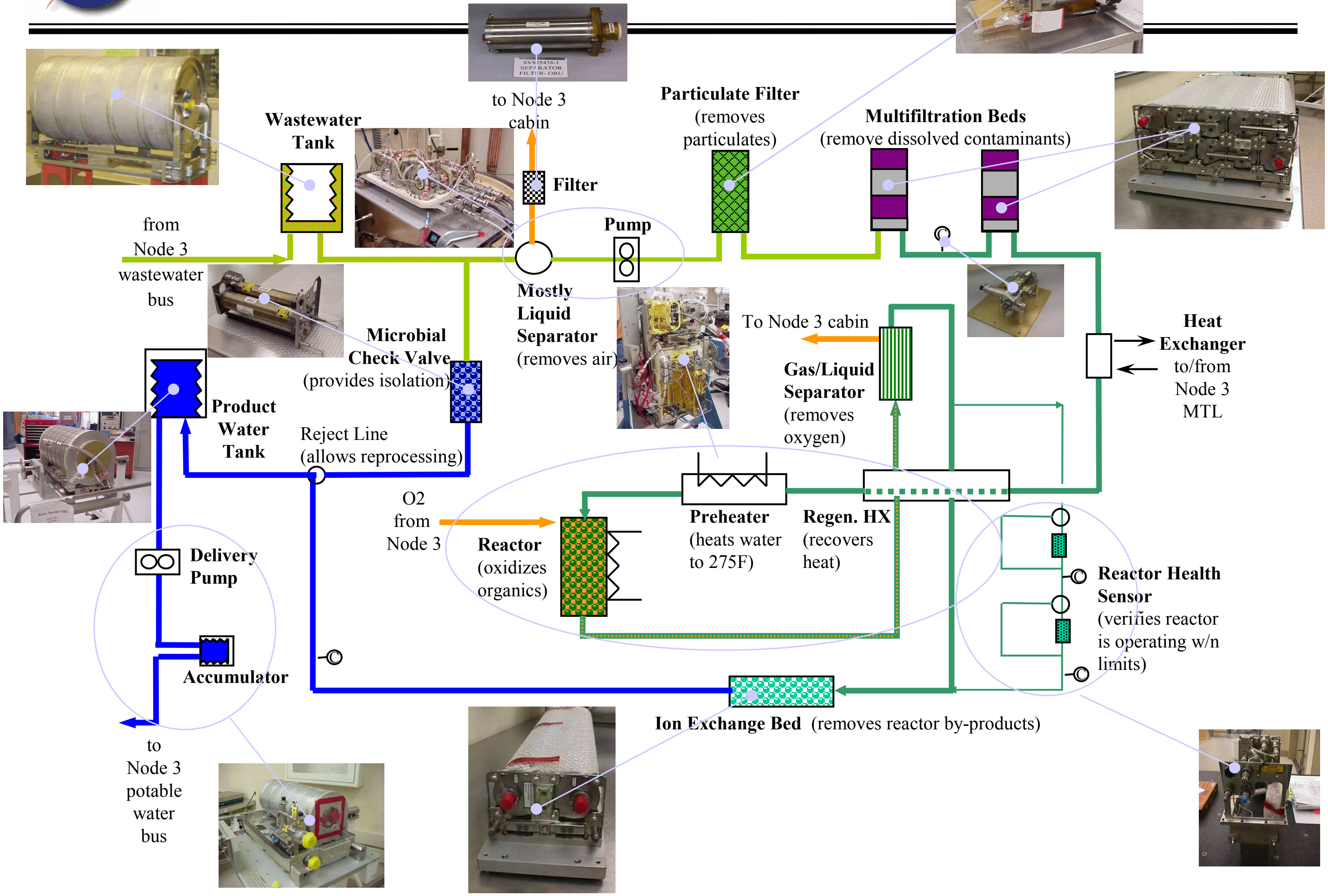
RDU

“Successful Demo”

ISS Water Processor Development History

- **Technology Selection**: based on comparative testing & analysis conducted during SSF
  - Selection methodology and rationale documented in NASA TM 4340, February 1992.
- **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
  - O_2 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



from Node 3 wastewater bus

Wastewater Tank

to Node 3 cabin

Filter

Particulate Filter (removes particulates)

Multifiltration Beds (remove dissolved contaminants)

Pump

Mostly Liquid Separator (removes air)

Microbial Check Valve (provides isolation)

Product Water Tank

Reject Line (allows reprocessing)

To Node 3 cabin

Gas/Liquid Separator (removes oxygen)

Heat Exchanger to/from Node 3 MTL

O2 from Node 3

Reactor (oxidizes organics)

Preheater (heats water to 275F)

Regen. HX (recovers heat)

Reactor Health Sensor (verifies reactor is operating w/n limits)

Delivery Pump

Accumulator

to Node 3 potable water bus

Ion Exchange Bed (removes reactor by-products)

ISS OGA Development History (page 1)

- **Technology Selection**: based on comparative testing & analysis conducted during Space Station Freedom program
  - Selection methodology and rationale documented in NASA TM 4340, February 1992.
- **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

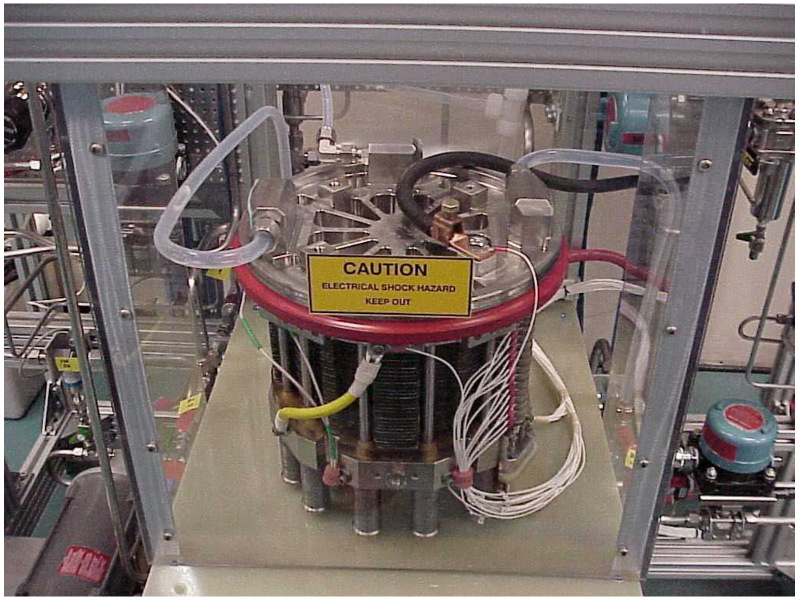
ISS OGA Development History (page 2)

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

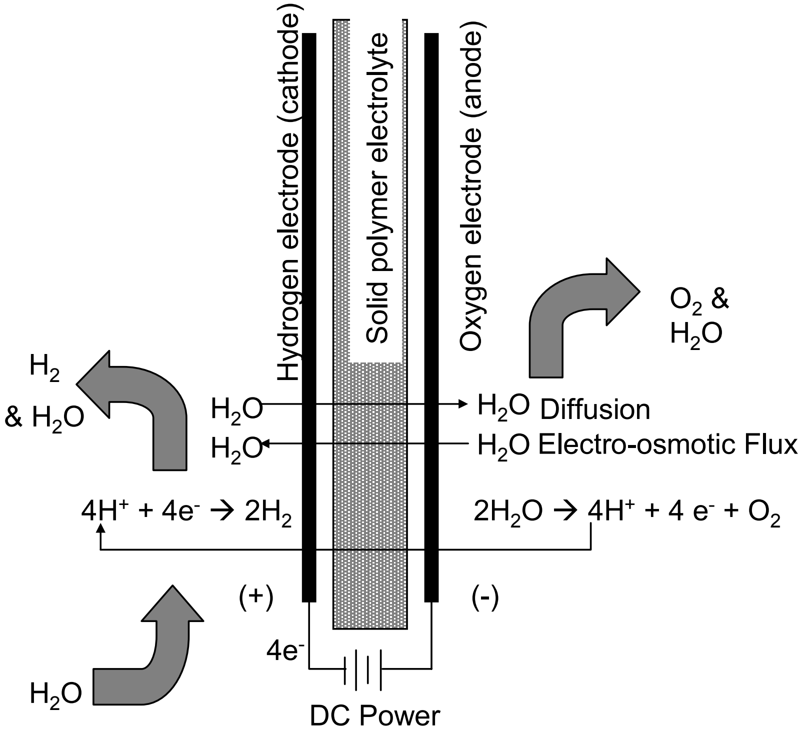
International Space Station Oxygen Generator System (OGS) Description

- Core Technology: Solid Polymer Electrolysis (cathode feed)

Cell Stack



Electrolysis Cell Reactions



Hydrogen electrode (cathode)

Solid polymer electrolyte

Oxygen electrode (anode)

H_2 & H_2O

O_2 & H_2O

H_2O → H_2O Diffusion

H_2O ← H_2O Electro-osmotic Flux

$4H^+ + 4e^- \rightarrow 2H_2$

$2H_2O \rightarrow 4H^+ + 4\,e^- + O_2$

(+)

(-)

$4e^-$

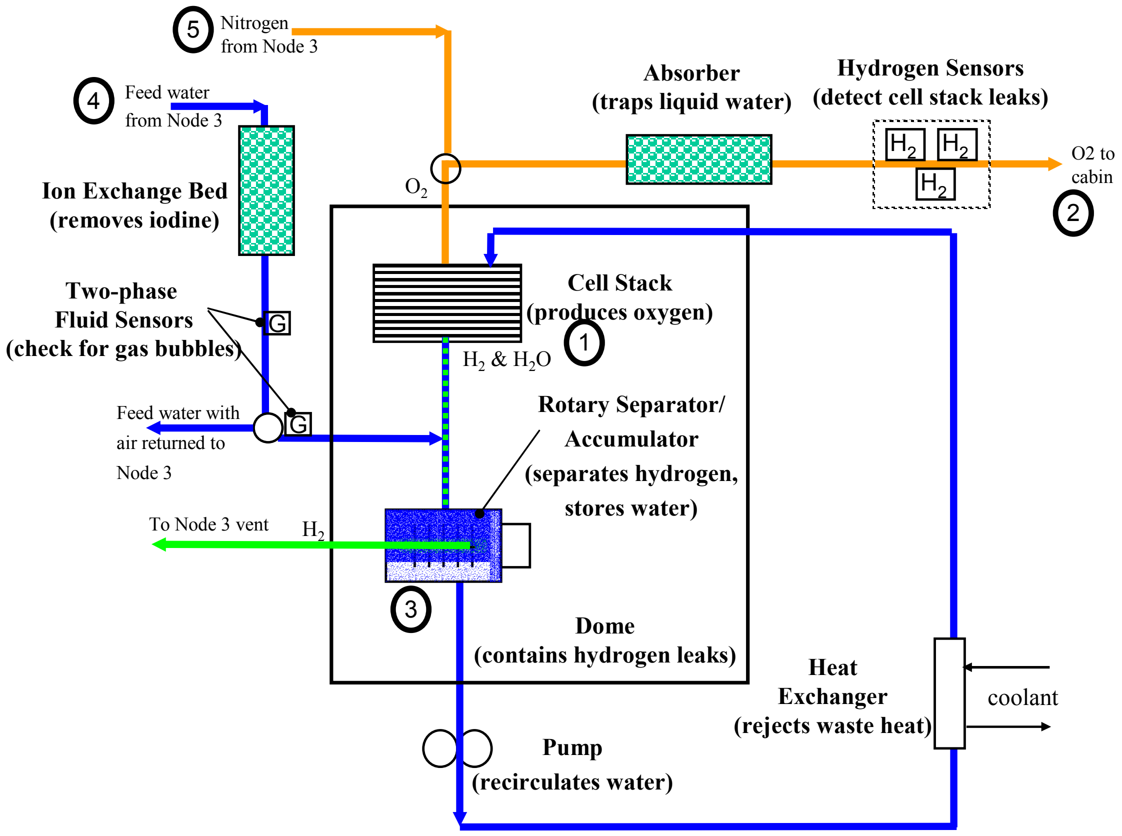
H_2O

DC Power

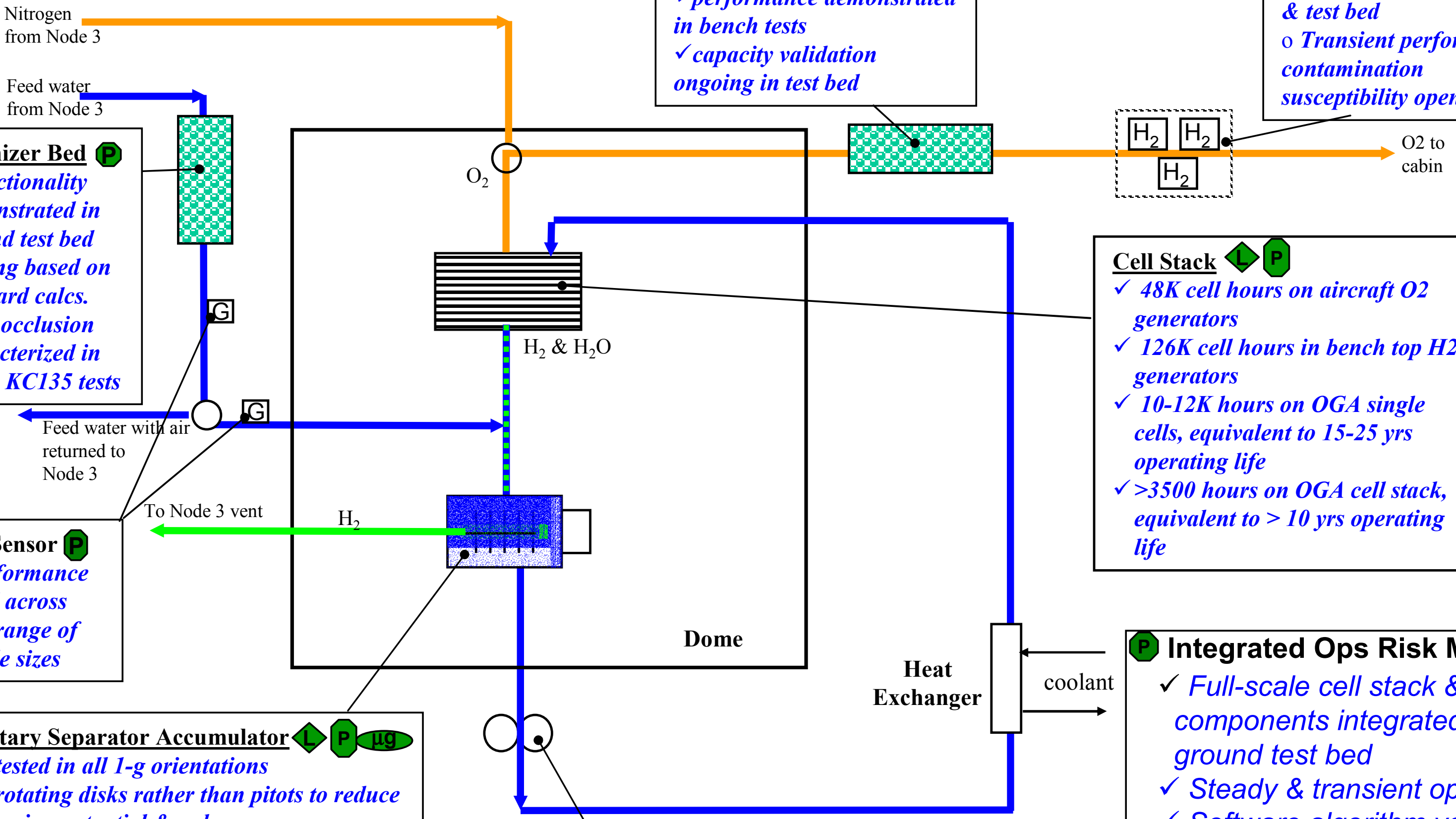
ISS Oxygen Generator System Description

Integrated Process

1. Oxygen & hydrogen produced in 28-cell stack
2. O_2 delivered to cabin
3. 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



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

H_2 Sensor P
✓ *general performance demonstrated in bench tests & test bed*
o *Transient performance & contamination susceptibility open issues*

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

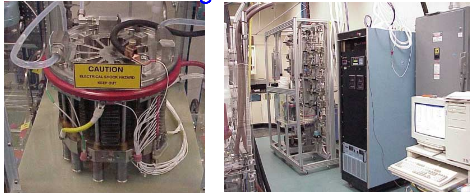
Cell Stack L P
✓ *48K cell hours on aircraft O2 generators*
✓ *126K cell hours in bench top H2 generators*
✓ *10-12K hours on OGA single cells, equivalent to 15-25 yrs operating life*
✓*>3500 hours on OGA cell stack, equivalent to > 10 yrs operating life*

Gas Sensor P
✓*performance tested across wide range of bubble sizes*

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

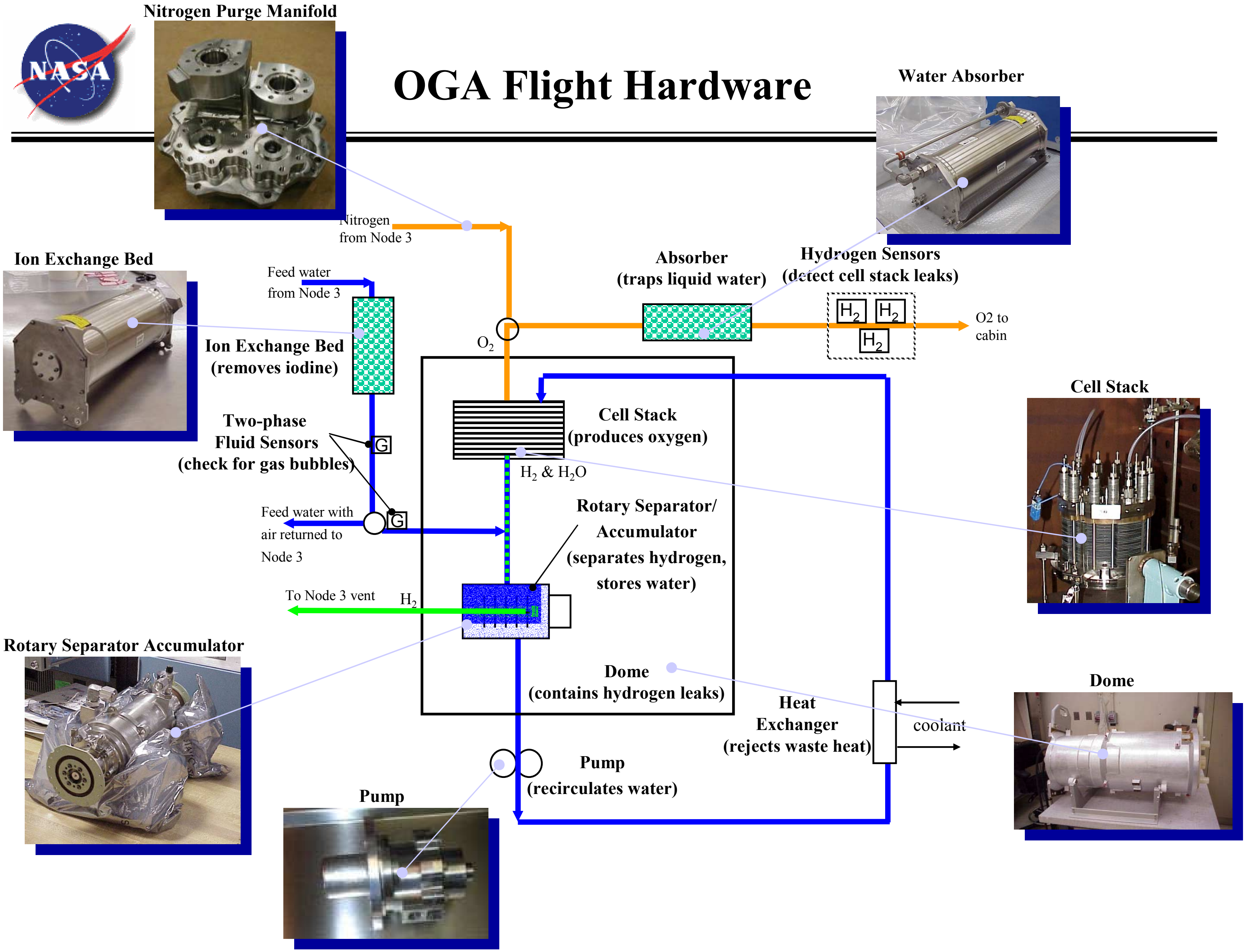
Pump L
✓***pump: dev pump 2.4x life tested w/o degradation***
o ***pump: WPA qual pump cycle failures; redesign complete, retest in 6/03***
✓ ***motor: 1.3x life tested w/o degradation***

P **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
µg Microgravity Sensitivities
L Life
P Performance

OGA Flight Hardware



Nitrogen Purge Manifold

Water Absorber

Ion Exchange Bed

Nitrogen from Node 3

Feed water from Node 3

Absorber (traps liquid water)

Hydrogen Sensors (detect cell stack leaks)

H_2 H_2 H_2

O2 to cabin

O_2

Ion Exchange Bed (removes iodine)

Cell Stack

Cell Stack (produces oxygen)

Two-phase Fluid Sensors (check for gas bubbles)

G

G

H_2 & H_2O

Rotary Separator/ Accumulator (separates hydrogen, stores water)

Feed water with air returned to Node 3

To Node 3 vent

H_2

Rotary Separator Accumulator

Dome (contains hydrogen leaks)

Dome

Heat Exchanger (rejects waste heat)

coolant

Pump (recirculates water)

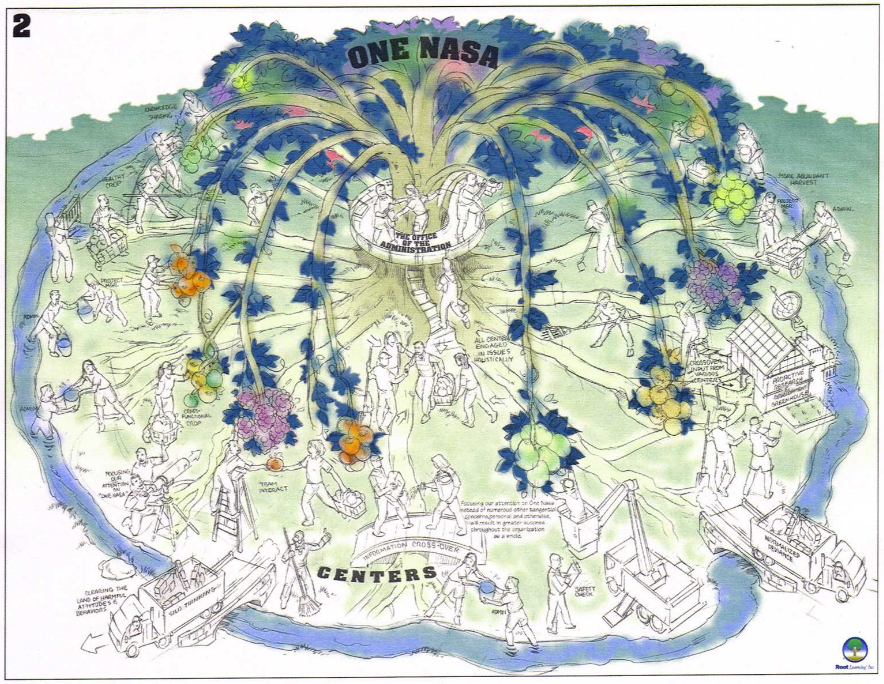
Pump

What's Next?

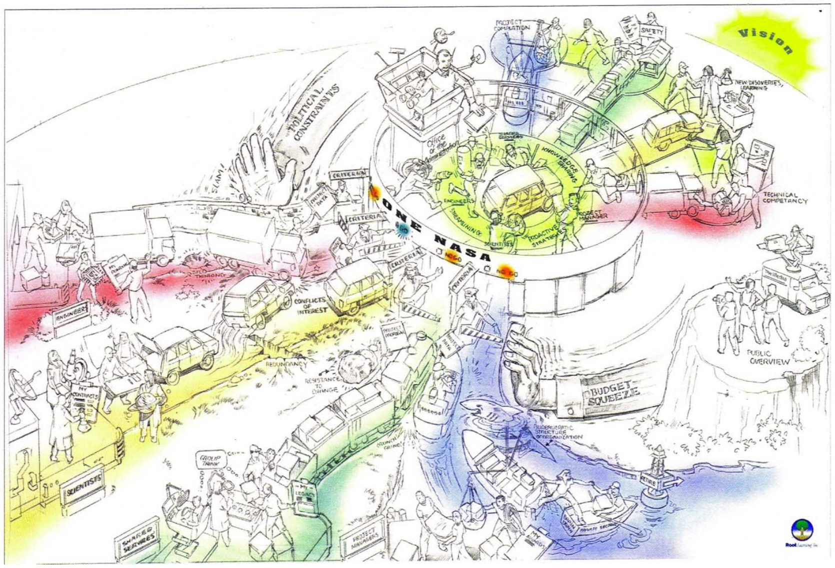
Advanced ECLSS for New Space Initiative

Strategic Roadmap to Success

THIS!



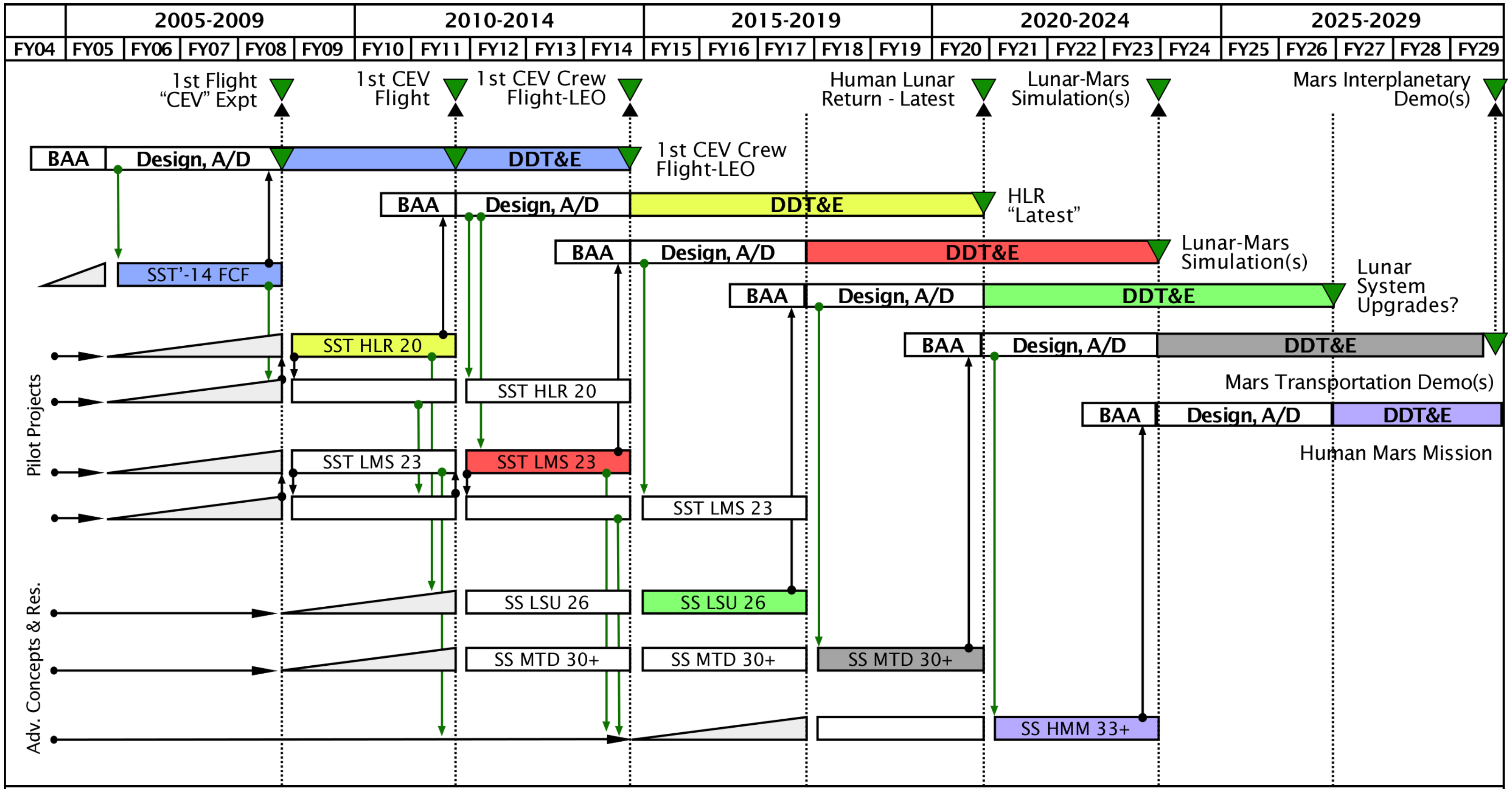
NOT THIS!



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

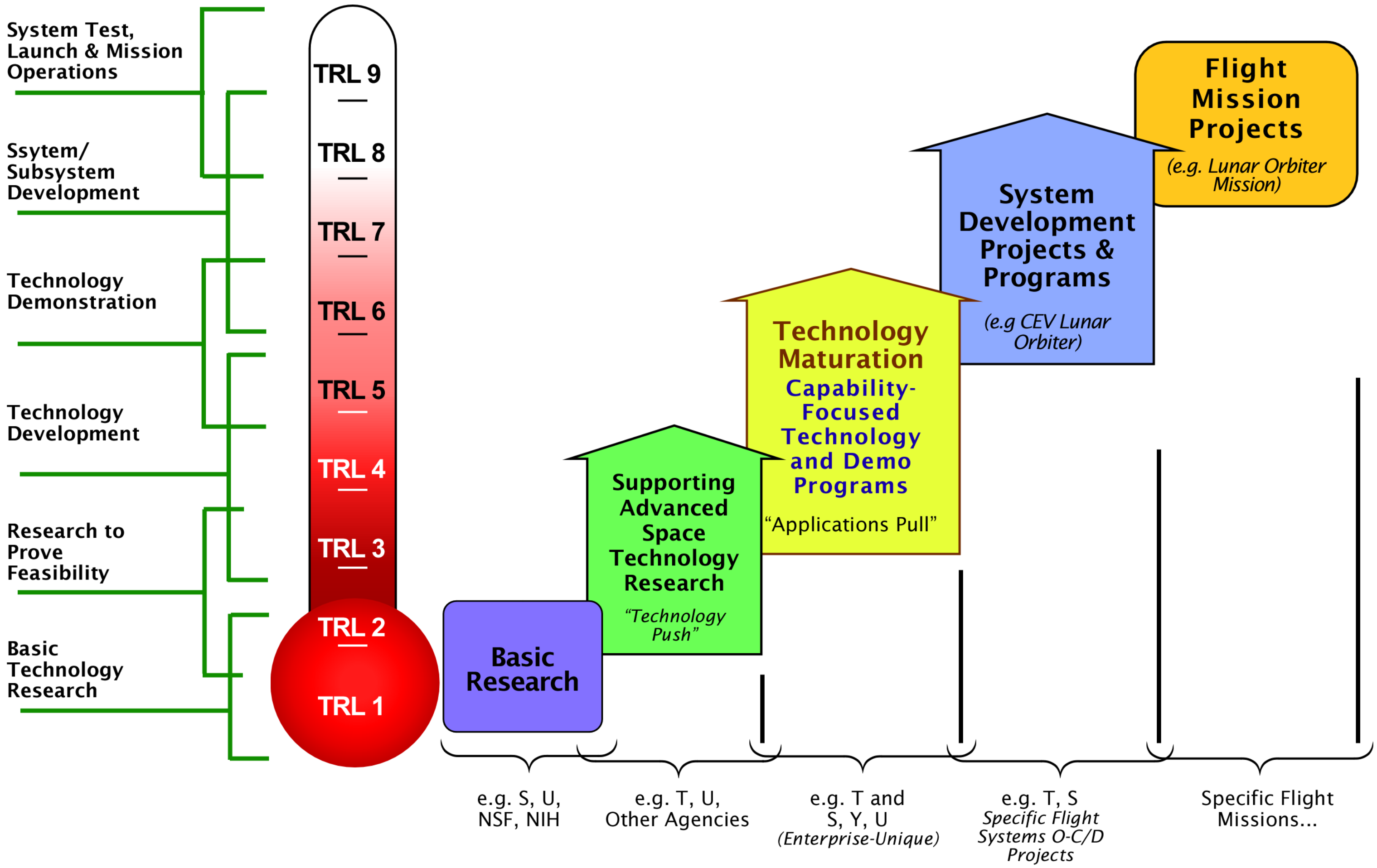


BAA - Broad Area Announcement
DDT&E - Design, Development, Test & Eng.
A/D - Advanced Development

HLR - Human Lunar Return
LMS - Lunar-Mars Simulator(s)
LSS - Lunar System Simulator(s)

LSU - Lunar System Upgrades
SST - Sub-System Level-Impact Technology
SS - System-of-System Level Impact Technology

Code T/H&RT Strategic Technology/Systems Model



System Test, Launch & Mission Operations

Ssytem/ Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

TRL 9

TRL 8

TRL 7

TRL 6

TRL 5

TRL 4

TRL 3

TRL 2

TRL 1

Basic Research

Supporting Advanced Space Technology Research

"Technology Push"

Technology Maturation

Capability-Focused Technology and Demo Programs

"Applications Pull"

System Development Projects & Programs

(e.g CEV Lunar Orbiter)

Flight Mission Projects

(e.g. Lunar Orbiter Mission)

e.g. S, U, NSF, NIH

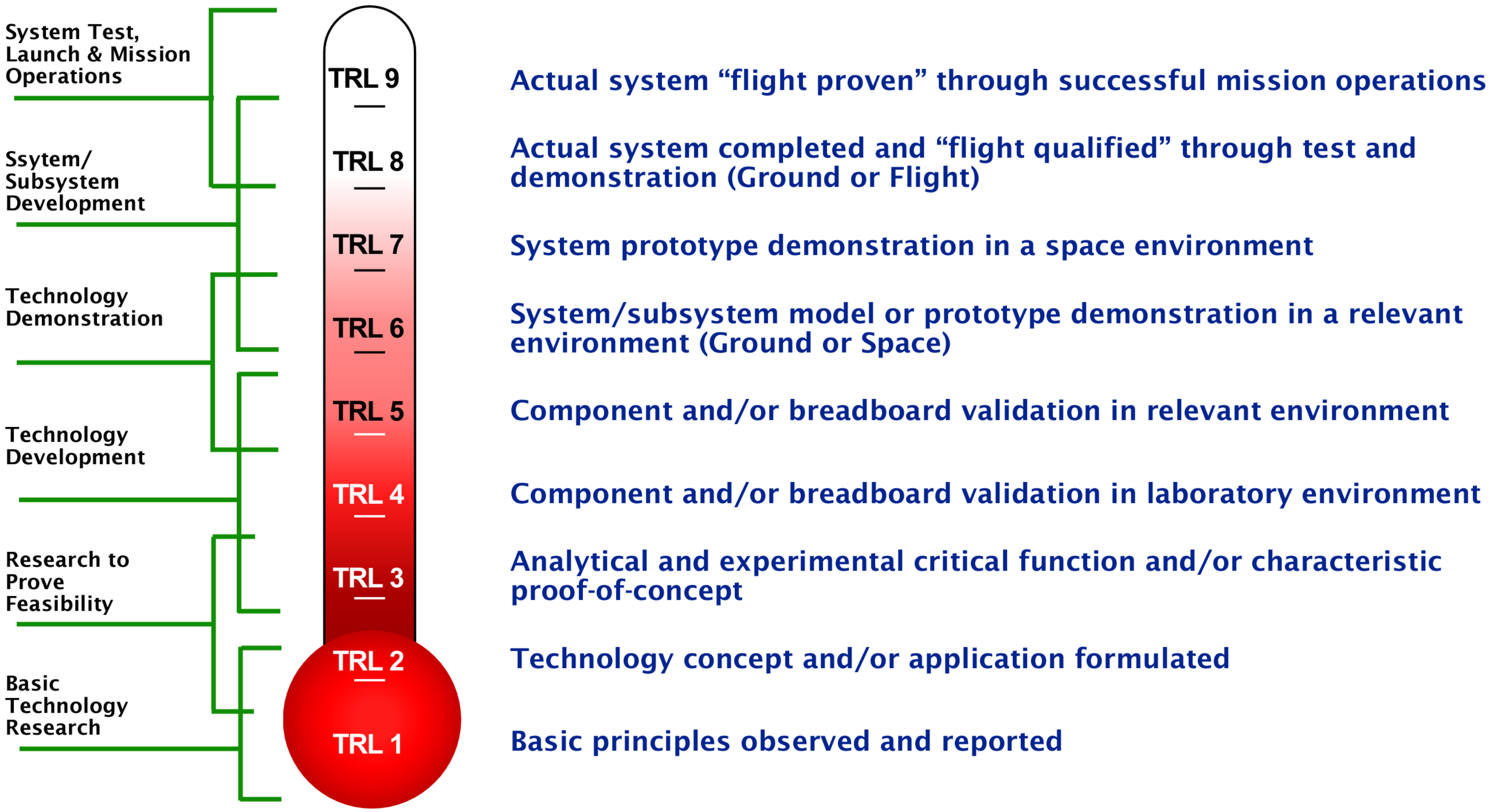
e.g. T, U, Other Agencies

e.g. T and S, Y, U *(Enterprise-Unique)*

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

Specific Flight Missions...

Technology Readiness Levels (TRLs)



System Test, Launch & Mission Operations

Ssytem/ Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

TRL 9 Actual system “flight proven” through successful mission operations

TRL 8 Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)

TRL 7 System prototype demonstration in a space environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

TRL 5 Component and/or breadboard validation in relevant environment

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2 Technology concept and/or application formulated

TRL 1 Basic principles observed and reported

Defining ECLSS Technology Development Terminology

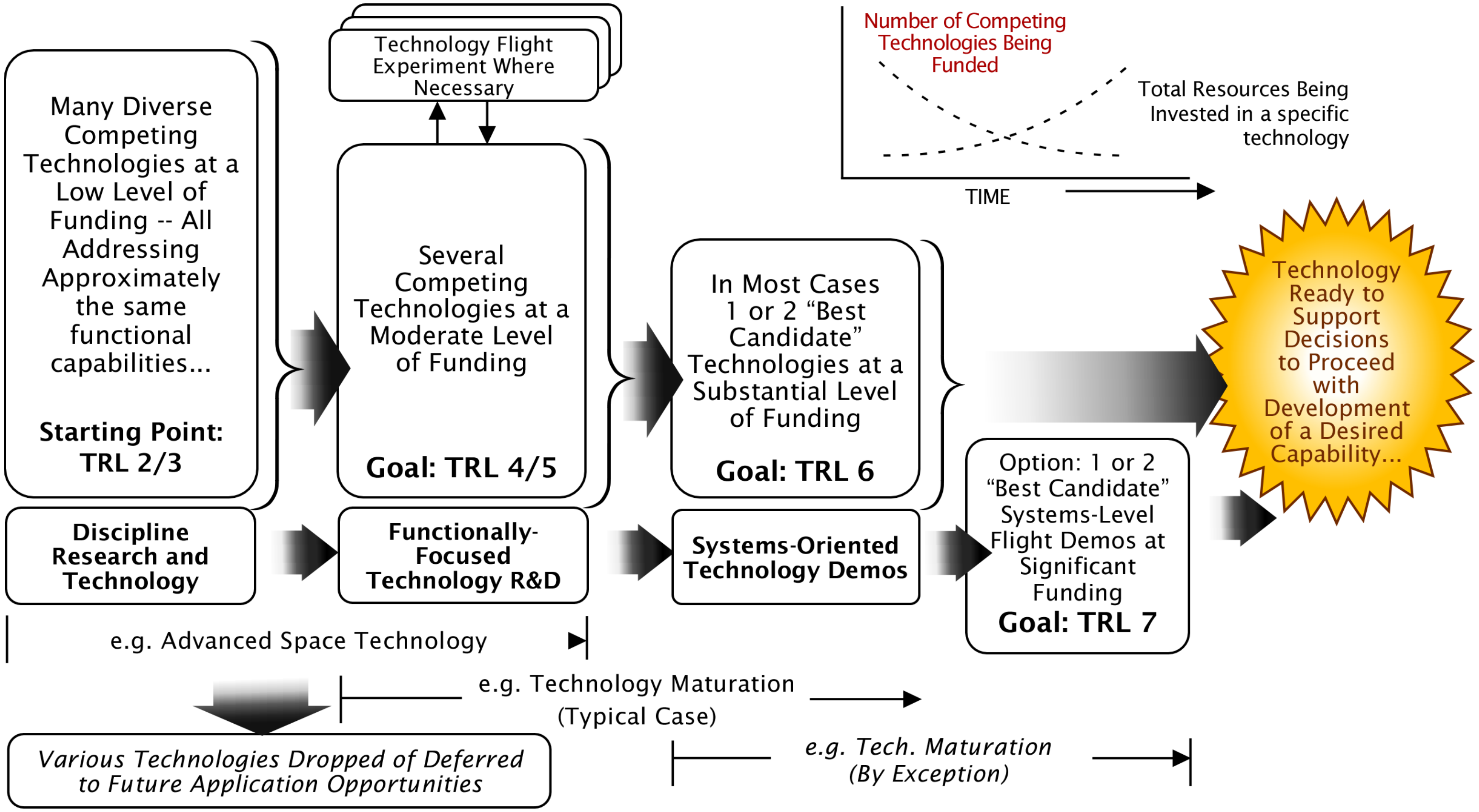
(Calendar Year 2004)

- **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

Discipline Research and Technology

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

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

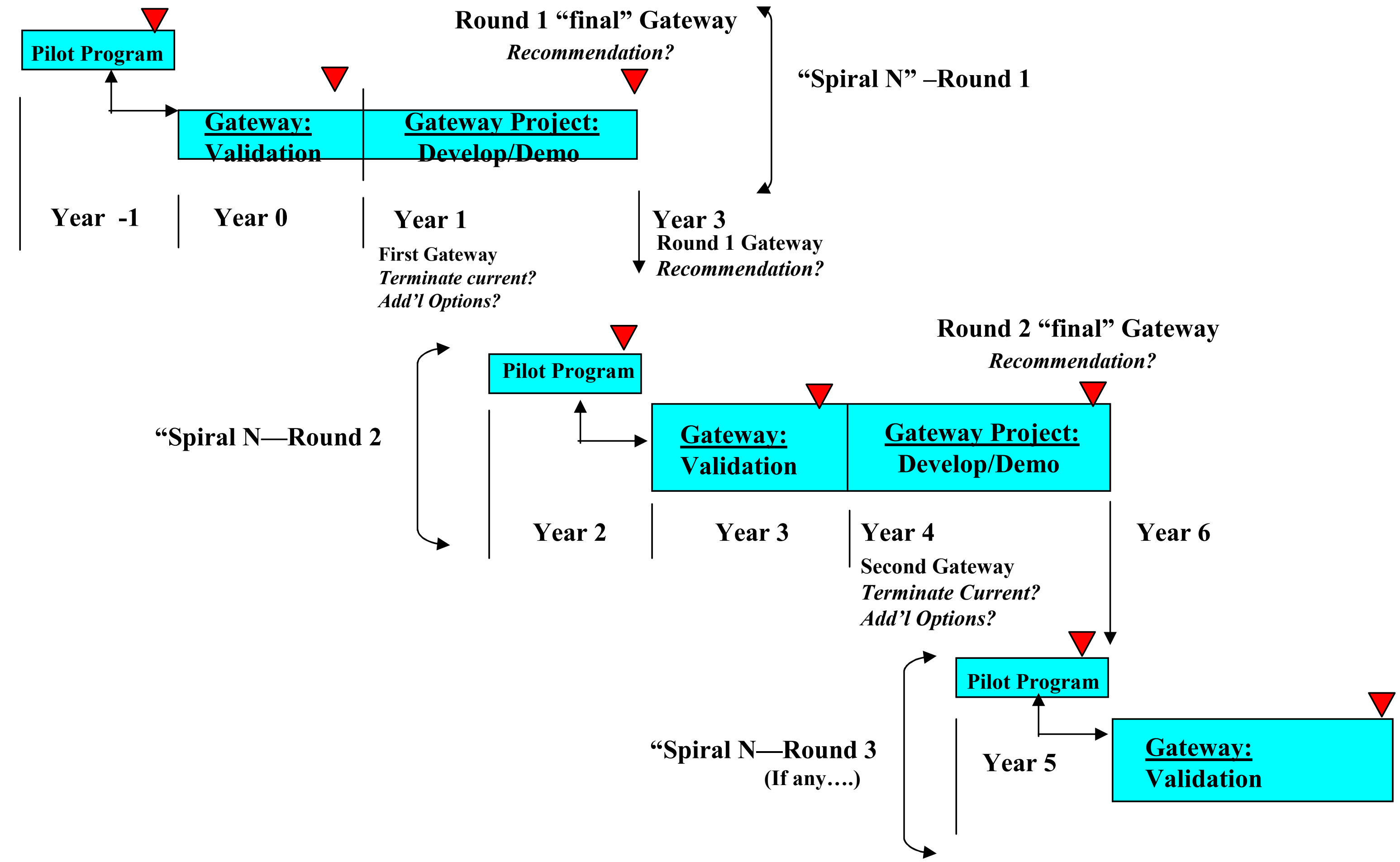
e.g. Advanced Space Technology

e.g. Technology Maturation (Typical Case)

e.g. Tech. Maturation (By Exception)

Various Technologies Dropped of Deferred to Future Application Opportunities

Code T Implementing a Competition-Rich R&D Portfolio Phasing Approach
(Typical Life Cycle of a Technology Project within HR&T)



Round 1 "final" Gateway

Recommendation?

"Spiral N" –Round 1

Pilot Program

Gateway: Validation

Gateway Project: Develop/Demo

Year -1

Year 0

Year 1

First Gateway

Terminate current?

Add'l Options?

Year 3

Round 1 Gateway

Recommendation?

Round 2 "final" Gateway

Recommendation?

"Spiral N—Round 2

Pilot Program

Gateway: Validation

Gateway Project: Develop/Demo

Year 2

Year 3

Year 4

Second Gateway

Terminate Current?

Add'l Options?

Year 6

"Spiral N—Round 3

(If any….)

Pilot Program

Year 5

Gateway: Validation

Code T/H&RT Strategic Technical Challenges Regarding "System-of-System" Level Issues.

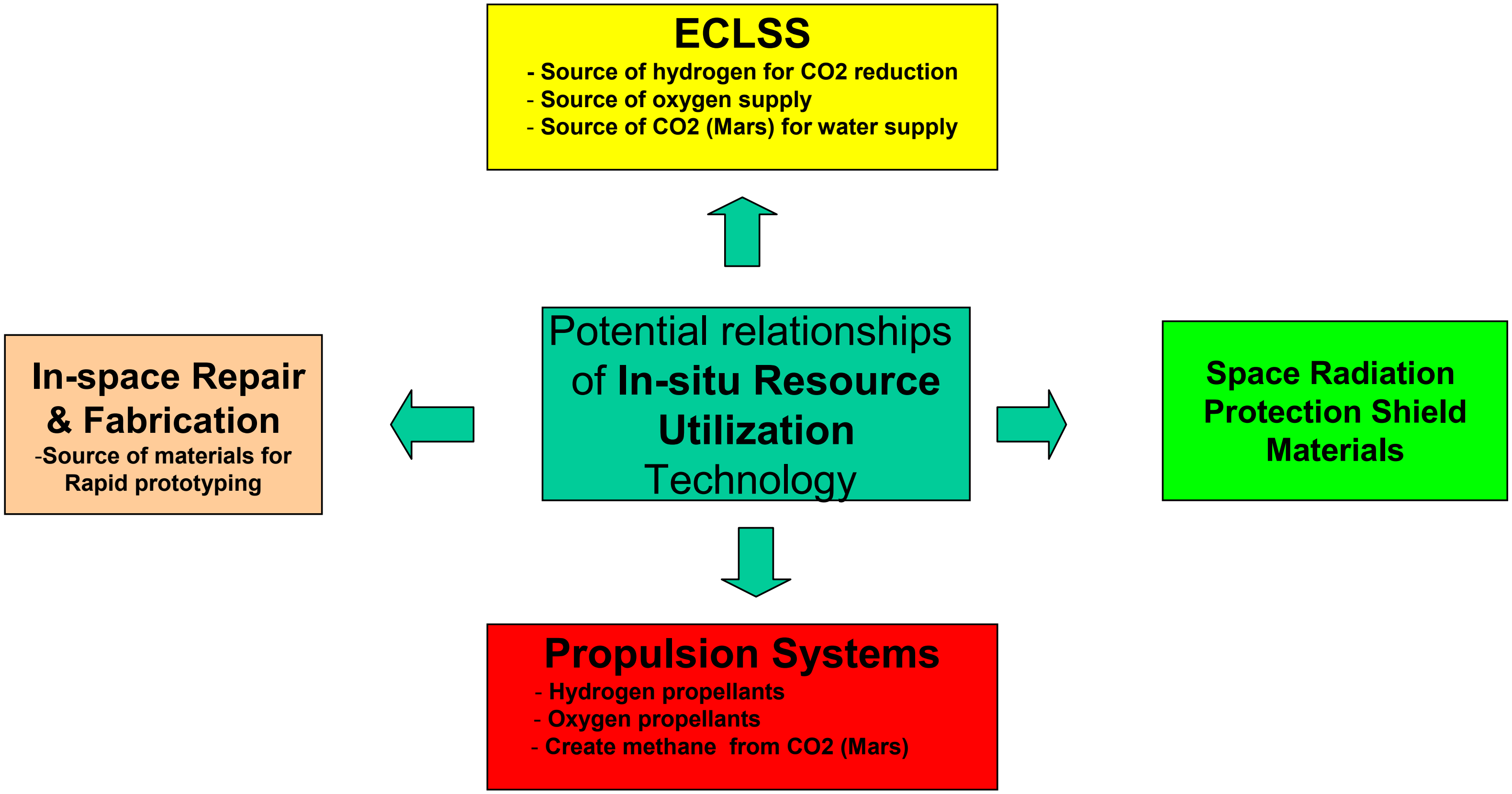
- **Margins and redundancy** in diverse subsystems, systems and systems-of-systems---but particularly those that must execute mission critical operations (such as transportation or life support) with the prospect of significant improvements in robustness in operations, reliability and safety.
- **Reusability**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

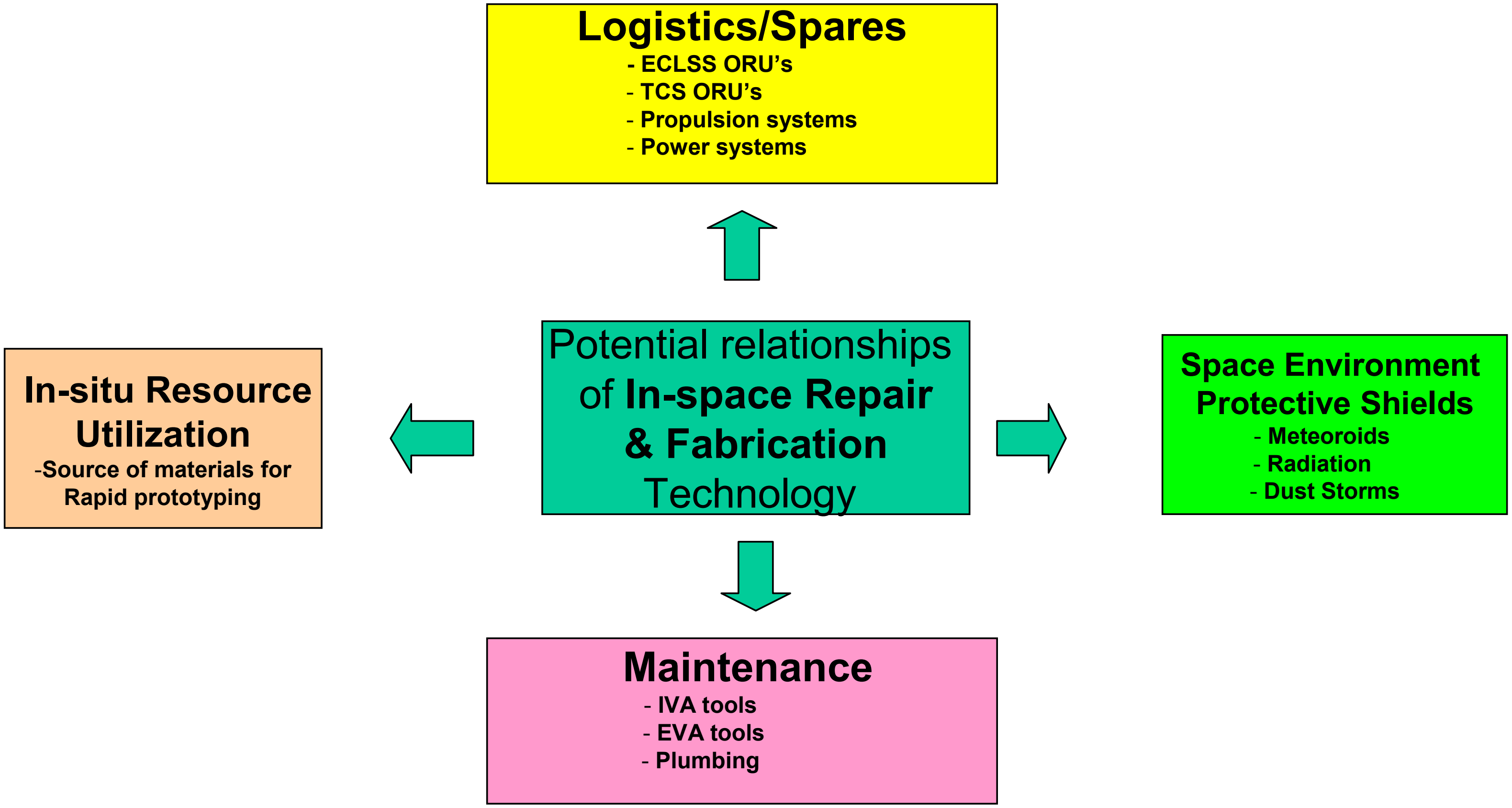
Space Radiation Protection Shield Materials

Propulsion Systems

- Hydrogen propellants
- Oxygen propellants
- Create methane from CO2 (Mars)

ECLSS Partnership with *In-space Repair & Fabrication* Proposals

(Surface Manufacturing and Construction Systems)



Logistics/Spares

- ECLSS ORU's
- TCS ORU's
- Propulsion systems
- Power systems

In-situ Resource Utilization

-Source of materials for Rapid prototyping

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

Space Environment Protective Shields

- Meteoroids
- Radiation
- Dust Storms

Maintenance

- IVA tools
- EVA tools
- Plumbing

ECLSS Partnership with *Lab-on-a-Chip* Research Proposals

(Advanced Sensor Concepts)

Potential benefits of **Lab-on-a-chip** Technology

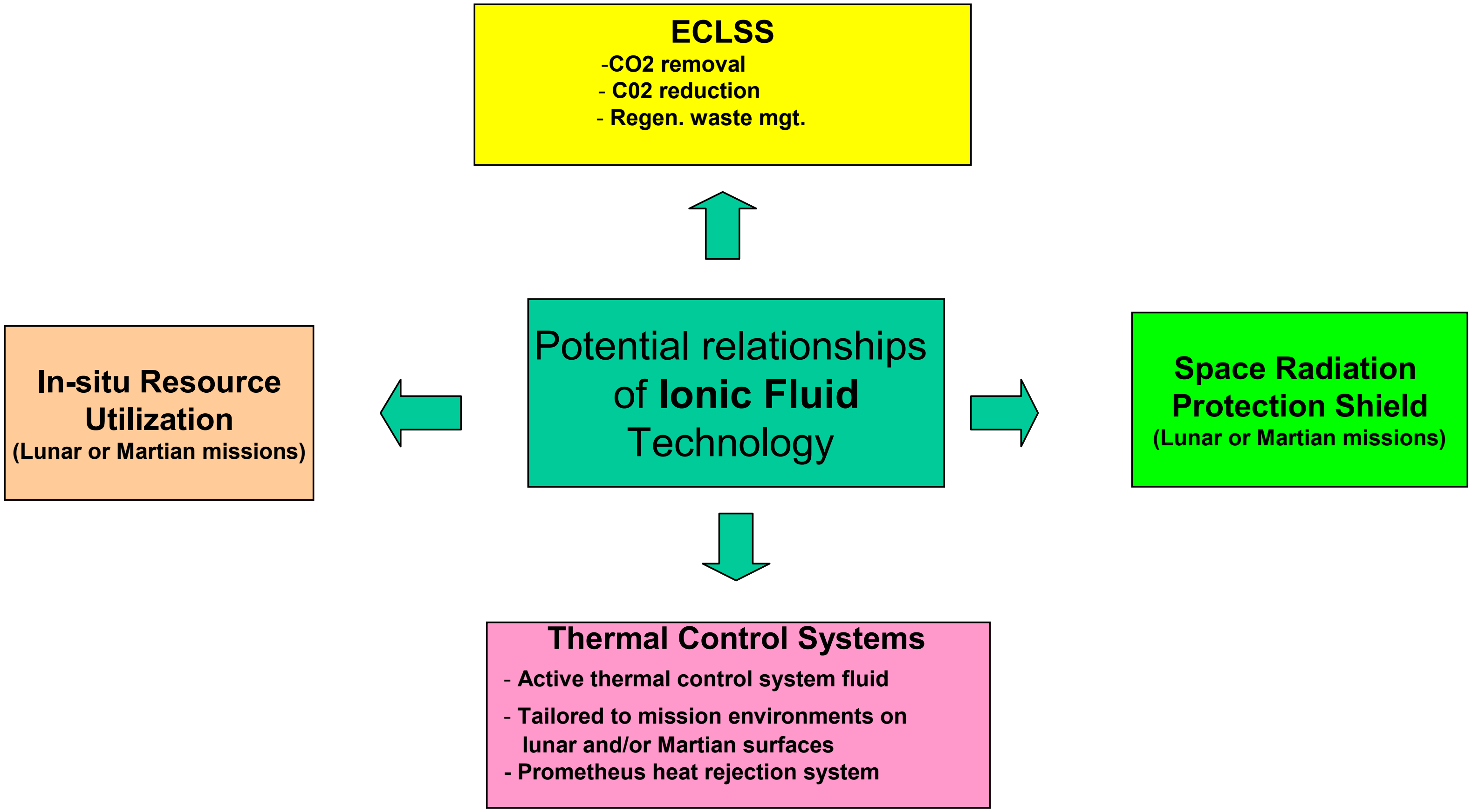
- **Advanced atmosphere monitoring**
  - **Habitable environments**
  - **Martian surface environments**
- **Microbial monitoring of TCS fluids**
- **Microbial monitoring of ECLSS water systems**
- **Specific trace contaminant monitoring**
- **Portable systems**
- **Reliable**
- **Lower weight**
- **Flexible applications (upgraded in-situ)**

How Can NASA Use Ionic Liquids?

- In-Situ Resource Utilization or Analysis?
- CO2 Removal/O2 Release?
- Space Lubricants?
- Biomaterials Processing?
- New Materials?
- Thermal Fluids?
- Radiation Shielding?
- Fuel Cells?
- Batteries?
- Energetic Liquid Propellants?
- Ion Drive Propulsion?

ECLSS Partnership with *Ionic Fluid* Technology Proposals

(Advanced Materials)



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

Potential relationships of **Ionic Fluid** Technology

In-situ Resource Utilization
(Lunar or Martian missions)

Space Radiation Protection Shield
(Lunar or Martian missions)

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

FIXED PACKED BED REACTORS IN REDUCED GRAVITY

Brian J. Motil
NASA Glenn Research Center
Cleveland, OH 44135

Vemuri Balakotaiah
Department of Chemical Engineering
University of Houston
Houston, TX 77204

Yasuhiro Kamotani
Department of Mechanical and Aerospace Engineering,
Case Western Reserve University
Cleveland, OH

Mark J. McCready
Department of Chemical Engineering
University of Notre Dame
Notre Dame, IN

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_La and k_Ga (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

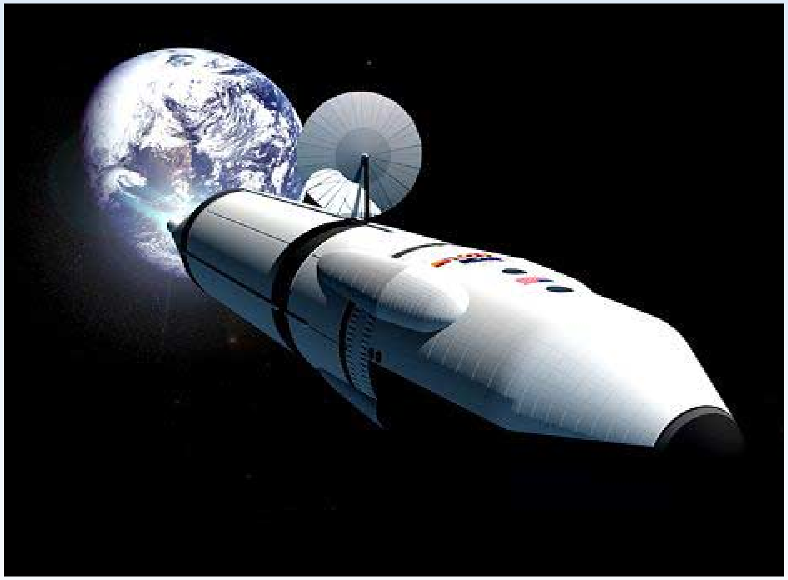
Brian J. Motil

NASA Glenn Research Center
Cleveland, Ohio

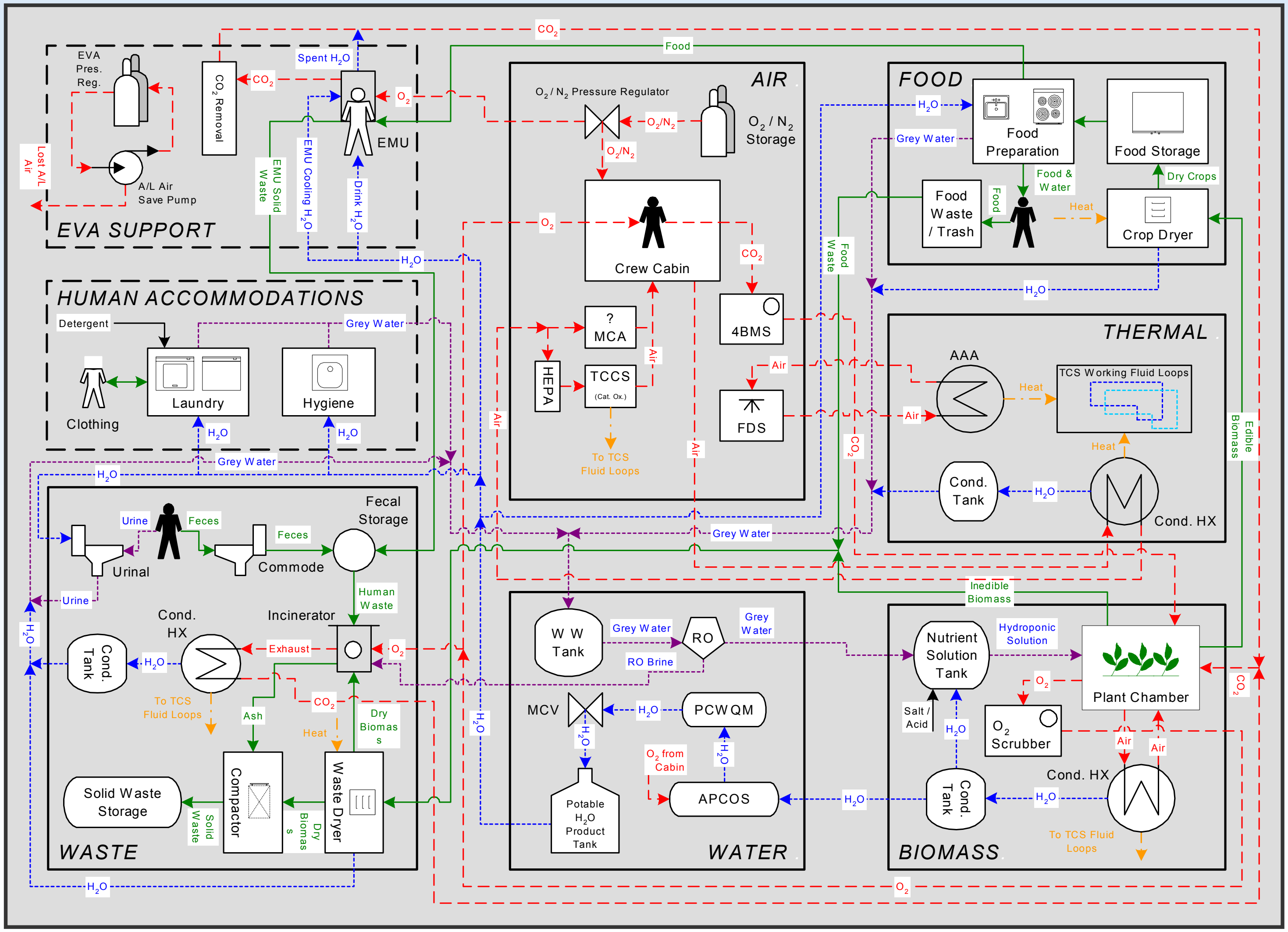
Strategic Research to Enable NASA's Exploration Missions

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.


EVA SUPPORT
EVA Pres. Reg.
Lost A/L Air
A/L Air Save Pump
CO₂ Removal
CO₂
Spent H₂O
O₂
EMU
EMU Solid Waste
EMU Cooling H₂O
Drink H₂O
H₂O
Food
HUMAN ACCOMMODATIONS
Detergent
Clothing
Laundry
Hygiene
Grey Water
H₂O
AIR
O₂ / N₂ Pressure Regulator
O₂/N₂
O₂ / N₂ Storage
Crew Cabin
O₂
CO₂
MCA
TCCS
(Cat. Ox.)
HEPA
4BMS
FDS
Air
To TCS Fluid Loops
FOOD
Food Preparation
Food Storage
Food & Water
Dry Crops
Food Waste / Trash
Food
Heat
Crop Dryer
Food Waste
THERMAL
AAA
TCS Working Fluid Loops
Heat
Cond. Tank
Cond. HX
Edible Biomass
WASTE
Fecal Storage
Urine
Feces
Urinal
Commode
Human Waste
Cond. HX
Incinerator
Exhaust
Cond. Tank
To TCS Fluid Loops
Ash
Heat
Dry Biomass
Solid Waste Storage
Compactor
Solid Waste
Waste Dryer
WATER
W W Tank
Grey Water
RO
RO Brine
MCV
PCWQM
Potable H₂O Product Tank
O₂ from Cabin
APCOS
BIOMASS
Inedible Biomass
Nutrient Solution Tank
Hydroponic Solution
Plant Chamber
Salt / Acid
O₂ Scrubber
Cond. HX
Cond. Tank
To TCS Fluid Loops
Air

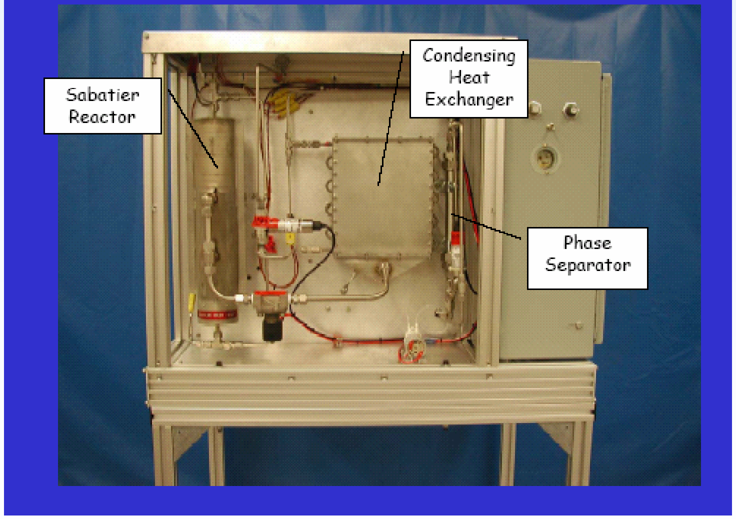
Mission Drives Life Support Requirements

	Lunar Transit Vehicle	Lunar Outpost (LO)	Mars Transit Vehicle	Mars Habitat
Duration (Human Tended)	7 – 14 days (Roundtrip)	1 – 18 months	12 – 24 months (Roundtrip)	17 – 20 months
Environment	0-g	~ 1/6-g	0-g	~ 1/3-g
Air Revitalization	Open	Closed 75% by mass	Closed >75% by mass	Closed >75% by mass Resupplied by ISRU
Water Recovery	Collection and Storage	Closed 90% by mass Resupplied by ISRU	Closed >90% by mass	Closed >90% by mass Resupplied by ISRU
Waste Management	Stored	Volume Reduction Mineralization Stabilization Resource Recovery	Volume Reduction Stabilization De-watering	Volume Reduction Mineralization Stabilization Resource Recovery
Thermal Systems	Low Power	High Power	High Power	High Power
Food Systems	Conventional Stored	Conventional Stored with Fresh Food Augmentation	Extended Shelf Life with Fresh Food Augmentation	Extended Shelf Life with Fresh Food Augmentation

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

Sabatier EDU Front View



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)

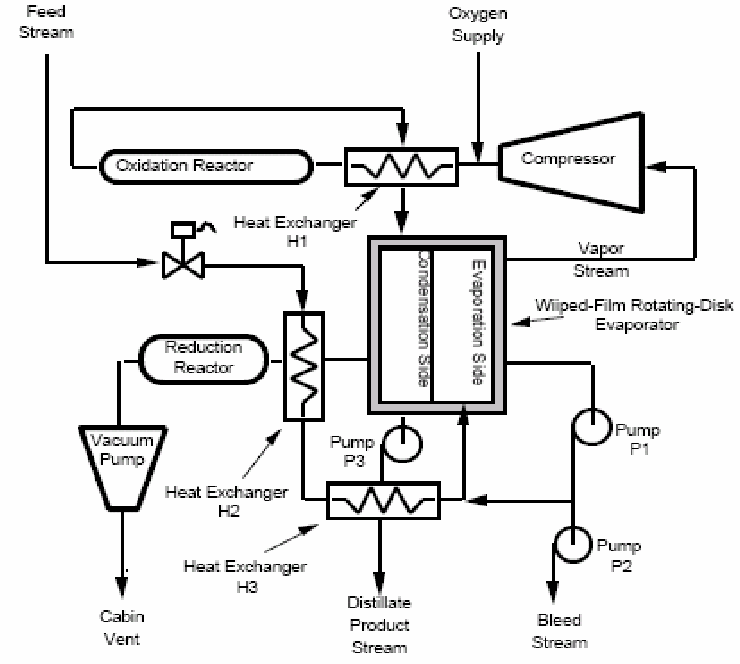


Fig. 1. VPCAR process flow diagram.

- **Hygiene Recovery and Potable Processing**
    - Reverse Osmosis (PO)
    - Multifiltration (MF)
    - Electrodialysis

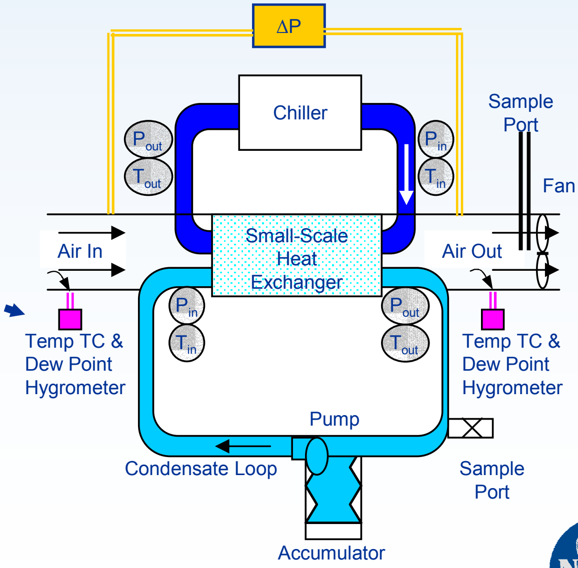
- **Water Recovery from Condensate**
    - Condensation/Separation

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/*
- 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/*
- 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

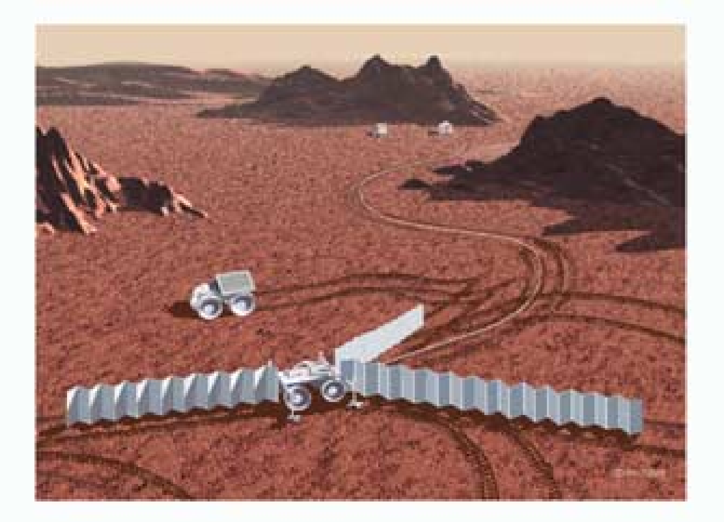
- Two Phase Flow Facility (ToFFy): Flow Boiling, Condensation, Phase Separation, System Stability
- AHLS-1: Reactor technologies: Fixed and Moving Beds
- AHLS-2: Condensing Heat Exchanger for Space Systems (CHESS)
- AHLS-3: Two-Phase/TBD

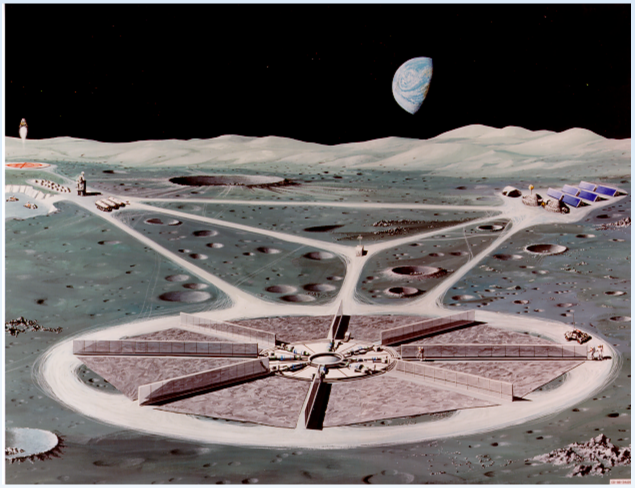
- LMM (CVB), BXF (MABE, NPBX), LME, MOBI, CCF

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.*

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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

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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

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Significance

NASA/TM-2004-212940: Workshop on Critical Issues in Microgravity Fluids, Transport, and Reaction Processes in Advanced Human Support Technology

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

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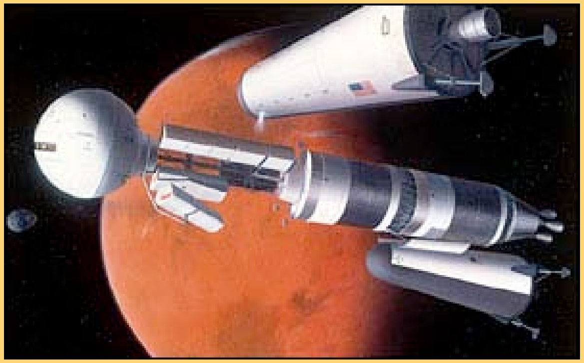
Significance

Pertinent AHST System: Power Generation Cycles, high power-to-weight ratio Rankine cycle for long-duration missions



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!!!

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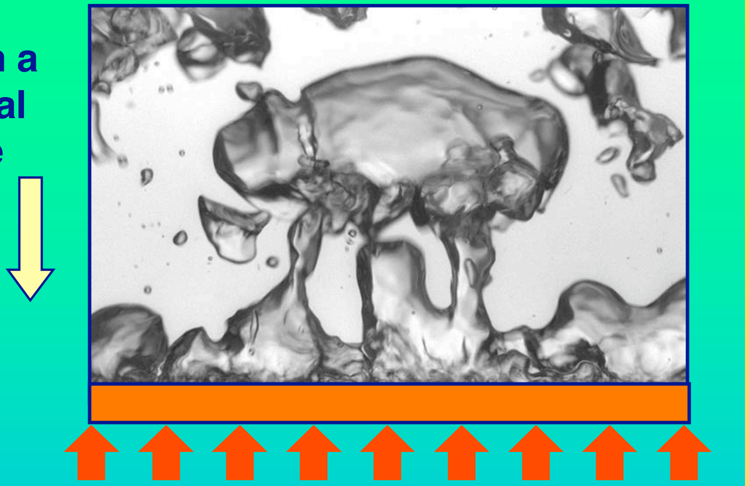
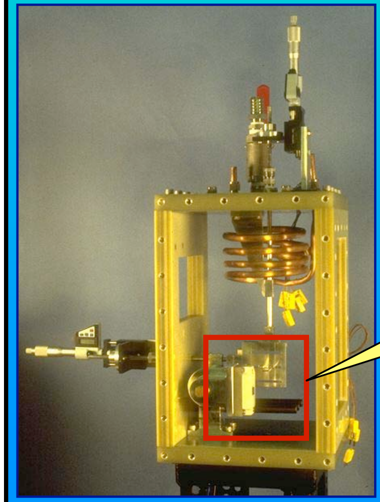
Effects of Orientation on Pool Boiling CHF at One g_e

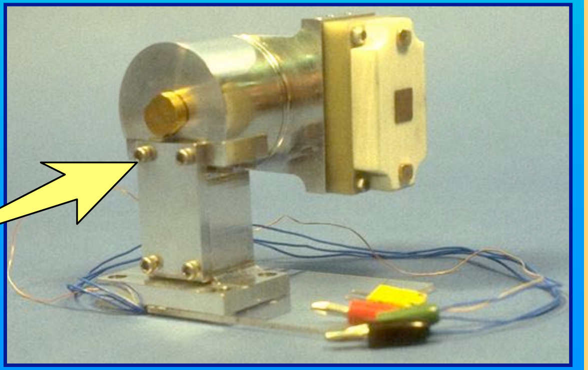
CHF from a horizontal surface

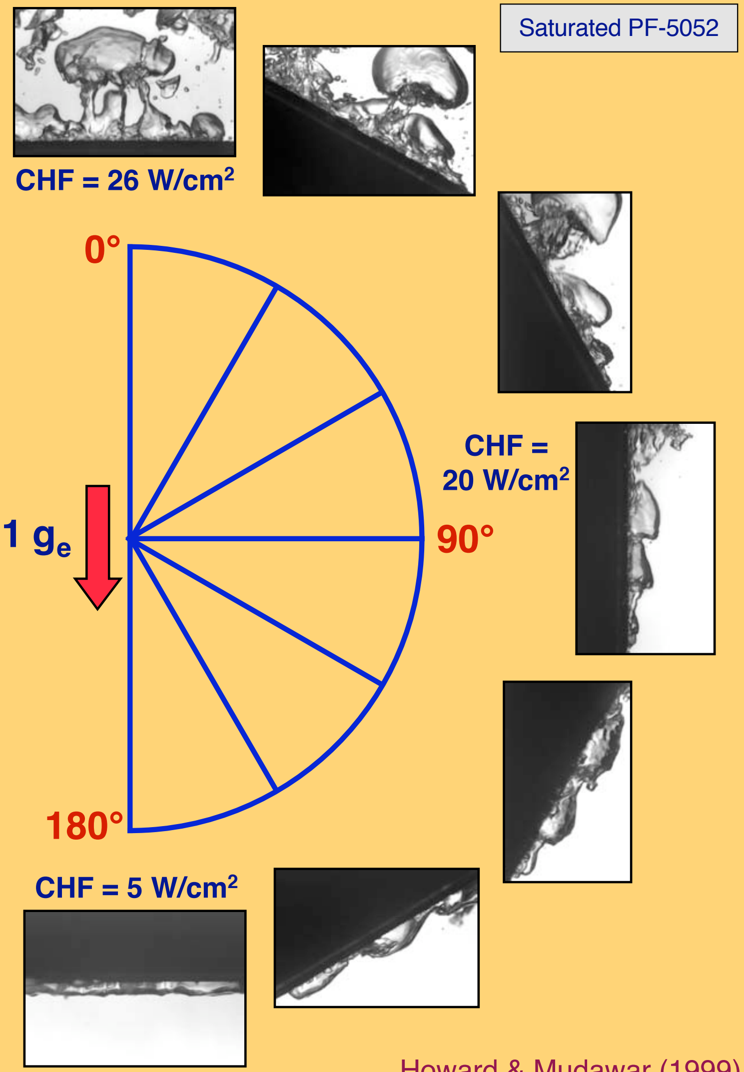


Heat Flux



Phase Change Photo Library
(Mudawar, 1984 - 2004)





Howard & Mudawar (1999)

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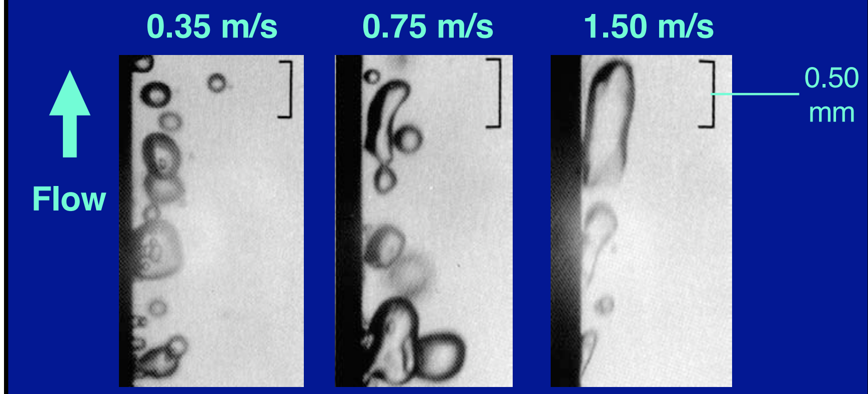
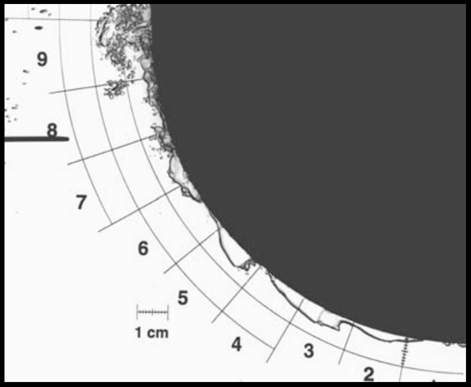
Bubble Coalescence Effects

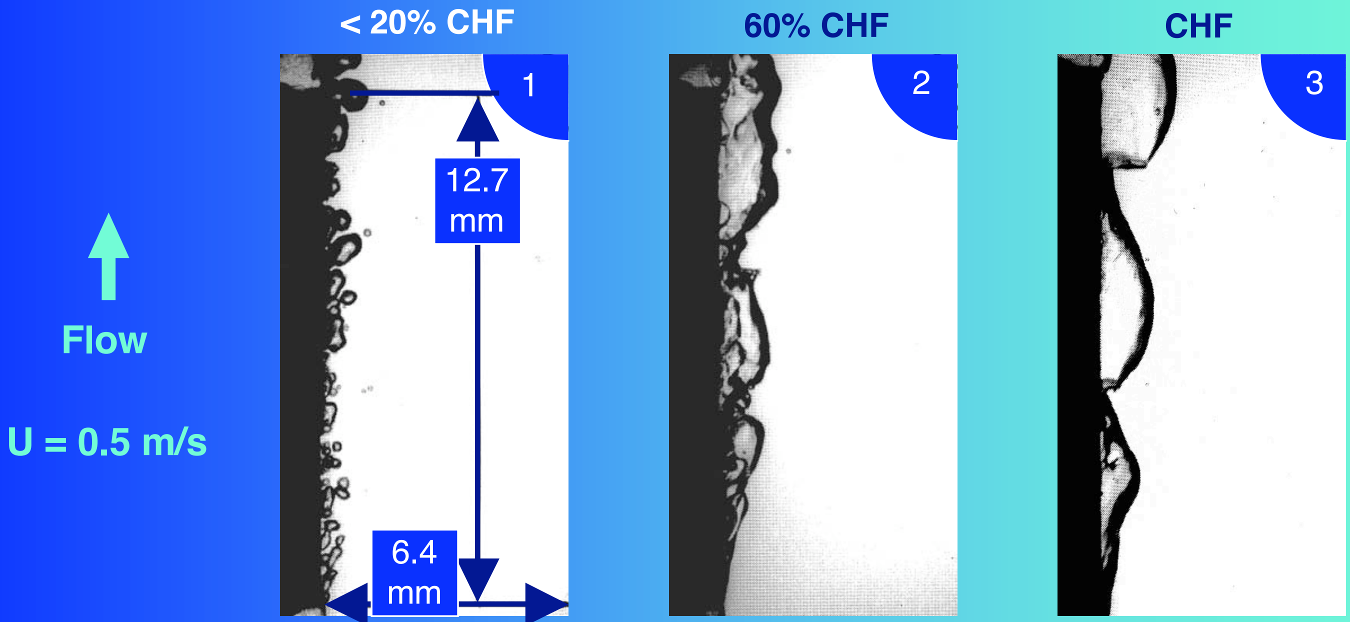
Incipient Flow Boiling



Pool Boiling

(50% CHF)





Flow Boiling

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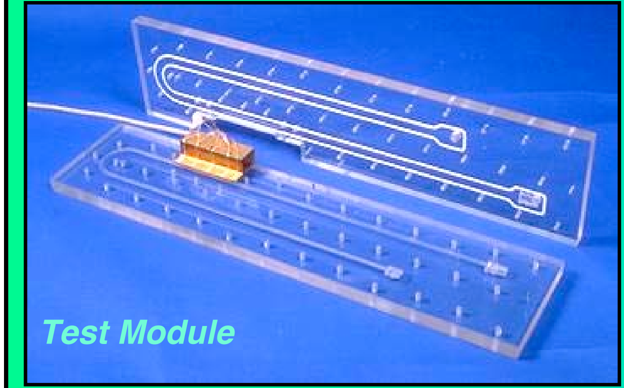
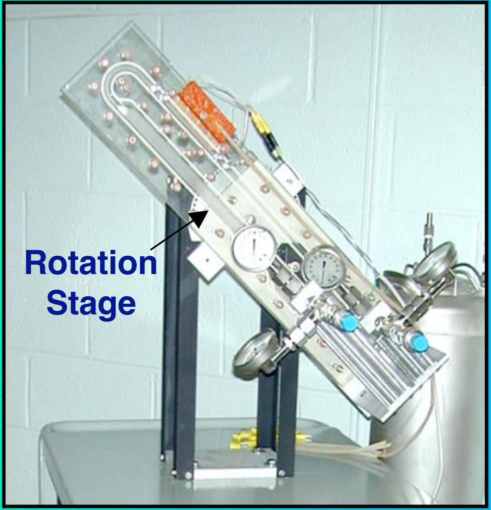
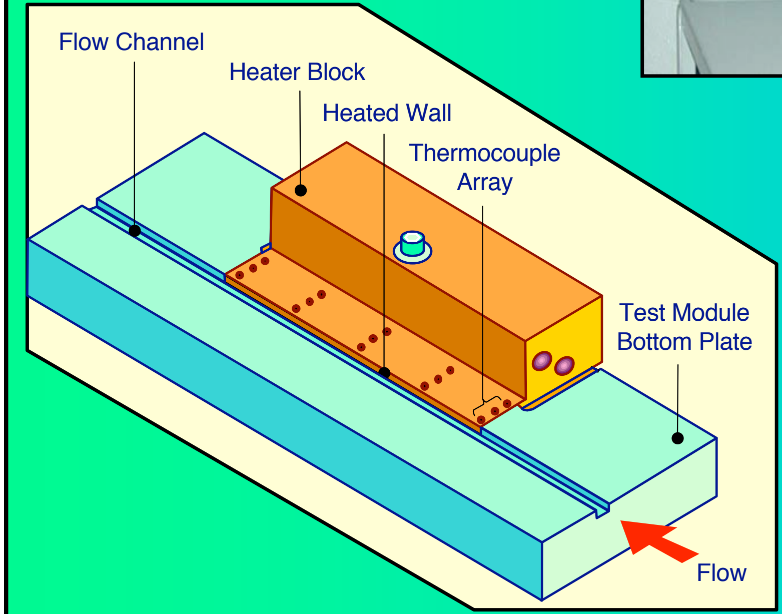
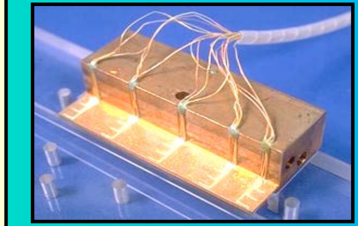
One-g_e Flow Boiling CHF Apparatus









Heater

Boiling Apparatus

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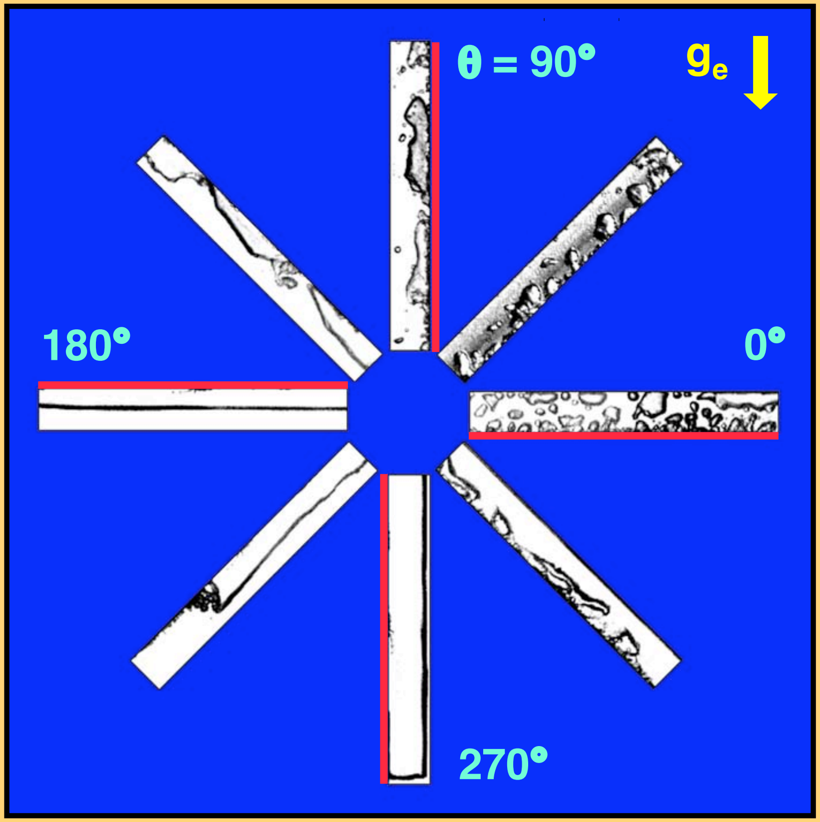
Vapor Behavior for Saturated Flow

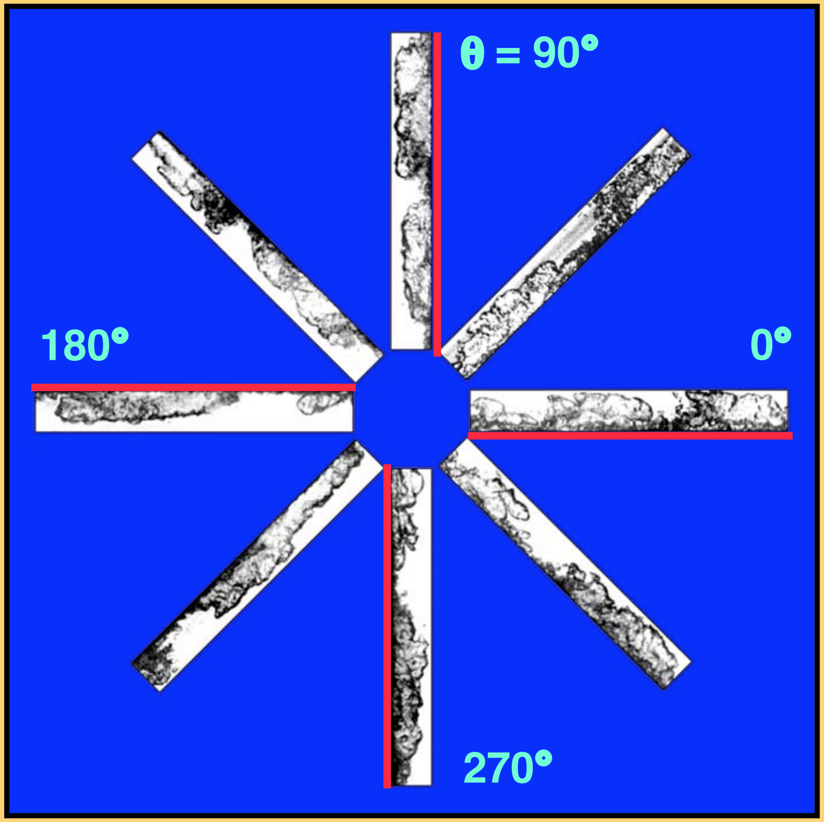
Downward-facing heater ← → **Upward-facing heater**

↑ **Upflow**



U = 0.1 m/s

↓ **Downflow**



U = 1.5 m/s

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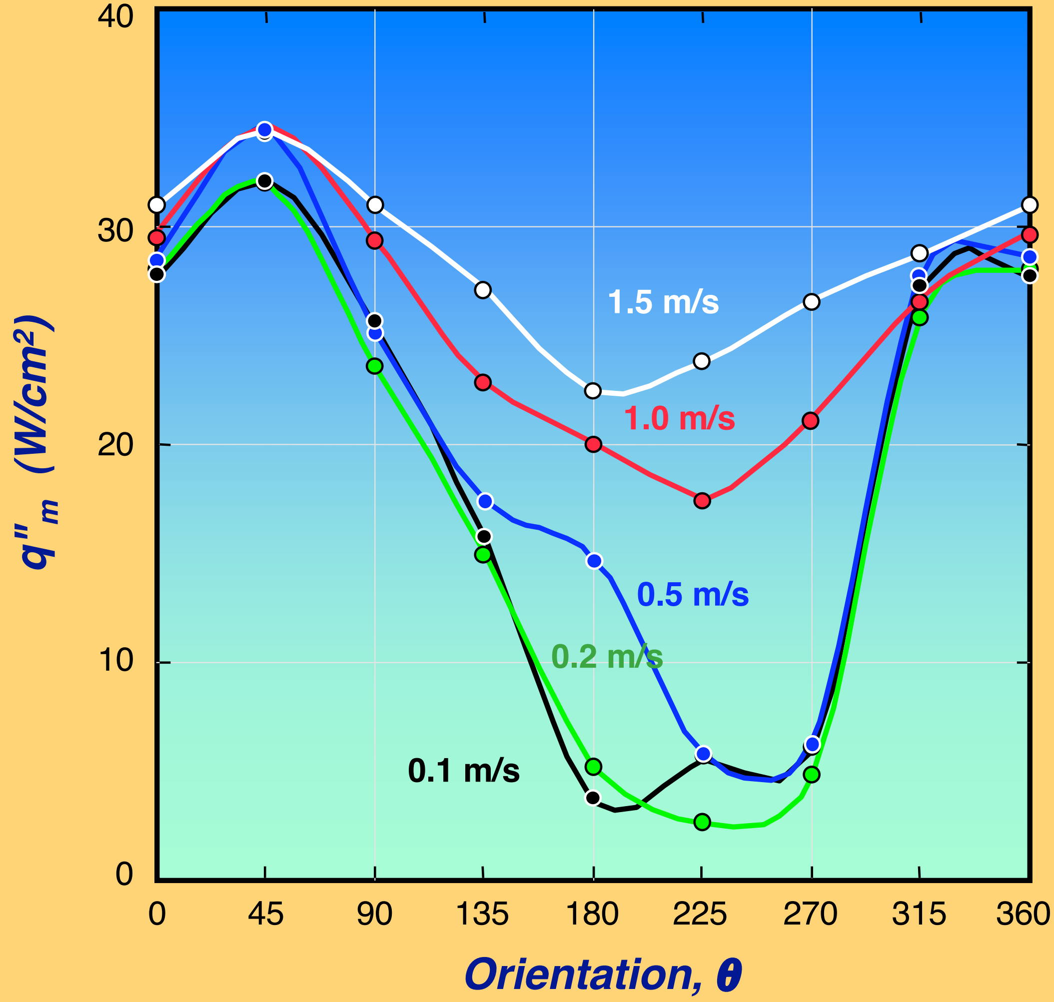
Variation of CHF with Orientation and Flow Velocity at 1 g_e



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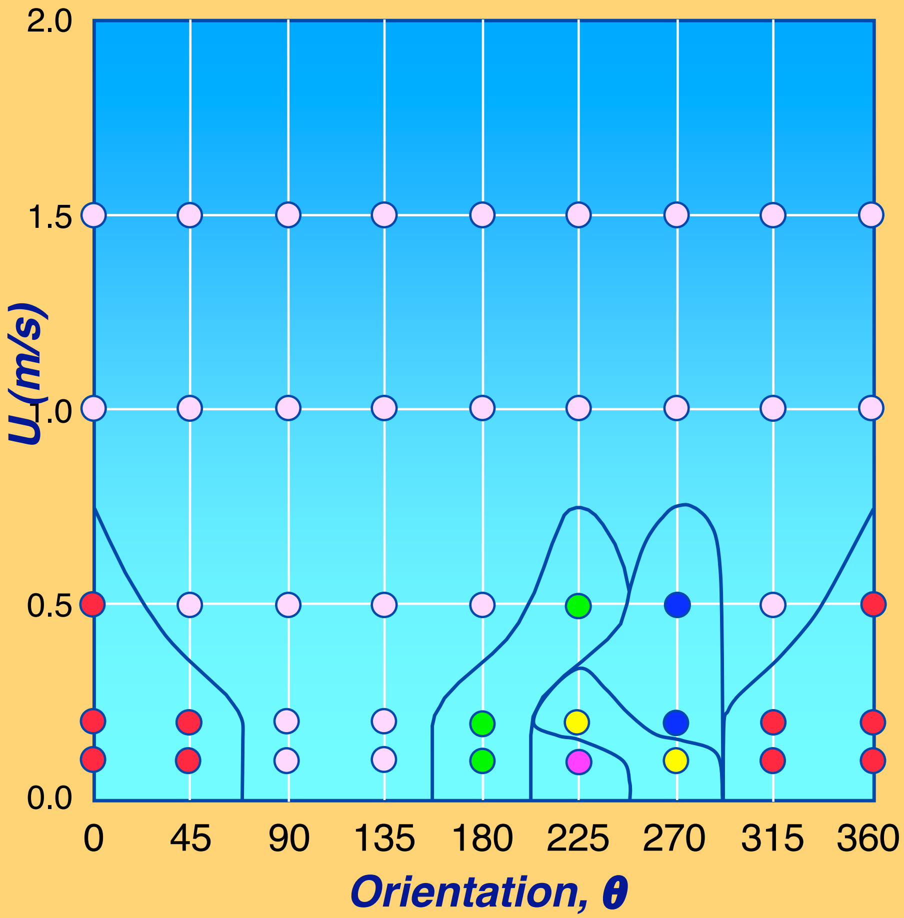
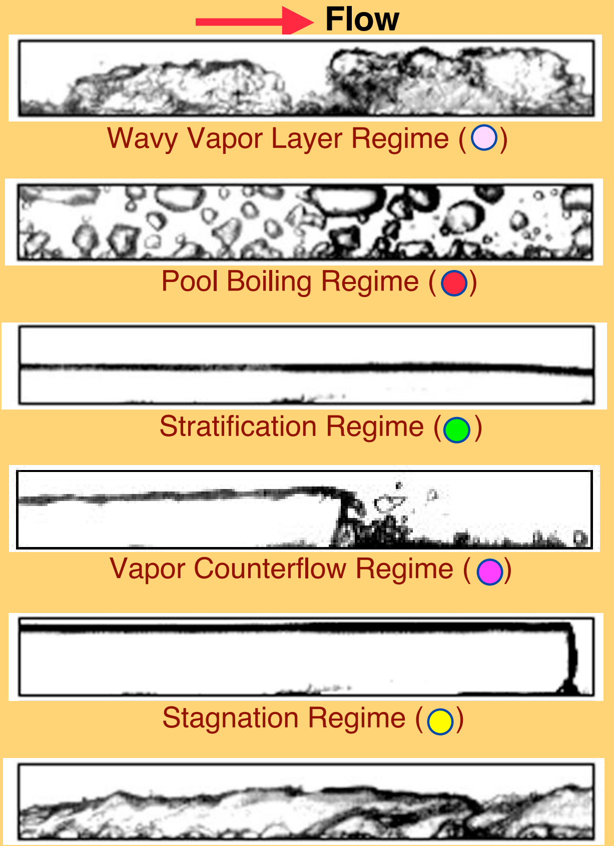
CHF Regime Map





Wavy Vapor Layer Regime (○)

θ = 90°
U = 1.5 m/s

Pool Boiling Regime (●)

θ = 0°
U = 0.1 m/s

Stratification Regime (●)

θ = 180°
U = 0.1 m/s

Vapor Counterflow Regime (●)

θ = 225°
U = 0.1 m/s

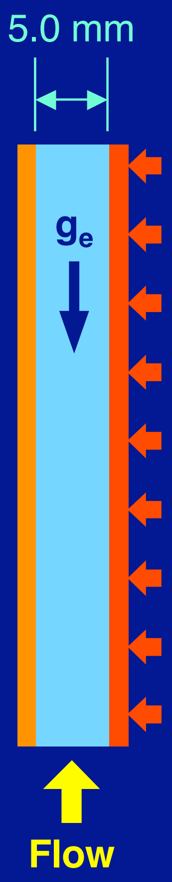
Stagnation Regime (●)

θ = 270°
U = 0.1 m/s

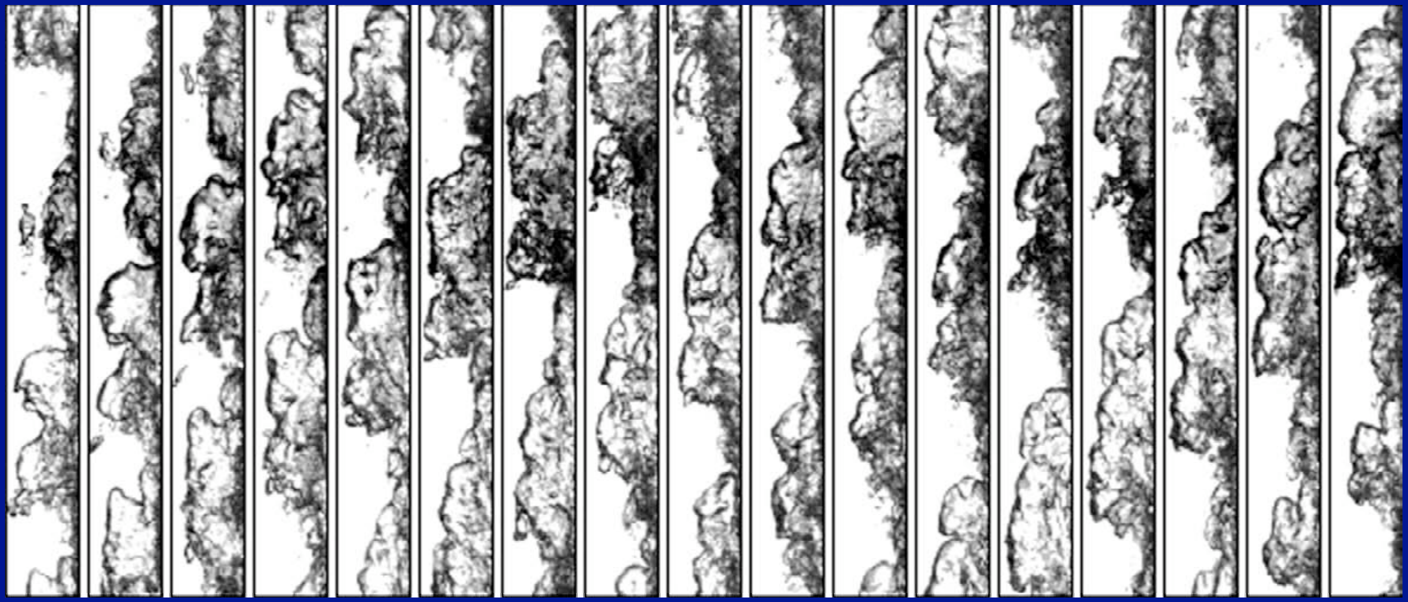
Separated Concurrent Vapor Flow Regime (●)

θ = 270°
U = 0.5 m/s

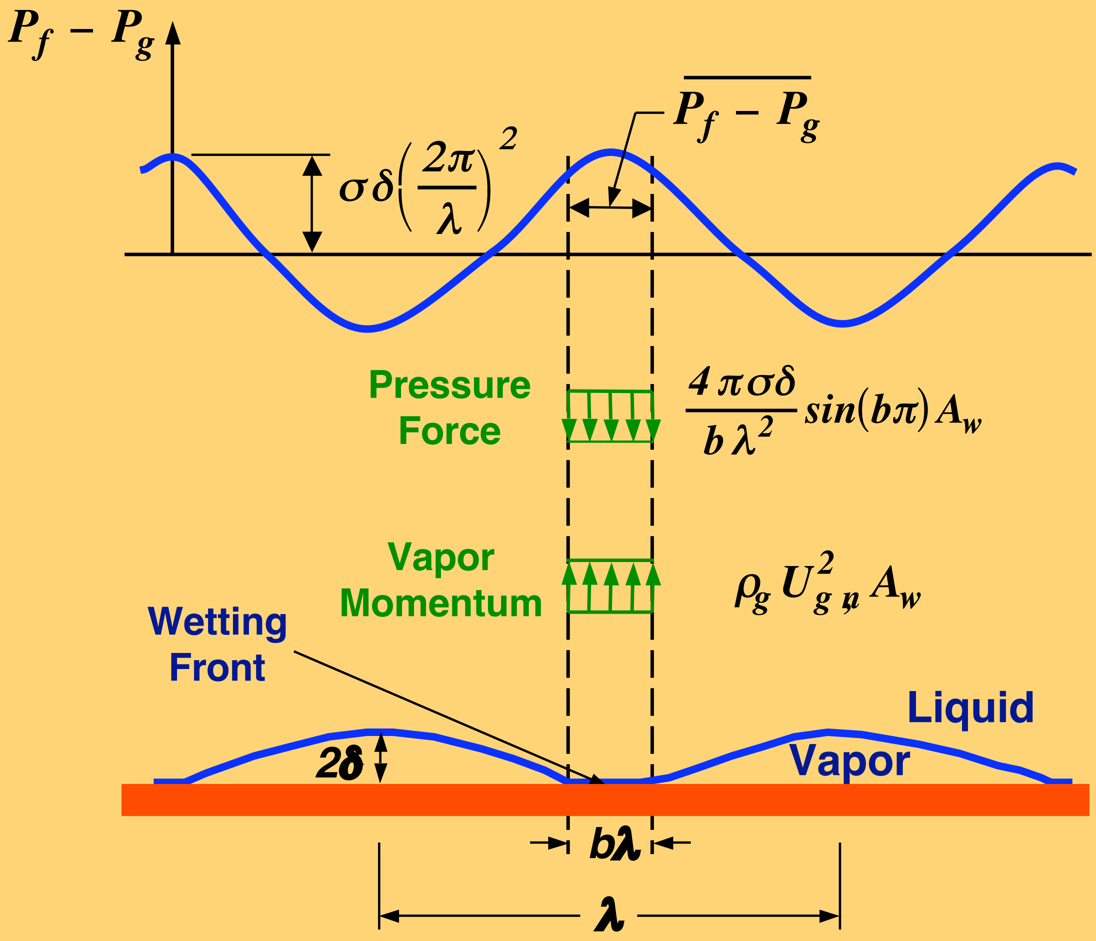
Wavy Vapor Layer Regime



U = 1.5 m/s



Vapor Momentum vs Interfacial Pressure



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Interfacial Lift-off Model

- **Critical Wavelength:**

$$\frac{2\pi}{\lambda_c} = \frac{\rho''_f \rho''_g (U_g - U_f)^2}{2\sigma(\rho''_f + \rho''_g)} + \sqrt{\left[\frac{\rho''_f \rho''_g (U_g - U_f)^2}{2\sigma(\rho''_f + \rho''_g)}\right]^2 + \frac{(\rho_f - \rho_g) g \cos\theta}{\sigma}}$$

- **Interfacial Pressure Difference:**

$$\overline{P_f - P_g} = \frac{4\pi\sigma\delta}{b\lambda^2}\sin(b\pi)$$

- **Interfacial Lift-Off Heat Flux:**

$$q''_w = \rho_g (c_{p,f}\Delta T_{sub,i} + h_{fg}) \left(\frac{\overline{P_f - P_g}}{\rho_g}\right)^{1/2}$$

- **Heater Energy Balance:**

$$q''_m = b\, q''_w$$

- **Critical Heat Flux:**

$$q''_m = \rho_g (c_{p,f}\Delta T_{sub,i} + h_{fg}) \left[\frac{4\pi\sigma b \sin(b\pi)}{\rho_g}\right]^{1/2} \left(\frac{\delta^{1/2}}{\lambda_c}\right)$$

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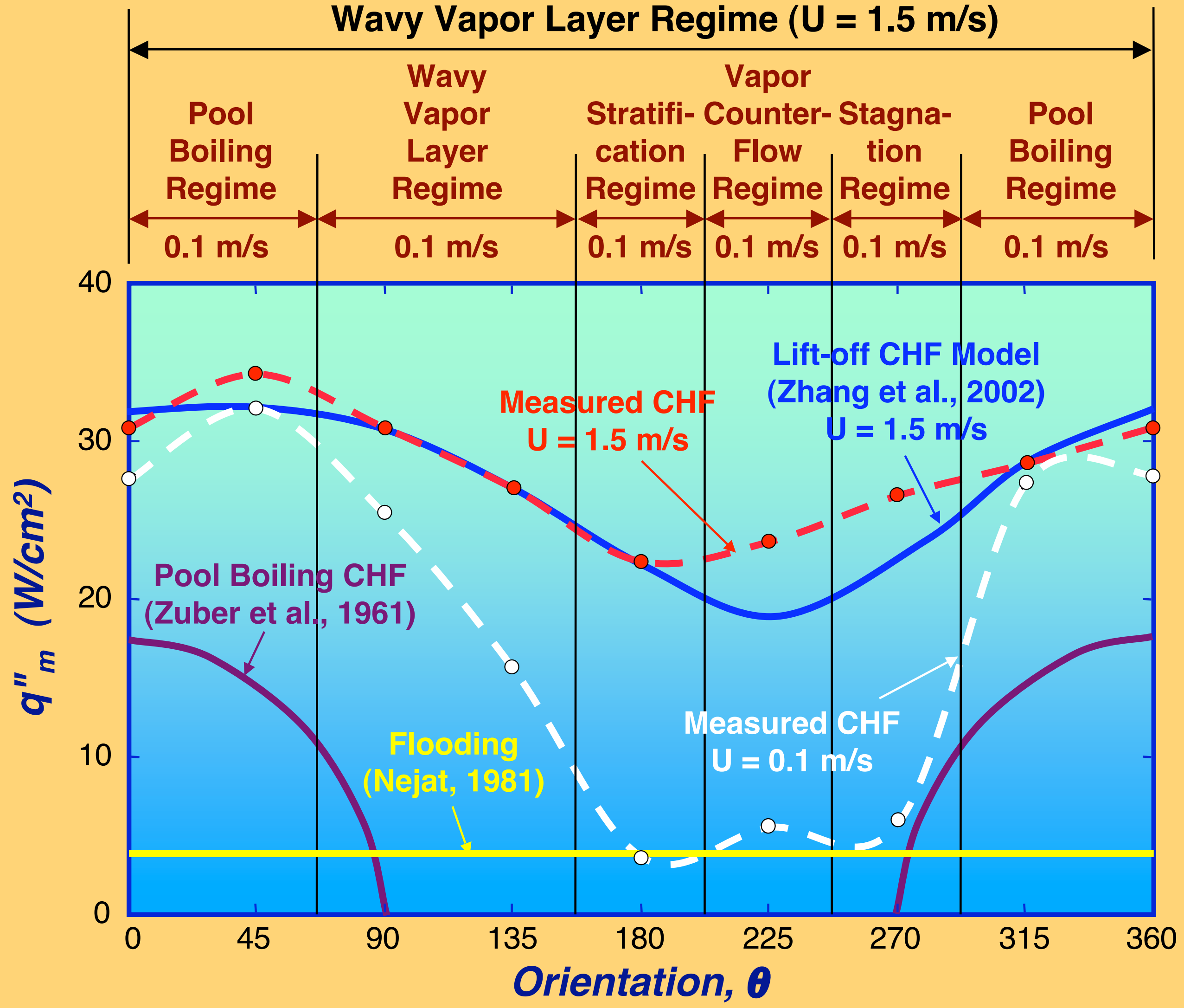
Comparison of Measured and Predicted CHF at 1 g_e



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Minimum Velocity Required to Overcome Body Force Effects

Negligible Component of Body Force Perpendicular to Wall

$$\frac{2\pi}{\lambda_c}\frac{\sigma(\rho_f+\rho_g)}{\rho_f\rho_g(\Delta U)^2} = \frac{1}{2}\left\{1+\sqrt{1+4\frac{(\rho_f-\rho_g)(\rho_f+\rho_g)^2\sigma g}{\rho_f{}^2\rho_g{}^2(\Delta U)^4}}\right\}$$

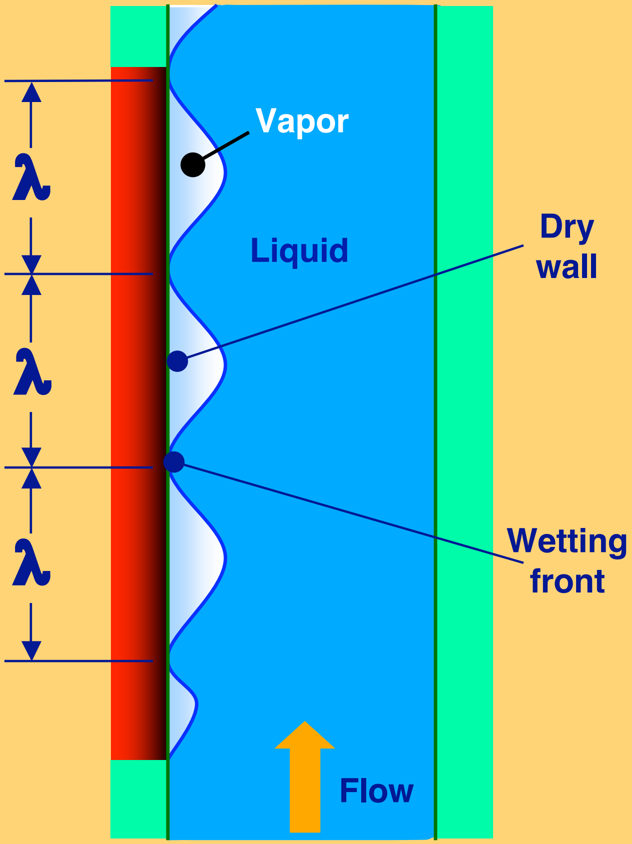
$$\boxed{\frac{Bo}{We^2} = \frac{(\rho_f-\rho_g)(\rho_f+\rho_g)^2\sigma g}{\rho_f^2\,\rho_g^2\,U^4} \le 0.09}$$

$$Bo = \frac{(\rho_f-\rho_g)gL^2}{\sigma} \qquad We = \frac{\rho_f\rho_g U^2 L}{(\rho_f+\rho_g)\sigma}$$

Negligible Component of Body Force Parallel to Wall

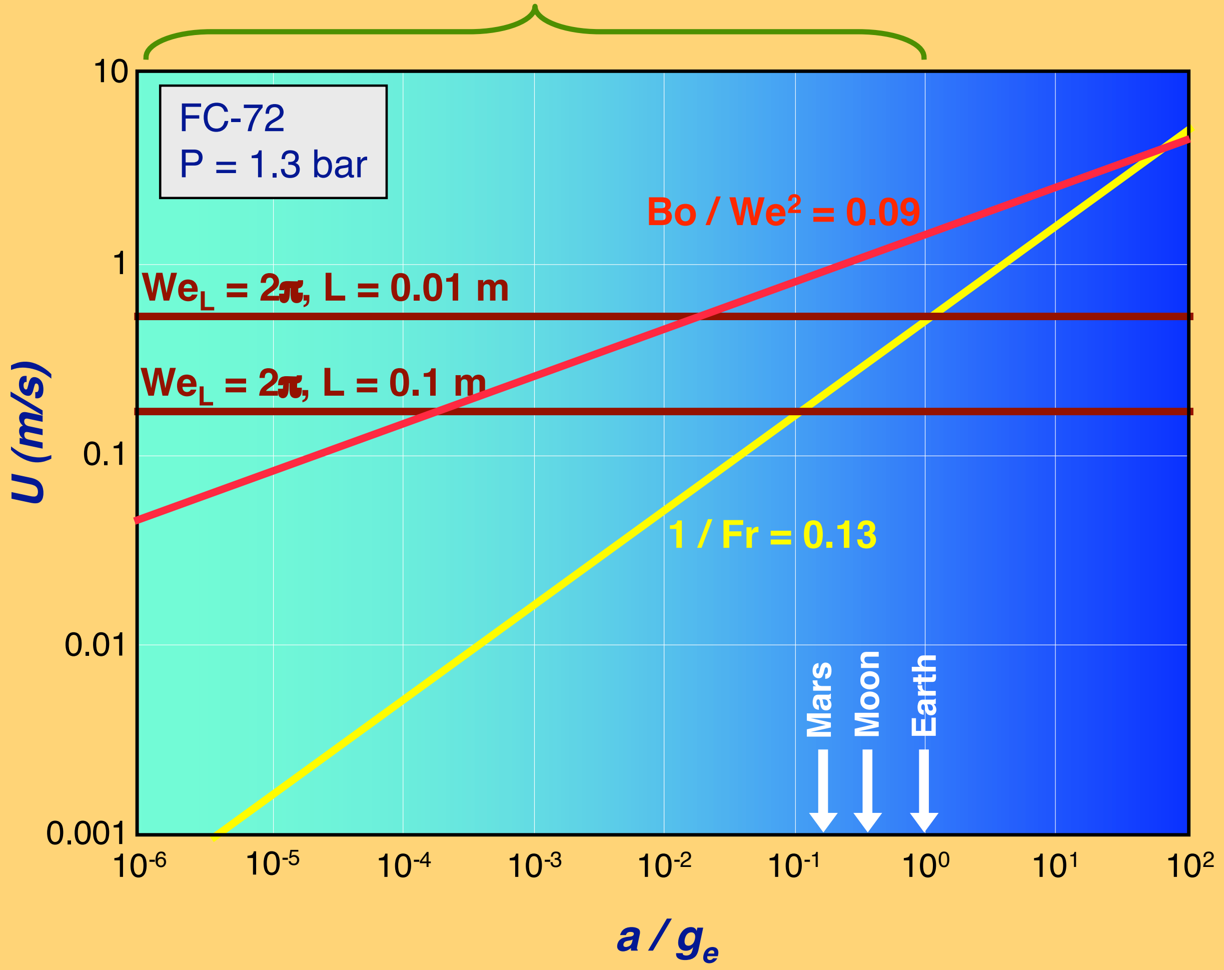
$$U_\infty \sim \frac{\left[(\rho_f-\rho_g)gD_h\right]^{1/2}}{\rho_f^{1/2}} << U$$

$$\boxed{\frac{1}{Fr} = \frac{(\rho_f-\rho_g)gD_h}{\rho_f\,U^2} \le 0.13}$$



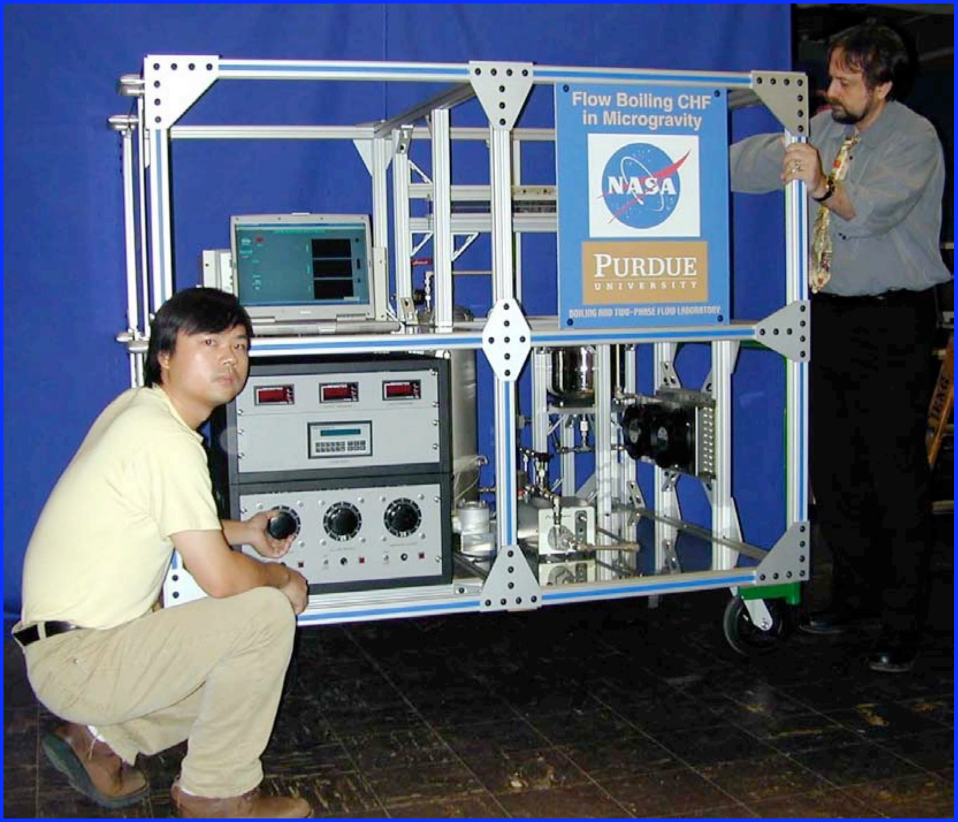
Minimum Velocity Required to Overcome Body Force Effects

U > 1.5 m/s to overcome body force effects below 1 g_e



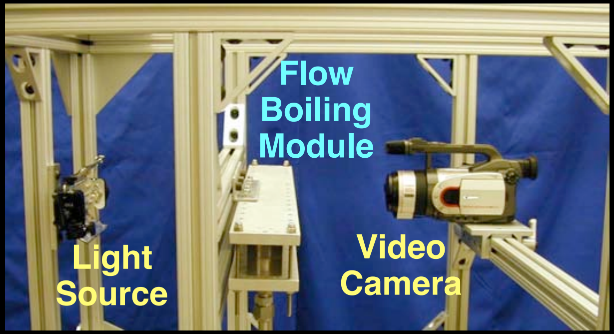
PURDUE UNIVERSITY

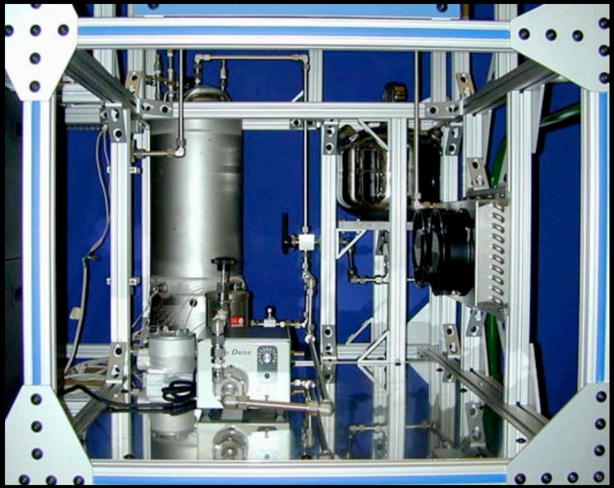
Reduced Gravity Flow Boiling CHF Apparatus



Flight Rack

Phase Change Photo Library (Mudawar, 1984 - 2004)





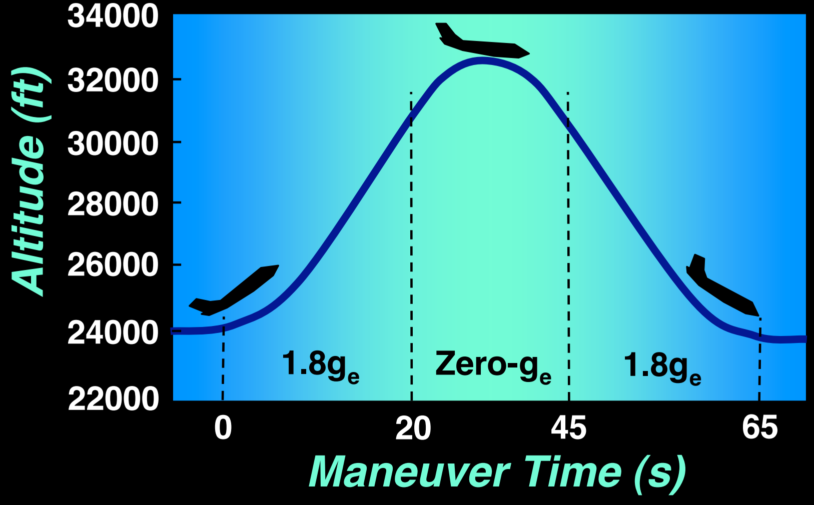
Two-Phase Loop

PURDUE
UNIVERSITY

KC-135 Microgravity Experiments

NASA Glenn Research Center, April 2004

Flight Trajectory

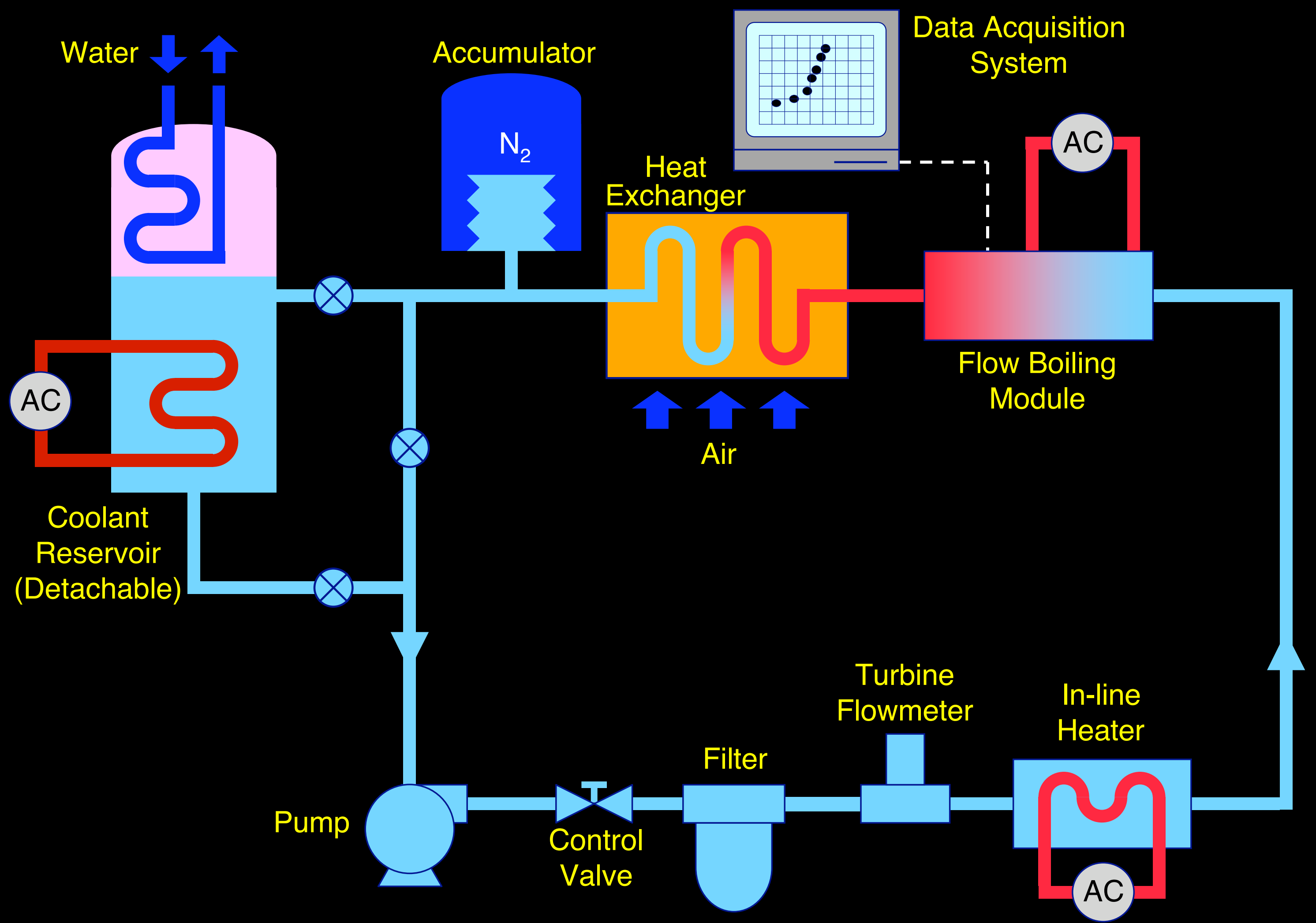


Operators:

Dwayne Kiefer (QSS)
Dr. Charles Niederhaus (NASA)
Dr. Juan Agui (NASA)

Phase Change Photo Library
(Mudawar, 1984 - 2004)

Reduced Gravity Flow Loop



Reduced Gravity Flow Loop


Coolant Reservoir

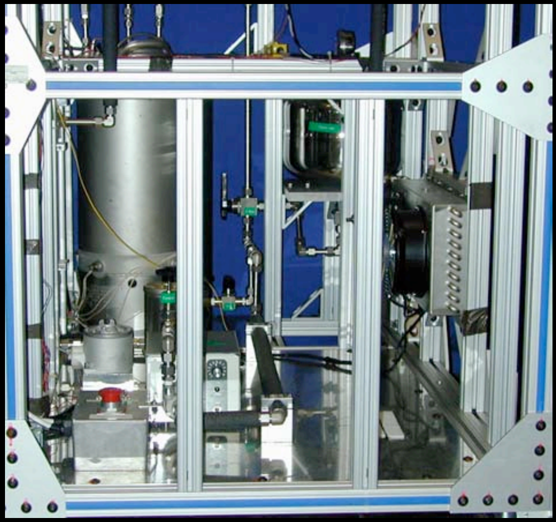

Accumulator


Heat Exchanger


Flow Boiling Module


Pump

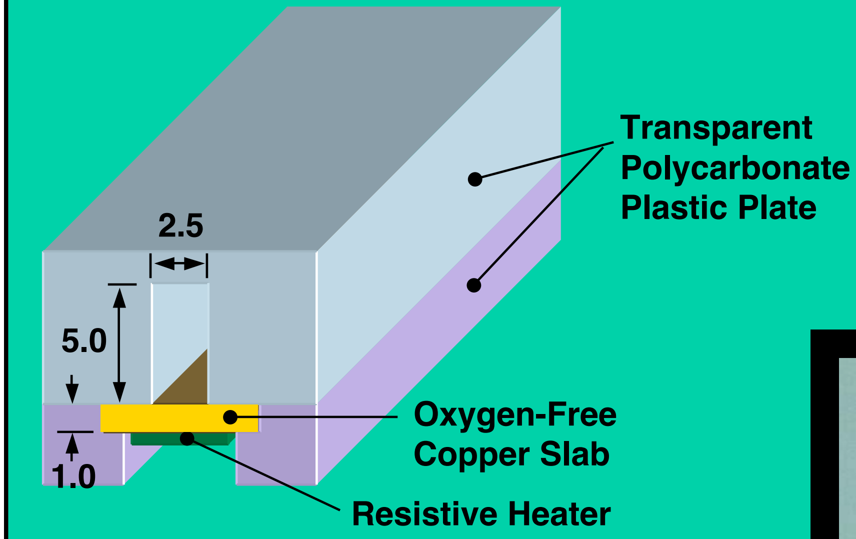

Filter

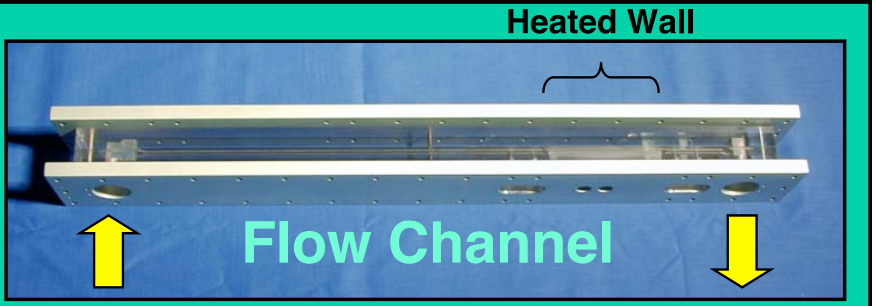


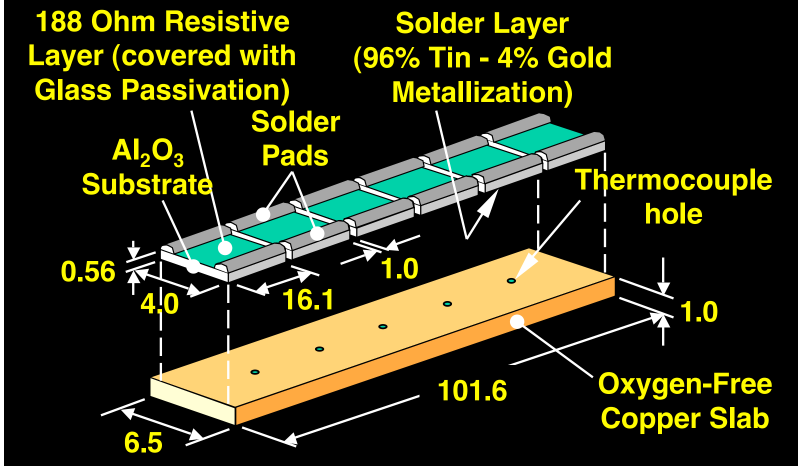

Turbine Flowmeter


In-Line Heater

Flow Boiling Module







All dimensions in mm

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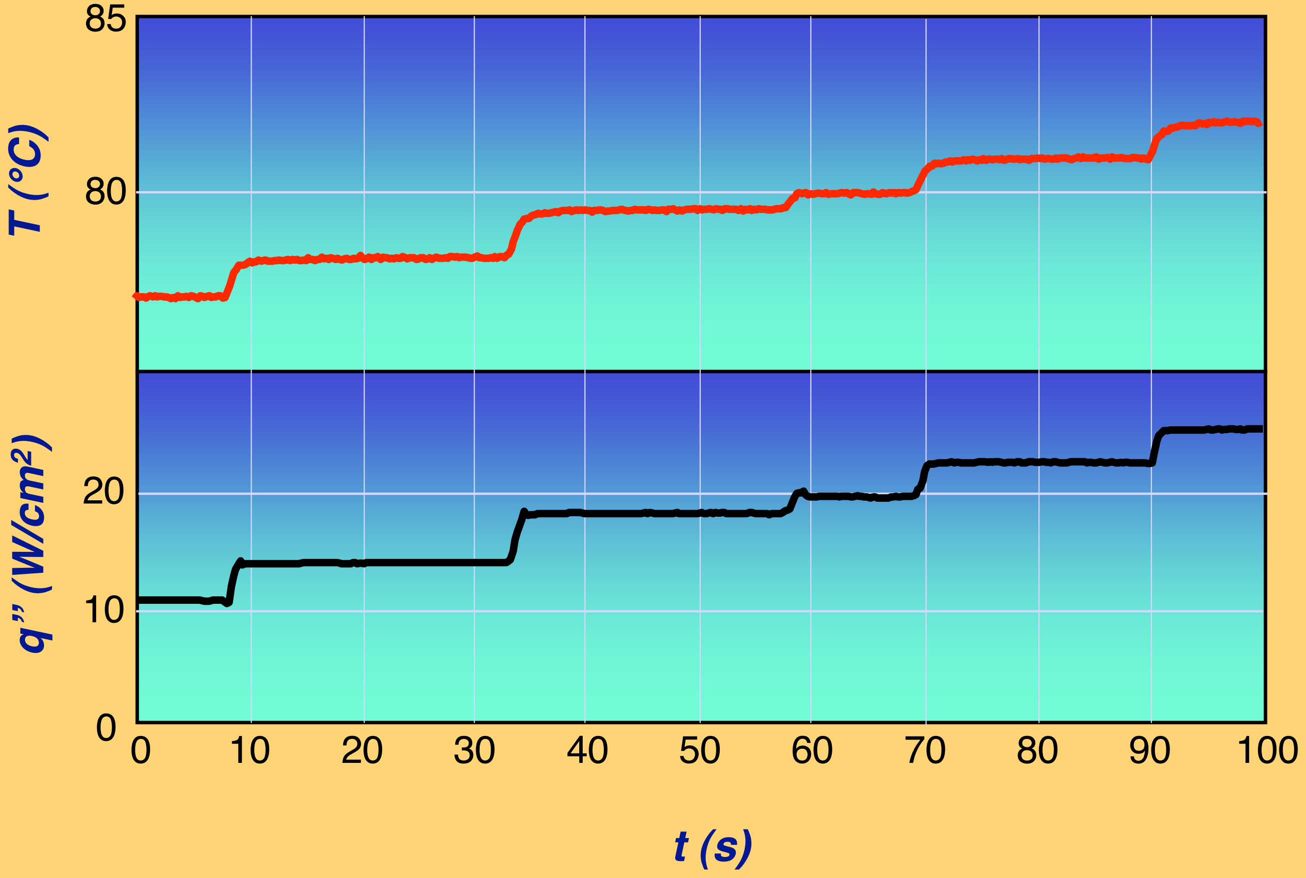
Thermal Response of Heater



June 23, 2004

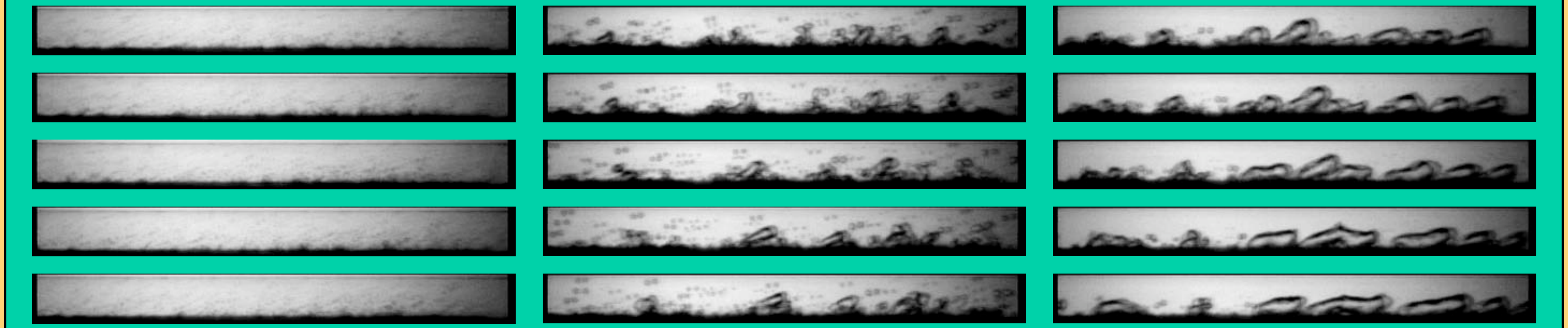
Conference on Strategic Research to Enable NASA's Space Exploration Missions

Prof. I. Mudawar

PURDUE UNIVERSITY

Parabolic Flight Results

FC-72, U = 0.14 m/s



$1.8g_e$

$0.17g_e$ (Lunar)

Zero-g_e

Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)

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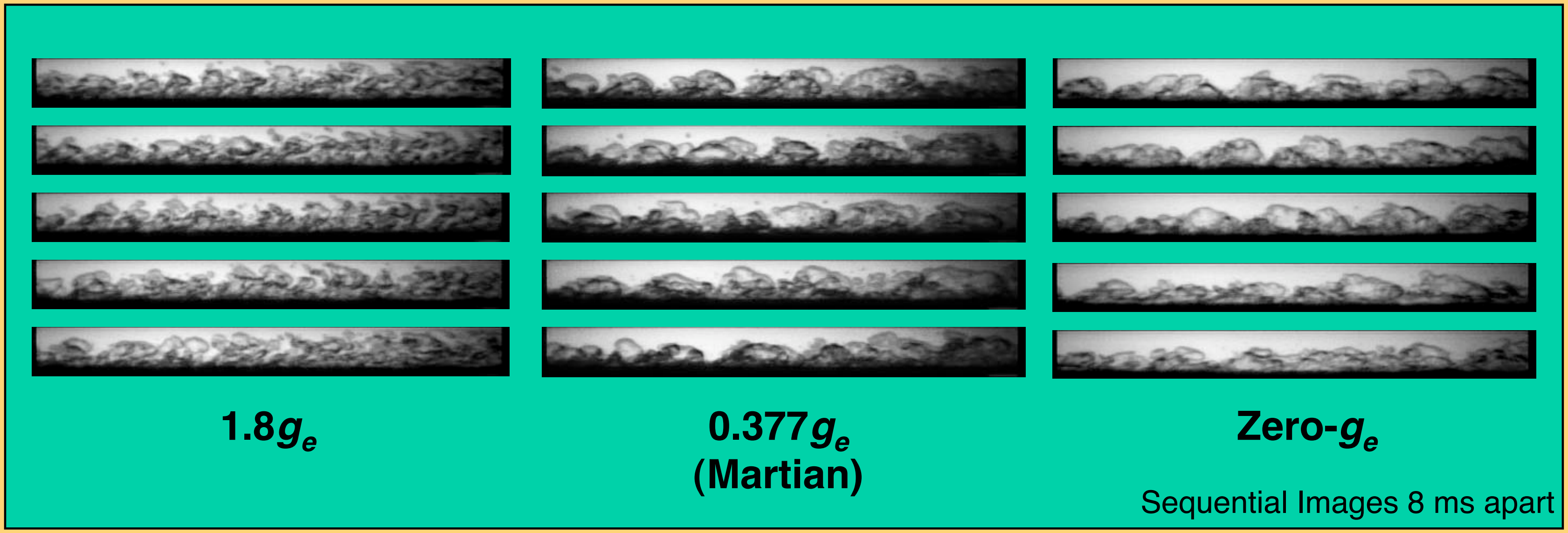
Parabolic Flight Results

FC-72, U = 1.40 m/s

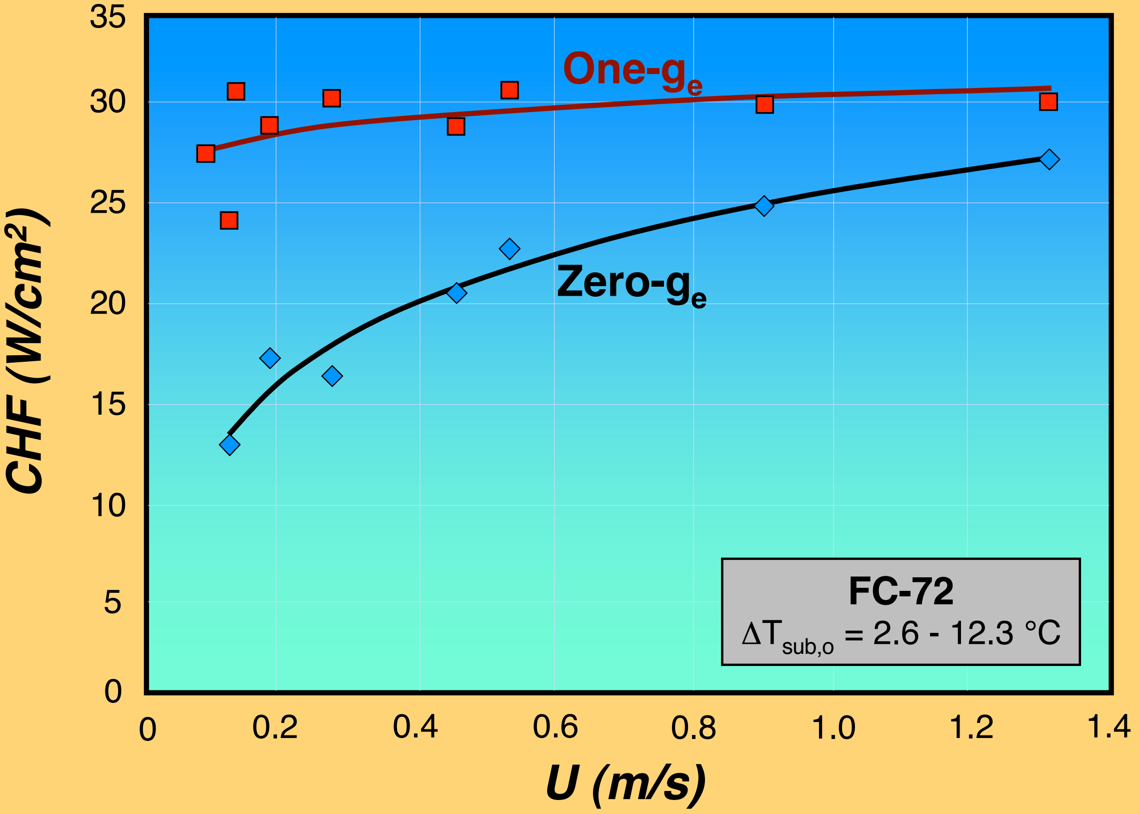


Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)

PURDUE UNIVERSITY

Parabolic Flight Results



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

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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/

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

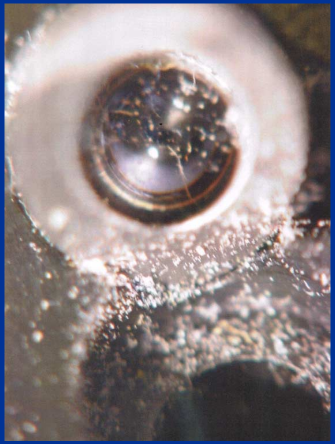
		Survival	Health/Safety
Getting There		Oxygen supply CO_2 removal	Fire detection & suppression Suspended particulates* removal
Living There	Habitats	Oxygen supply CO_2 removal	Fire detection & suppression Suspended particulates* removal
	EVA	Oxygen supply CO_2 removal ISRU	Dust Mitigation ISRU

*Particulates: solid, liquid and microbe

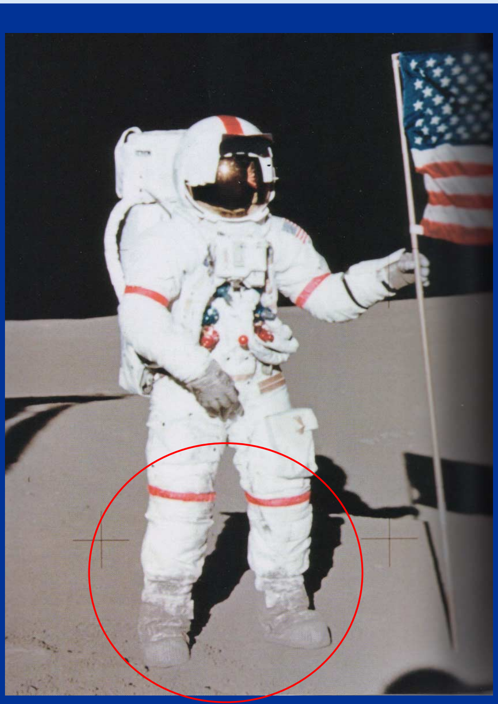
Space Exploration & Particulate Control

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

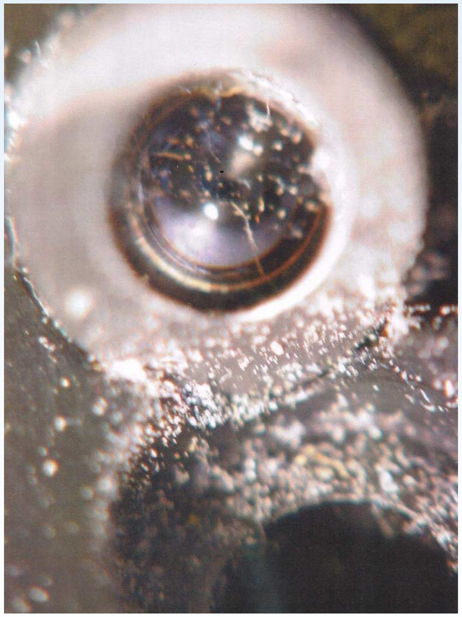
1. Develop robust packed bed technology, particularly monolithic substrates or other non-particulate bed morphology for catalyst and adsorbent media supports.

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**

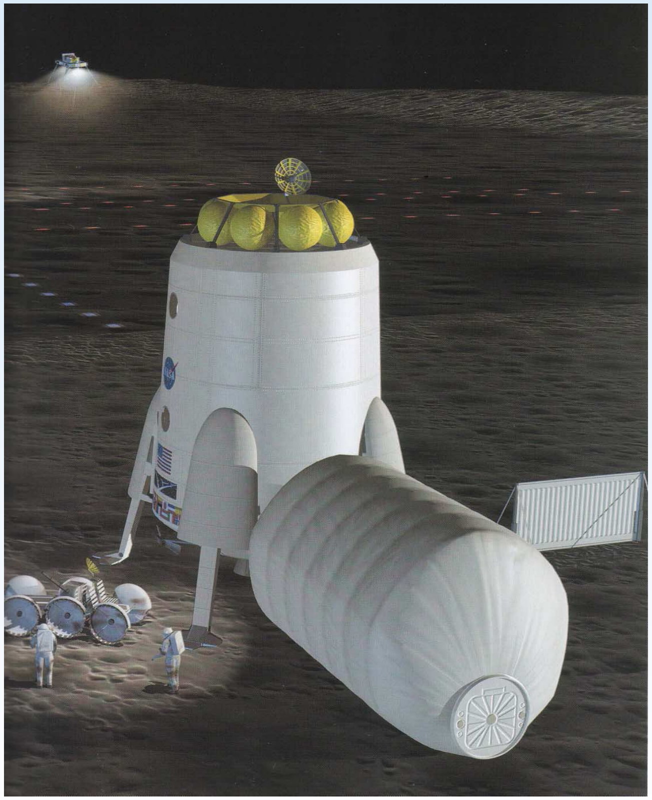
1. No gravitational screening ---> longer residence time
2. A wide size distribution ---> dynamic interactions
3. Agglomeration process ---> effective filter design

Real time monitoring
of dynamic interaction
of airborne particulates
DATA

Implementation

Modeling

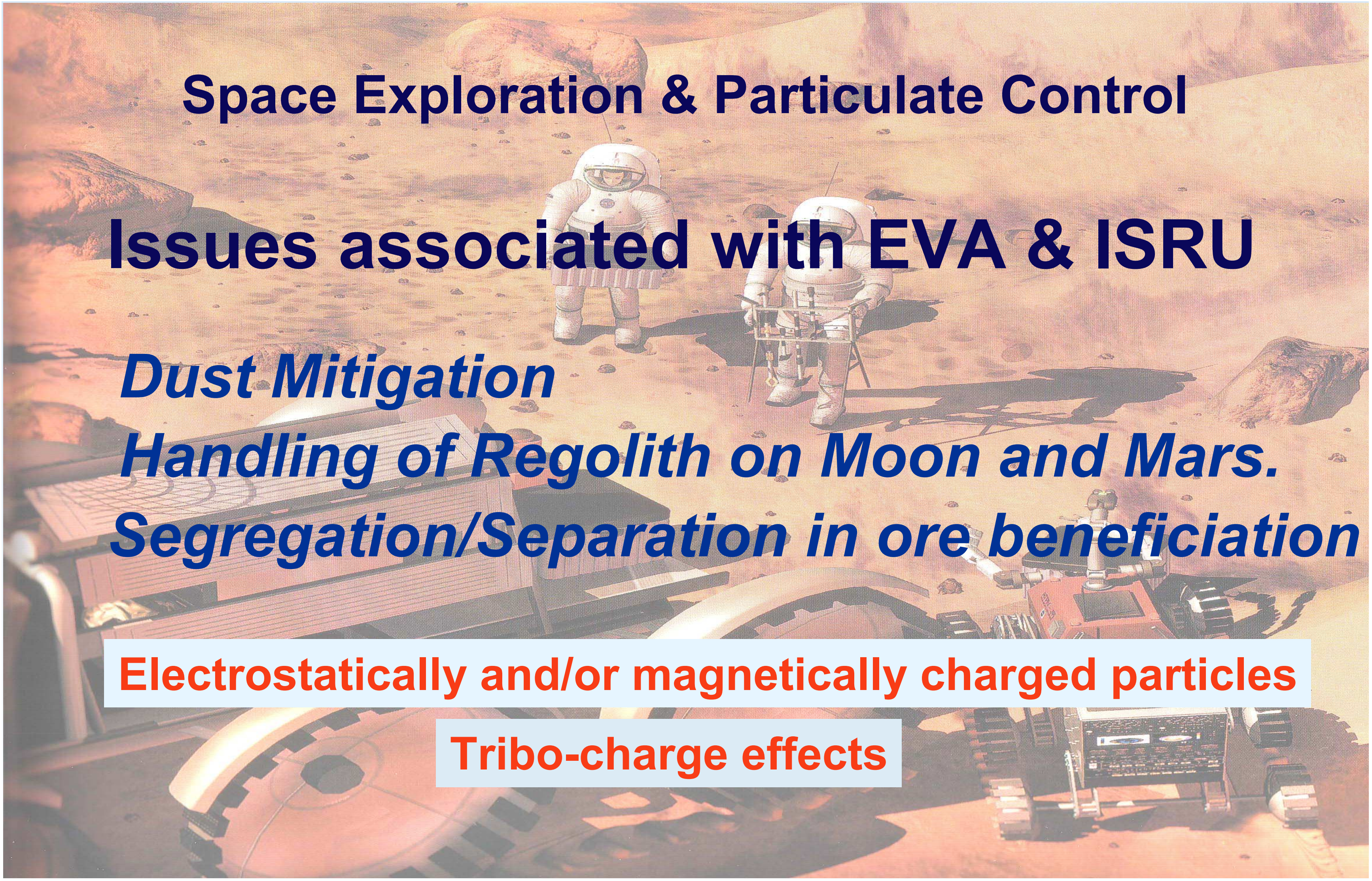
Space Exploration & Particulate Control



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

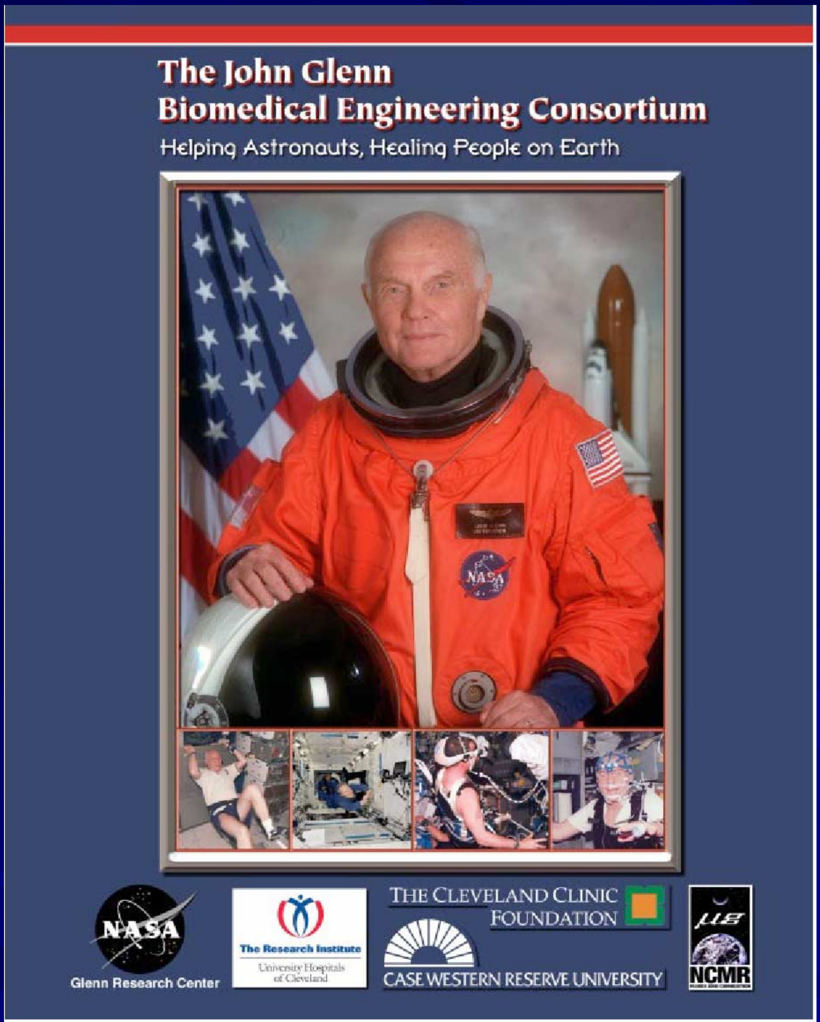
ISRU
- Soil characterization
- Processing
- Tribocharge effects

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



The John Glenn Biomedical Engineering Consortium

Helping Astronauts, Healing People on Earth

Glenn Research Center

The Research Institute
University Hospitals of Cleveland

THE CLEVELAND CLINIC FOUNDATION

CASE WESTERN RESERVE UNIVERSITY

NCMR

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.

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

Wilson, CWRU Co-I: UH	In-Vivo Bioluminescent Molecular Imaging with Application to the Study of Secretory Clusterin, a Potential Biodosimeter during Space Exploration
Ansari, GRC Co-I: UH	Integrating Non-invasive Technologies to Enable Effective Countermeasures During Prolonged Space Travel
Gratzel, CWRU	Micro-miniature Sensing Platform For Painless, Infection-Free, And Continuous In Vivo Monitoring Of Glucose And Electrolytes Of Astronauts
Knothe, CCF Co-I: CWRU, GRC	Development of a “Decompression Chamber” to Prevent Loss of Bone in Space through Exogenous Application of Acoustic Energy
York, GRC Co-I: CWRU	Remote and On-board Detection, Diagnoses and Treatment of Serious Cardiac Dysrhythmias
Dietrich, GRC Co-I: NCMR, UH	Development of a Portable Metabolic Measurement Device
Roy, CCF Co-I: CWRU, GRC	Controlled-release Microsystems for Pharmacological Agent Delivery
Chait, GRC Co-I: NCMR, CWRU	Rapid Design and Simulation Tools for Space-Bound BioChip Devices
D'Andrea, CCF Co-I: GRC	An Instrumented, Dual-Track, Actuated Treadmill in a Virtual Reality Environment as a Countermeasure for Neurovestibular Adaptations in Microgravity
Zimmerli, GRC Co-I: CCF	Confocal And Two-Photon Microscopy For The Assessment Of Countermeasures In Bone Loss, Hematology, And Immunology

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

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

In vivo bioluminescence imaging system.

NASA Application:

Clusterin biodosimeter will measure the biological effect of radiation exposure

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:

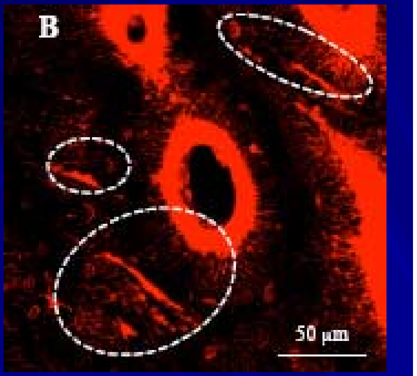
Microminiature sensor placed under the skin using non-invasive optical techniques for continuous *in vivo* monitoring of astronaut electrolytes and metabolite levels

Glenn Research Center

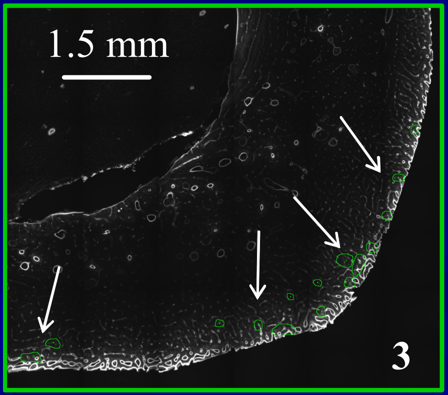
at Lewis Field

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



Images collected with confocal Microscope at 20x magnification showing overt microdamage



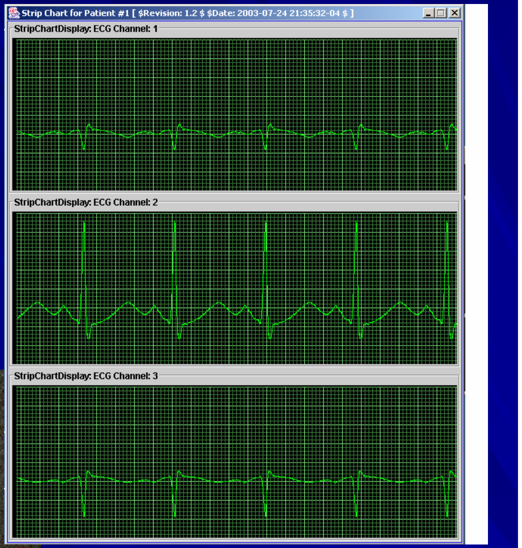
Observed areas of microdamage (arrows)

NASA Application:

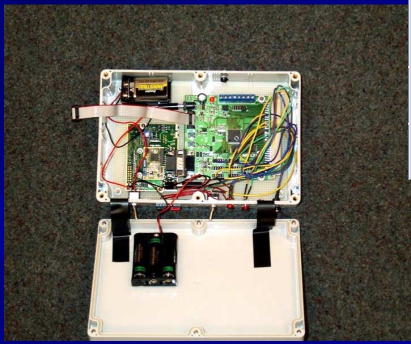
Through process of ultrasound therapy, which induces bone microdamage and natural rebuilding, develop a countermeasure device to maintain astronaut bone mass for space application.

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.



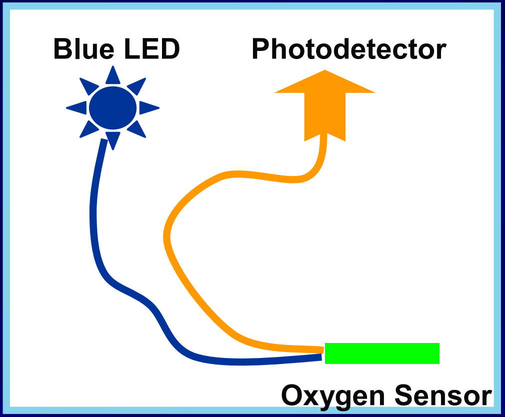
3-Channel ECG Display on Call Center
Data transmitted from Wearable Server to
Central Server to Call Center



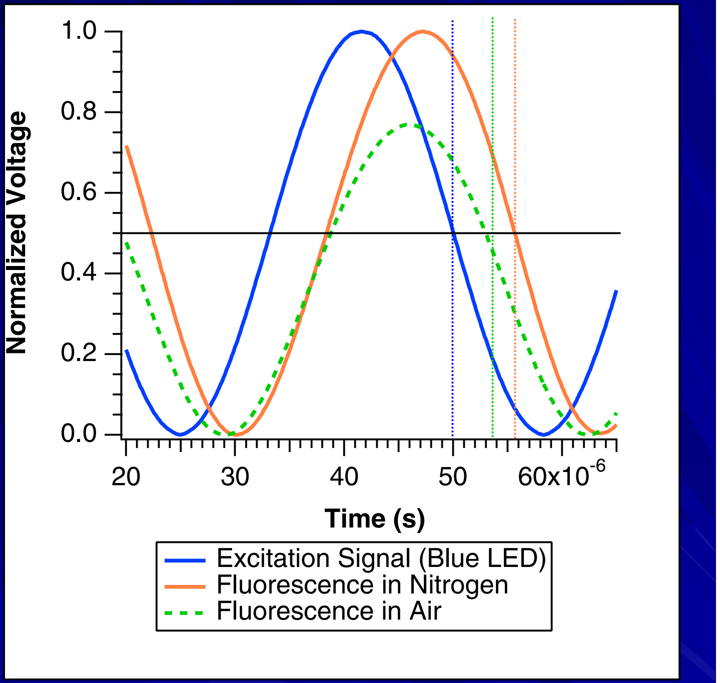
Wearable server with 8051 single chip
processor and Bluetooth cards

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

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

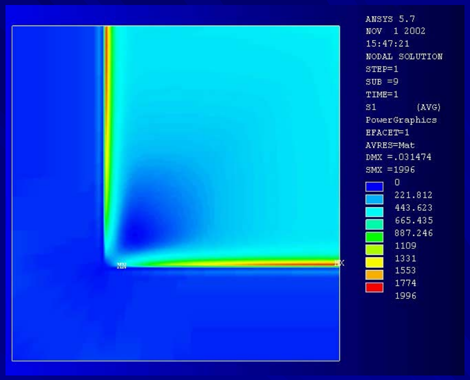
Glenn Research Center

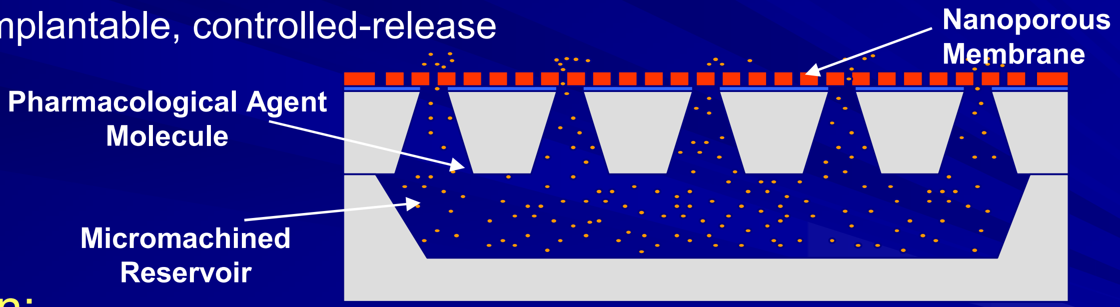
at Lewis Field

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

FEM Model of Solid Polysilicon Membrane



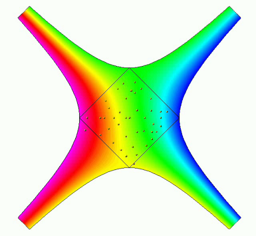


NASA Application:

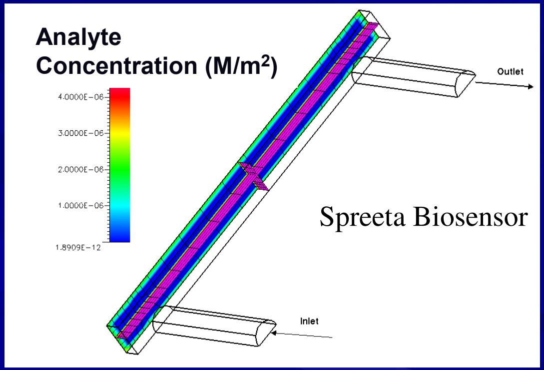
Controlled continuous drug delivery system for administering pharmacological agents as countermeasures to adverse effects of microgravity on astronaut health

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.



Dielectrophoresis Particle Focusing



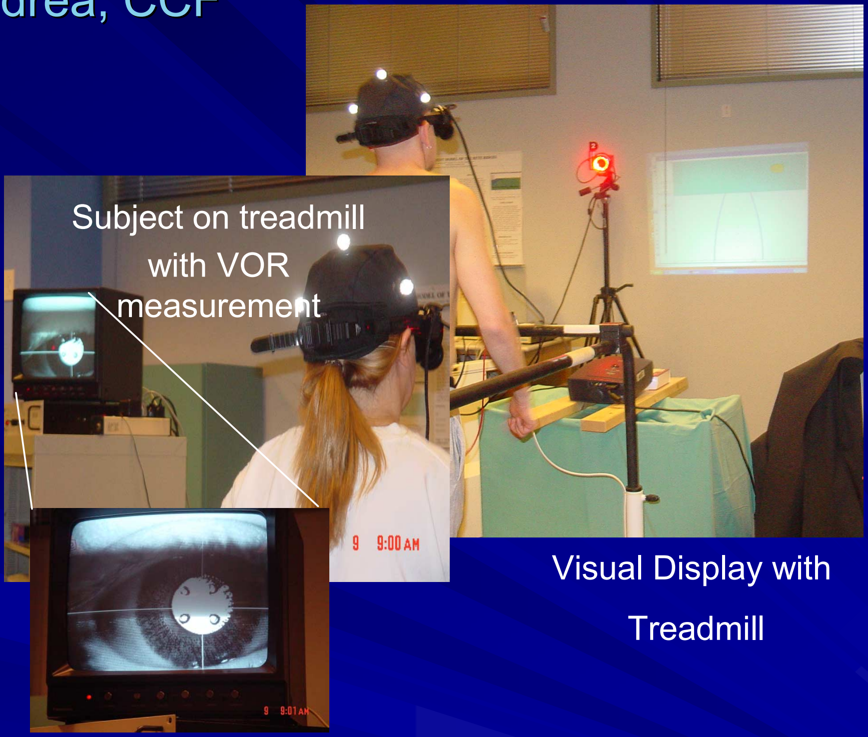
Spreeta Biosensor

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

A Dual-Track Actuated Treadmill in a Virtual Reality Environment: A Countermeasure for Neurovestibular Adaptation in Microgravity –Susan D'Andrea, CCF

- 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



Subject on treadmill with VOR measurement

Visual Display with Treadmill

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

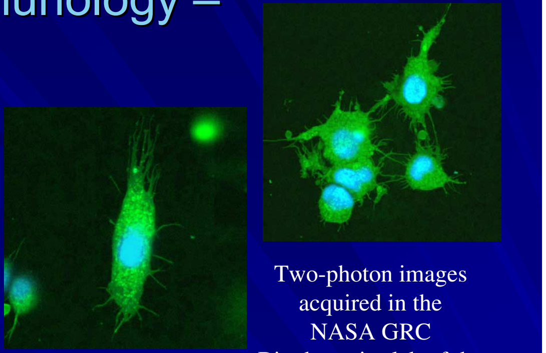
Glenn Research Center

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



Two-photon images acquired in the NASA GRC Biophotonics lab of the UMR-106 osteosarcoma cells

Two-photon images acquired in the NASA GRC Biophotonics lab of Human femoral head section Sample provided by M.K. Tate CCF

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.

THE CLEVELAND CLINIC FOUNDATION

CWRU

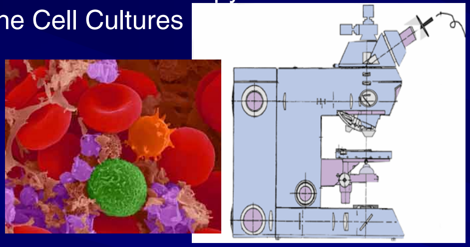
NASA

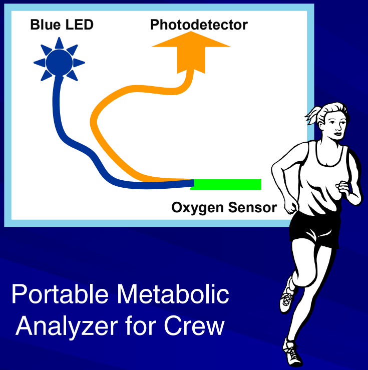
NCMR
FLUIDS AND COMBUSTION

The Research Institute
University Hospitals
of Cleveland

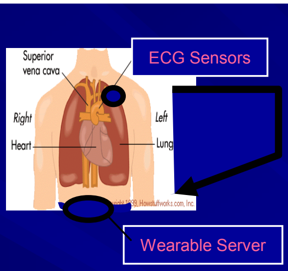
Biomedical Engineering Consortium Projects

Fluorescent Microscopy of Bone Cell Cultures



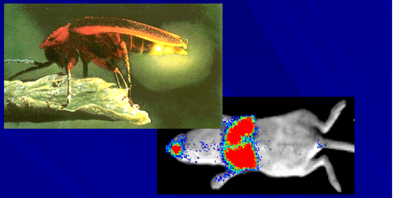


Portable Metabolic Analyzer for Crew

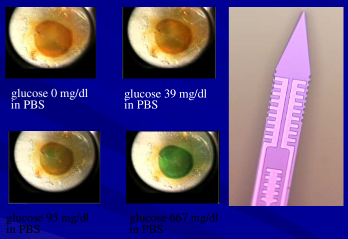


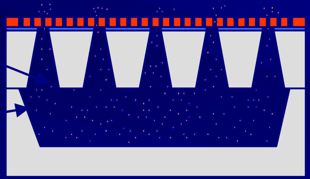
Detection and Web-based Reporting of Cardiac Dysrhythmia

Bioluminescent imaging for radiation dosimetry

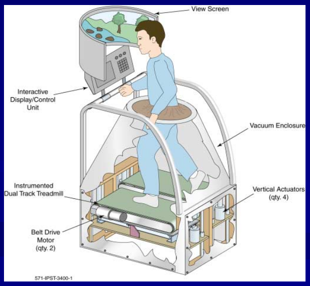


Microminiature Glucose Sensor

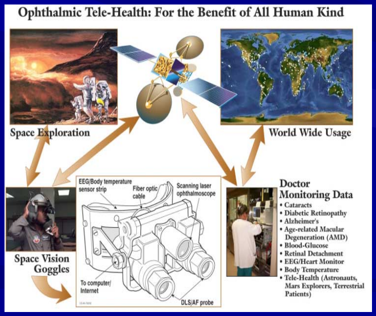




Controlled-Release Microsystems for Pharmacological Agent Delivery



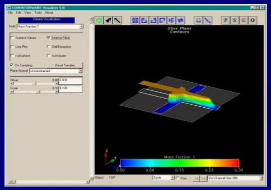
Virtual Reality Dual-Action Treadmill for Improved Neurovestibular Adaptation



Doctor Monitoring Data

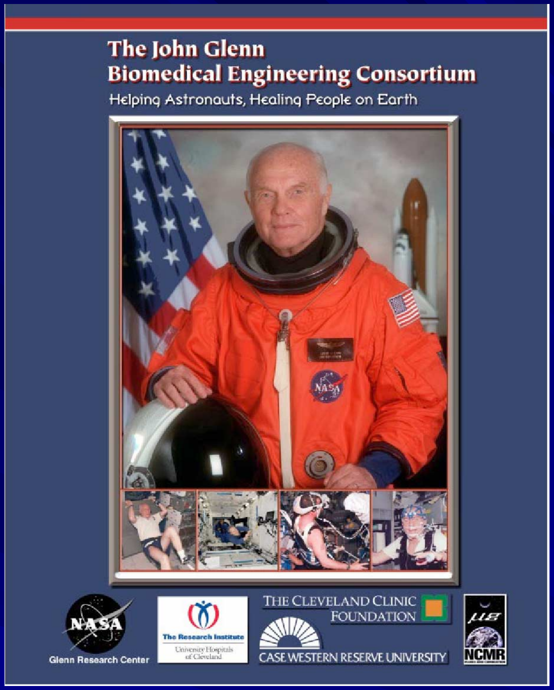
- Cataracts
- Diabetic Retinopathy
- Alzheimer's
- Age-related Macular Degeneration (AMD)
- Blood-Glucose
- Retinal Detachment
- EEG/Heart Monitor
- Body Temperature
- Tele-Health (Astronauts, Mars Explorers, Terrestrial Patients)

Non-invasive Eye Measurements to Reveal the Body's Health



Rapid Design and Simulation Tools of Space-bound Biochips

Acoustically Induced Micro-damage to Prevent Bone Loss.



The John Glenn
Biomedical Engineering Consortium
Helping Astronauts, Healing People on Earth

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

CASE
SCHOOL OF ENGINEERING

NCMR
FLUIDS AND COMBUSTION

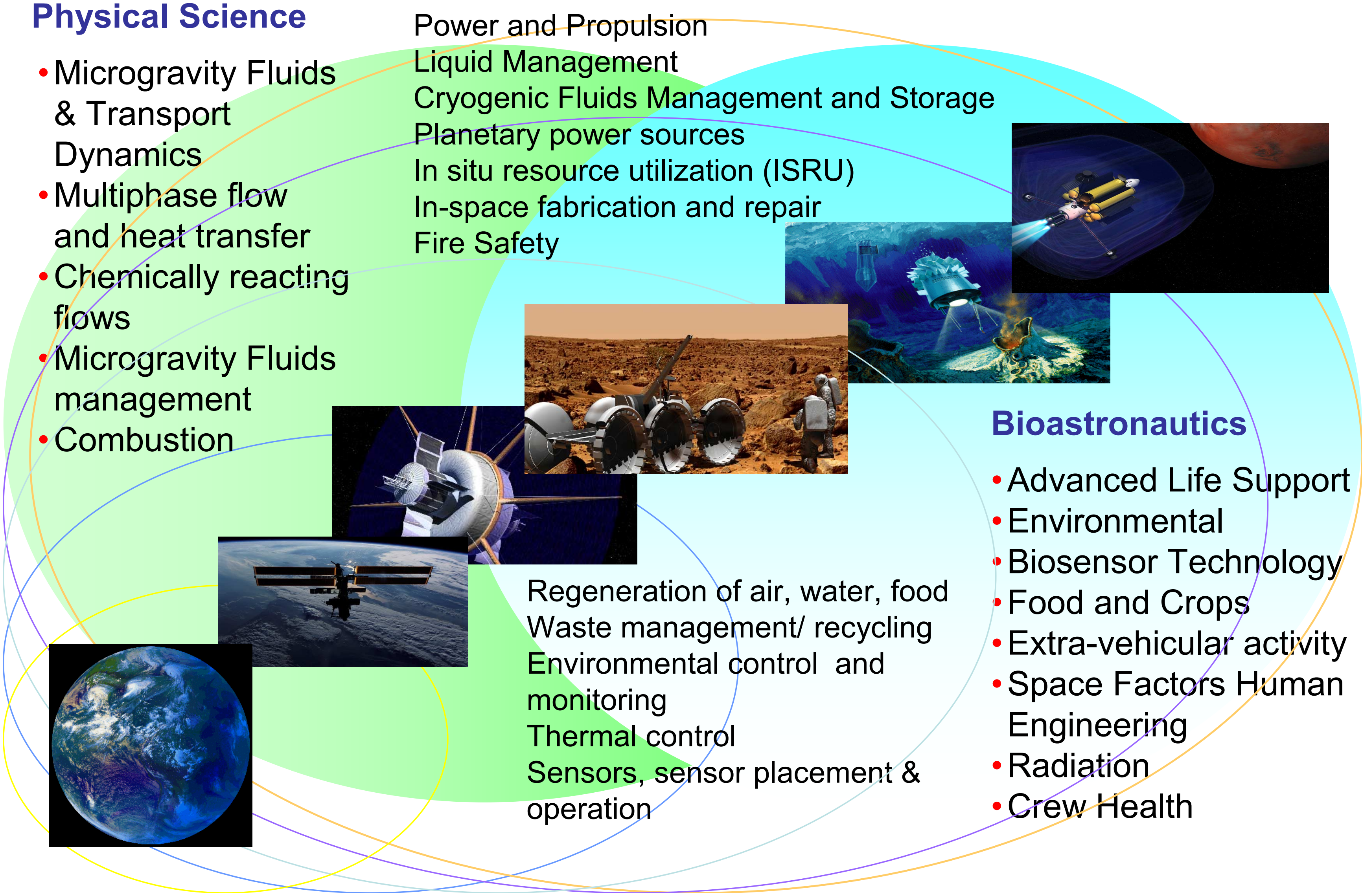
Strategic Research to Enable NASA's Exploration Missions

"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.

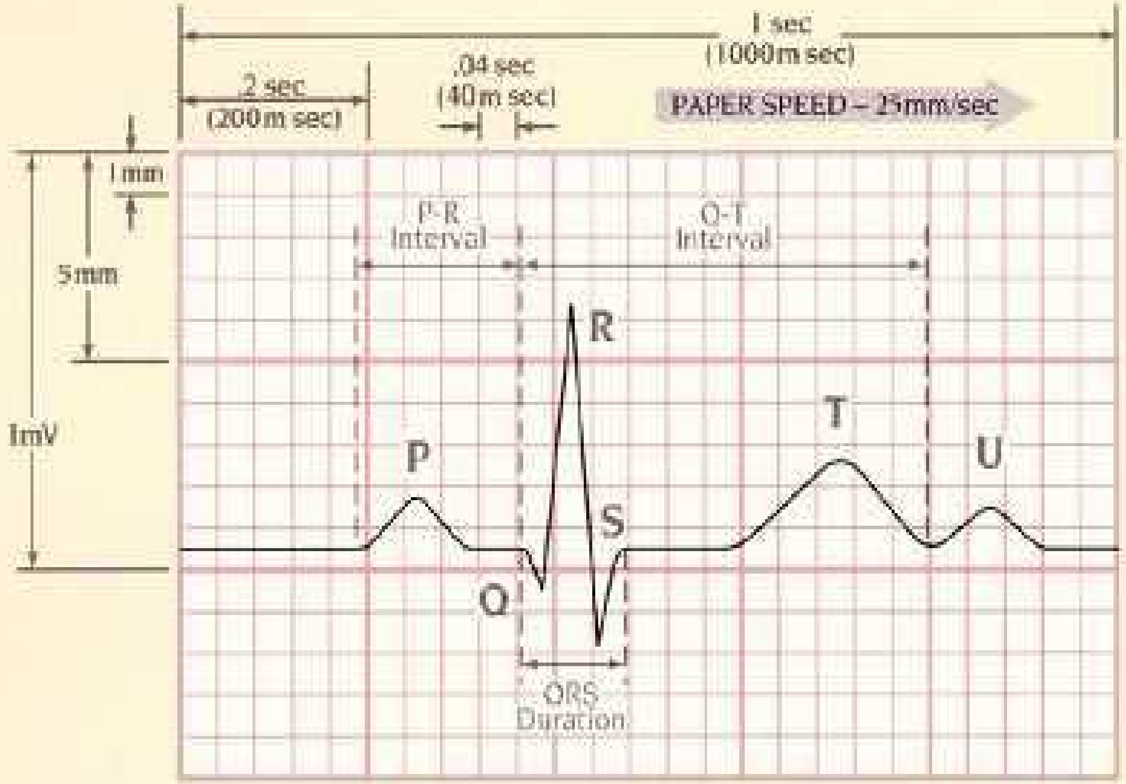
Detection and Prevention of Arrhythmias during Space Flight

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

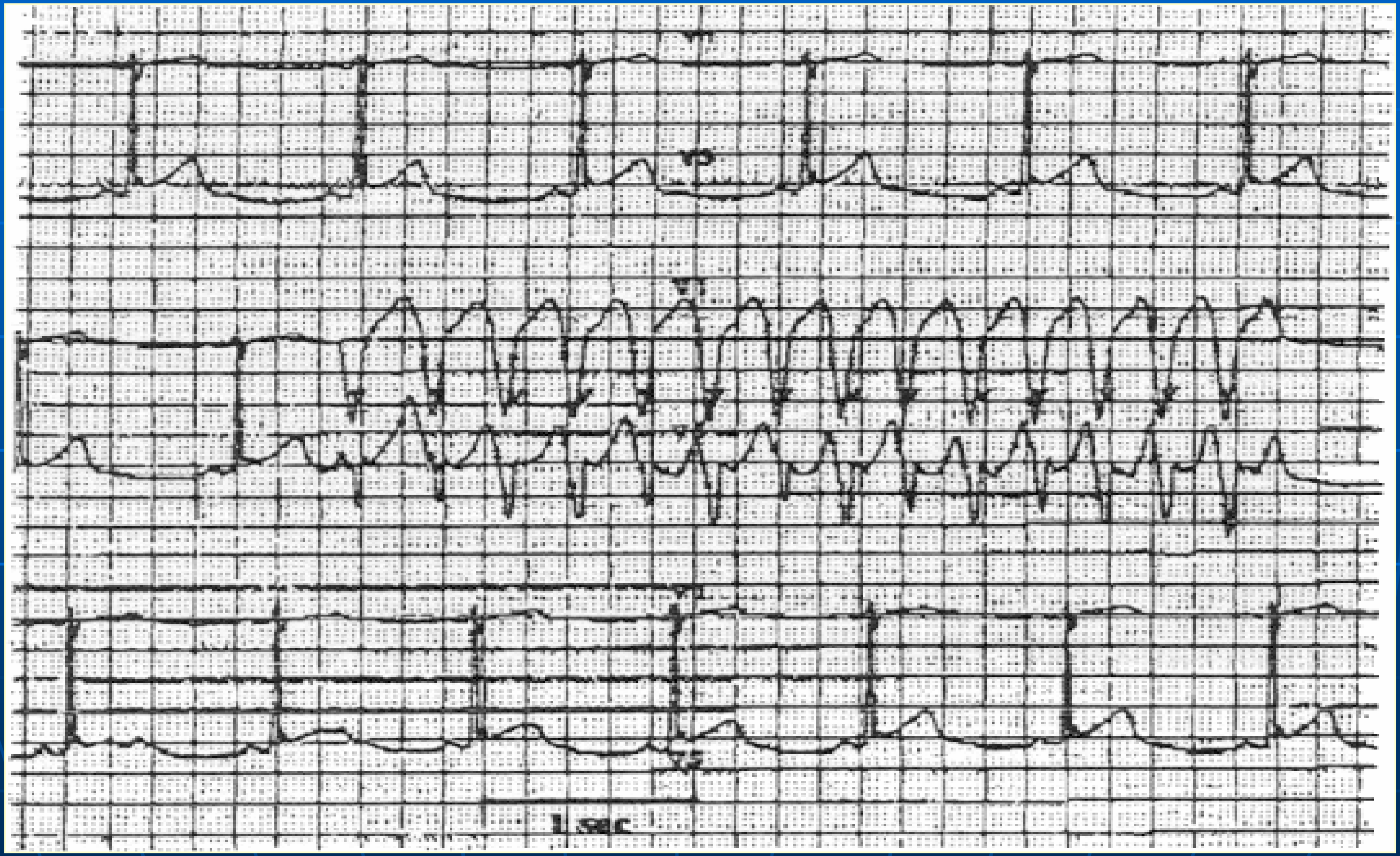
- Effects of prolonged microgravity on the electrical stability of the heart are unknown.
- Documented ventricular arrhythmias in Russian and US space programs.
- Structural remodeling of the heart in microgravity may predispose to arrhythmia.
- Fatal arrhythmias could be the first presentation of underlying cardiac disease.



VERTICAL AXIS	
	1 Small Square = 1mm (0.1mV)
	1 Large Square = 5mm (0.5mV)
	2 Large Squares = 1mV

HORIZONTAL AXIS	
	1 Small Square = .04 sec (40 m sec)
	1 Large Square = .2 sec (200 m sec)
	5 Large Squares = 1 sec (1000 m sec)

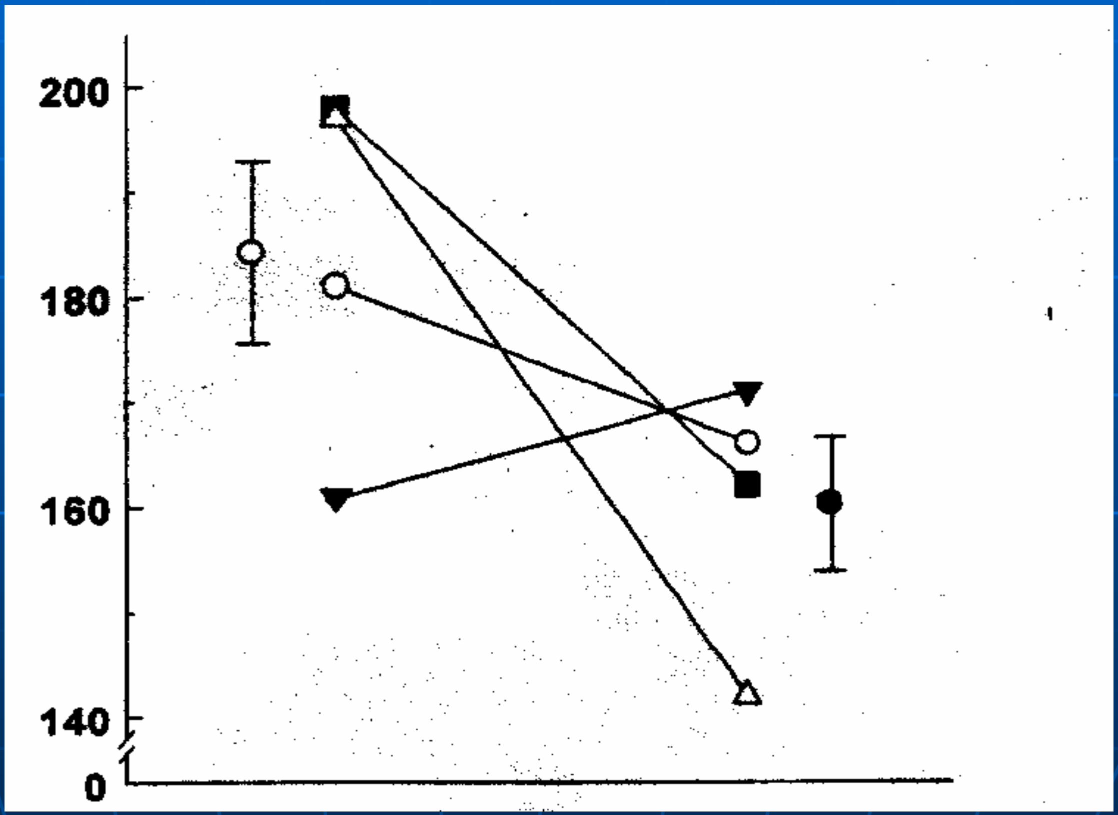
An Episode of Ventricular Tachycardia during Long-duration Spaceflight



Fristch-Yelle JM et al. Am. J. Cardiol 1998;81:1391-2.

Cardiac atrophy after space-flight

Perhonen et al, J Appl Physiol 2001; 91:645-653.

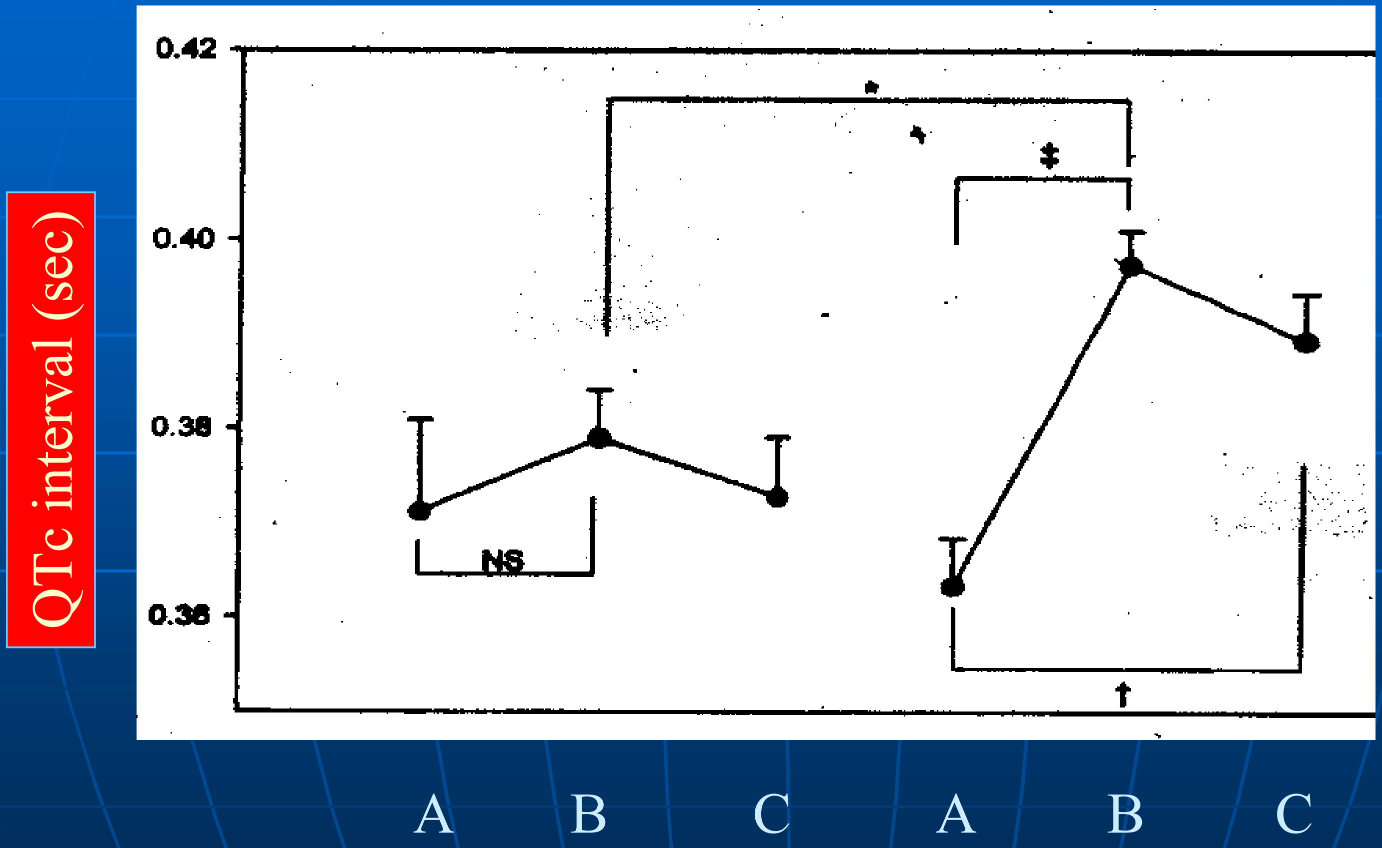


LV mass (g)

preflight

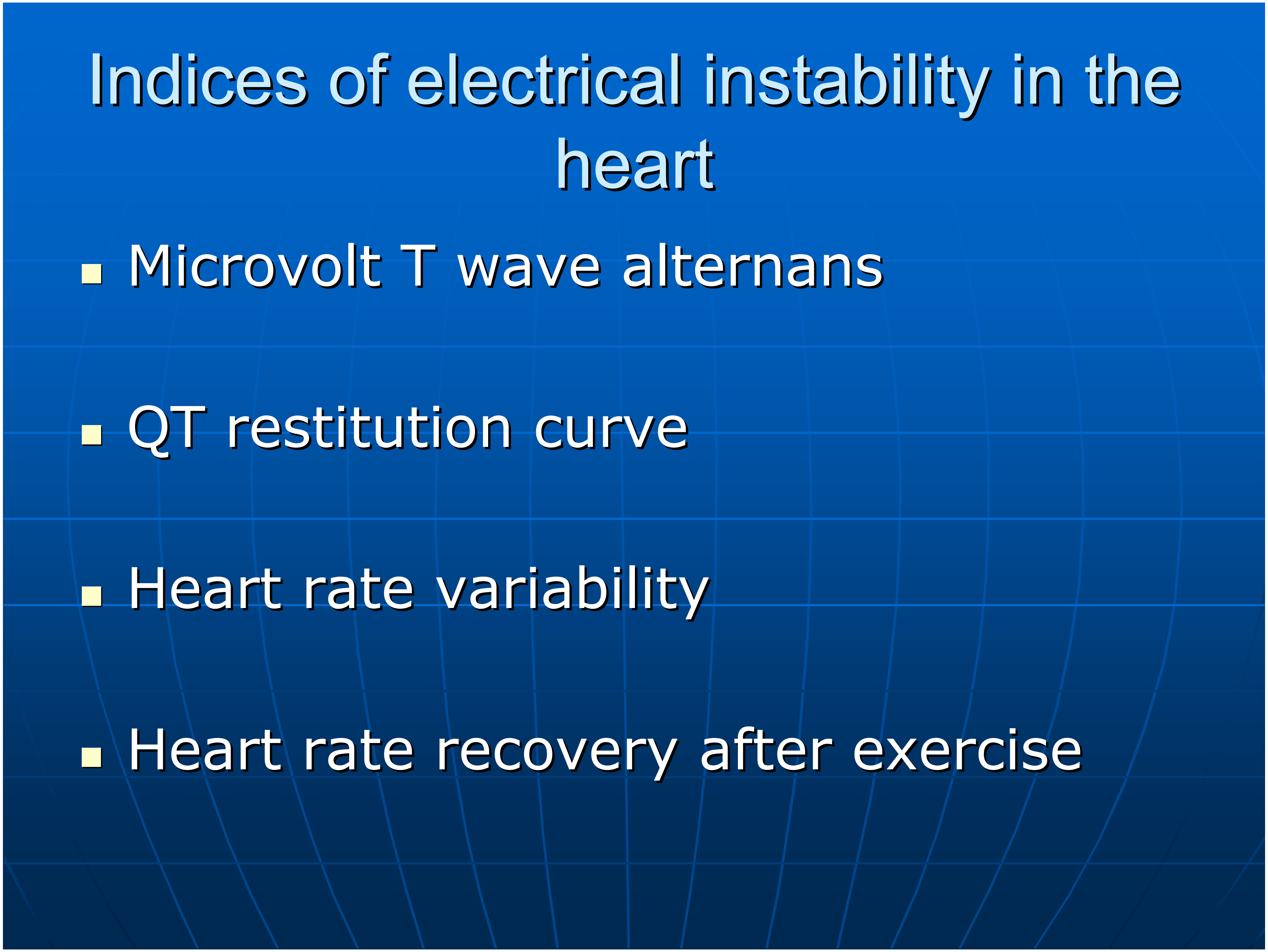
postflight

Effect of short and long duration spaceflight on QTc intervals in Healthy Astronauts



A preflight
B landing
C postflight

D'Aunno DS et al. Am J Cardiol 2003;91:494-7.



Indices of electrical instability in the heart

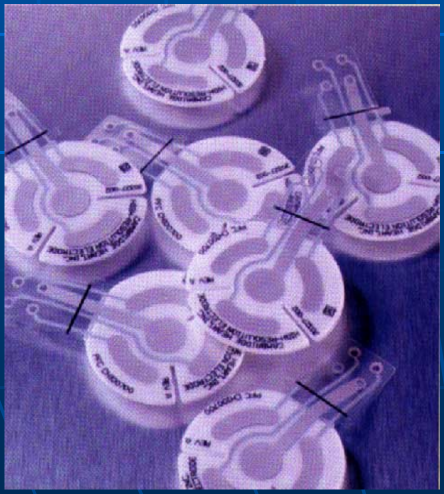
- Microvolt T wave alternans
- QT restitution curve
- Heart rate variability
- Heart rate recovery after exercise

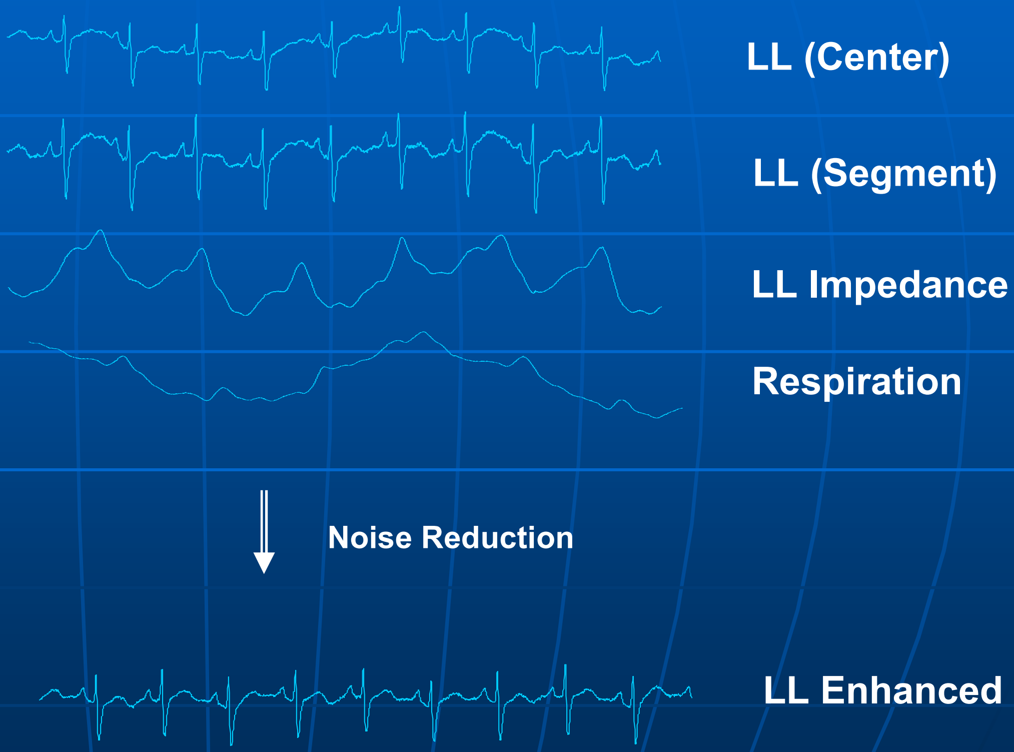
Natural History Electrical Alternans?

Raeder E, et al. N. Engl. J. Med 1992; 326: 272-73.

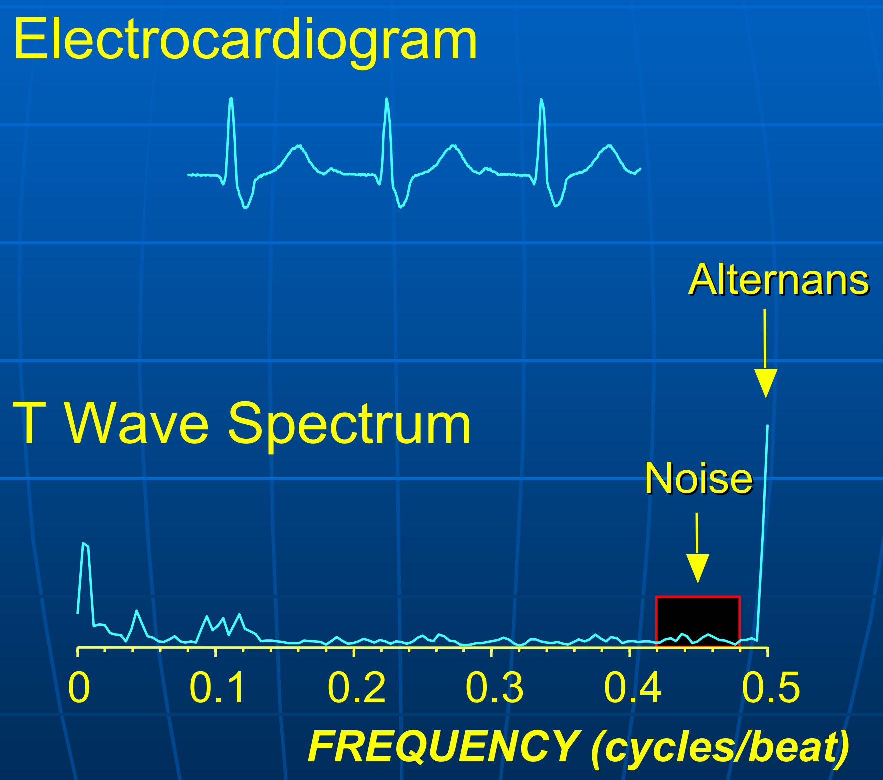
Electrode Enhancement

Reduction of noise through adaptive cancellation of artifact





T Wave Alternans Measurement

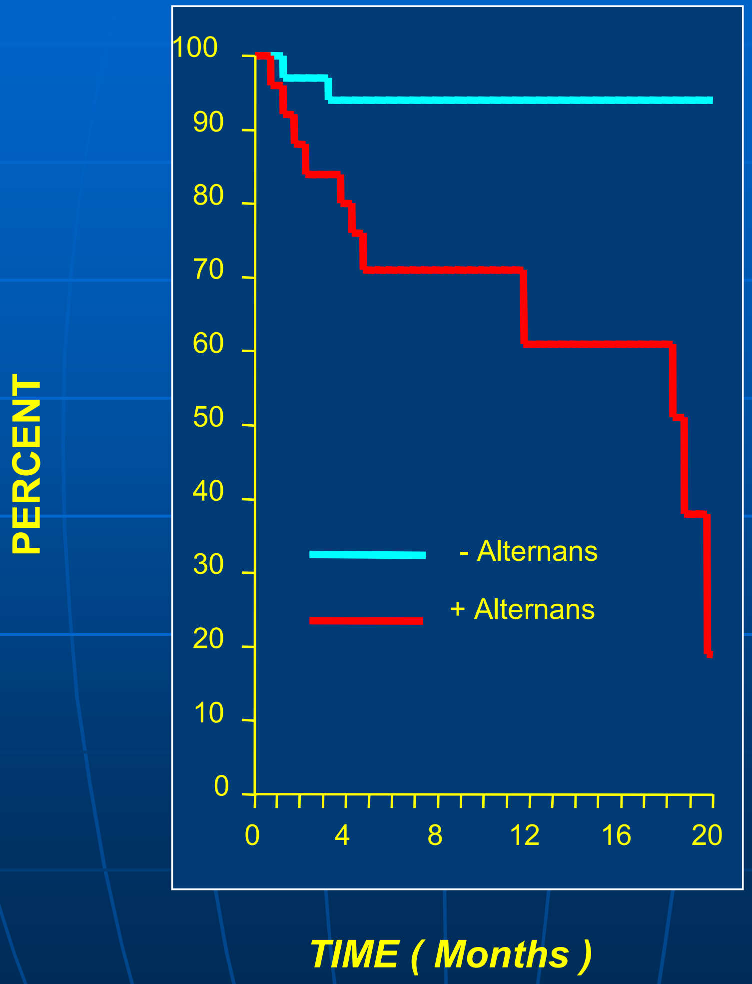


Electrocardiogram

T Wave Spectrum

Rosenbaum DS, et al. *N.Engl.J.Med.* 1994;330:235-241.

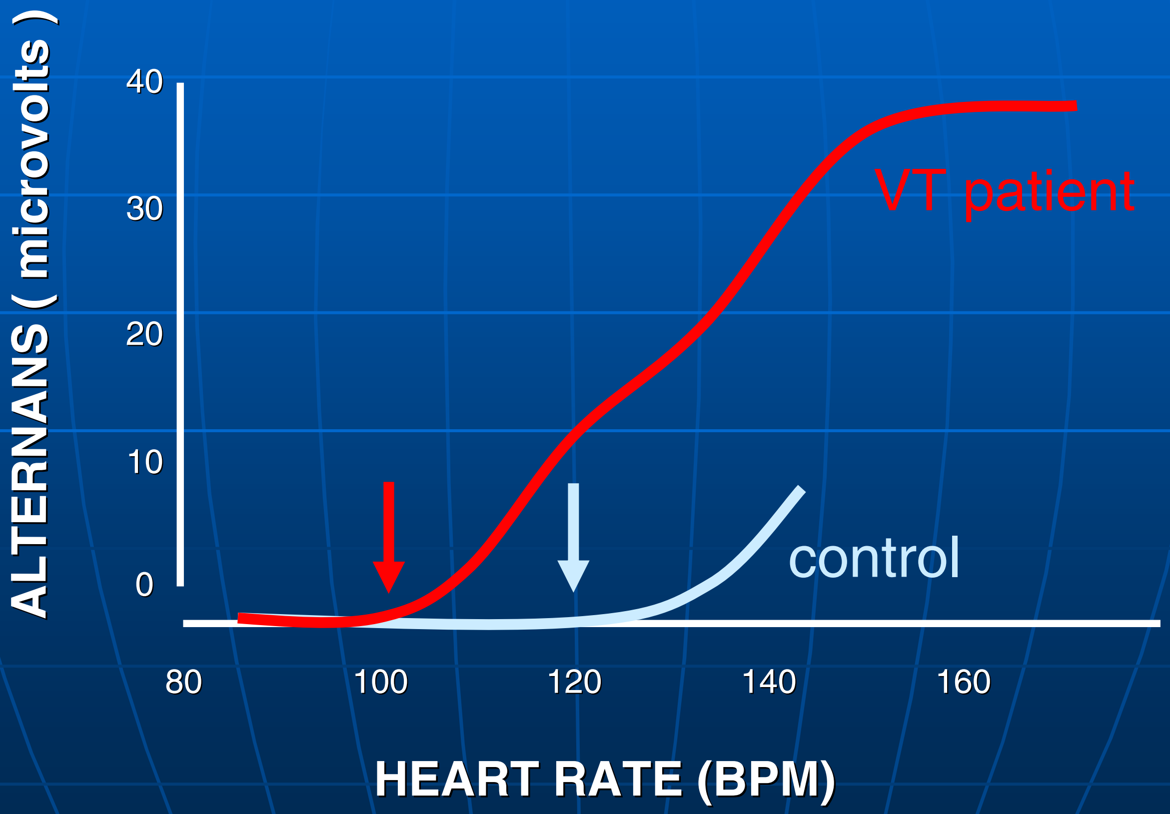
Arrhythmia-Free Survival



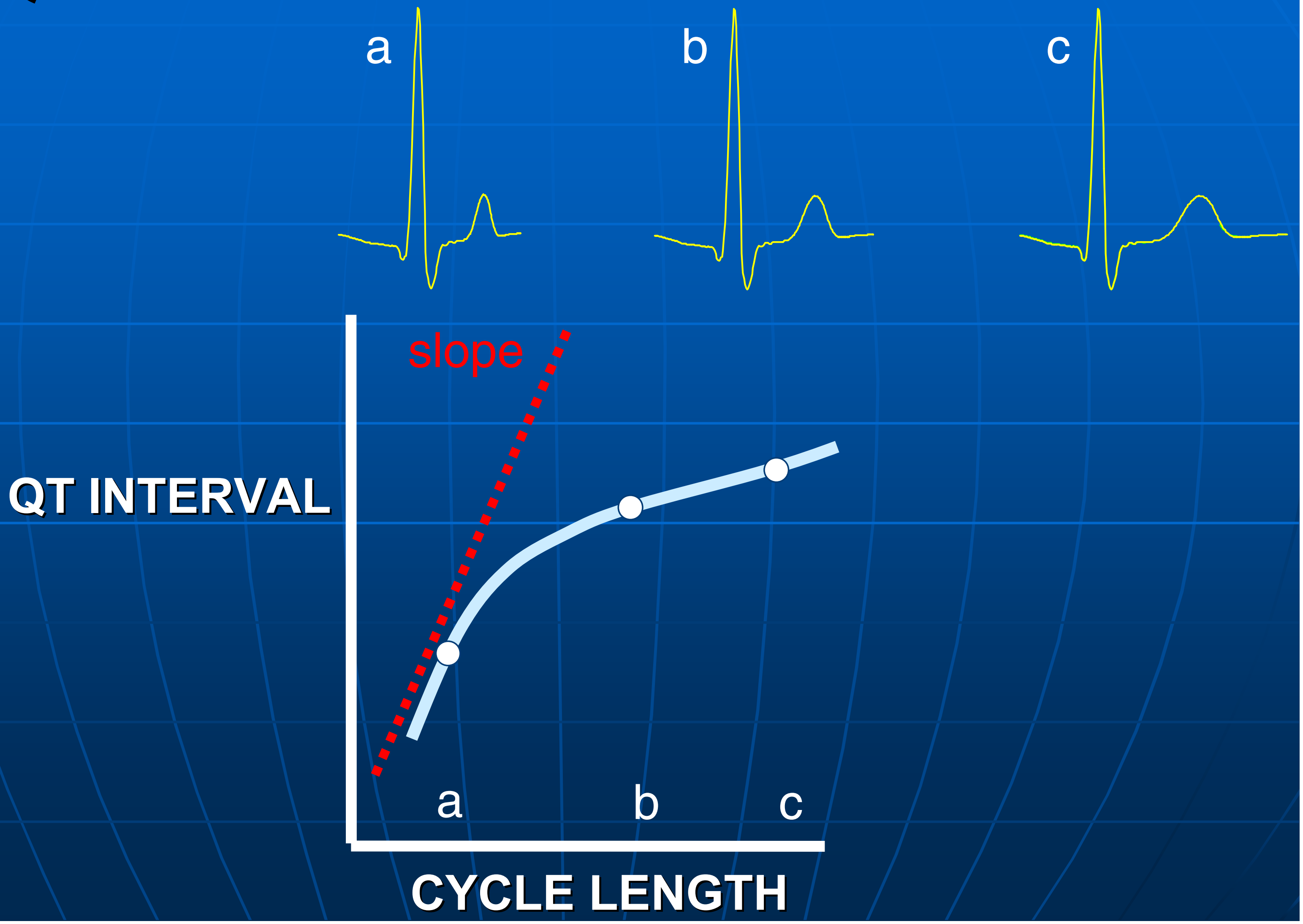
Rosenbaum et al. *N Engl J Med* 1994;330:235-241

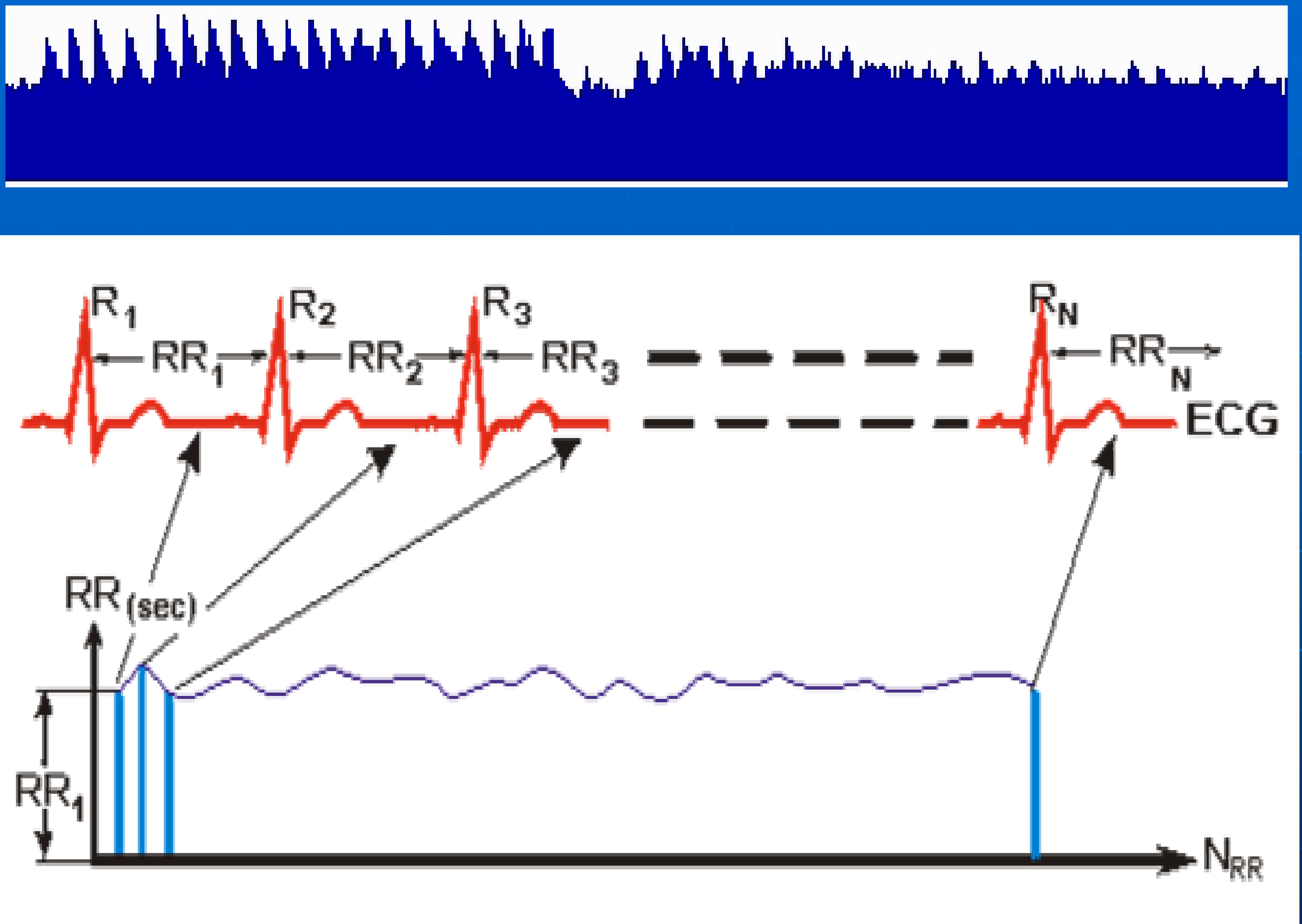
Heart Rate Dependence of T Wave Alternans

Kaufman E, et al. *Am J Physiol*. 2000;279:H1248-H1255.



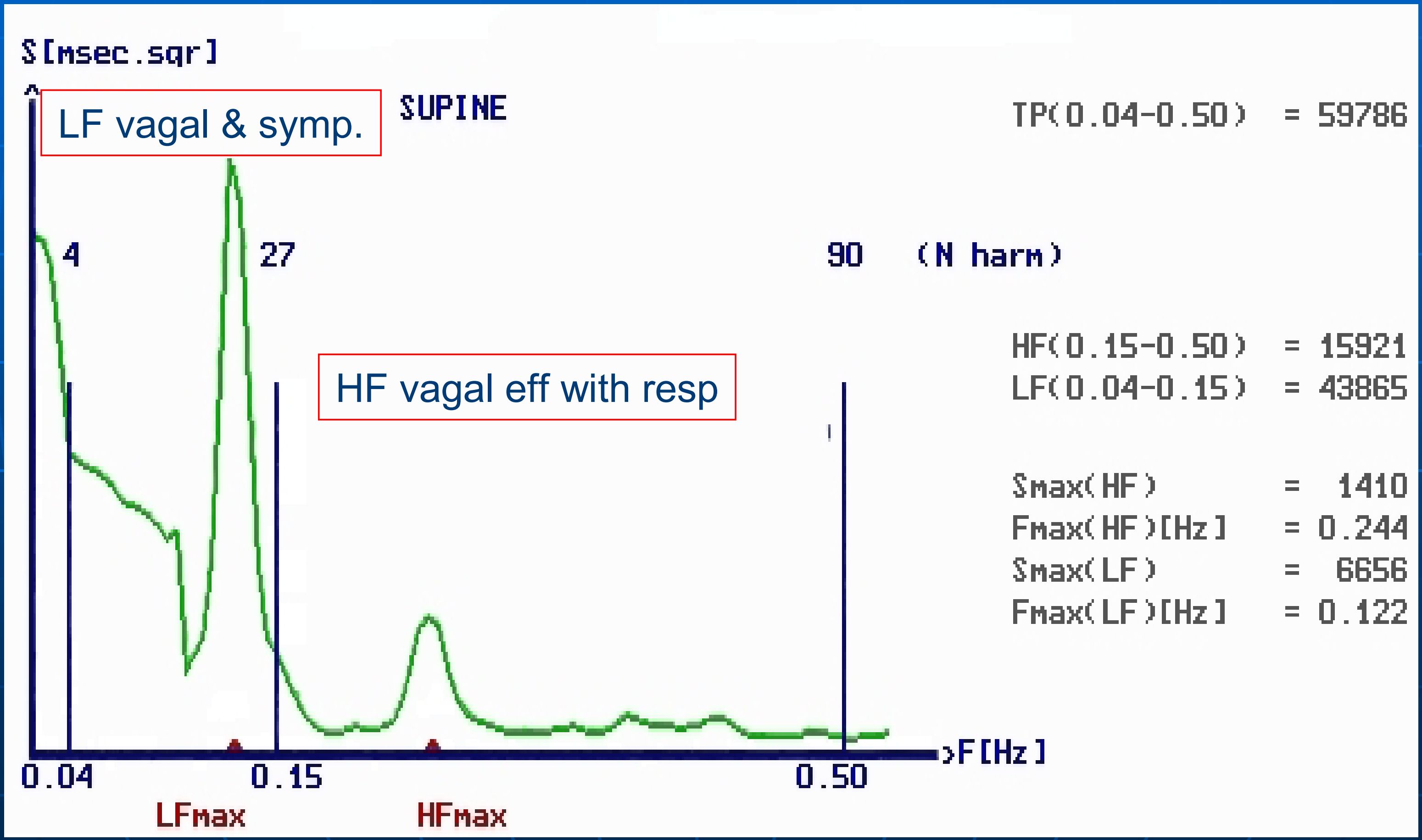
QT INTERVAL RESTITUTION





HEART RATE VARIABILITY

POWER SPECTRAL ANALYSIS OF HRV



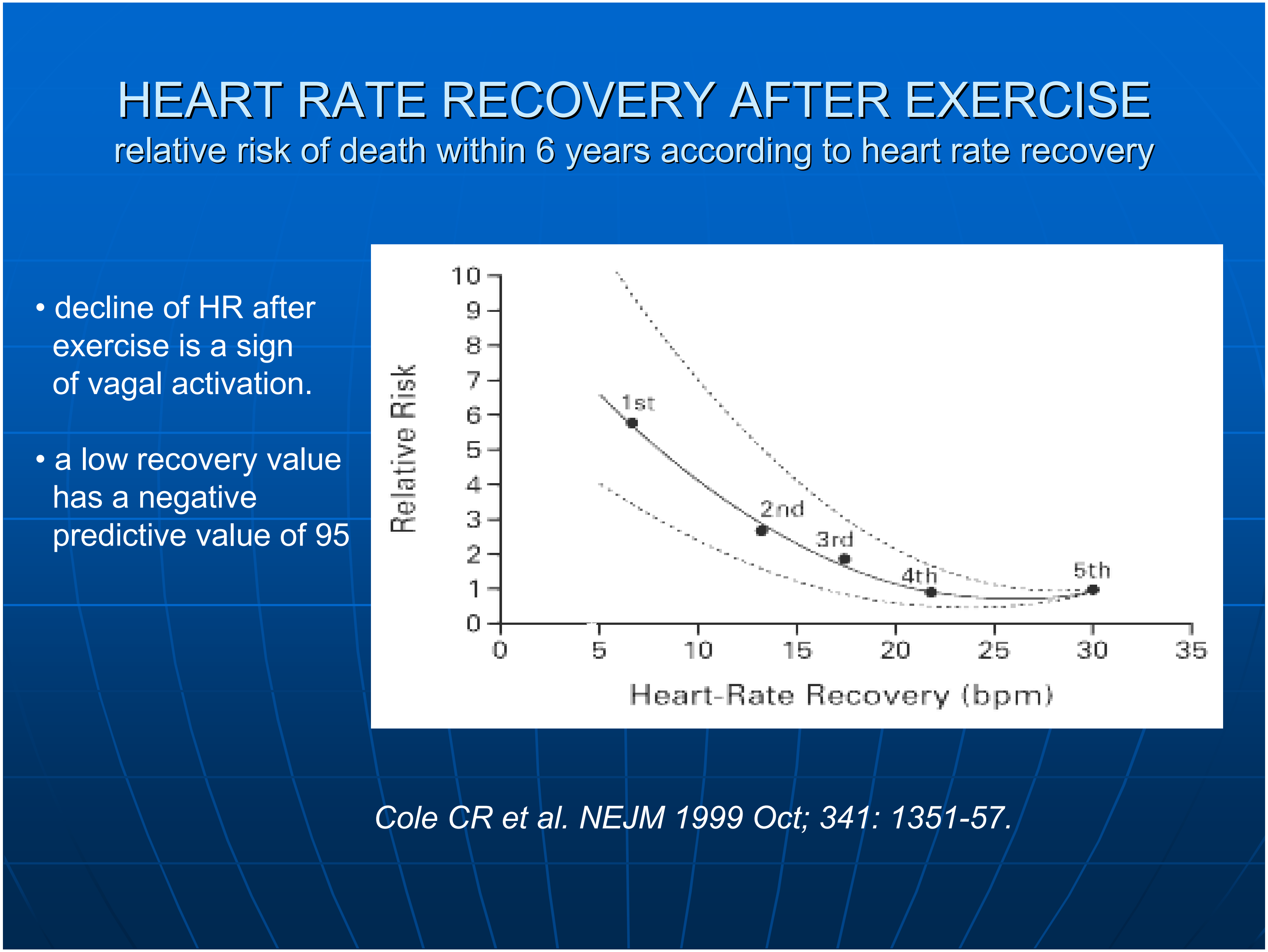
LF vagal & symp.

HF vagal eff with resp

```
TP(0.04-0.50)   = 59786

HF(0.15-0.50)   = 15921
LF(0.04-0.15)   = 43865

Smax(HF)        =  1410
Fmax(HF)[Hz]    = 0.244
Smax(LF)        =  6656
Fmax(LF)[Hz]    = 0.122
```



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

Cole CR et al. NEJM 1999 Oct; 341: 1351-57.

Bicycle ergometer in space station

[redacted]

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.

CONSTRAINED VAPOR BUBBLE

Joel L. Plawsky and Peter C. Wayner, Jr.
Isermann Department of Chemical and Biological Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180

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

J.L. PLAWSKY & P.C. WAYNER, JR.

HOWARD P. ISERMANN DEPARTMENT OF
OF CHEMICAL & BIOLOGICAL ENGINEERING
RENSSELAER POLYTECHNIC INSTITUTE
TROY, NEW YORK

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]

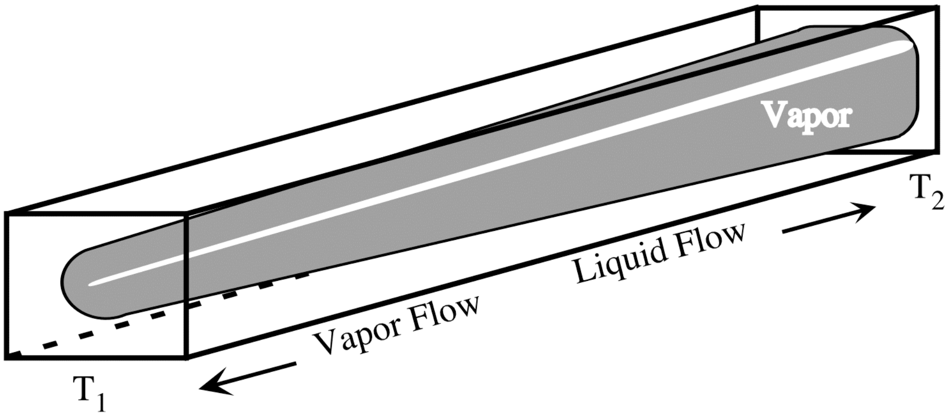
CONSTRAINED VAPOR BUBBLE GENERIC SYSTEM

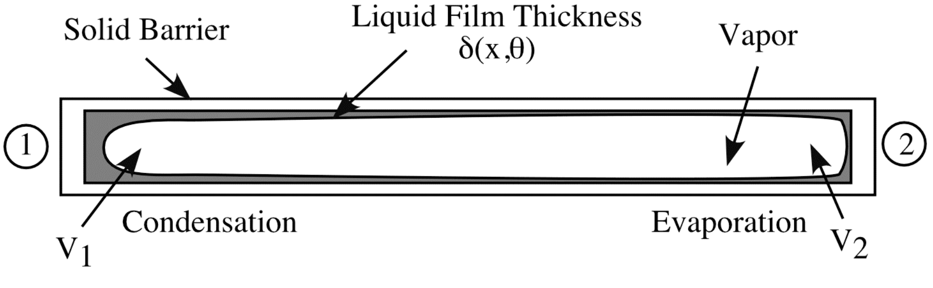
A PASSIVE ENGINEERING SYSTEM [PES] CONTROLLED BY INTERFACIAL PHENOMENA WHICH RESPONDS TO SURFACE TEMPERATURE

$T_1 < T_2$

$P_{v2} > P_{v1} > P_{l1} > P_{l2}$

$$P_v = P_l + \sigma\kappa + \frac{(-B)}{\delta^n}$$

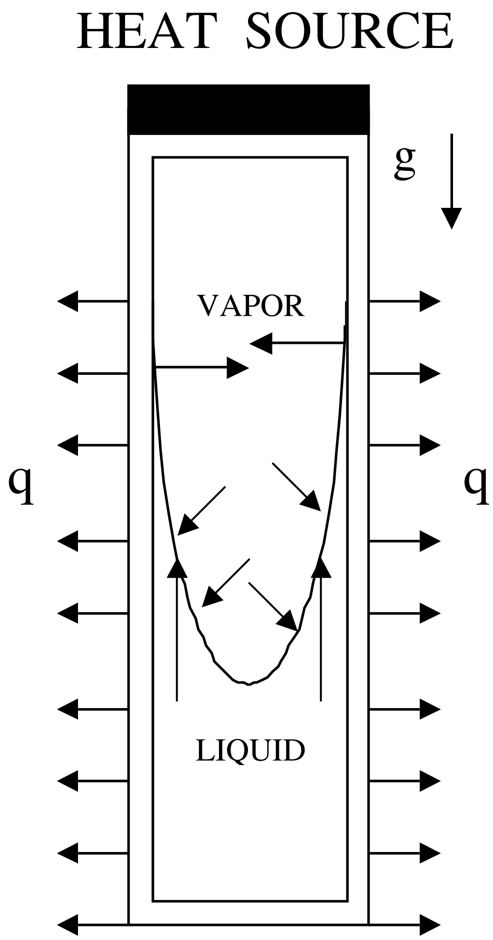


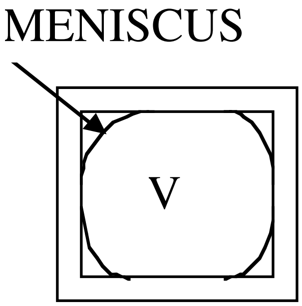


EXAMPLE SYSTEMS

1) SCHEMATIC OF CVB FIN HEAT EXCHANGER

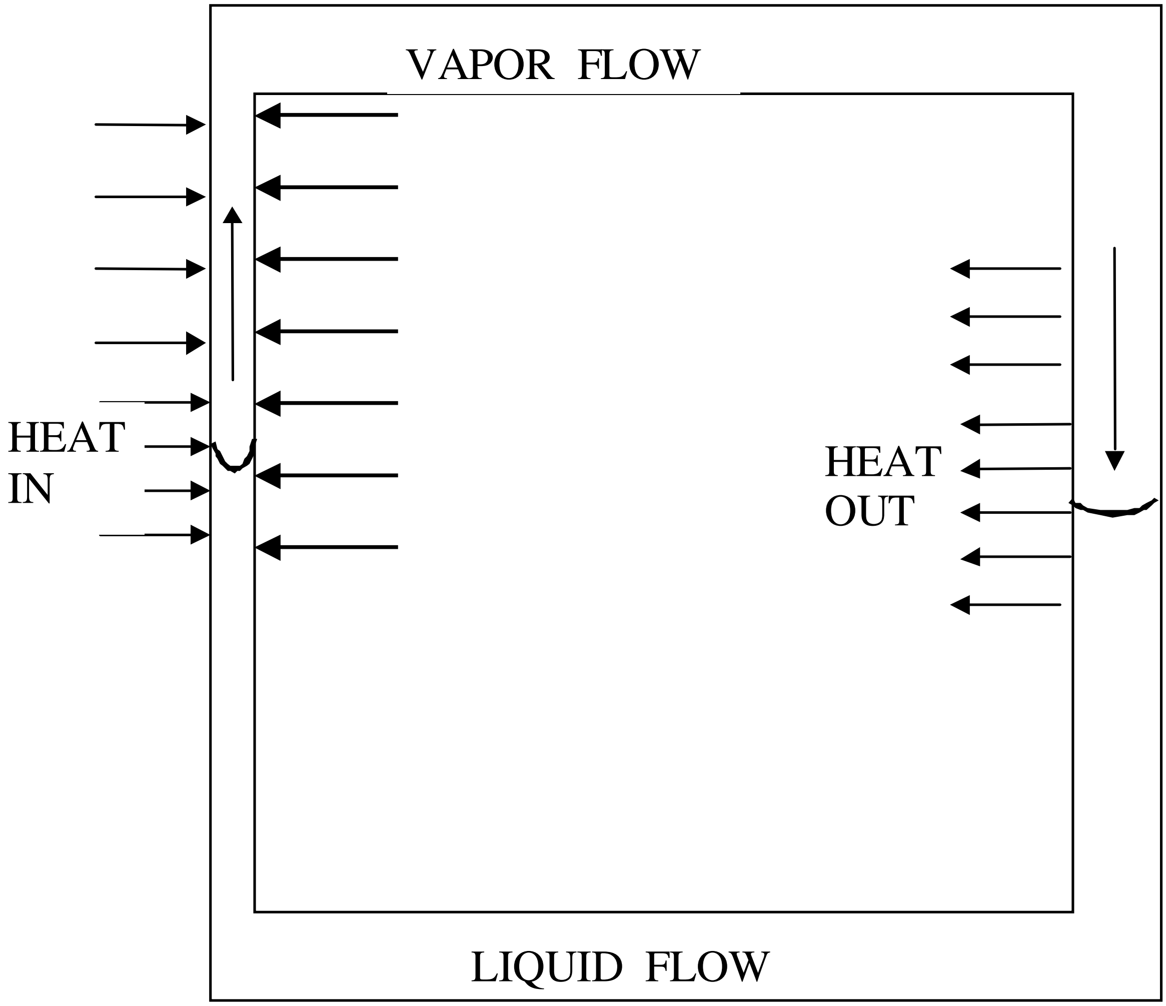
INSIDE DIMENSIONS OF CURRENT VERTICAL 1g SYSTEM BEING STUDIED AT RPI: 3 X 3 X 40 mm





EXAMPLE 2:

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 **MACRO**SCOPIC 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 **MICRO**SCOPIC 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 $g \rightarrow 0$

$$Q_m = \frac{C \sigma h_{fg} H^3}{\upsilon k_{fl} L} \propto \frac{H^3}{L}$$

H = INTERNAL WIDTH ; L = INTERNAL LENGTH

MAXIMUM AXIAL HEAT FLUX, q_m''

$$q_m'' = \frac{Q_m}{H^2} = \frac{C \sigma h_{fg} H}{\upsilon k_{fl} L} \propto \frac{H}{L}$$

e.g., with H/L = 3/30, $q_m'' = 4.79$ W/ cm^2

THEREFORE, RELATIVELY LARGE SYSTEMS ARE NEEDED FOR MAXIMUM HEAT FLUX

HOWEVER, THE CHARACTERISTICS OF SYSTEMS WITH LOW CAPILLARY PRESSURES ARE UNKNOWN

$$\frac{dK}{dx} = -\frac{\upsilon k_{fl} Q}{C_l^3 \sigma h_{fg}} K^4 - \frac{\rho g}{\sigma}$$

CORNER CURVATURE, K, VERSUS AXIAL POSITION FOR VARIOUS HEAT FLOW RATES BASED ON VISCOUS LOSSES IN THE CORNER MENISCUS IN REGION III: “ μ g” ON ISS VERSUS 1 g

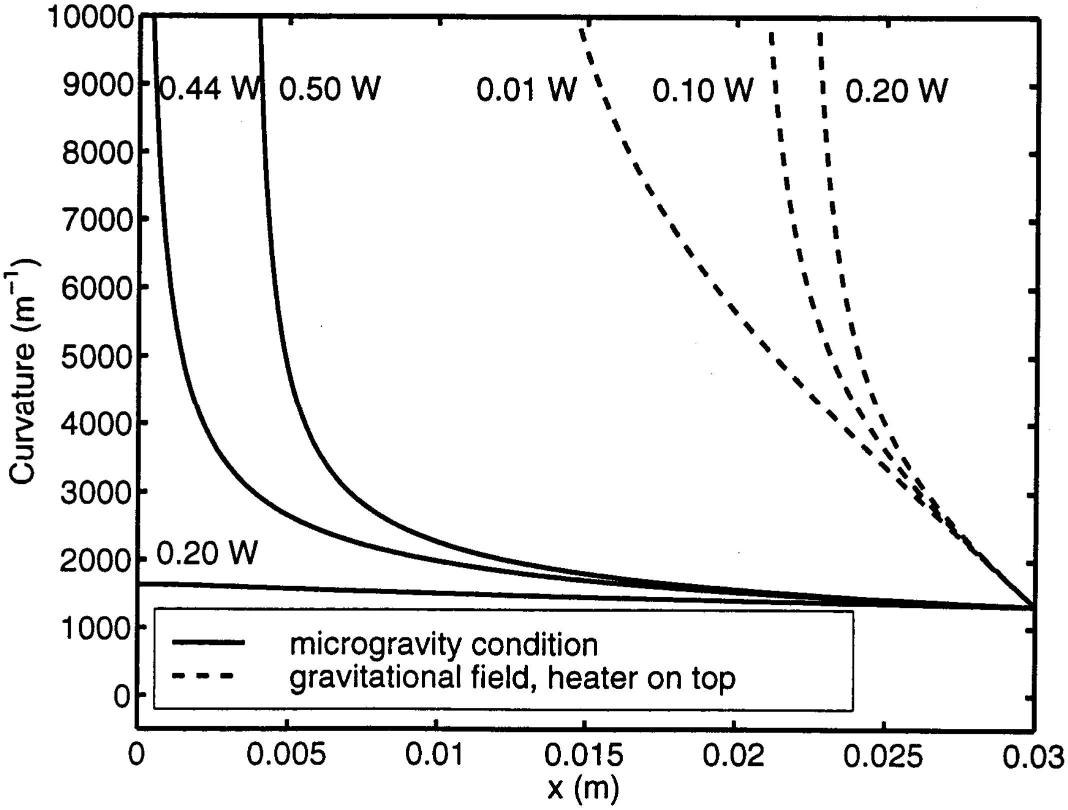
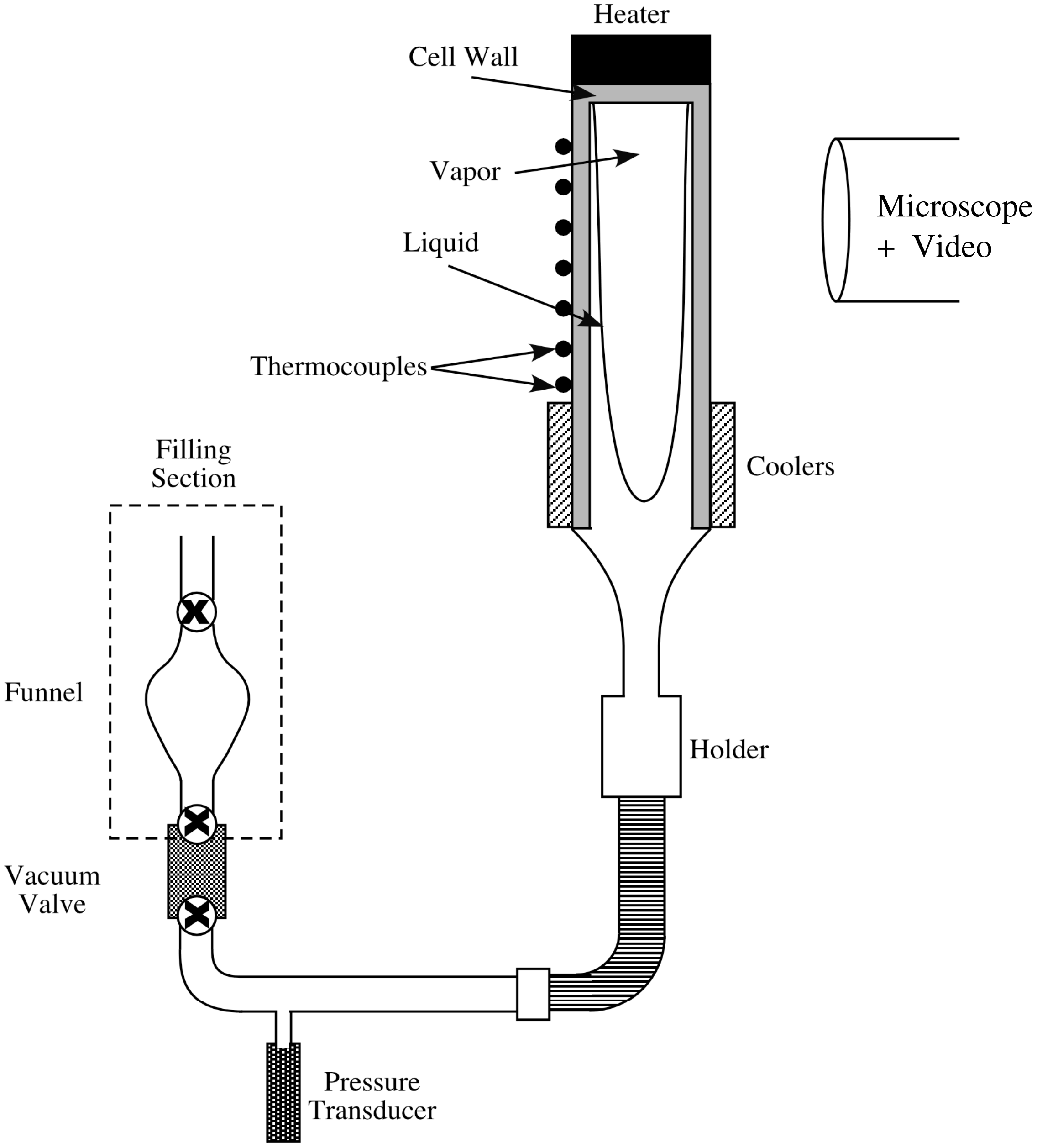


Figure 8. Curvature versus axial position

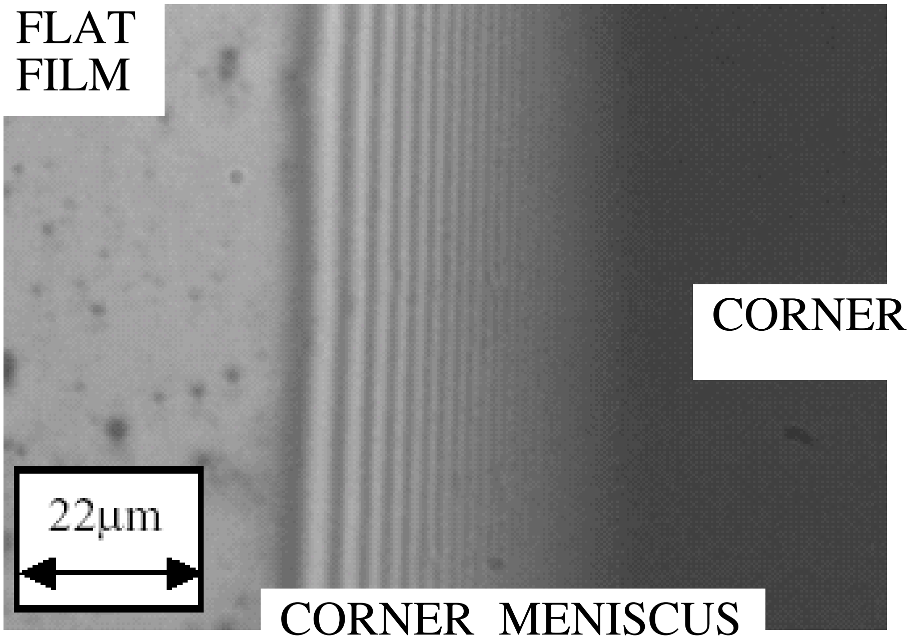
EXPERIMENTAL TECHNIQUES

SCHEMATIC OF 1g EXPERIMENT AT RPI USING QUARTZ TRANSPARENT CELL



THE THICKNESS PROFILE OF A CURVED LIQUID FILM IS OBTAINED USING IMAGE ANALYZING

INTERFEROMETRY, IAI, WHICH RECORDS THE NATURALLY OCCURRING REFLECTIVITY PROFILE

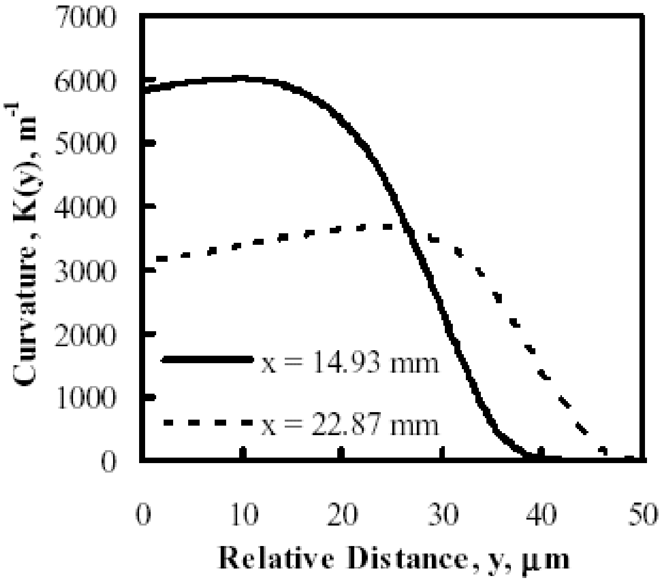


REFLECTIVITY PROFILE GIVES THICKNESS PROFILE WHICH GIVES THE CURVATURE PROFILE , K (x, y), AND THE PRESSURE FIELD, P (x, y)

$$P_l = P_v - \sigma K - \left(\frac{-B}{\delta^n} \right)$$

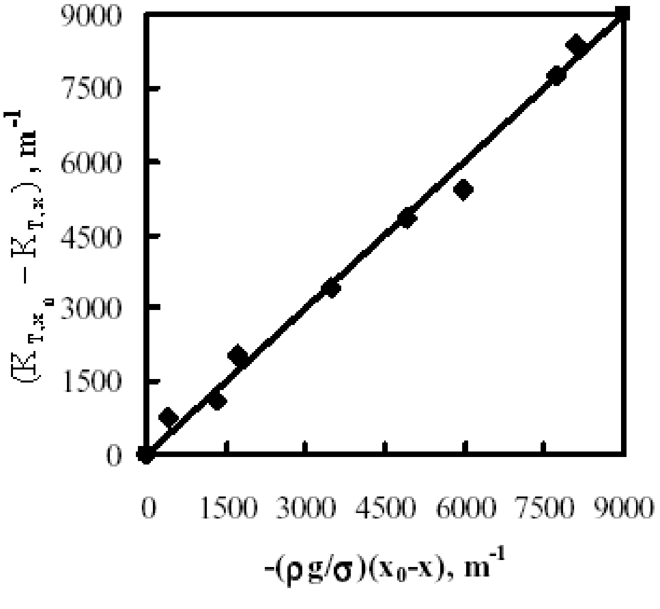
MENISCUS CURVATURE PROFILE

IN CONTACT LINE REGION, K VS y :



ISOTHERMAL CONFIRMATION OF IAI TECHNIQUE

AXIAL VARIATION OF CURVATURE, $\Delta K = \frac{\rho g}{\sigma} \Delta x$



EFFECT OF HEAT INPUT ON AXIAL CURVATURE PROFILE FOR ETHANOL/QUARTZ SYSTEM

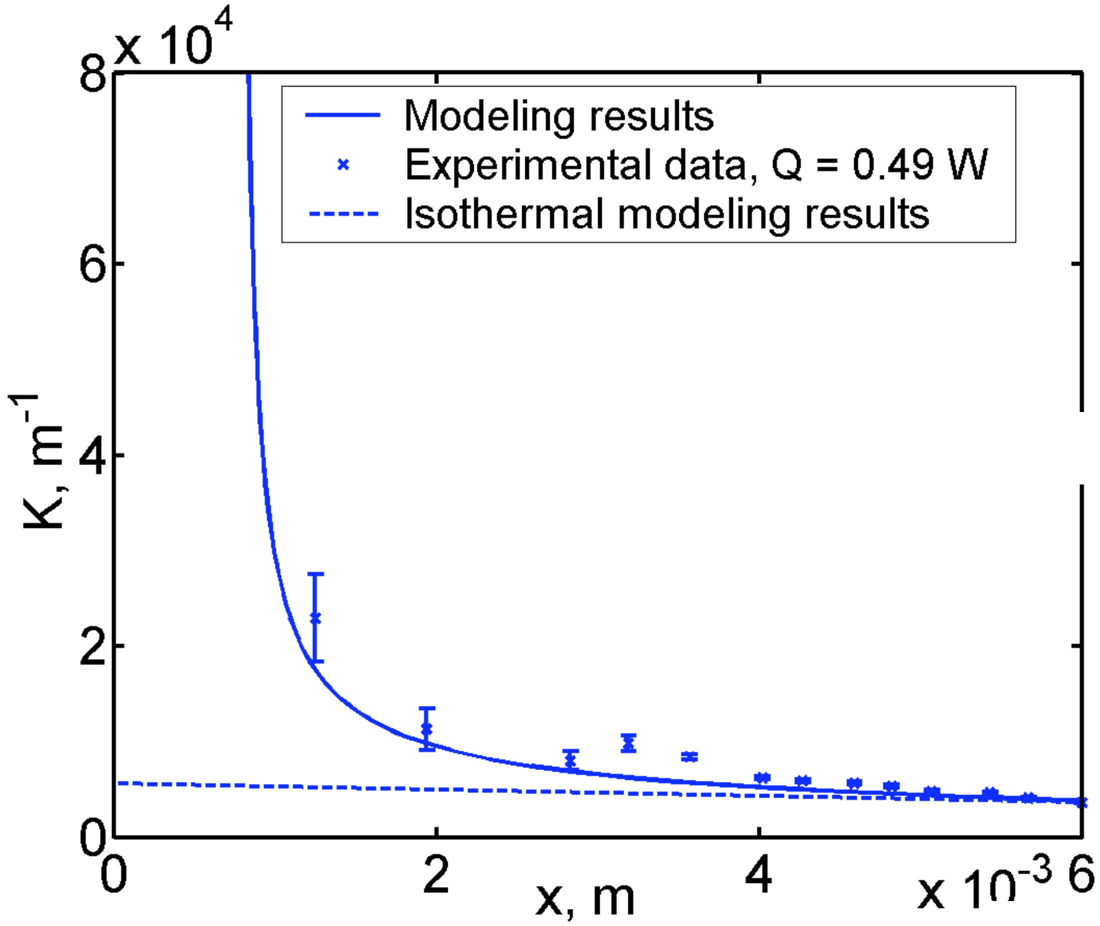
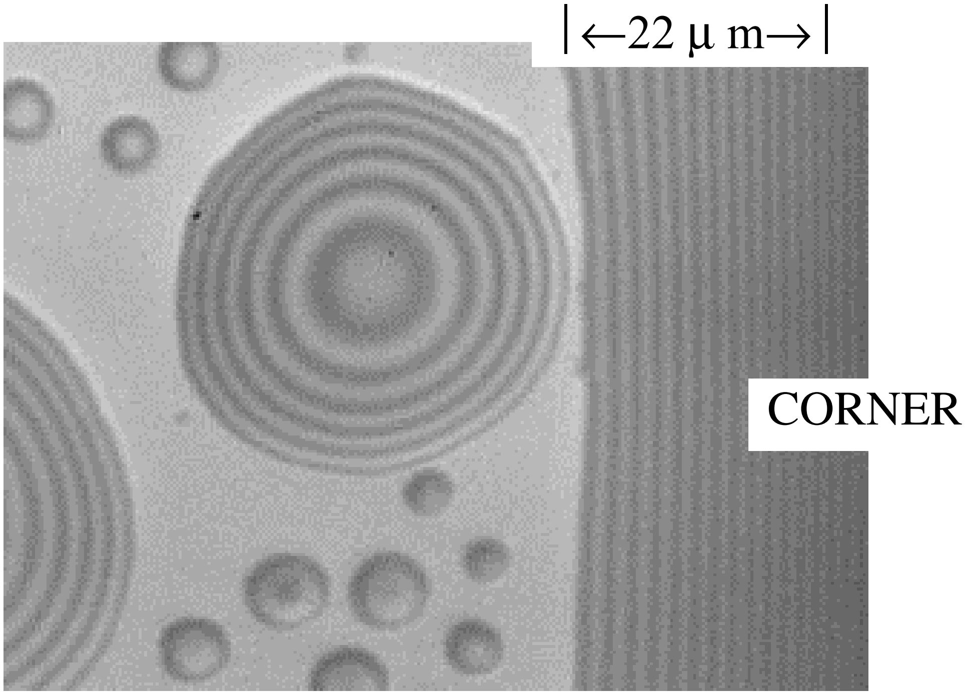
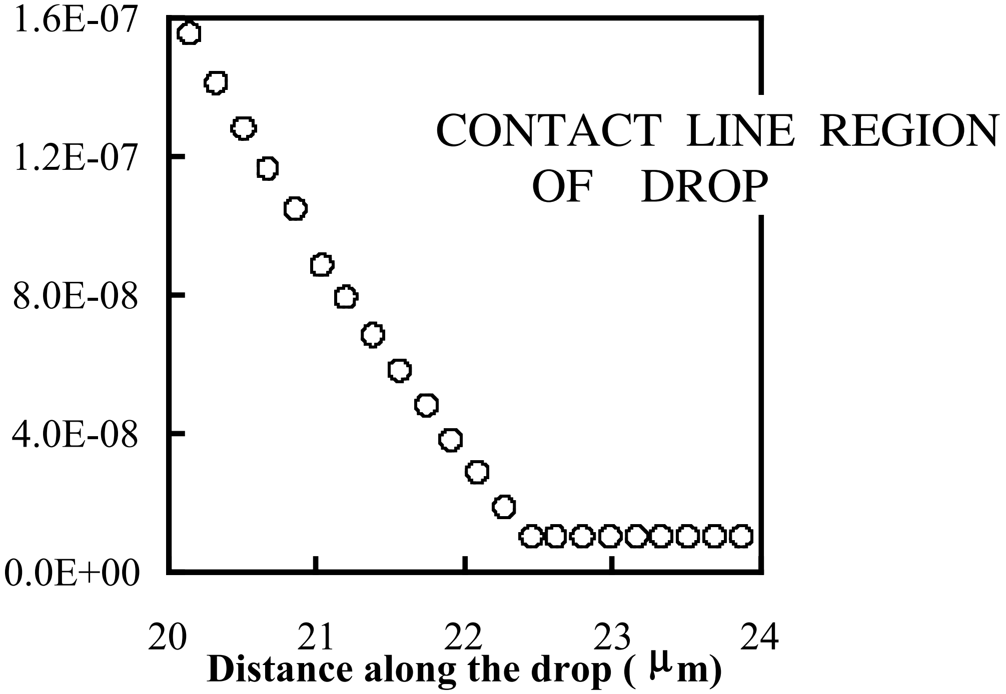


IMAGE OF DROPWISE CONDENSATION WITH CONDENSATE BEING REMOVED BY THE CORNER MENISCUS: 2-PROPANOL ON QUARTZ

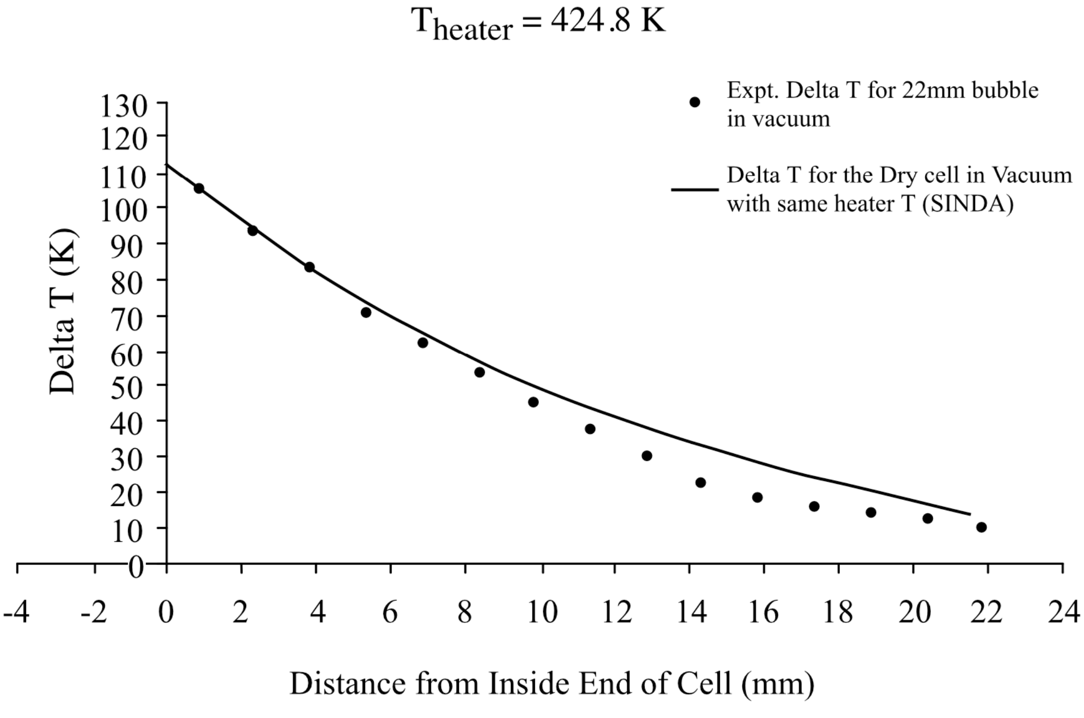




TEMPERATURE DIFFERENCE, $T_{SURFACE} - T_{\infty}$, VERSUS AXIAL DISTANCE

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



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 [$\Theta > O$; APOLAR]
2-PROPANOL [$\Theta > O$; POLAR]

CONCLUSIONS

1. USING 1g PREPARATORY EXPERIMENTS, EXPERIMENTAL TECHNIQUES TO STUDY THE HEAT TRANSFER CHARACTERISTICS OF THE CVB HAVE BEEN DEVELOPED.

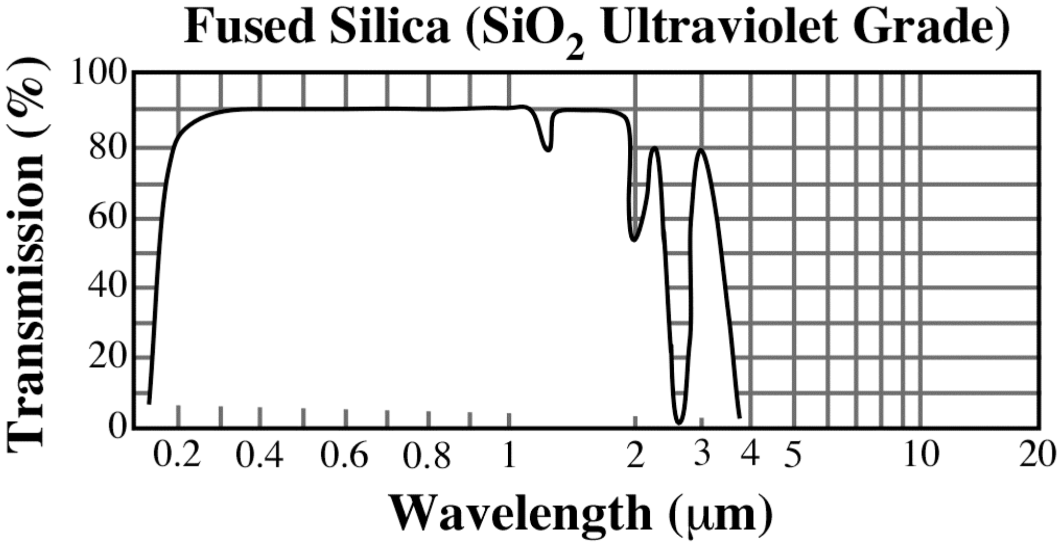
2. IMAGE ANALYZING INTERFEROMETRY CAN BE USED TO OBTAIN THE PRESSURE GRADIENT FOR LIQUID FLOW AND STABILITY.

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.

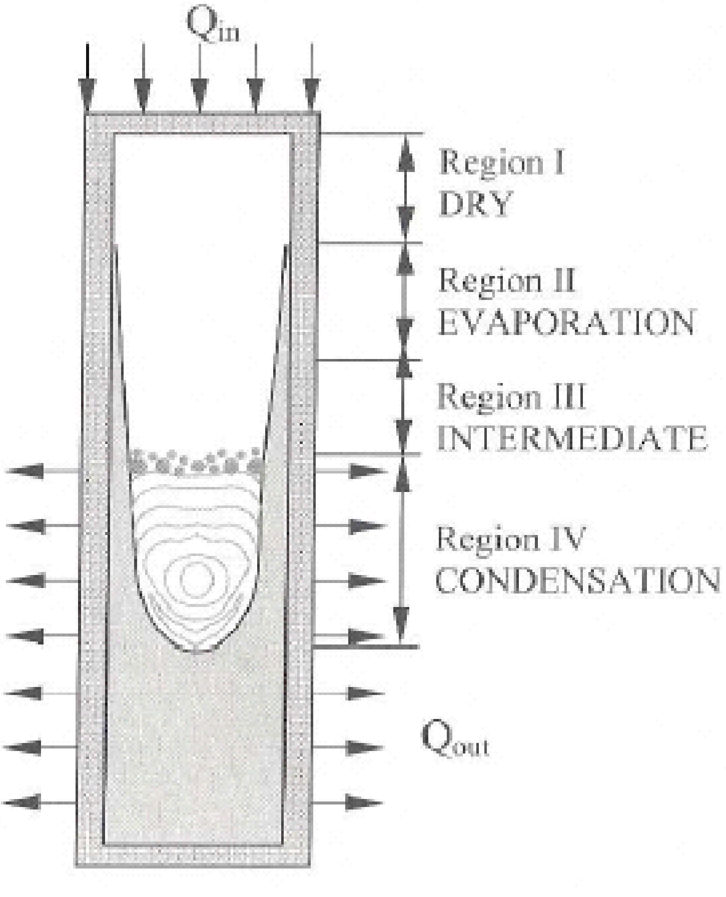
5. FLIGHT HARDWARE AND SOFTWARE ARE BEING DEVELOPED BY NORTHROP-GRUMMAN UNDER SEPARATE CONTRACT FROM NASA FOR FLIGHT EXPERIMENTS IN 2006 ON THE INTERNATIONAL SPACE STATION, ISS.

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 <u>μg</u> <u>REGION III CAN BE LARGE</u>

National Aeronautics and
Space Administration
John H. Glenn Research Center

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

Bioastronautics Initiative - History

- **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

NASA Bioastronautics Initiative – Combustion Science

- ***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

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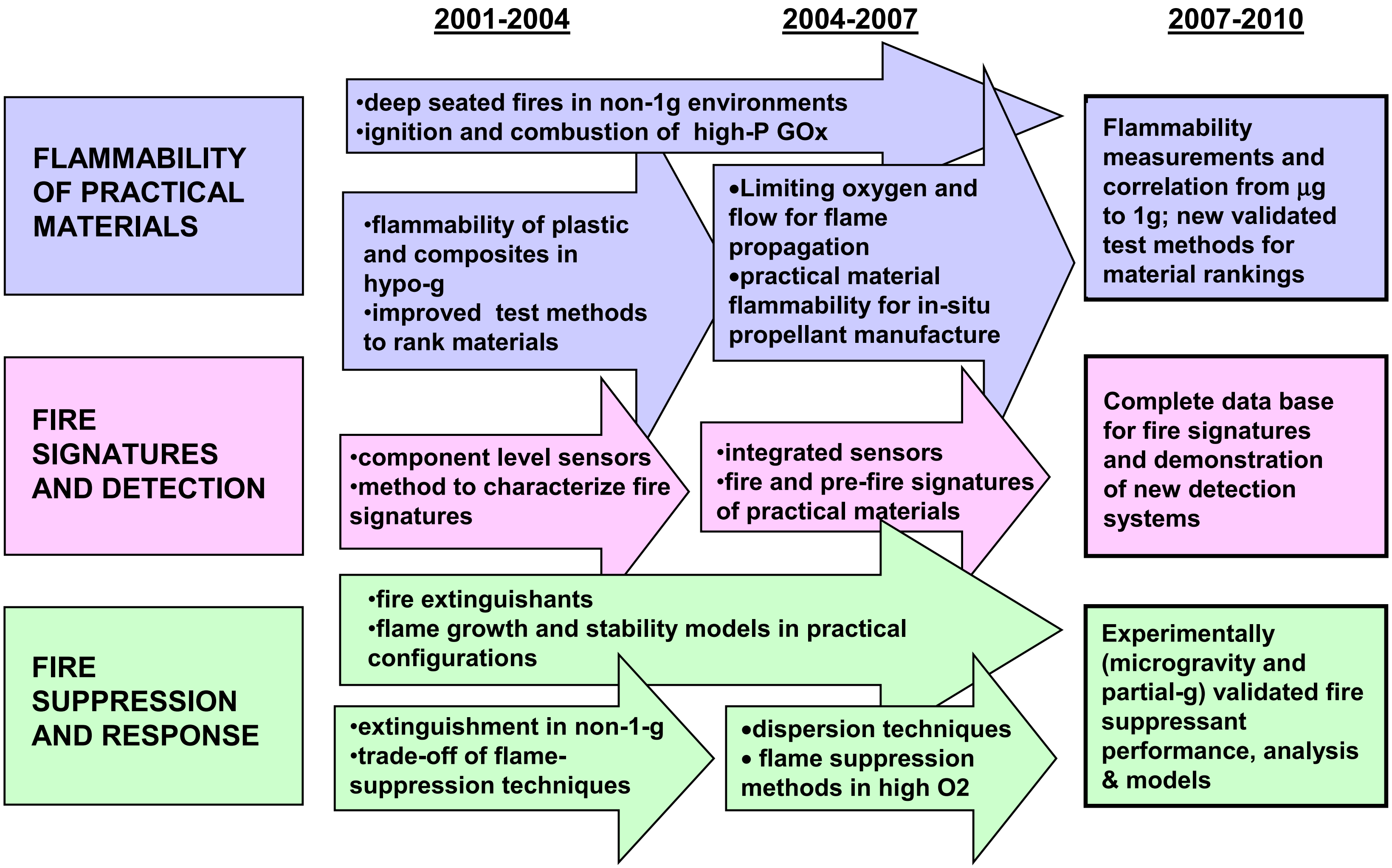
Spacecraft Fire Safety Research Roadmap



2001-2004 | **2004-2007** | **2007-2010**

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

- Limiting oxygen and flow for flame propagation
- practical material flammability for in-situ propellant manufacture

Flammability measurements and correlation from μg to 1g; new validated test methods for material rankings

FIRE SIGNATURES AND DETECTION

- component level sensors
- method to characterize fire signatures

- integrated sensors
- fire and pre-fire signatures of practical materials

Complete data base for fire signatures and demonstration of new detection systems

FIRE SUPPRESSION AND RESPONSE

- fire extinguishants
- flame growth and stability models in practical configurations

- extinguishment in non-1-g
- trade-off of flame-suppression techniques

- dispersion techniques
- flame suppression methods in high O2

Experimentally (microgravity and partial-g) validated fire suppressant performance, analysis & models

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)**

Combustion Integrated Rack (CIR) Launch: Oct 2006

Microgravity Science Glovebox (MSG) in the Destiny laboratory on the ISS (Astronaut: Peggy A. Whitson)

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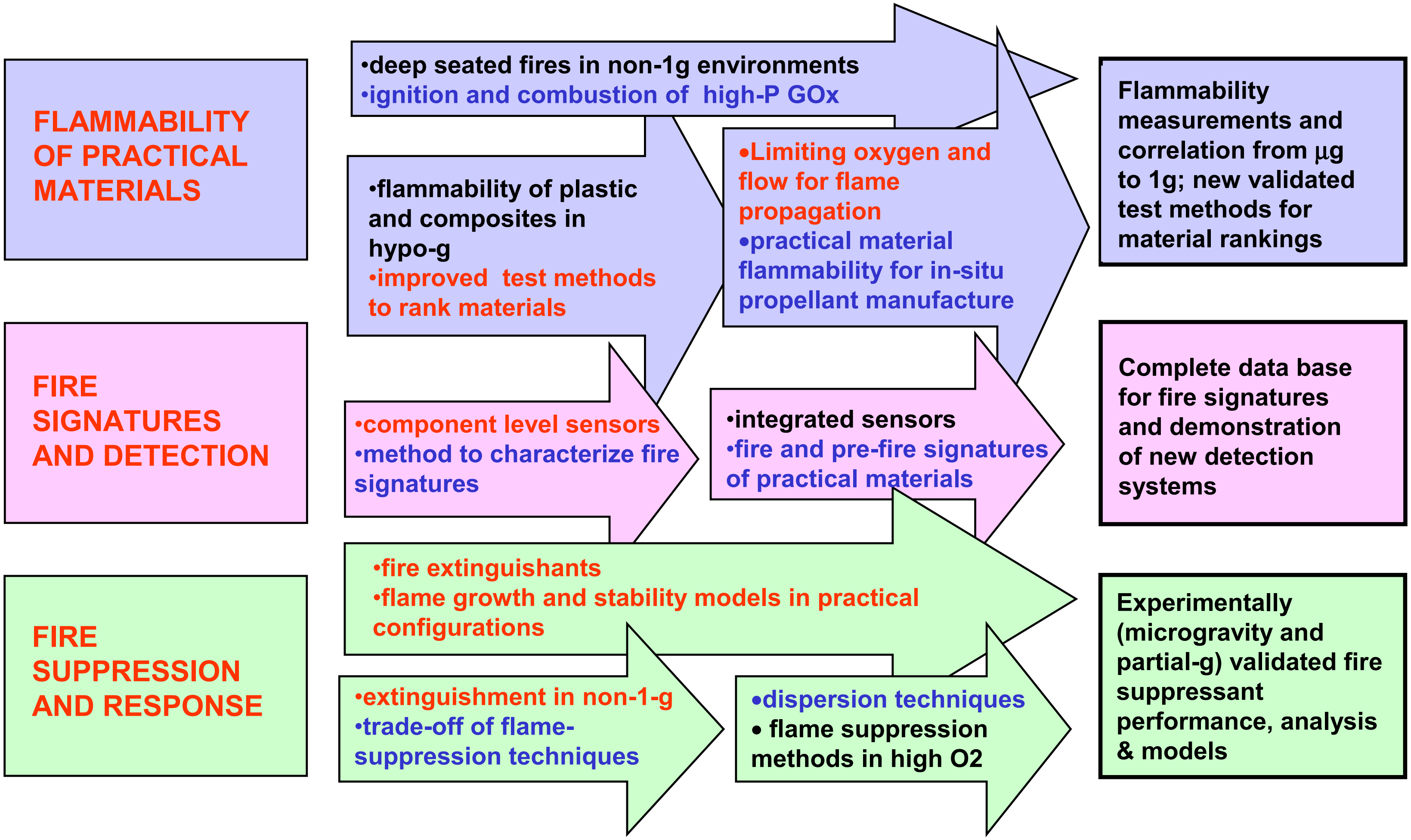
Spacecraft Fire Safety Research Roadmap



	2001-2004	2004-2007	2007-2010
FLAMMABILITY OF PRACTICAL MATERIALS	•deep seated fires in non-1g environments •ignition and combustion of high-P GOx		Flammability measurements and correlation from µg to 1g; new validated test methods for material rankings
	•flammability of plastic and composites in hypo-g •improved test methods to rank materials	•Limiting oxygen and flow for flame propagation •practical material flammability for in-situ propellant manufacture	
FIRE SIGNATURES AND DETECTION	•component level sensors •method to characterize fire signatures	•integrated sensors •fire and pre-fire signatures of practical materials	Complete data base for fire signatures and demonstration of new detection systems
FIRE SUPPRESSION AND RESPONSE	•fire extinguishants •flame growth and stability models in practical configurations		Experimentally (microgravity and partial-g) validated fire suppressant performance, analysis & models
	•extinguishment in non-1-g •trade-off of flame-suppression techniques	•dispersion techniques • flame suppression methods in high O2	

Vision for Space Exploration

“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

What Do We Do Now?

Needs

- Identify needs and issues from “customers”
    - ISS Materials and Processes
    - ISS Environmental Control and Life Support
    - ISS Fire Detection and Suppression

Potential Products

Questions

- Scientific and technological questions that must be answered to deliver the products
    - assessment of knowns and unknowns
    - incomplete answers increases risk

Concepts

- How do you answer the questions?
    - experiments (flight and ground)
    - modeling
    - system verifications

Products

- What is finally used by the customer
    - contract specification
    - design rules
    - procedures

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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

"Research Needs in Fire Safety for the Human Exploration and Utilization of Space," NASA/CP-2003-212103, April 2003.

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

"Research Needs in Fire Safety for the Human Exploration and Utilization of Space," NASA/CP-2003-212103, April 2003.

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 senor give an indication of the danger level?
    - What capability is require for post-fire sensing?

"Research Needs in Fire Safety for the Human Exploration and Utilization of Space," NASA/CP-2003-212103, April 2003.

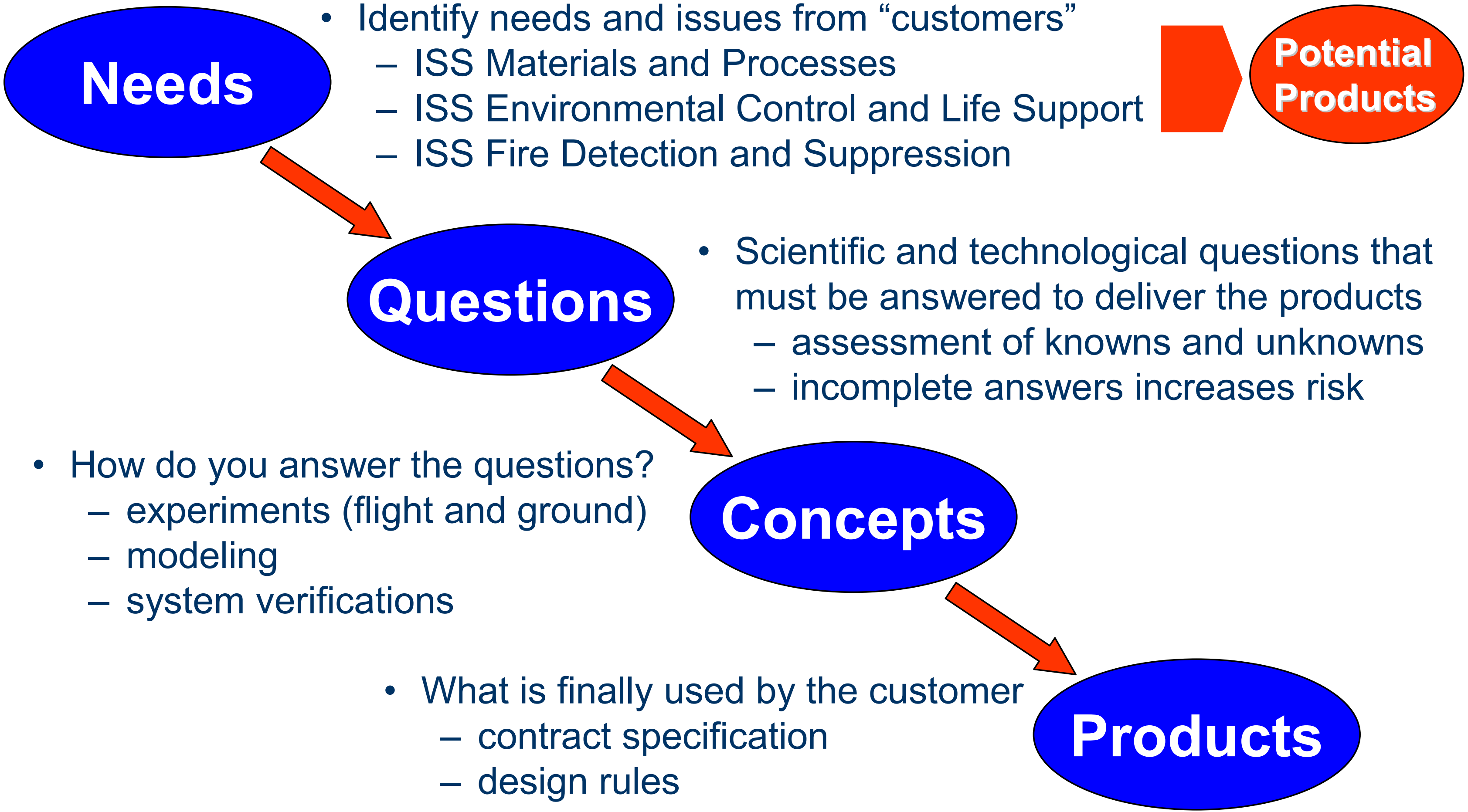
Issues and Needs Identified in 2001 Workshop

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

"Research Needs in Fire Safety for the Human Exploration and Utilization of Space," NASA/CP-2003-212103, April 2003.

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

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- How do you answer the questions?
  - experiments (flight and ground)
  - modeling
  - system verifications

- What is finally used by the customer
  - contract specification
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Fire Prevention, Detection, and Suppression Sub-Element 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% O_2 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

Fire Prevention, Detection, and Suppression Sub-Element Products

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

Fire Prevention, Detection, and Suppression Sub-Element Products

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

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John H. Glenn Research Center

What Do We Do Now?

Needs

- Identify needs and issues from “customers”
  - ISS Materials and Processes
  - ISS Environmental Control and Life Support
  - ISS Fire Detection and Suppression

Potential Products

Questions

- Scientific and technological questions that must be answered to deliver the products
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Concepts

- How do you answer the questions?
  - experiments (flight and ground)
  - modeling
  - system verifications

Products

- What is finally used by the customer
  - contract specification
  - design rules
  - procedures

FPDS Organizing Questions

- 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

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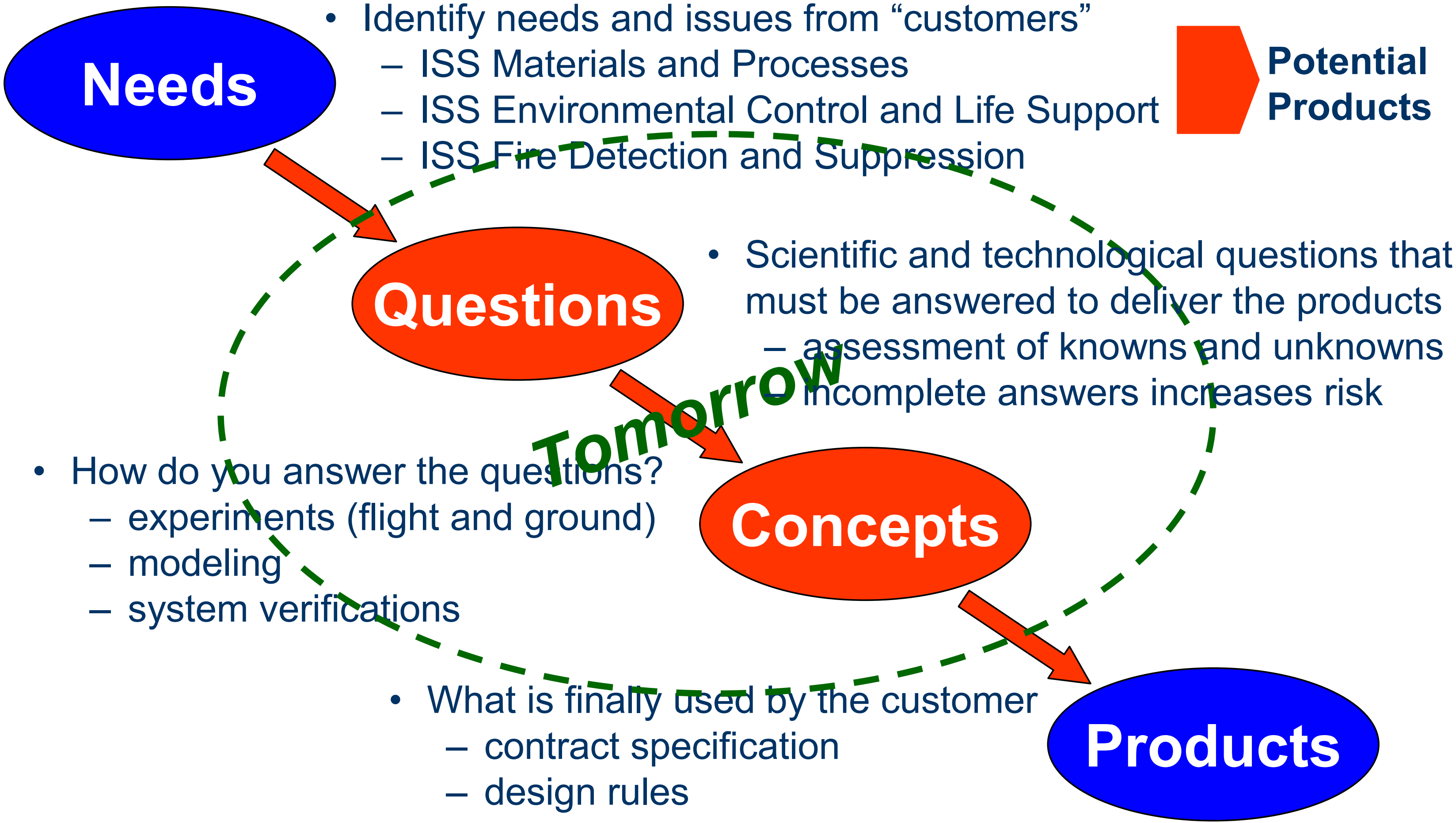
Advanced Human Support Technology

What Do We Do Now?



Needs

- Identify needs and issues from “customers”
  - ISS Materials and Processes
  - ISS Environmental Control and Life Support
  - ISS Fire Detection and Suppression

Potential Products

Questions

- Scientific and technological questions that must be answered to deliver the products
  - assessment of knowns and unknowns
  - incomplete answers increases risk

Tomorrow

- 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 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)
  - CO_2 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_2 mole fraction, low-pressure environments?

- CO_2, N_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 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 μg 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 CO_2
- 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 → MDCA or 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

NASA/CP—2004-213205/VOL1

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Fire Prevention, Detection, and Suppression

Research Plan for Fire Signatures and Detection

Strategic Research to Enable NASA's Exploration Missions

June 22 - 23, 2004
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Fire Prevention, Detection, and Suppression Sub-Element Products

3. Advanced fire detection system for gaseous and particulate pre-fire and fire signatures
    1. Quantification of pre-fire pyrolysis products in microgravity
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    4. Reduced gravity verification of advanced fire detection system
    5. Validated database of fire and pre-fire signatures in low and partial gravity
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    1. Development of LES models for large-scale transport in reduced gravity
    2. Validated CFD simulations of transport of fire precursors
    3. 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

SMOKE

Characterization of Smoke from Microgravity Fires for Improved Spacecraft Fire Detection

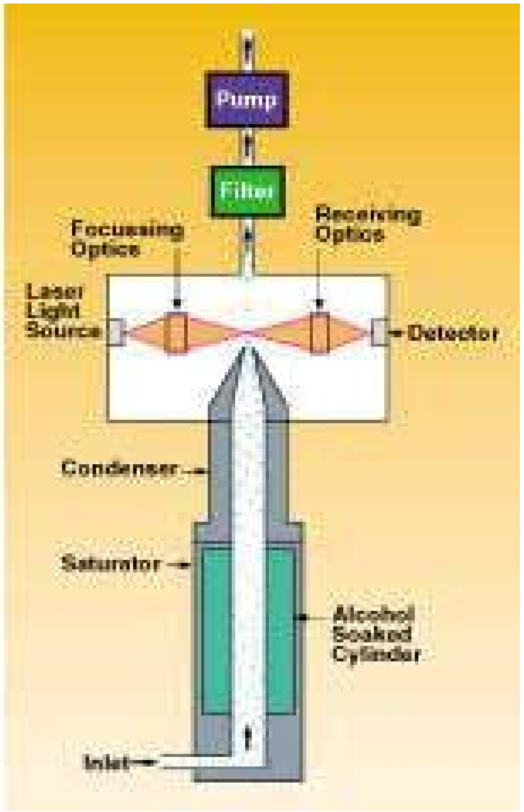
PI: Urban, NASA-GRC; co-I: Mulholland, Cleary, and Yang, NIST; Yuan, NCMR

- 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

- ***D***ust and ***A***erosol measurement ***F***easibility ***T***est (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)

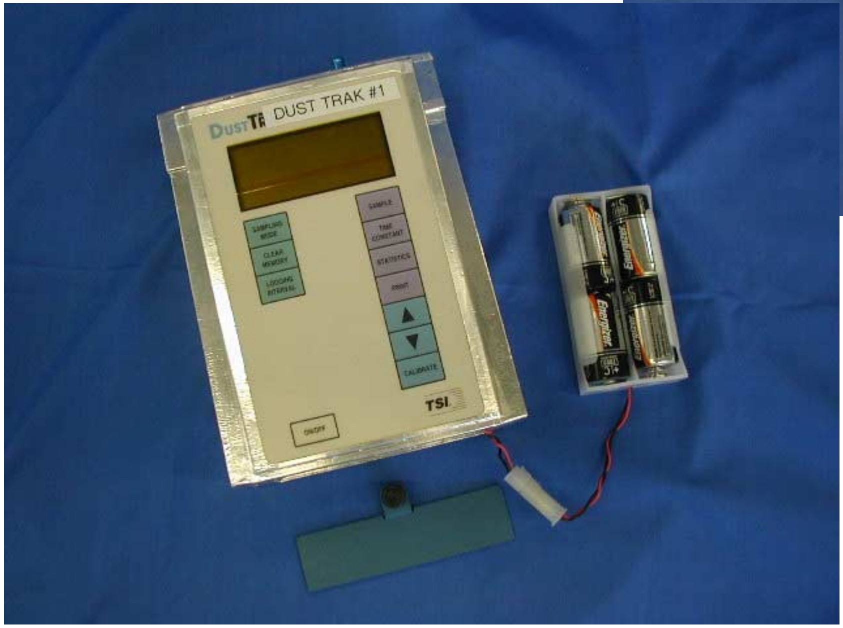


National Aeronautics and
Space Administration
John H. Glenn Research Center

Strategic Research to Enable NASA's Exploration Missions
June 22 - 23, 2004
Cleveland, OH

DAFT Hardware

P-Trak, Alcohol Wick (w/Container) and Batteries



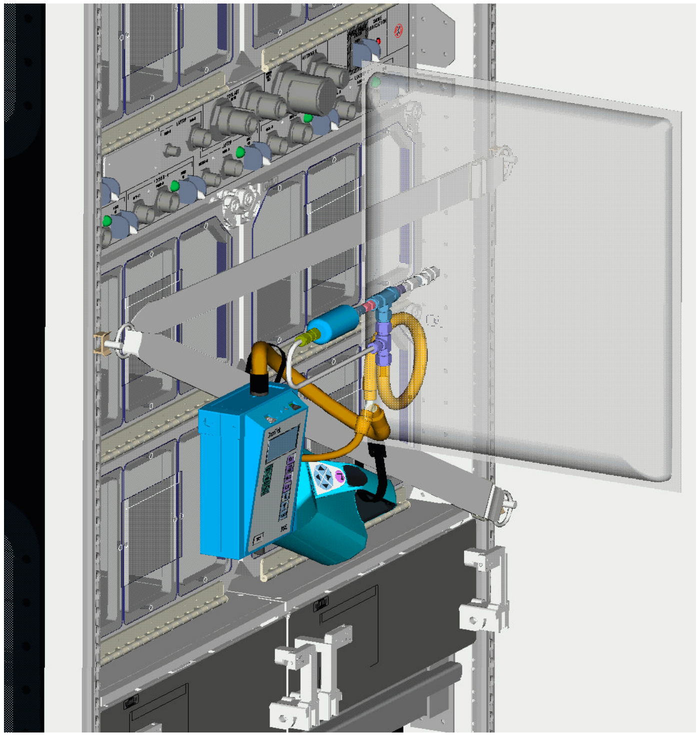
DustTrak and Batteries

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

Simulation of the Transport of Smoke and Fire Precursors

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?*
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?

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?

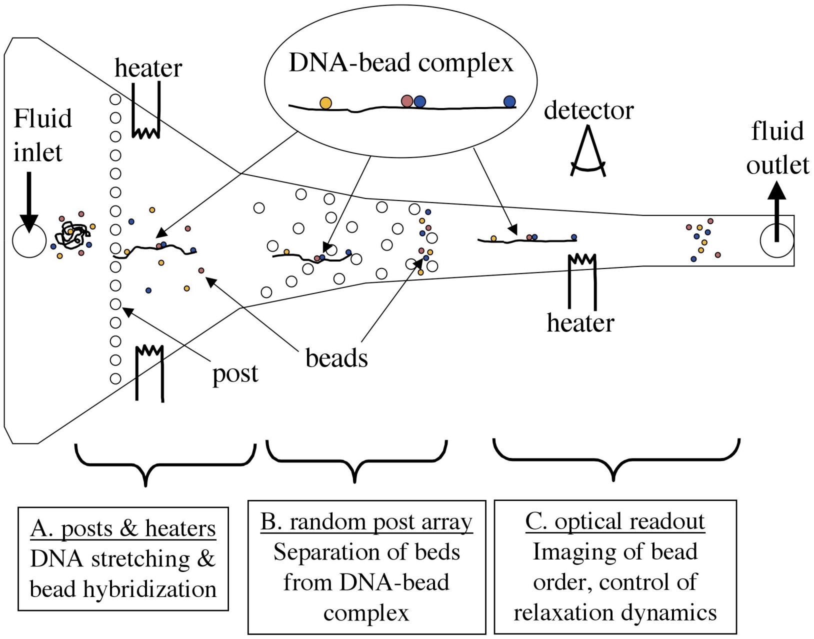
DNA Configurations in the Flow Through Arrays with Application to Biosensors

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 ton 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.

Conference-Workshop on Strategic Research to Enable NASA's Exploration Missions
Cleveland, Ohio, June 23, 2004

Space Experiment Concepts: Cup-Burner Flame Extinguishment

Fumiaki Takahashi
National Center for Microgravity Research
Cleveland, Ohio
Fumiaki.Takahashi@grc.nasa.gov

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 Cognion
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: μ*g*, lunar: 1/6*g*, Martian: 1/3*g*

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

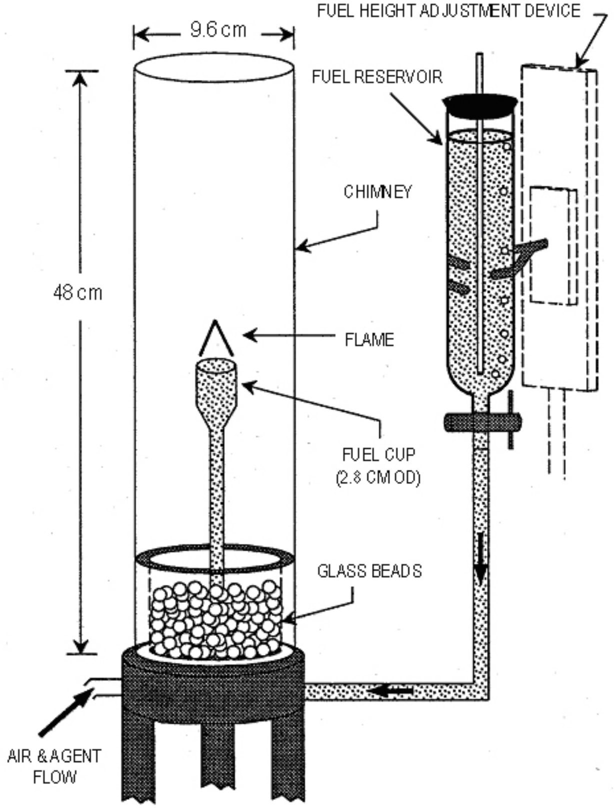
- *Standard Test*

⇒ 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 <u>incapable</u> of supporting diffusion flame combustion

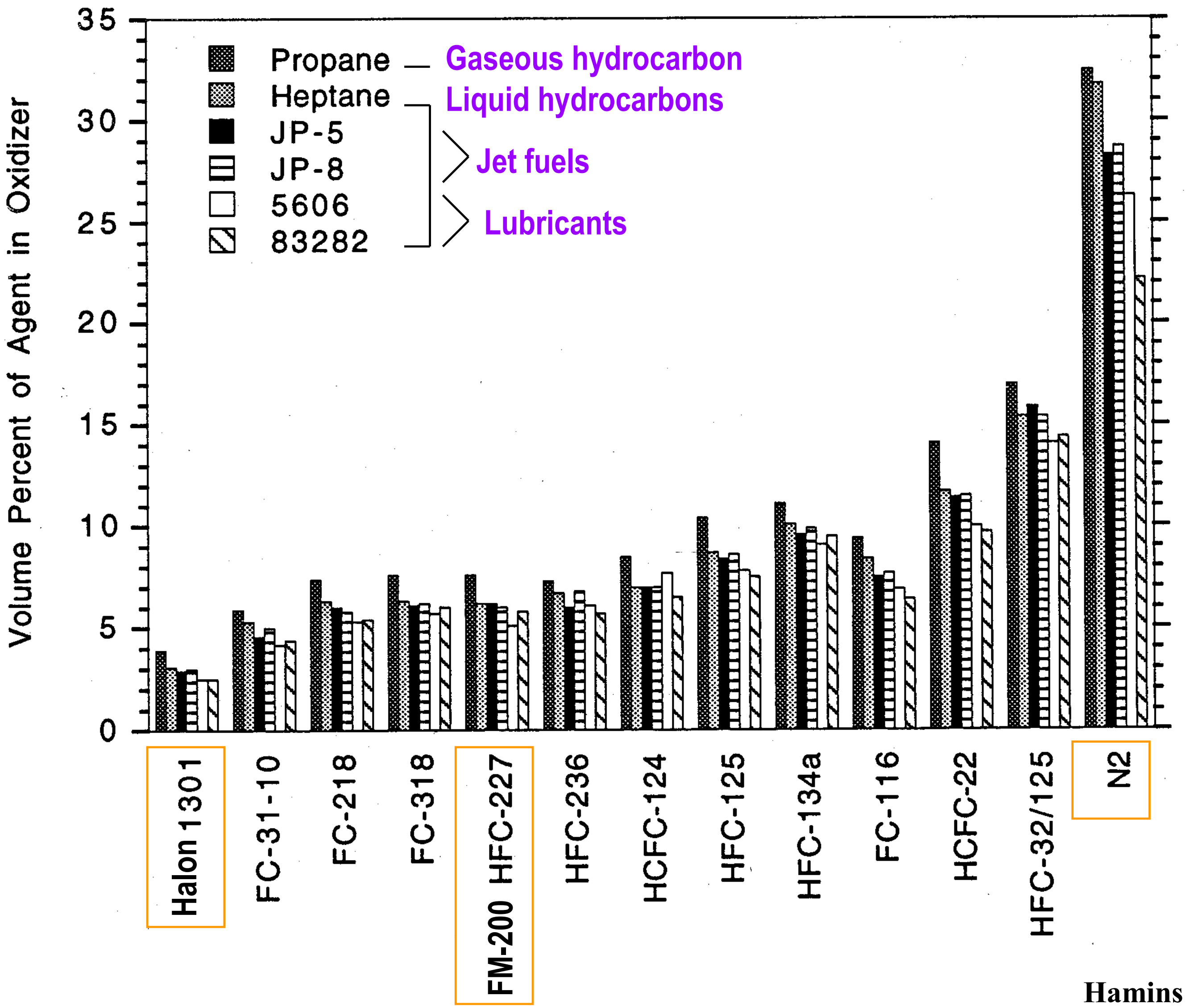
⇒ the minimum design concentration of a gaseous ***agent*** for a fire protection system is determined by adding at least 30% to the cup-burner MEC value by manufacturer

⇒ 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



Hamins et al. (1994)

MEC Minimum Extinguishing Concentration



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 counterfow 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 1*g*, 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

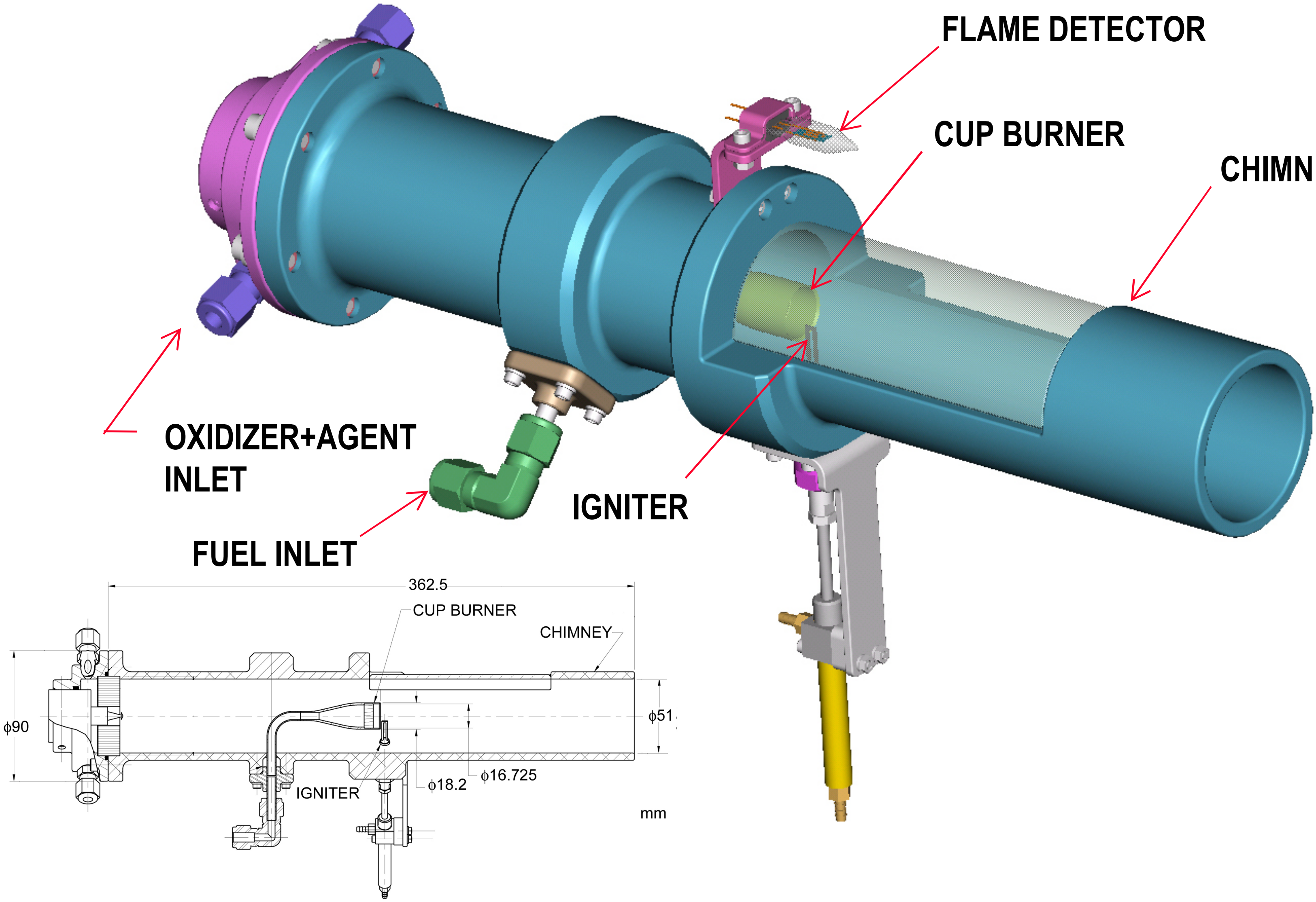
Click here to play movie

Cup Burner

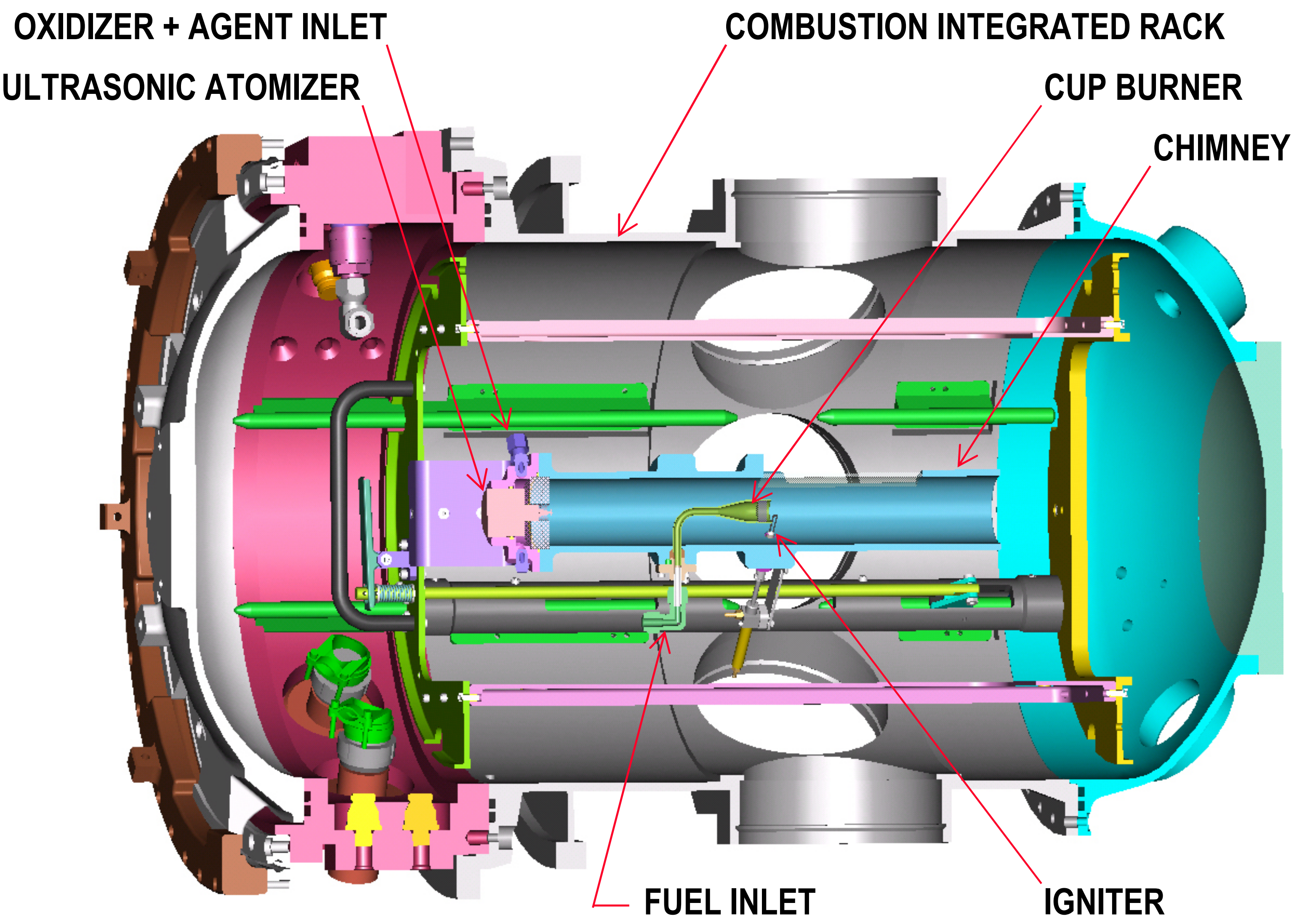
Pool Fire

http://www.me.uwaterloo.ca/~ew eckman/fire/firehome.htm

GBEX Gaseous Burner Extinguishment EXperiment



GBEX in CIR


OXIDIZER + AGENT INLET
ULTRASONIC ATOMIZER
COMBUSTION INTEGRATED RACK
CUP BURNER
CHIMNEY
FUEL INLET
IGNITER

GBEX Gaseous Burner Extinguishment EXperiment

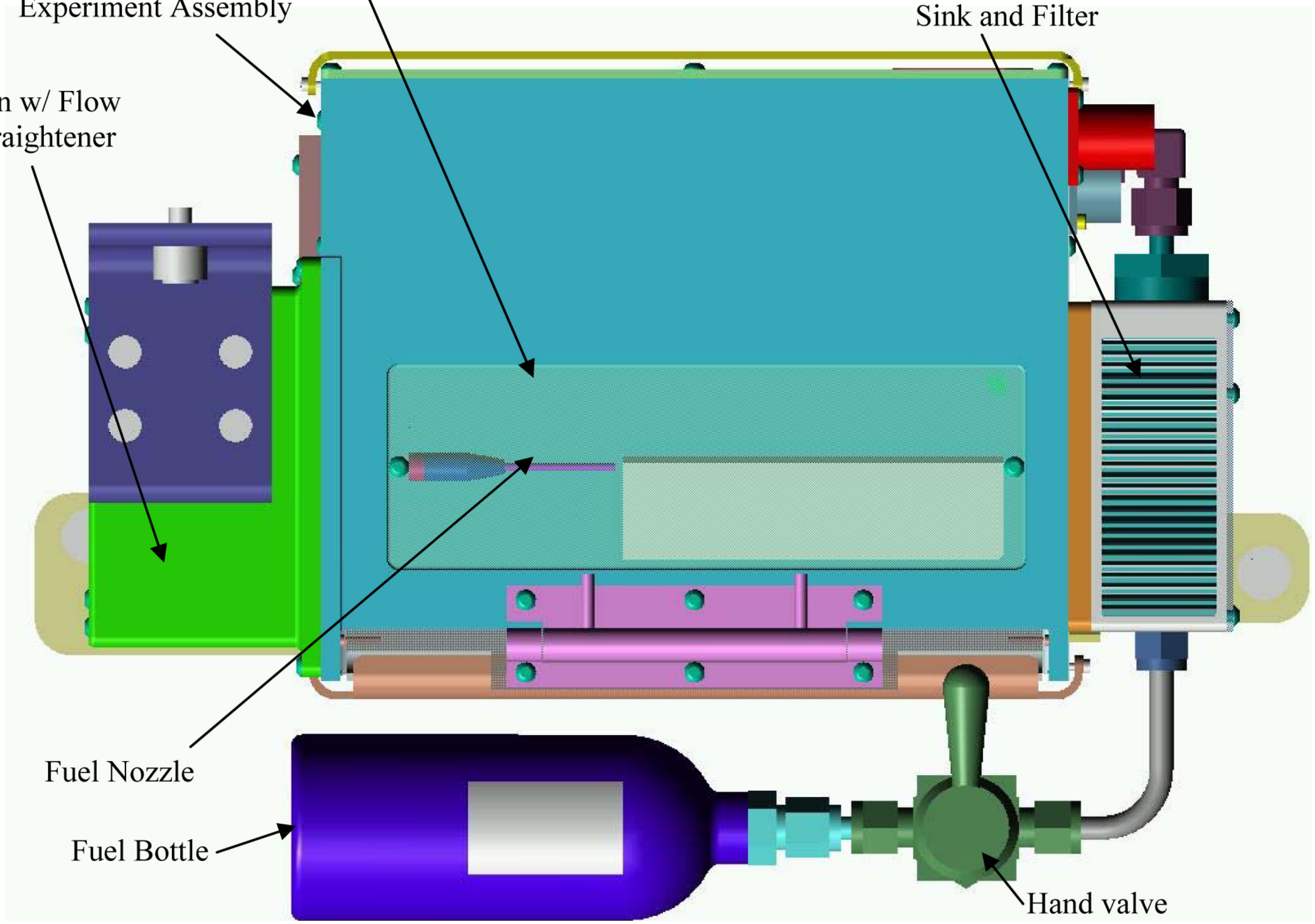
- **Dimensions:** 5/8 Scale

Burner :	17 mm ID
Chimney:	51 mm ID × 350 mm length

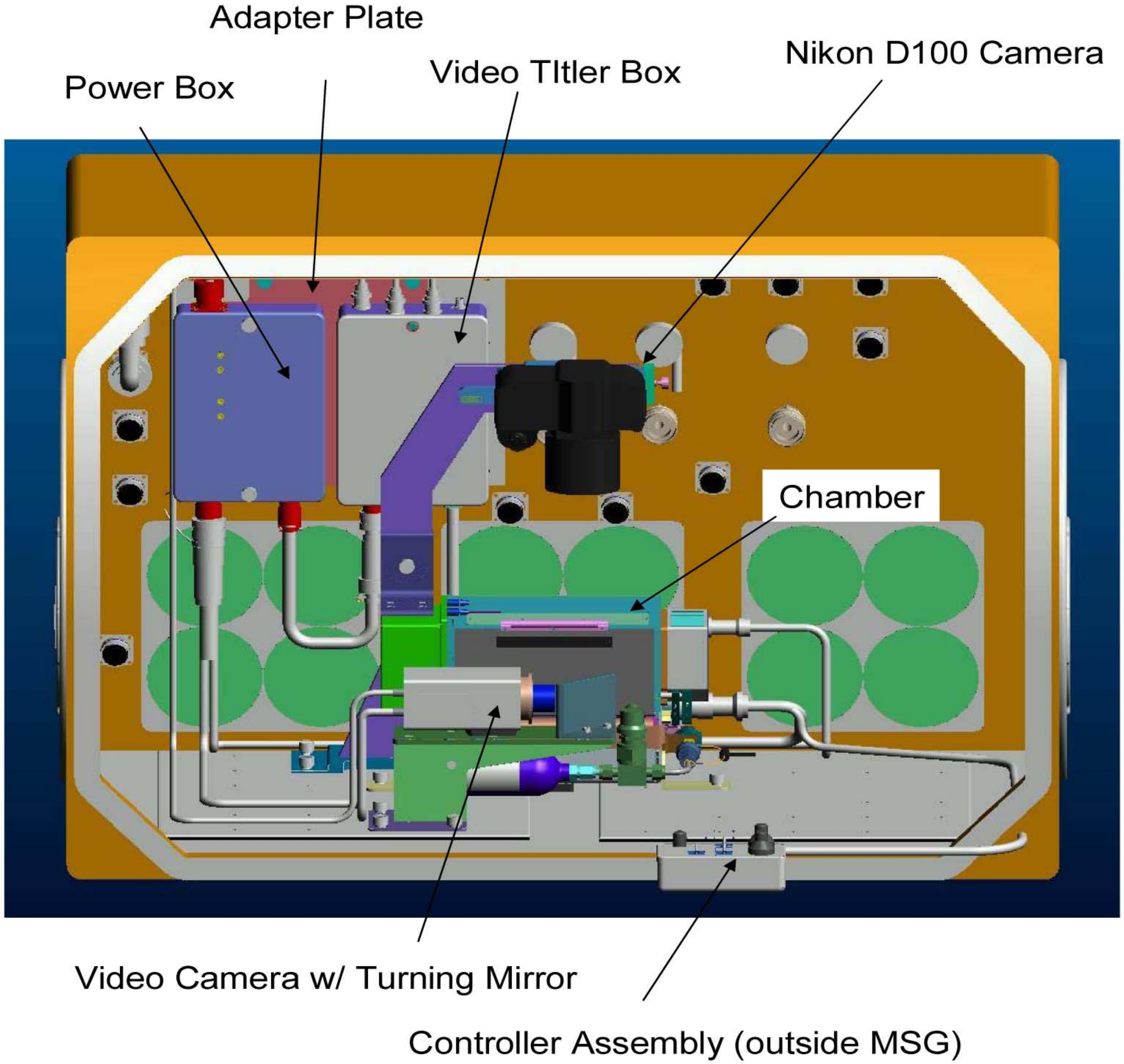
- **Test Matrix:**

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



MSG Microgravity Science Glovebox



MSG Microgravity Science Glovebox

◆ **Dimensions:**

Burner: 12 mm ID

Chimney: 79 mm square × 187 mm length

◆ **Test Matrix:**

Fuel: CH_4

Oxidizer: Air

Velocity : 1 – 50 cm/s

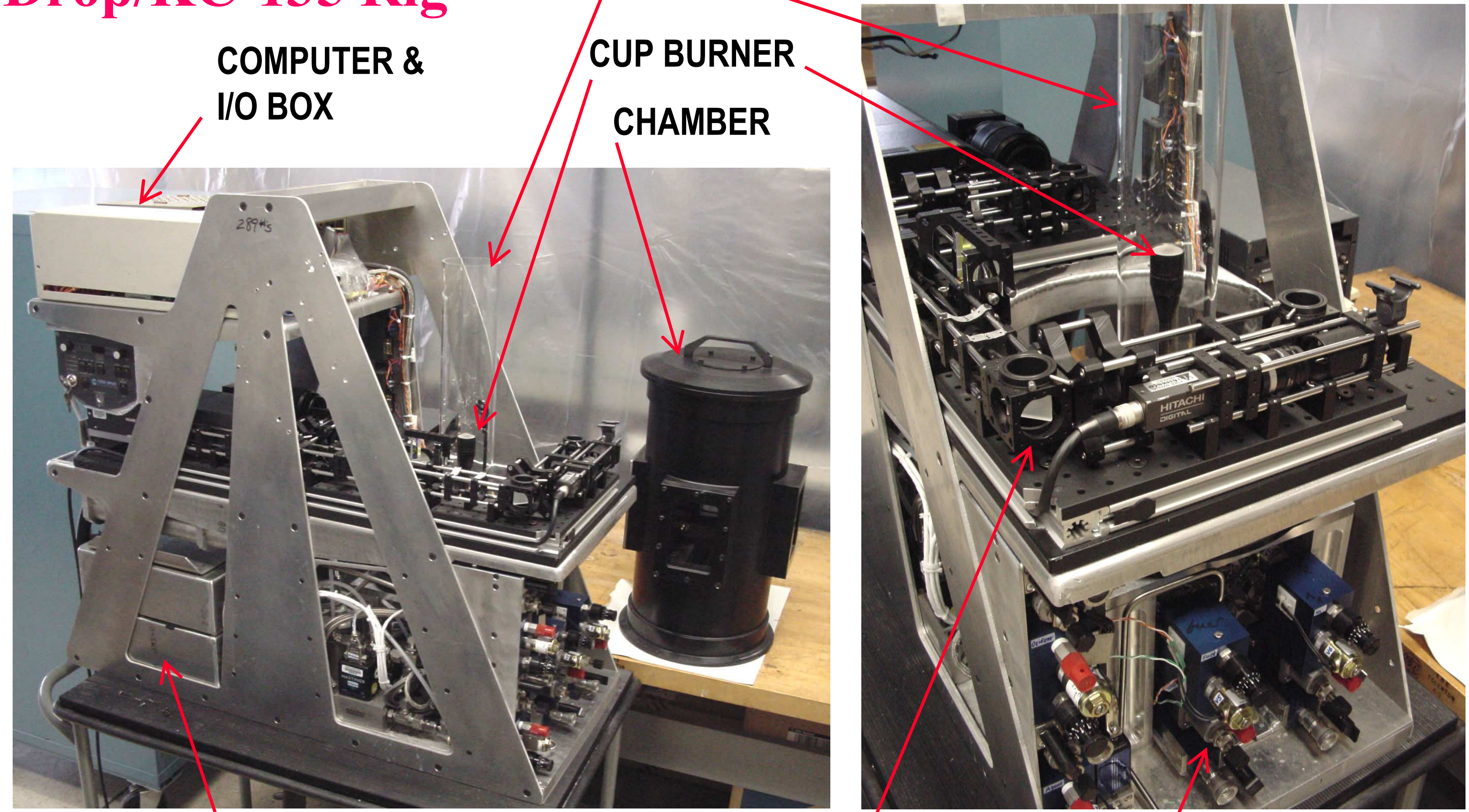
Agent: N_2

Gravity: μg

Pressure: 1 atm

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_4, C_2H_6, C_3H_8
- Liquid: n-C_7H_{16}, CH_3OH
- Solid: trioxane ($3[CH_2O]$), PMMA

Oxidizer:
- O_2-N_2 mixture
- Oxygen mole fraction: 0.21 – 0.3
- Velocity: 3 – 20 cm/s

Agent:
- CO_2, N_2, He, Ar
- CF_3H(HFC-23), C_3F_7H (HFC-227ea), CF_3Br (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%CO_2

U_{CH4}= 0.92 cm/s

U_{ox}= 6.7 cm/s

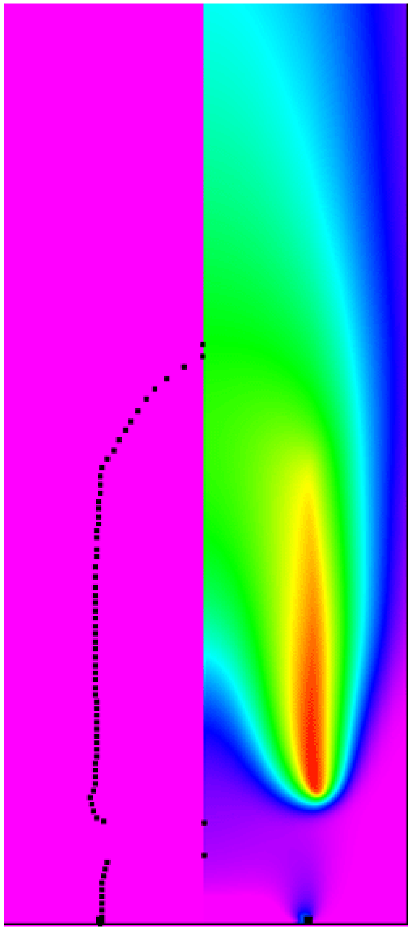
Direct Numerical Simulation (0g)

Methane

Air + 30.7% He

U_{CH4}= 0.92 cm/s

U_{ox}= 10.7 cm/s

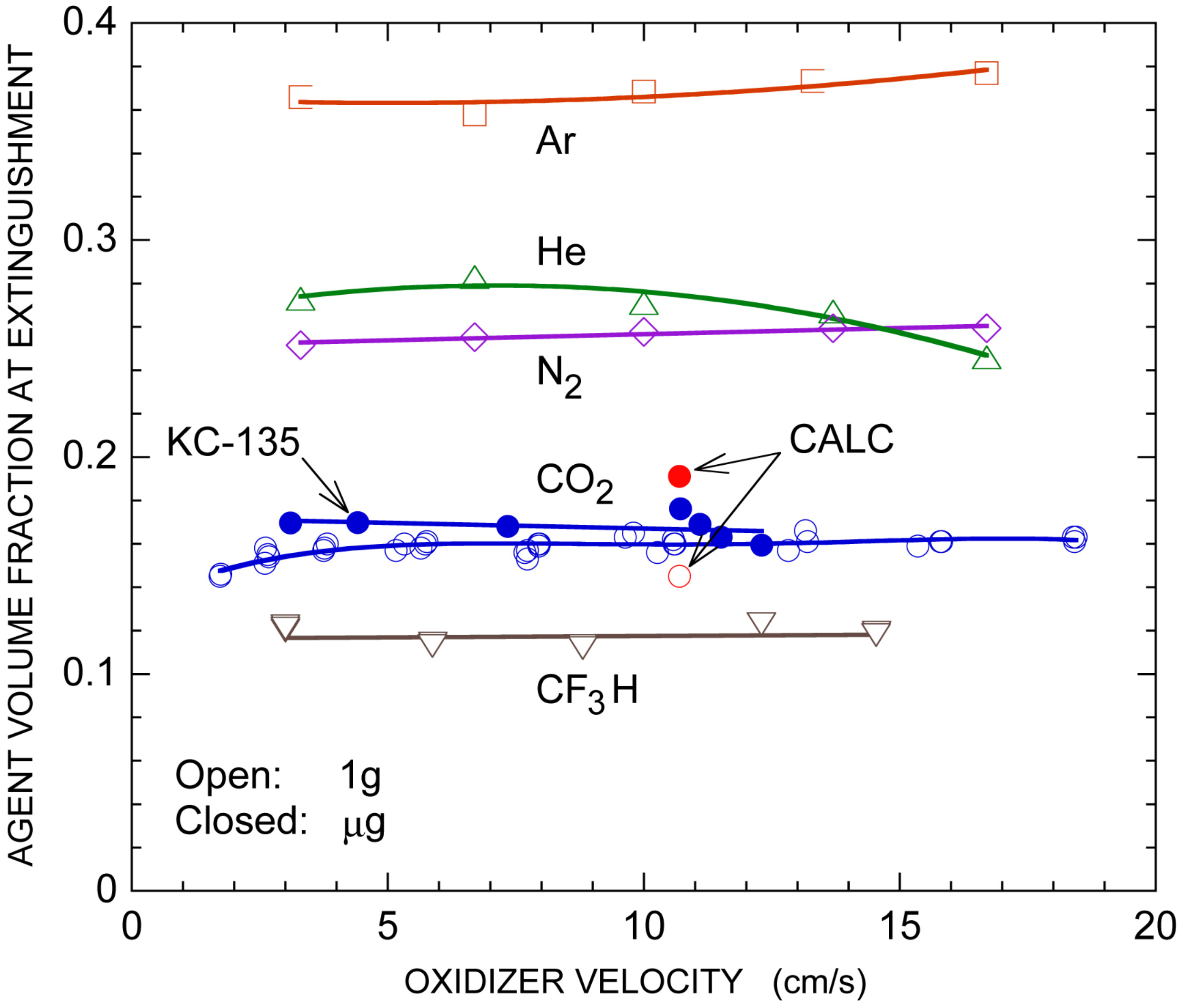


- Full chemistry (GRI Mech 1.2)
- Radiative loss
- Mixture rules

Click here to play movie

Takahashi, Linteris, and Katta, AIAA Paper No. 2004-0957, January 2004

Extinguishment Limits



Takahashi, Linteris, and Katta, AIAA Paper No. 2004-0957, January 2004

Answering to Organizing Questions

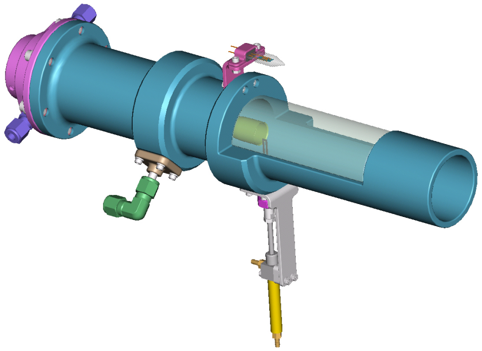
- *Cup-burner flame extinguishment experiment can:*

1. measure the relative effectiveness (MEC) of candidate suppressants in low-*g*, including high-O_2, low-P environments
2. determine the X_{O2} (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 sever diabetes: a growing health problem in the US and World-wide.

National Aeronautics and
Space Administration
John H. Glenn Research Center

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

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

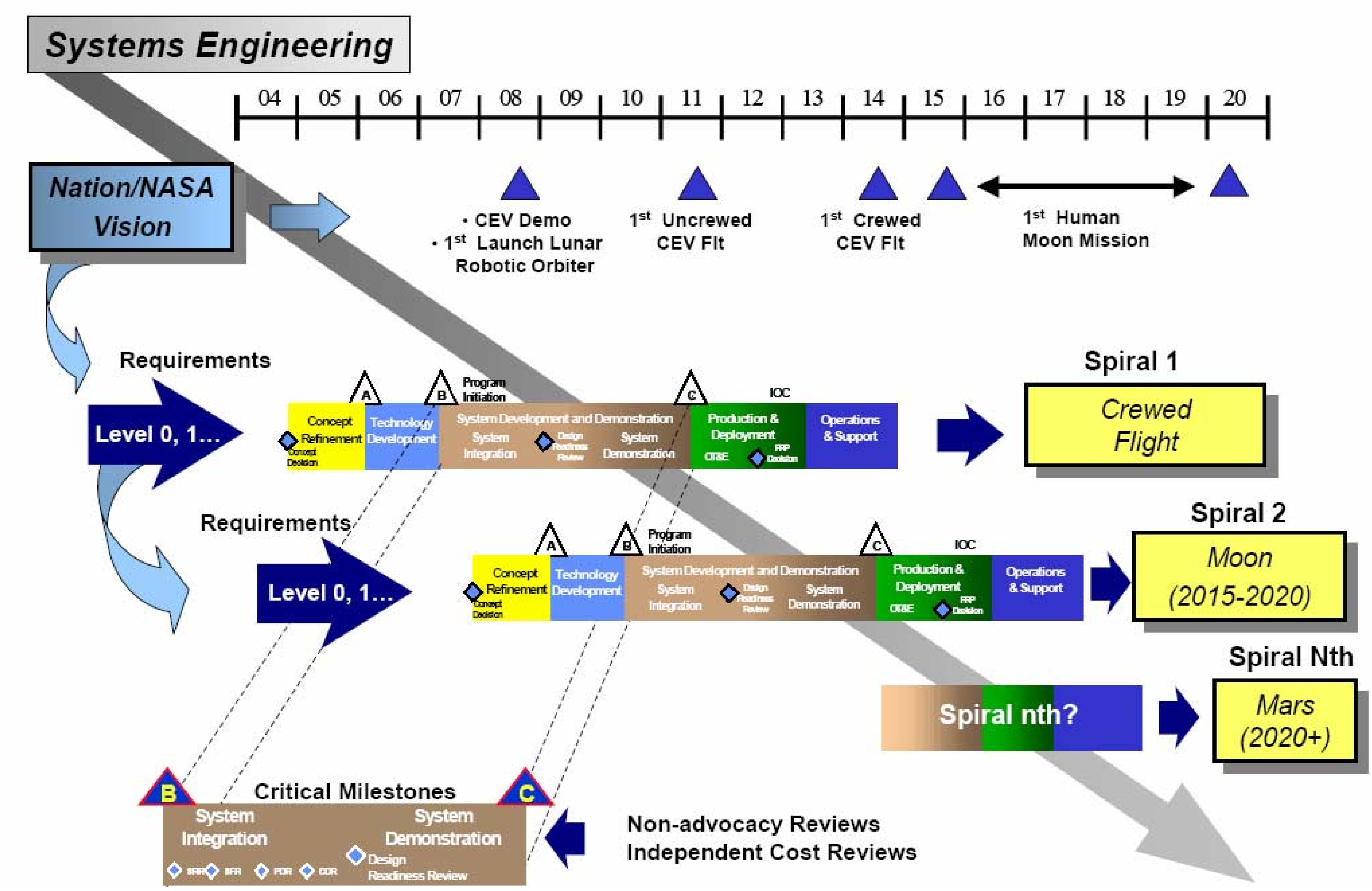
Experiments must be carefully developed to make efficient use of flight opportunities and meet schedule milestones

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

04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20

Nation/NASA Vision

- CEV Demo
- 1st Launch Lunar Robotic Orbiter

1st Uncrewed CEV Flt

1st Crewed CEV Flt

1st Human Moon Mission

Requirements

Level 0, 1…

Spiral 1

Crewed Flight

Requirements

Level 0, 1…

Spiral 2

Moon (2015-2020)

Spiral Nth

Spiral nth?

Mars (2020+)

Critical Milestones

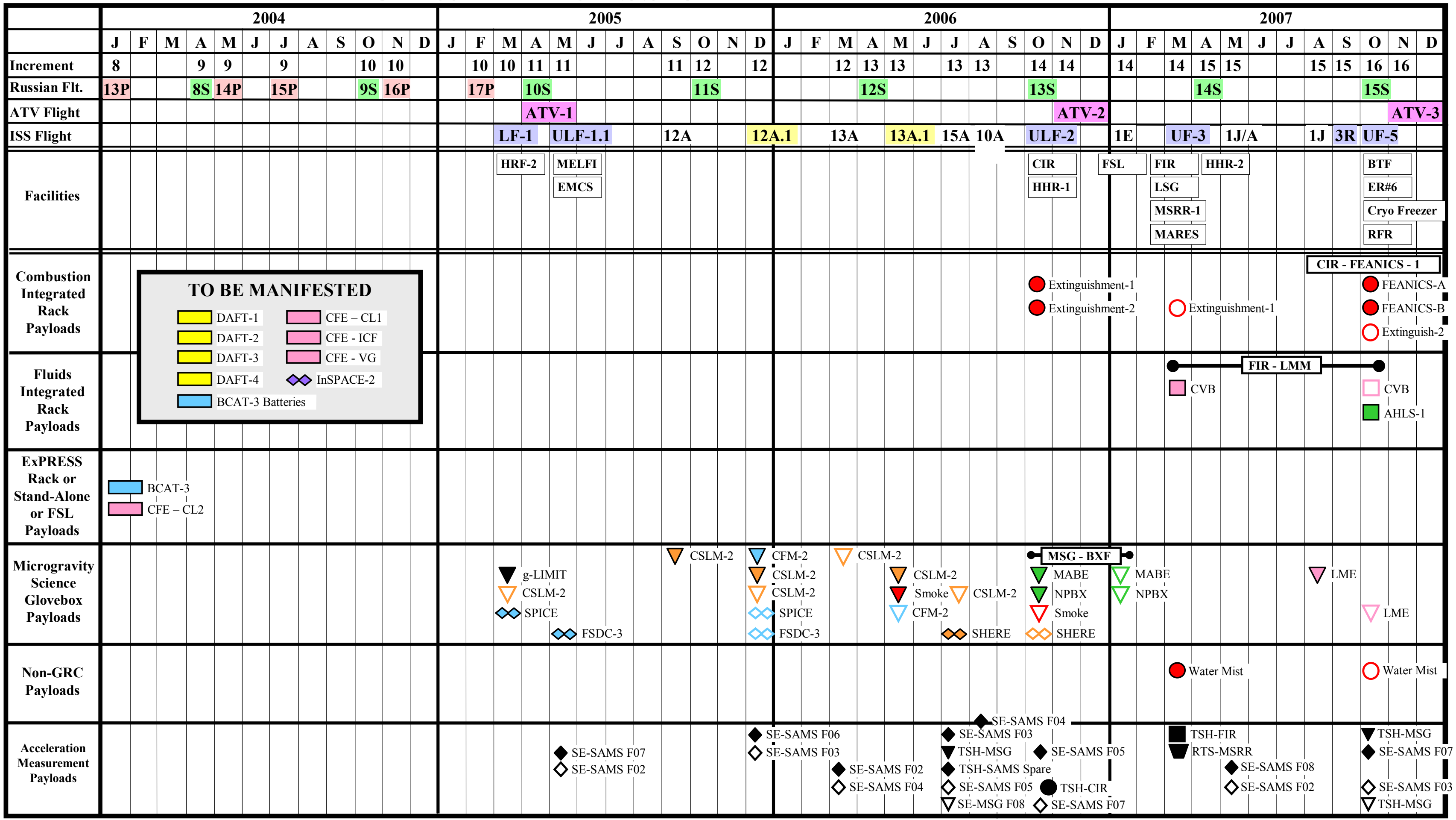
Non-advocacy Reviews
Independent Cost Reviews

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

Based on POP Assembly Sequence (RTF March 2005)
and BPRE POP 2004 Guidelines 3/15/04

GRC/BPRPO ISS Utilization Traffic Model



Legend:

CIR ●
FIR ■
MSG-GI ◆◆
MSG-PI ▼
ER ◆
MSRR ▼
FSL ▶
Stand-Alone ▬
MPLM Flight UF-2
Spacehab Flight 12A.1
ATV Flight ATV-1

●—Mini-Facility—●

Ascent - Filled
Descent - Empty

Progress Flight 13P
Soyuz Flight 8S

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
HRF – Human Research Facility
MELFI – Minus Eighty Laboratory Freezer
EMCS – European Modular Cultivation System
WORF – Window Observational Rack Facility
SpaceDRUMS – Space Dynamically Responding Ultrasonic Matrix System
HHR – Holding Habitat Rack
MARES – Muscle Atrophy Research and Exercise System
LSG – Life Sciences Glovebox
BTF – Biotechnology Facility
Cryo Freezer – Cryogenic Freezer
RFR – Refrigerator Freezer
AMS – Alpha Magnetic Spectrometer
CAM – Centrifuge Accommodations Module

🟩 Advanced Life Support Systems
🟥 Fire Prevention, Detection, & Suppression
🟨 Advanced Environmental Monitoring & Control
🟪 Advanced Extra Vehicular Activity
Low Gravity & Exploration Research
🟧 In-Situ Fabrication & Repair
🟫 In-Situ Resource Utilization
🟦 Fundamental Science

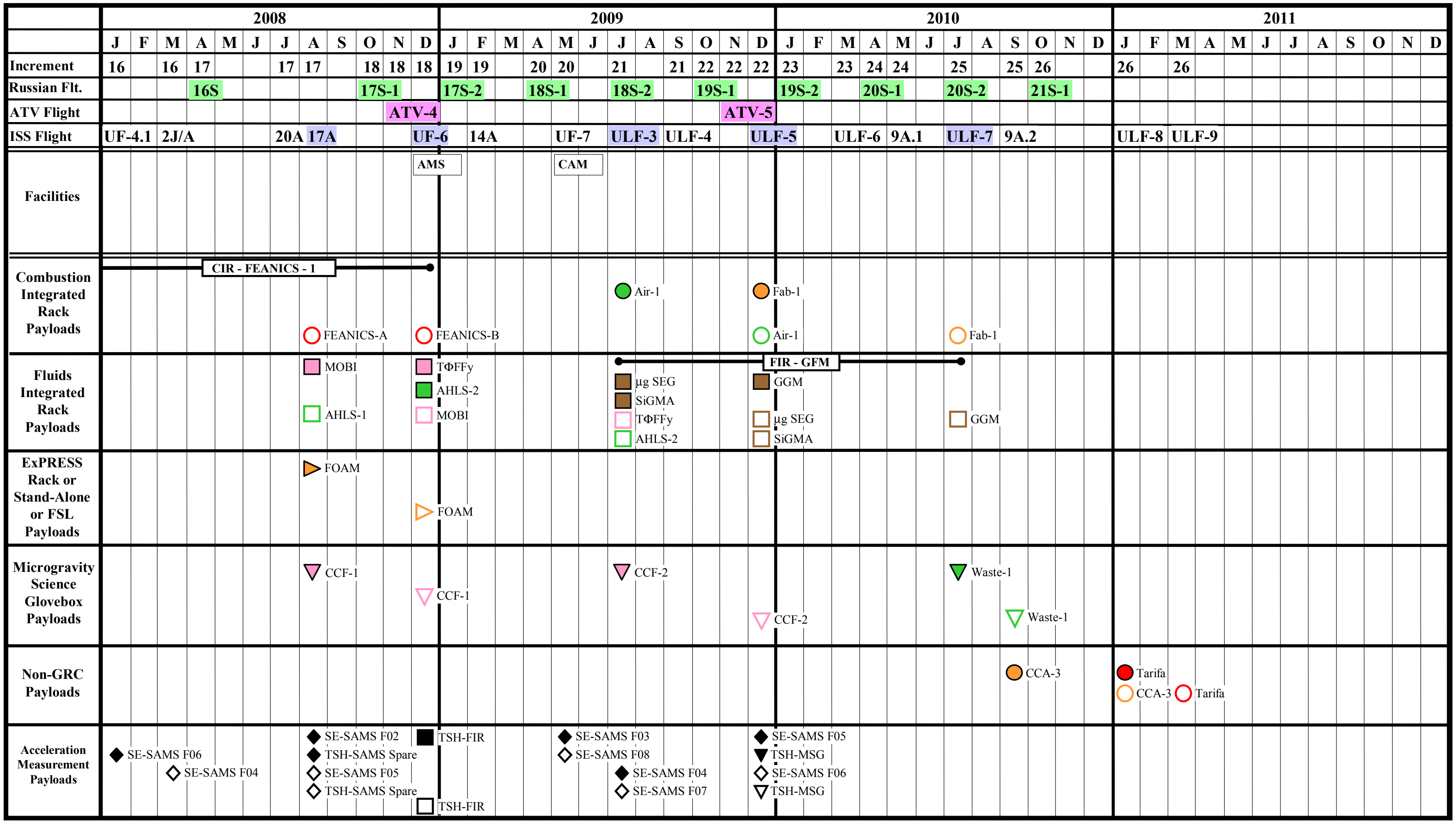
Notes:

1) InSPACE will conduct additional operations during Increment 9
2) SAMS has a Thinkpad and hard drives going up on ULF1.1
3) PCS+ has data disks returning on 13A.1, 15A, and ULF-2
4) CSLM-2 has 4 SC/SPUs each going up on 12A, 12A.1, and 13A.1 and hardware returning on ULF-2

GRC Biological & Physical Research Project Office Chief: /s/ Jack A. Salzman **6/15/04**

Based on POP Assembly Sequence (RTF March 2005)
and BPRE POP 2004 Guidelines 3/15/04

GRC/BPRPO ISS Utilization Traffic Model



Legend:

CIR	●
FIR	■
MSG-GI	◆◆
MSG-PI	▼
ER	◆
MSRR	▼
FSL	▶
Stand-Alone	▬
MPLM Flight	UF-2
Spacehab Flight	12A.1
ATV Flight	ATV-1

●—Mini-Facility—●

Ascent - Filled
Descent - Empty

Progress Flight	13P
Soyuz Flight	8S

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
HRF – Human Research Facility
MELFI – Minus Eighty Laboratory Freezer
EMCS – European Modular Cultivation System
WORF – Window Observational Rack Facility
SpaceDRUMS – Space Dynamically Responding Ultrasonic Matrix System
HHR – Holding Habitat Rack
MARES – Muscle Atrophy Research and Exercise System
LSG – Life Sciences Glovebox
BTF – Biotechnology Facility
Cryo Freezer – Cryogenic Freezer
RFR – Refrigerator Freezer
AMS – Alpha Magnetic Spectrometer
CAM – Centrifuge Accommodations Module

🟩 Advanced Life Support Systems
🟥 Fire Prevention, Detection, & Suppression
🟨 Advanced Environmental Monitoring & Control
🟪 Advanced Extra Vehicular Activity
Low Gravity & Exploration Research
🟧 In-Situ Fabrication & Repair
🟫 In-Situ Resource Utilization
🟦 Fundamental Science

Notes:

GRC Biological & Physical Research Project Office Chief: /s/ Jack A. Salzman **6/15/04**

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.

National Aeronautics and
Space Administration
John H. Glenn Research Center

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

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?

   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

David L. Wilson, PhD
David Boothman, PhD

Departments of Biomedical Engineering, Radiology, and Radiation Oncology
Case Western Reserve University
Cleveland, OH 44106
David.Wilson@case.edu

Acknowledgements

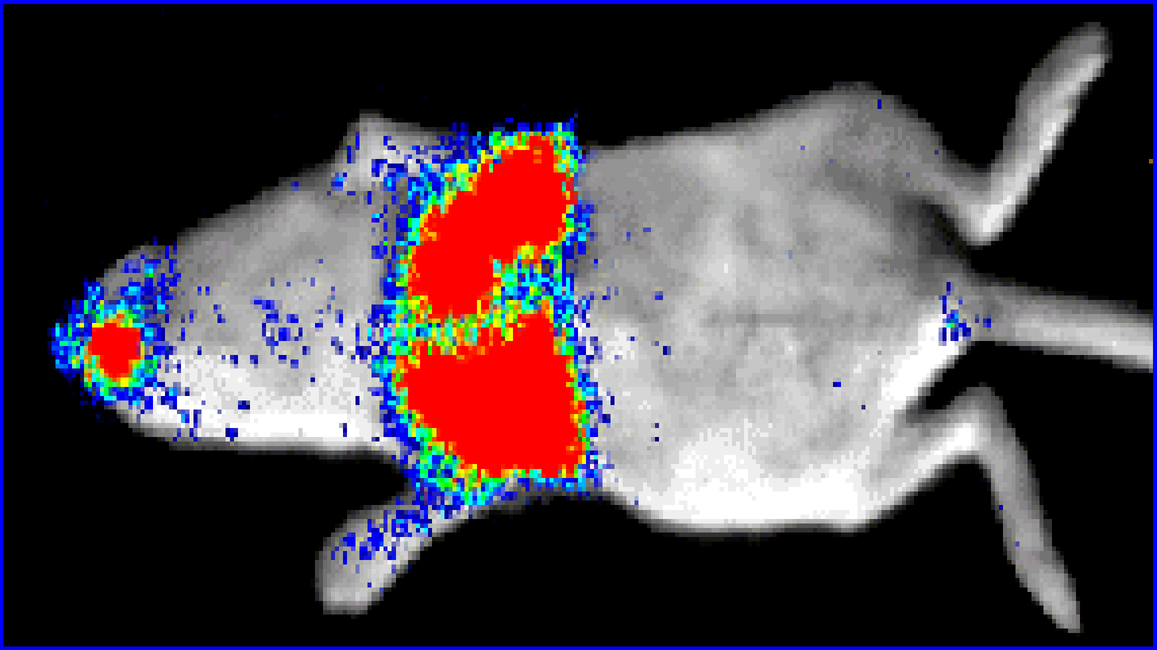
Research Team

- David Wilson, Professor of Biomedical Engineering and Radiology
- David Boothman, Professor of Radiation Oncology
- Andrew Rollins, Assistant Professor of Biomedical Engineering
- Lakshmi Sampath, BME graduate student
- Dmitry Klokov, PhD, postdoctoral fellow
- Perrin Cheung, BME graduate student
- Kristin Frinkley, BME undergraduate student

Funding

- John Glenn Biomedical Engineering Consortium, PI: David Wilson
- DOE funding, PI: Boothman

Imaging of Gene Expression



Nature Medicine 4(2):245-247

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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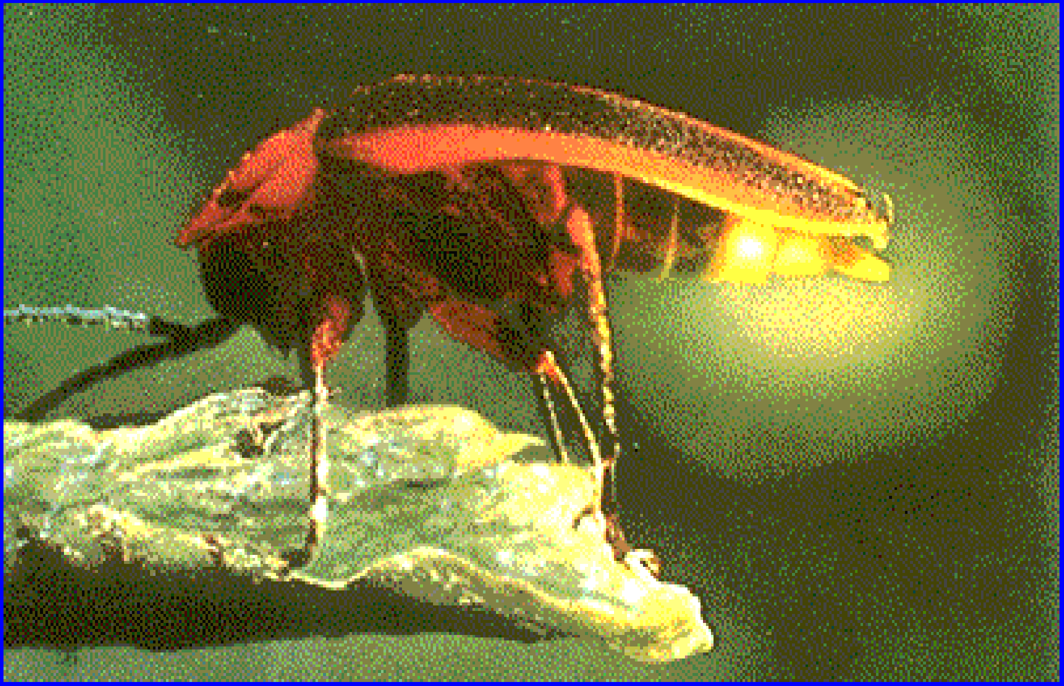
Bioluminescent Imaging

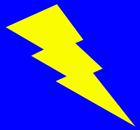


Start with gene originating from fireflies.

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.

$$\text{ATP} + \text{D-luciferin} + O_2 \xrightarrow{\text{Luciferace}} \text{oxyluciferin} + \text{AMP} + \text{PPi} + CO_2 + \text{light}$$



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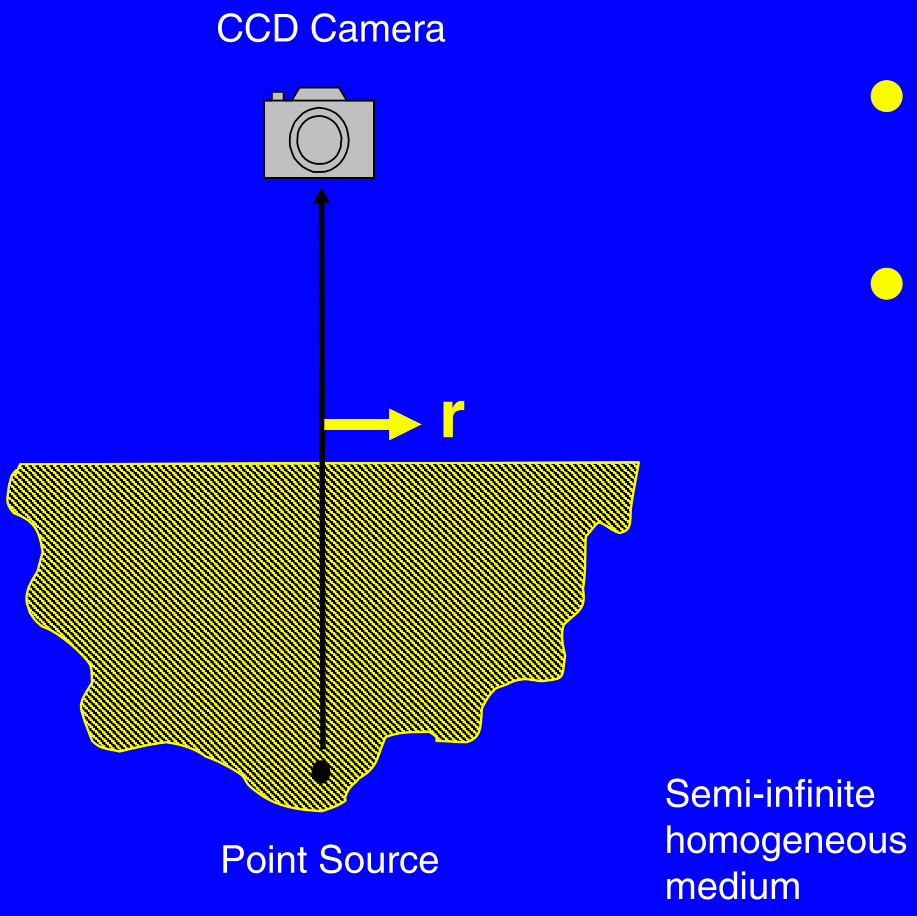
Bioluminescence Imager

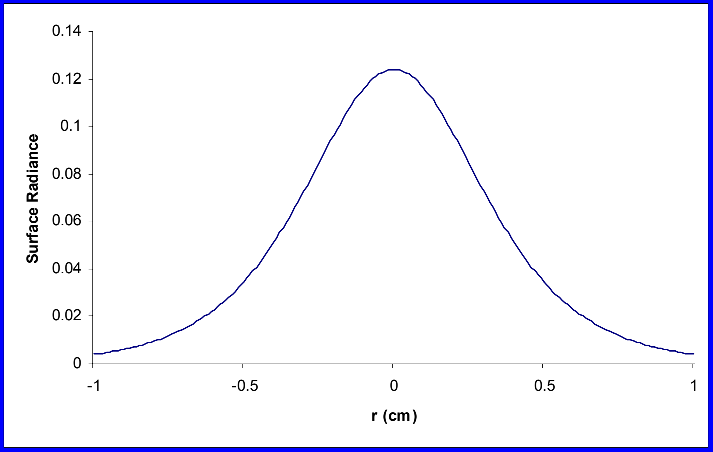
- Liquid nitrogen cooled camera
- Light tight box
- Collects ≈ 90% of light photons
- Image for 1 m – 6 m

Light Propagation



- **Light diffusion model**
- **Assumptions**
  - **Point Source**
  - **Semi-infinite homogeneous medium**

Surface Radiance Profile



Bacterial Clearance (Liver)

Assumptions

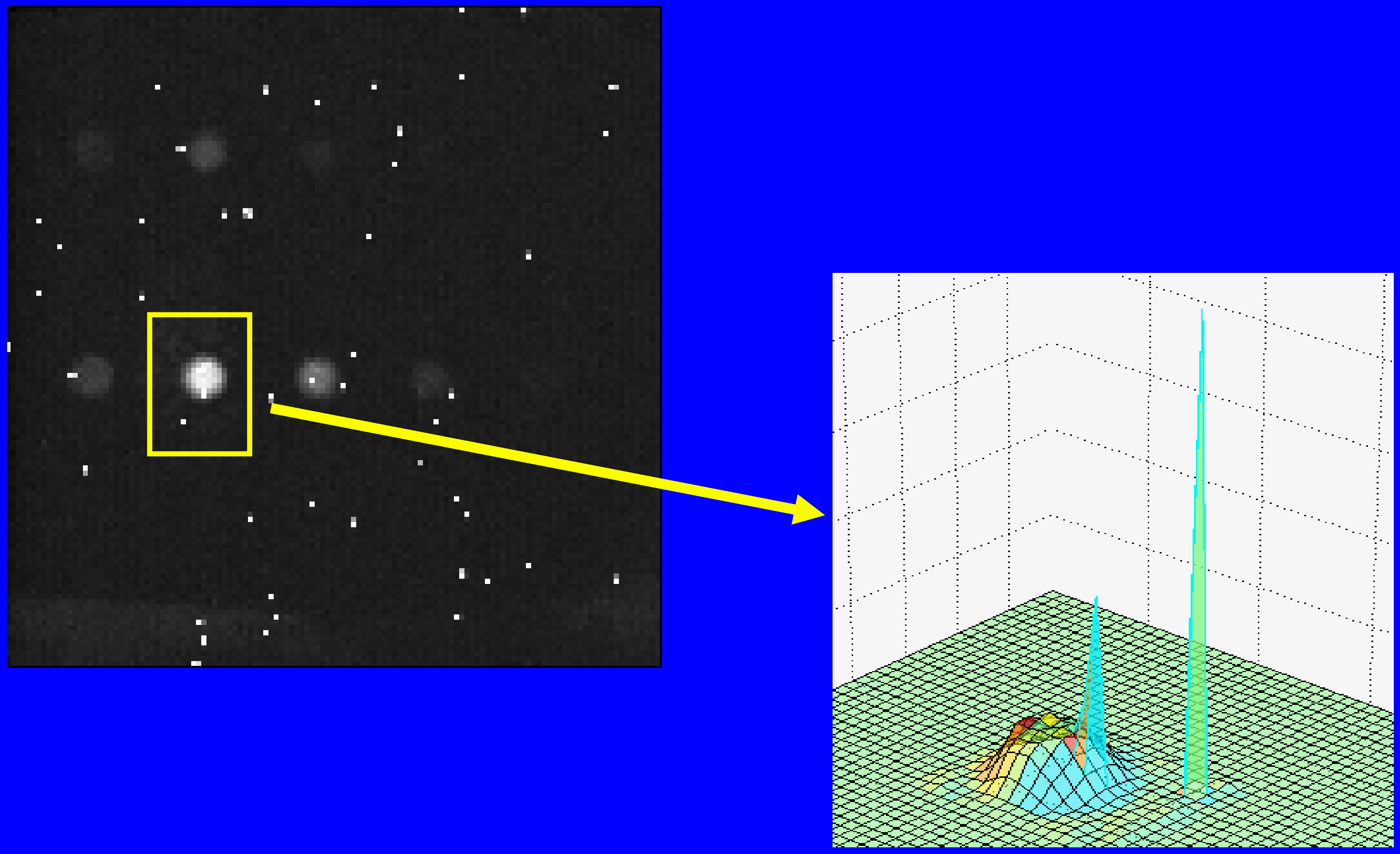
- $\lambda = 630$ nm
- depth = 5 mm
- $\mu_a = 0.25\ \text{cm}^{-1}$
- $\mu_s = 15\ \text{cm}^{-1}$

Light is spread and attenuated as it propagates through tissue.

What are these extra spots?

Cosmic ray artifacts!

Cosmic Ray Artifacts in BLI

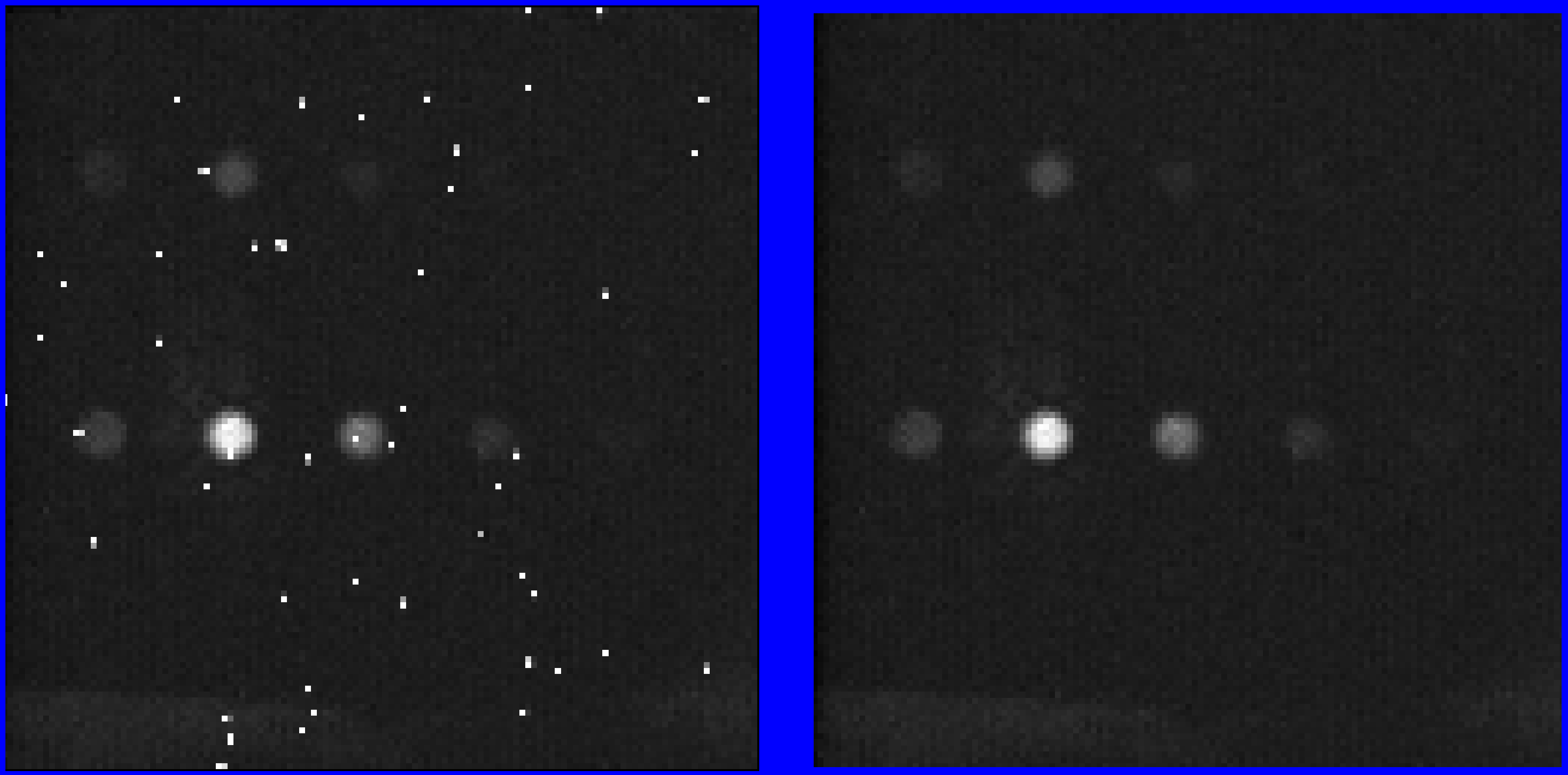


MDMC Algorithm for Cosmic Ray Correction

- 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.

Secretory Clusterin (sCLU)

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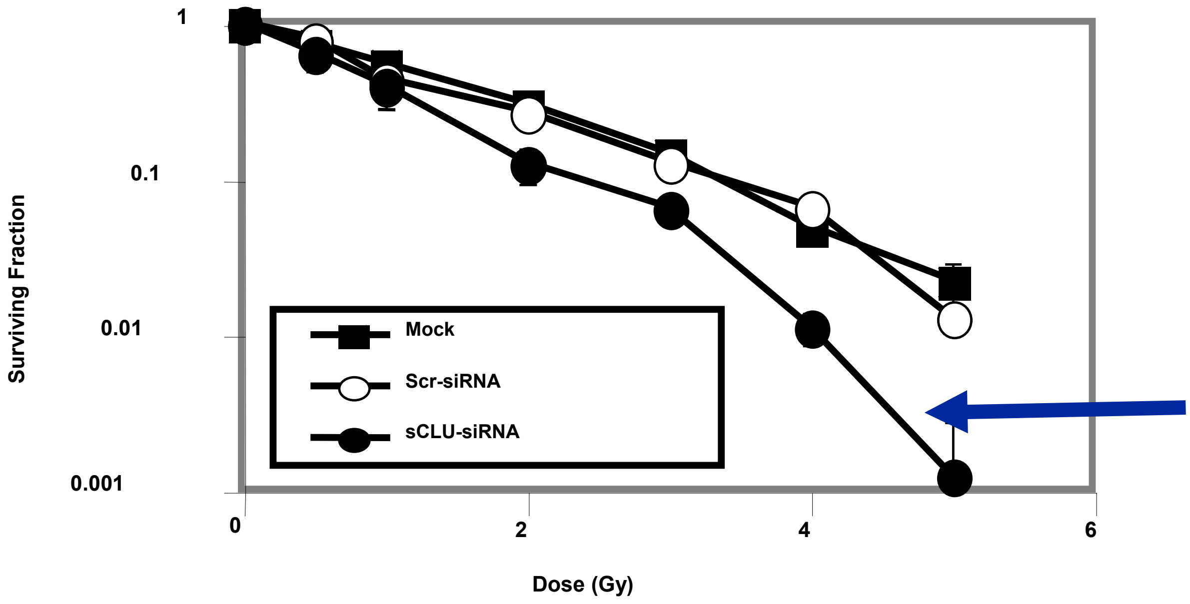
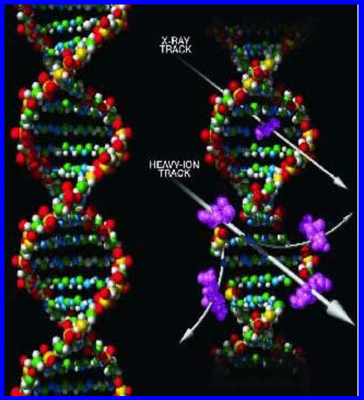
Cyto-protection and sCLU



Reduced sCLU

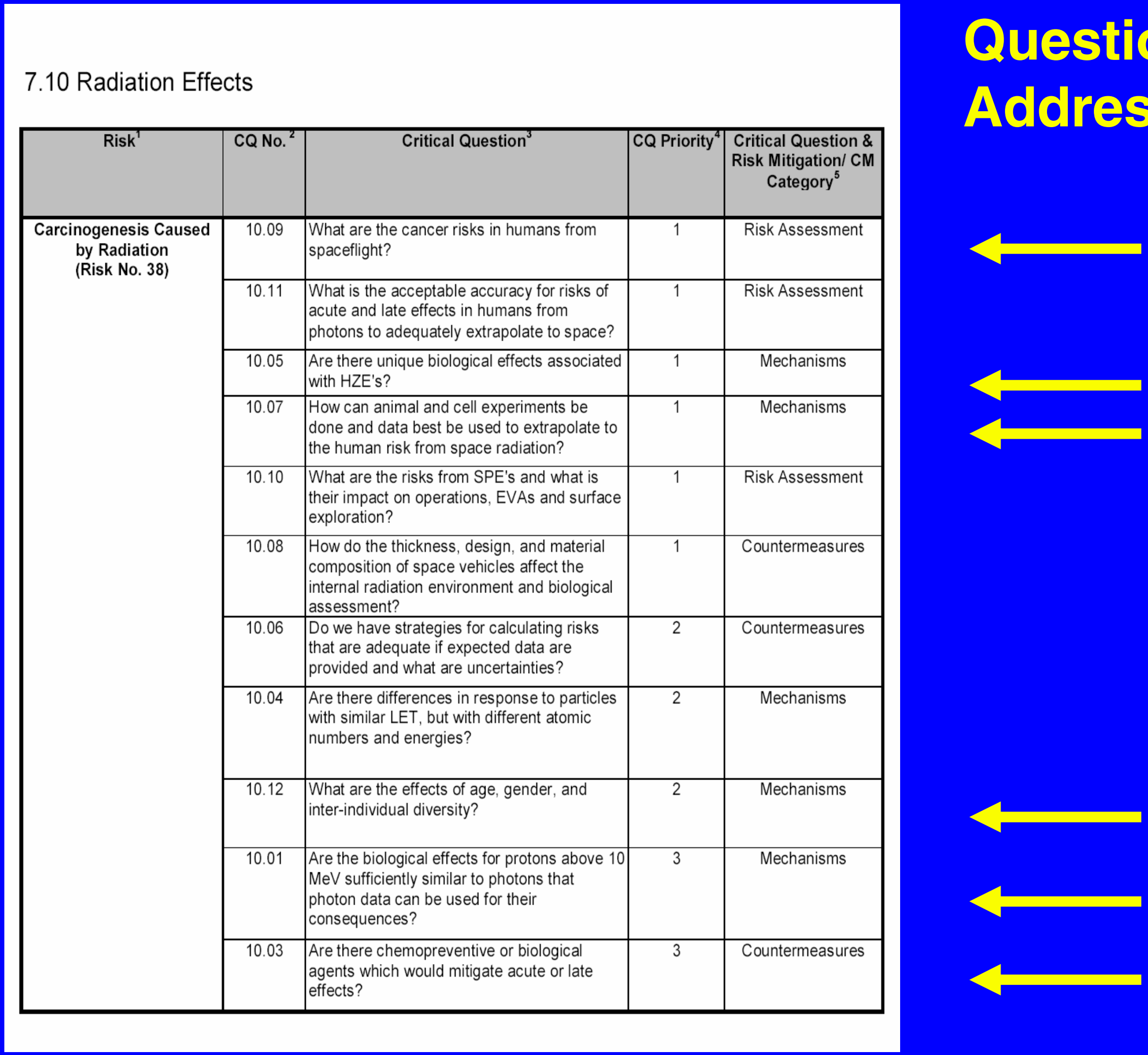
- **Reduces radiation lethality**
- **Reduces lethality from chemotherapy agents**
  - Adriamycin
  - Cisplatin
  - VP16
  - Topotecan
- **Reduces lethality from PDT**

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

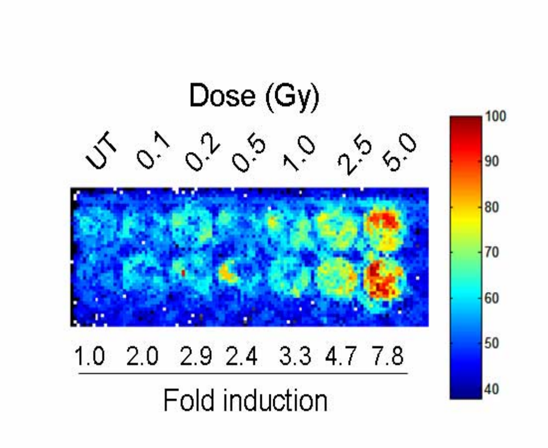
Questions Addressed

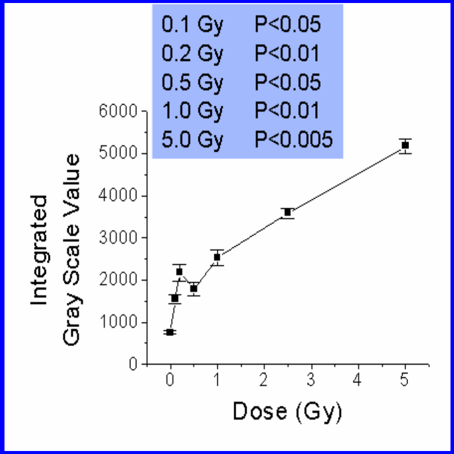


7.10 Radiation Effects

Risk[1]	CQ No.[2]	Critical Question[3]	CQ Priority[4]	Critical Question & Risk Mitigation/ CM Category[5]
Carcinogenesis Caused by Radiation (Risk No. 38)	10.09	What are the cancer risks in humans from spaceflight?	1	Risk Assessment
	10.11	What is the acceptable accuracy for risks of acute and late effects in humans from photons to adequately extrapolate to space?	1	Risk Assessment
	10.05	Are there unique biological effects associated with HZE's?	1	Mechanisms
	10.07	How can animal and cell experiments be done and data best be used to extrapolate to the human risk from space radiation?	1	Mechanisms
	10.10	What are the risks from SPE's and what is their impact on operations, EVAs and surface exploration?	1	Risk Assessment
	10.08	How do the thickness, design, and material composition of space vehicles affect the internal radiation environment and biological assessment?	1	Countermeasures
	10.06	Do we have strategies for calculating risks that are adequate if expected data are provided and what are uncertainties?	2	Countermeasures
	10.04	Are there differences in response to particles with similar LET, but with different atomic numbers and energies?	2	Mechanisms
	10.12	What are the effects of age, gender, and inter-individual diversity?	2	Mechanisms
	10.01	Are the biological effects for protons above 10 MeV sufficiently similar to photons that photon data can be used for their consequences?	3	Mechanisms
	10.03	Are there chemopreventive or biological agents which would mitigate acute or late effects?	3	Countermeasures

IR Dose Response

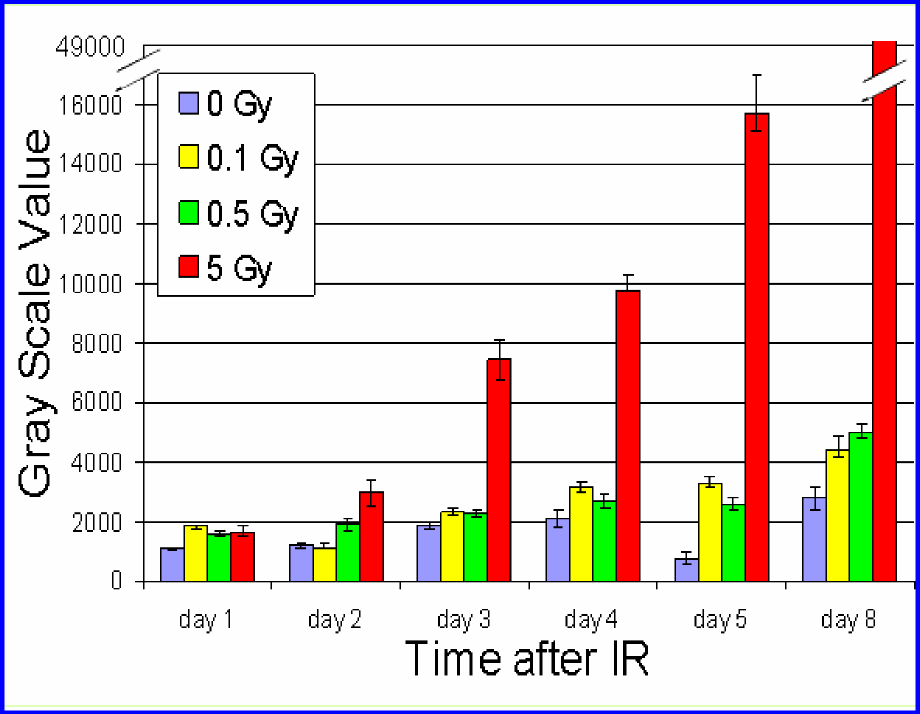




0.1 Gy	P<0.05
0.2 Gy	P<0.01
0.5 Gy	P<0.05
1.0 Gy	P<0.01
5.0 Gy	P<0.005

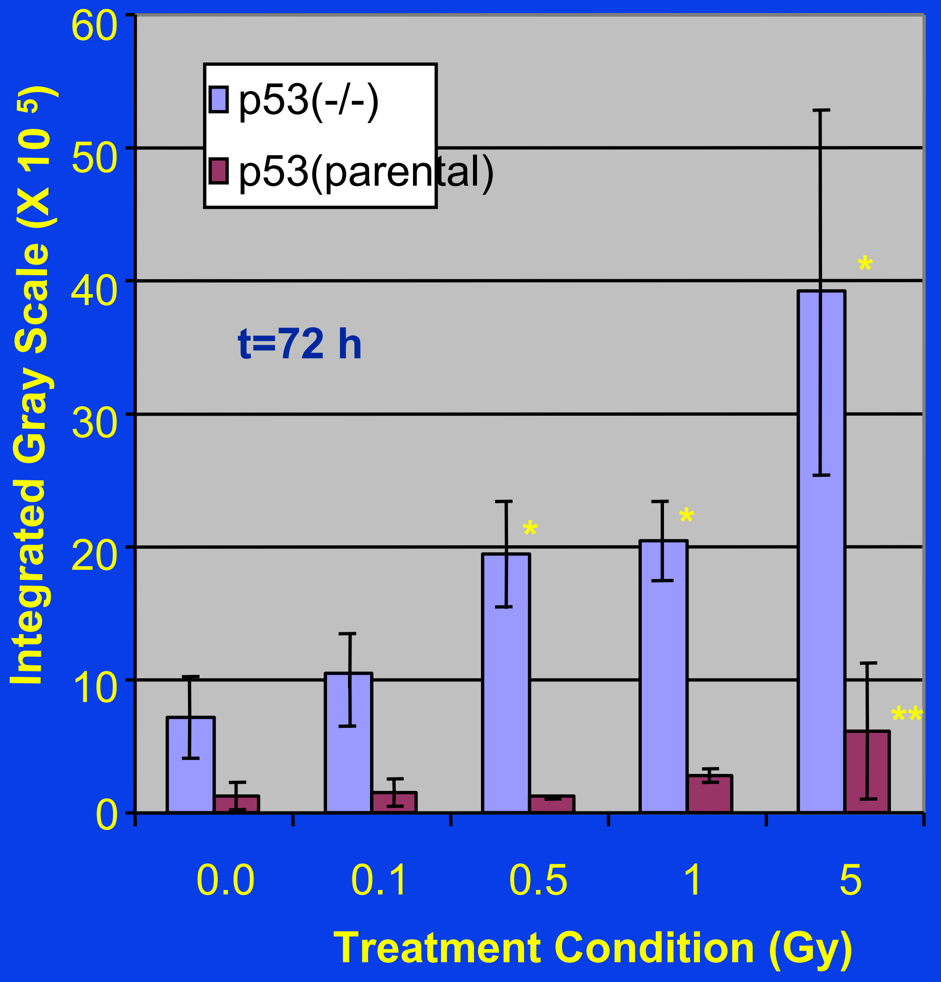
- Created well plates containing cells with luciferase under control of the CLU promoter
- Radiated cells with low energy radiation
- Induction of sCLU at exposures of 0.1 cGy
- Increasing dose response indicating the possibility of a biodosimeter

Temporal Response of CLU



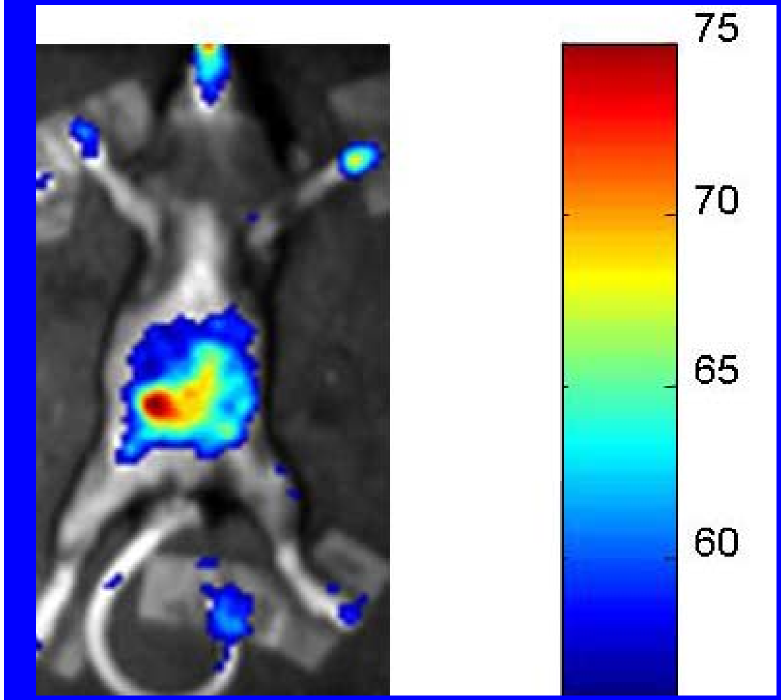
- Response of radiated cells depends upon exposure and time
- Strong response at 3-4 days post exposure

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

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

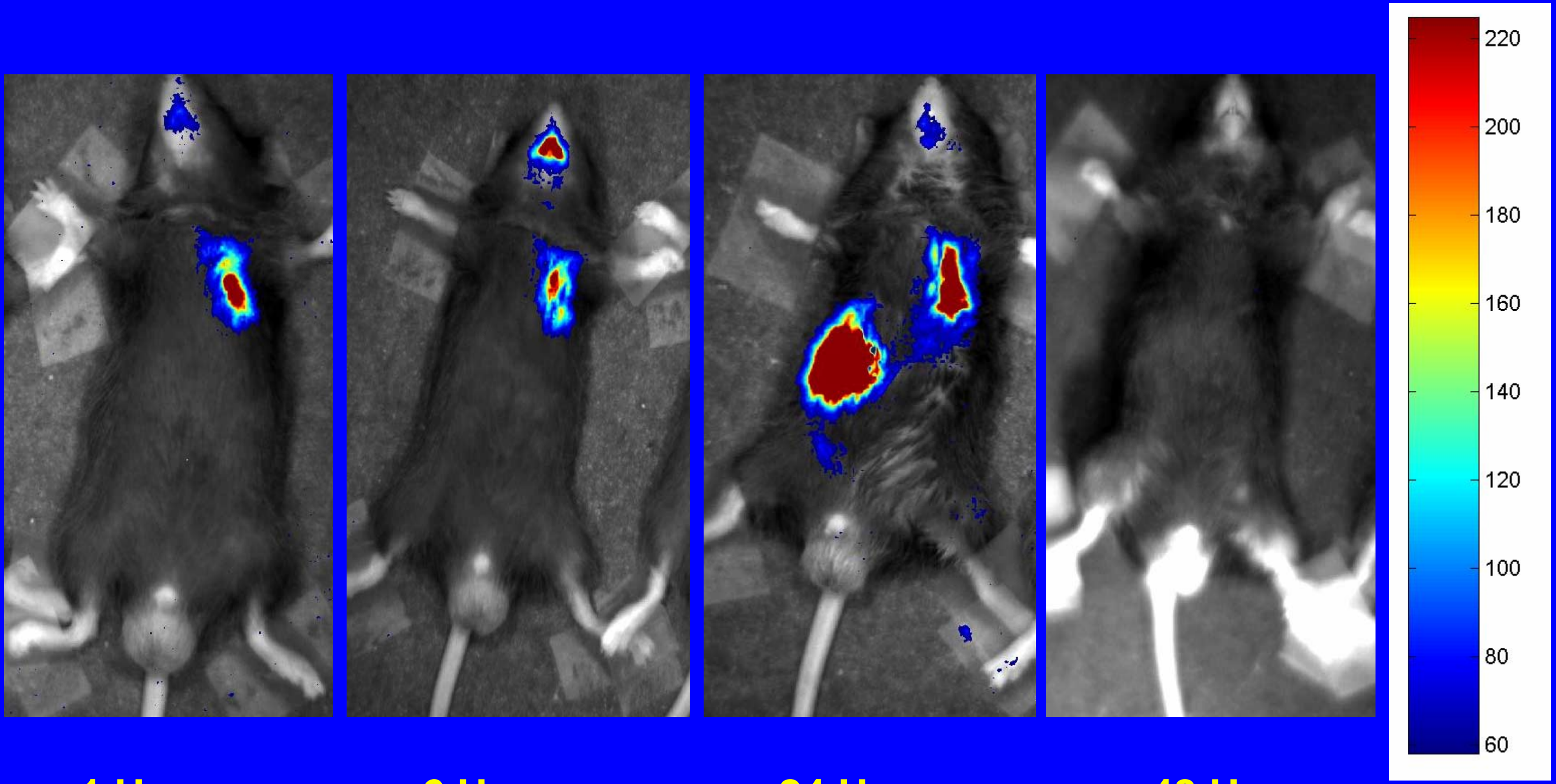
- Measure *in vivo* dose response in the sCLU-BLI mouse
  - Temporal response
  - Dose response
- Determine signaling pathways and modifiers; e.g., effect of testosterone
- Measure dose response to high LET radiation at Brookhaven National Laboratory and compare to low LET experiments

Towards the creation of a bio-dosimeter for astronauts

- 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

Develop radiation counter-measures

Clearance of Bacterial Pneumonia



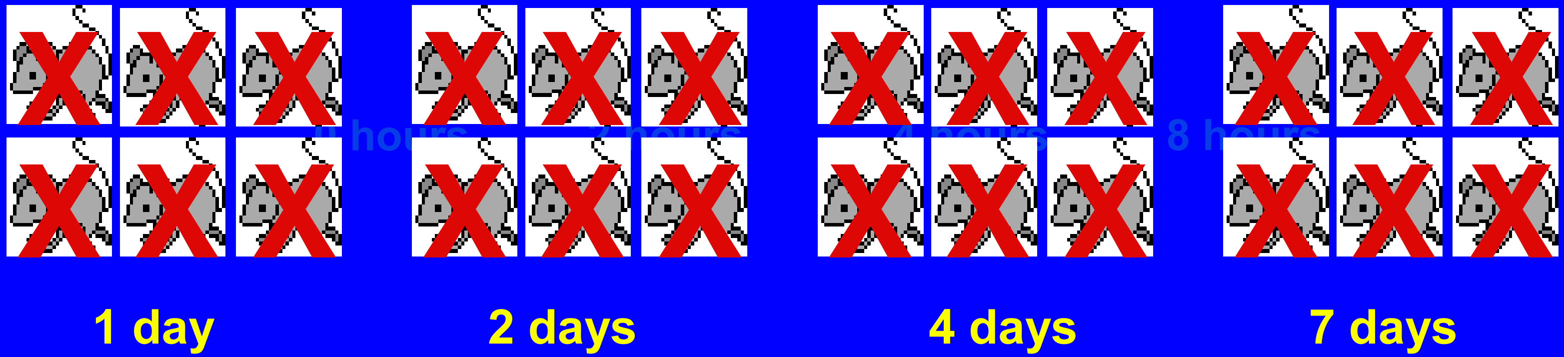
1 Hour **6 Hour** **24 Hour** **48 Hour**

Mouse 2, 1:3 dilution of bacteria

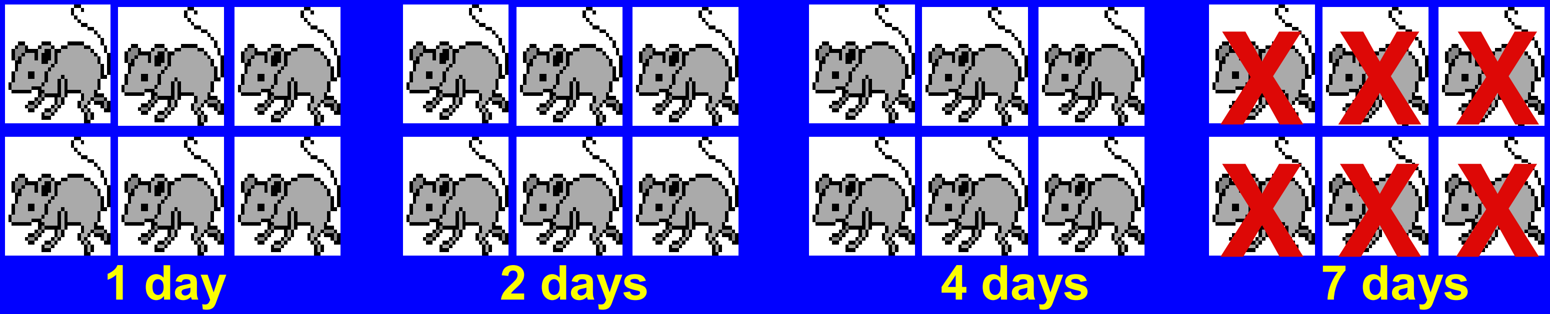
Doerschuk & Wilson

Fewer Mice in Space

Conventional Serial Sacrifice



Bioluminescent Molecular Imaging

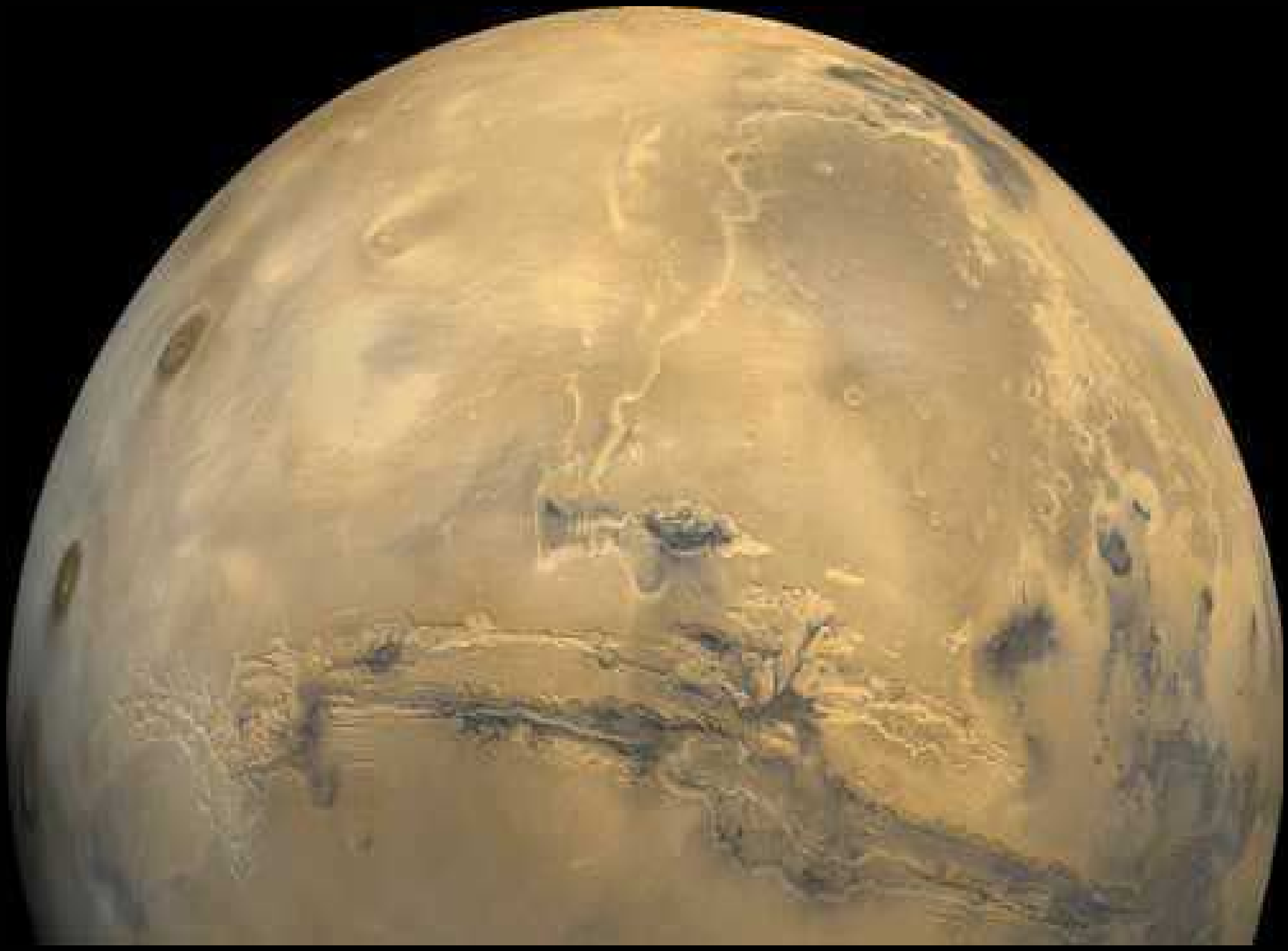


Summary

- 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

Mars

http://www.nineplanets.org/



BIOPHOTONICS AND BONE BIOLOGY

Gregory Zimmerli and David Fischer
NASA Glenn Research Center, Cleveland, OH

Marius Asipauskas, Chirag Chauhan, Nicole Compitello, and Jamie Burke
National Center for Microgravity Research, Cleveland, OH

Melissa Knothe Tate
Cleveland Clinic Foundation, Lerner Research Institute, Cleveland, OH

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.

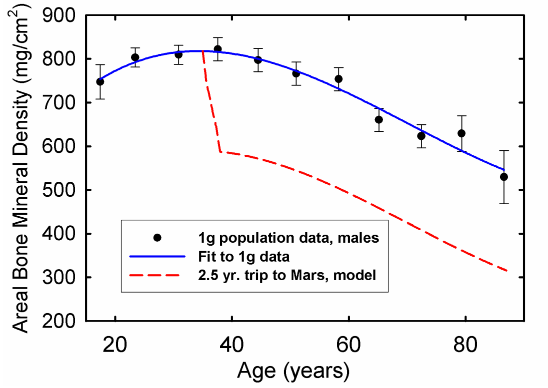


Figure 1. Age-related bone loss in a 1g population of males (data from Atlas of Clinical Endocrinology: Osteoporosis, 2003) compared to a hypothetical person exposed to microgravity and partial gravity during a 2.5 year Mars trip. The model assumes a linear response of bone loss with g-level, and does not account for the possibility of new bone growth upon returning to 1 g, as no data yet exists for such an effect.

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.

Contact: Gregory.A.Zimmerli@nasa.gov
NASA GRC, 21000 Brookpark Road, MS 110-3, Cleveland, OH 44135

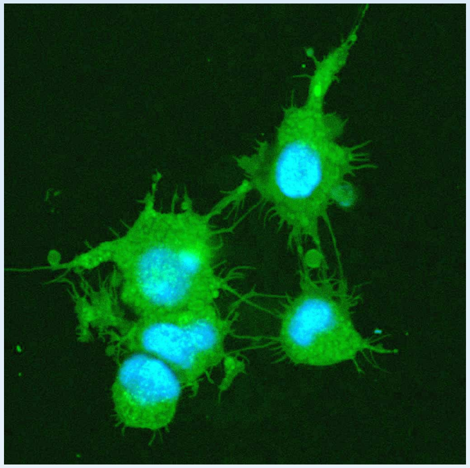
Biophotonics and Bone Biology

- Greg Zimmerli, Ph.D.
NASA Glenn Research Center

Colleagues:

David Fischer[1], Ph.D.; Marius Asipauskas[2];
Melissa Knothe Tate[3], Ph.D.; Chirag Chauhan[2,3],
Jamie Burke[2], Nicole Compitello[2]

[1] NASA Glenn Research Center
[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

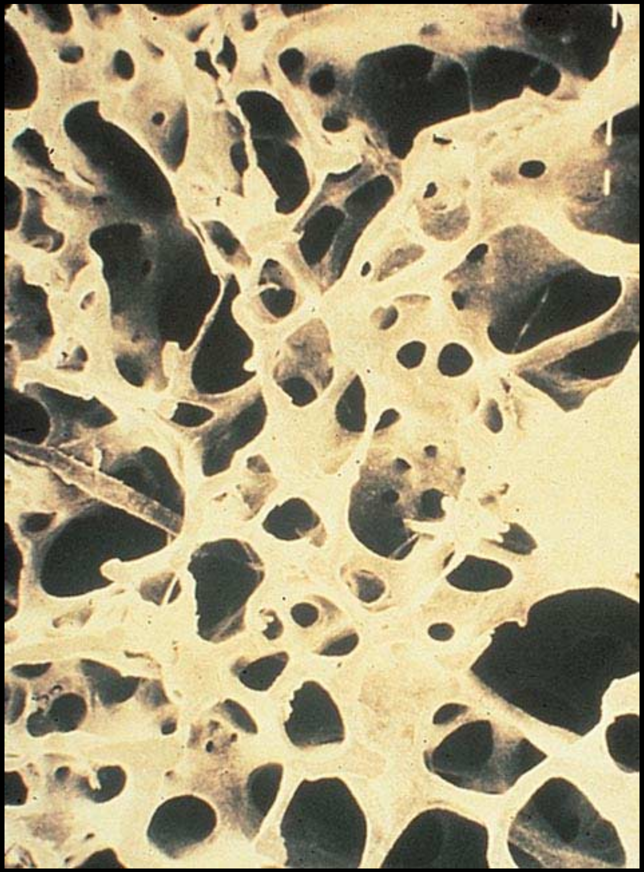
- Bone loss in hips and spine, 1% per month
- Immunodeficiency
- Loss of blood plasma, anemia
- Cardiac dysrhythmia

⋮

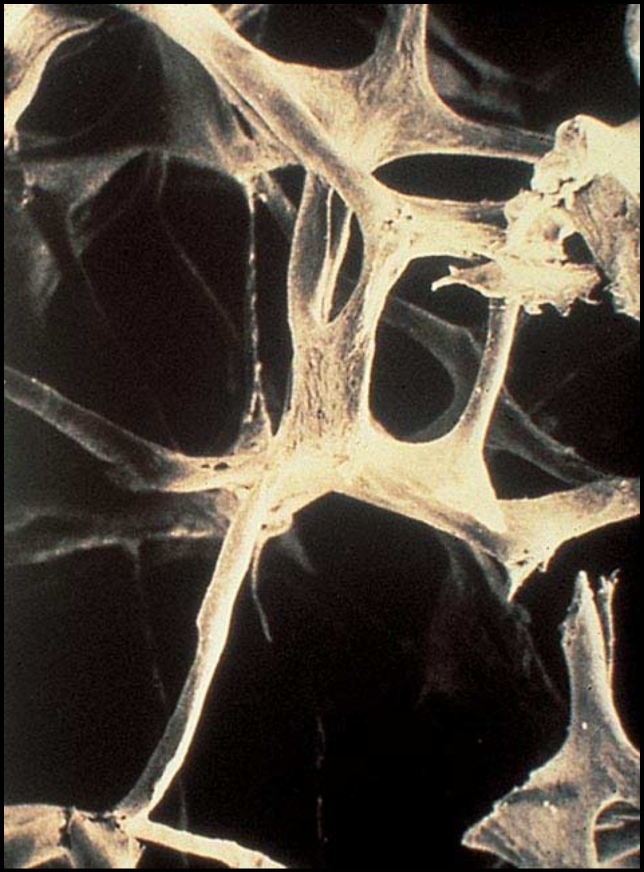
Like an accelerated osteoporosis

Ref. document: Bioastronautics Critical Path Roadmap

Normal trabecular
(spongy bone) structures

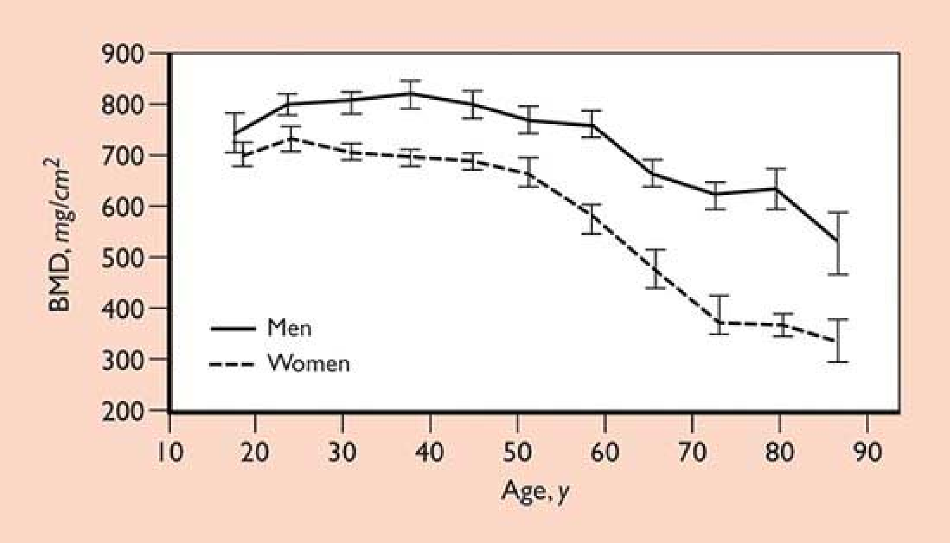


Osteoporotic trabecular structures



Source: Atlas of Clinical Endocrinology: Osteoporosis (2003)

Bone mineral density (BMD) loss: Effect of aging



Source:
Atlas of Clinical Endocrinology:
Osteoporosis (2003)

Microgravity BMD loss: 1.2% per month (Lang et al., *JBMR* 2004)

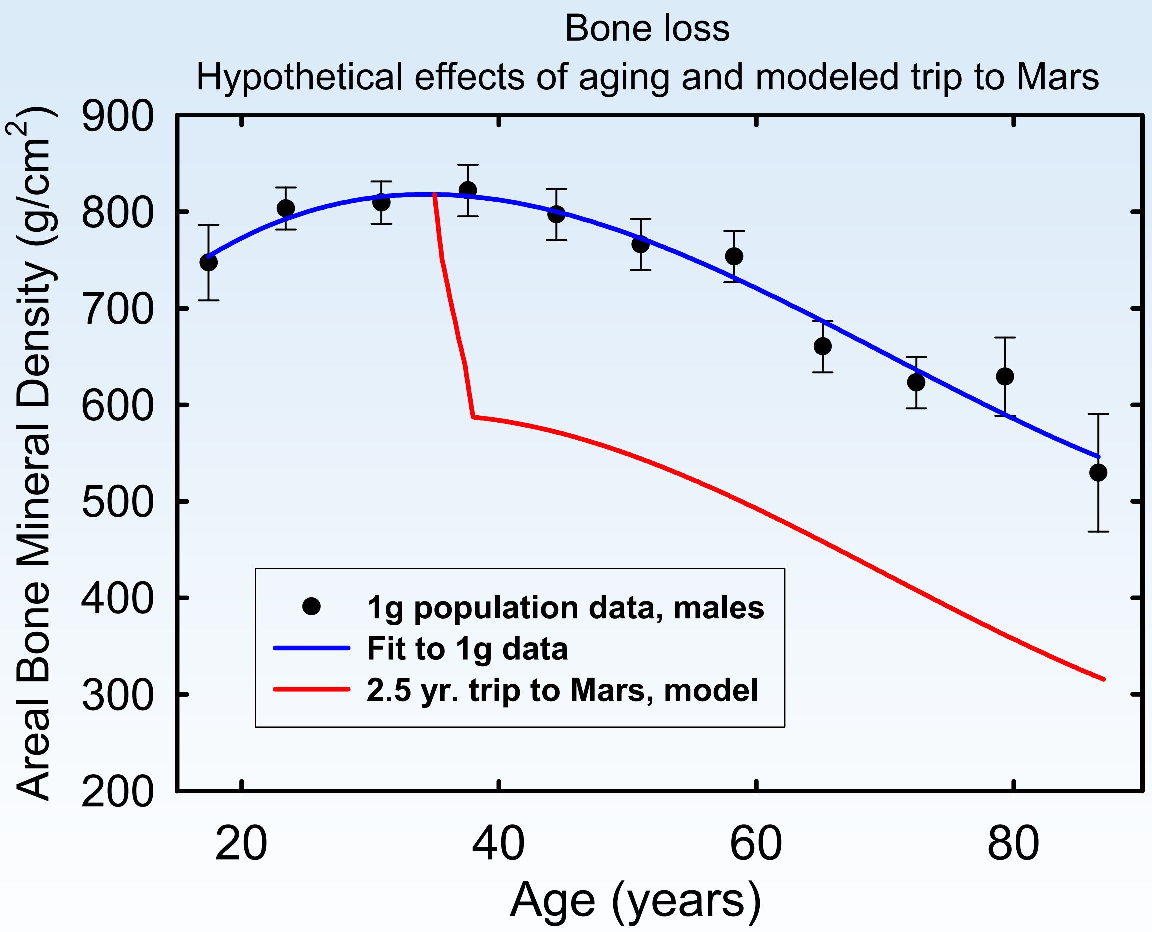
Model a trip to Mars: $\frac{d}{dt}BMD = \frac{d}{dt}BMD_{aging} + \frac{d}{dt}BMD_{g-level}$

$$\frac{d}{dt}BMD_{g-level} = \frac{0.012 \cdot BMD}{mo.}(g^* - 1)$$ Linear response model

$$g^* = \frac{local\ accel.}{9.8\ m/s^2}$$

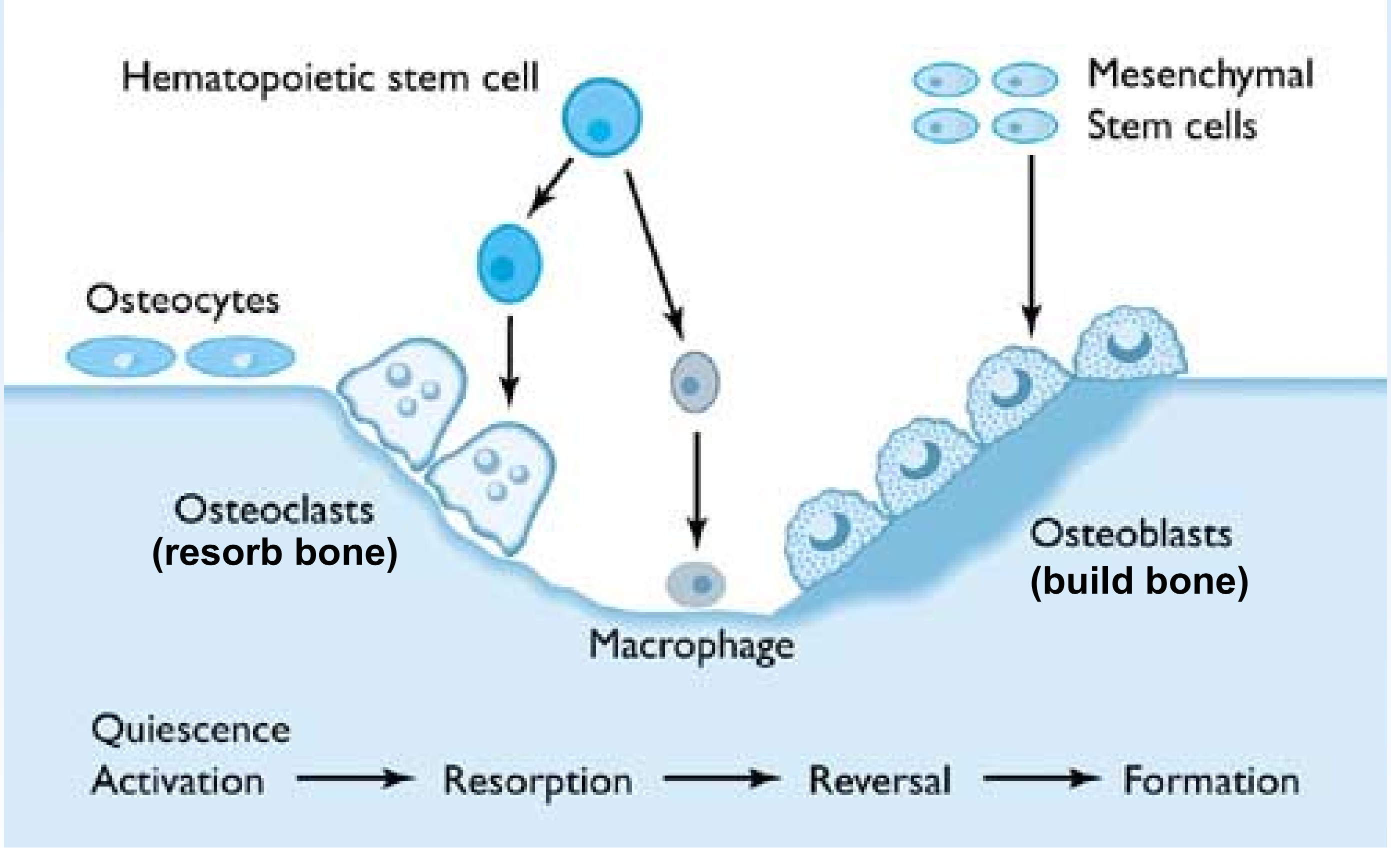
Calculate $BMD(t) = BMD(t_0) + \int_{t_0}^{t} \frac{d}{dt}BMD\ dt$


NASA Glenn Research Center
Cleveland, Ohio
Strategic Research to Enable
NASA's Exploration Missions
Conference 2004



Mars trip: 6 mo. out (0g), 18 mo. stay (0.38g), 6 mo. return (0g)

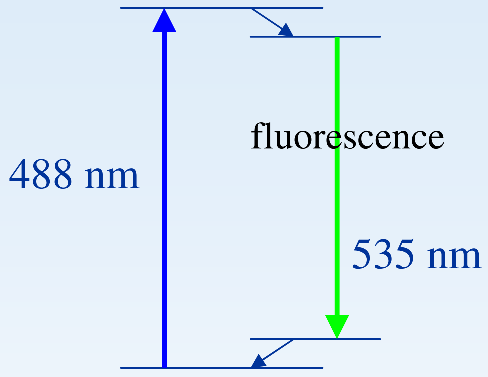
Bone Remodeling: Balance between osteoclasts and osteoblasts



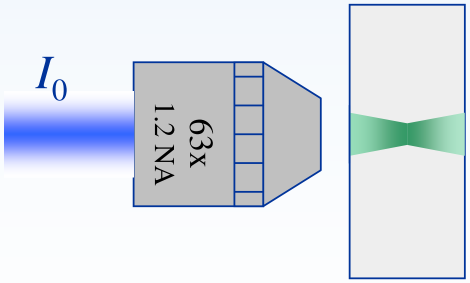
Use two-photon fluorescence microscopy to study macrophage, osteoclast and osteoblast cells

Background: Two-photon absorption

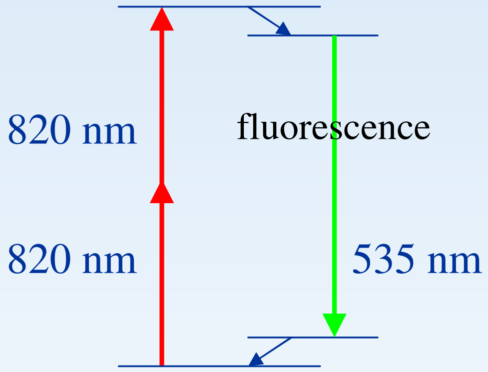
Single-photon absorption



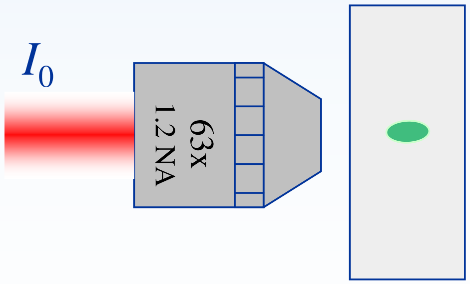
Fluorescence intensity ~ I_0



Two-photon absorption



Fluorescence intensity ~ I_0^2



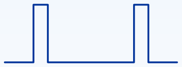
Excitation rate (photons/s), φ

1 - photon

$$\varphi_{1p} \approx 4P_0\eta_{1p}\sigma_{1p}\frac{(NA)^2}{hc\lambda}$$

2 - photon, pulsed laser

$$\phi_{2p} \approx 8\langle P_0\rangle^2 \frac{\eta_{2p}\sigma_{2p}}{\tau_p f_p}\frac{(NA)^4}{(hc\lambda)^2}$$



$$(\tau_p f_p)^{-1} \approx 10^5$$

$$\frac{\varphi_{2p}}{\varphi_{1p}} \approx 5\cdot 10^{-4}/mW$$

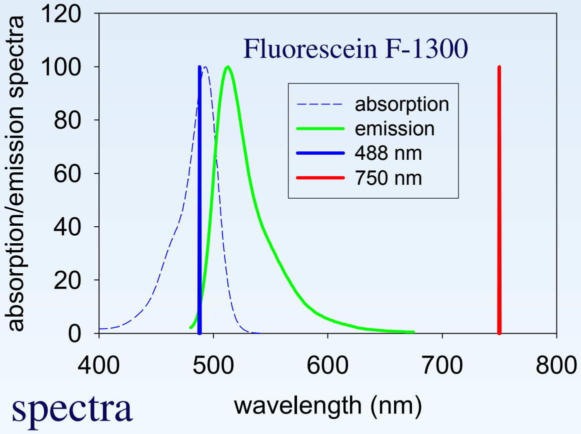
Advantages of two-photon excitation:

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

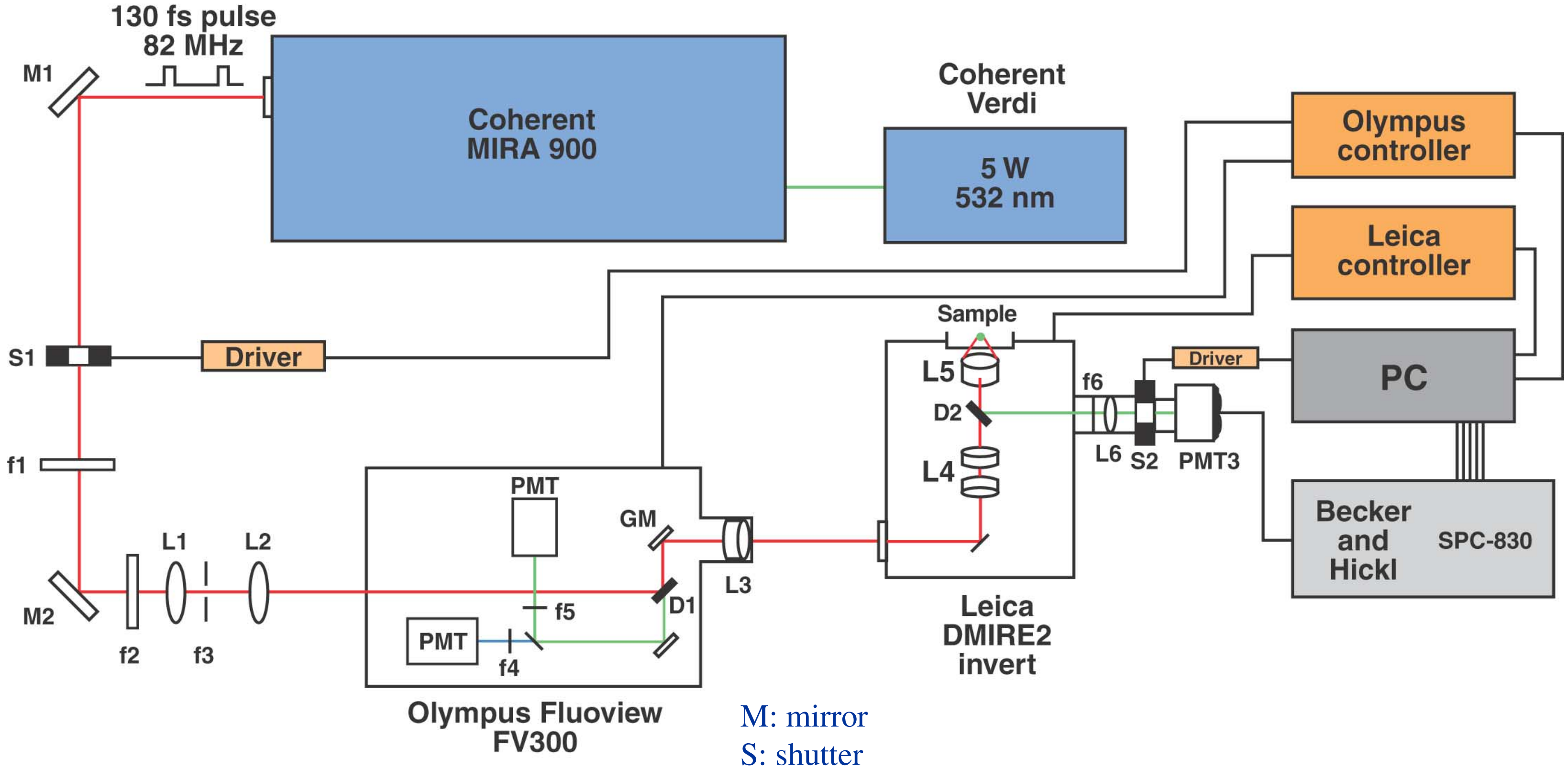
- reduced Rayleigh scattering ($1/\lambda^4$), better depth penetration
- less absorption/damage in tissue; biological "optical window"
- larger spectral gap in excitation/emission spectra



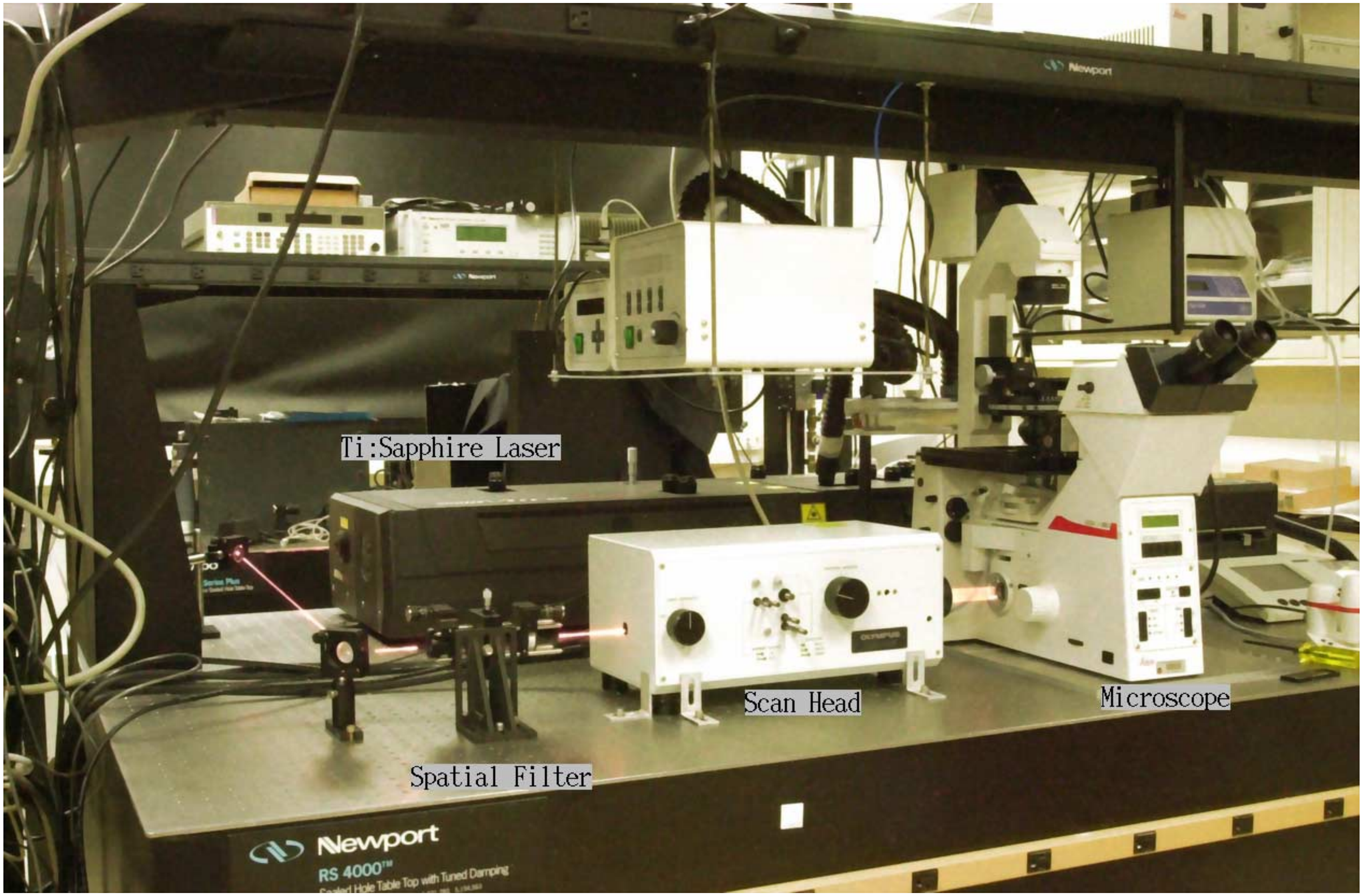
Disadvantages of two-photon:

- Large, expensive laser:
  - complete two-photon systems available commercially for \$500k-\$700k
- Slightly lower resolution due to longer excitation wavelength

Two-photon microscopy layout

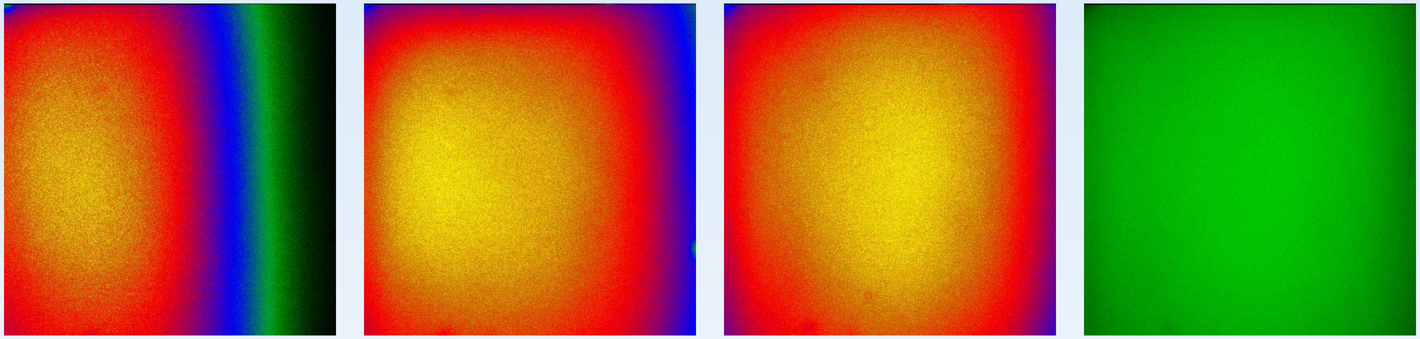


M: mirror
S: shutter
f: filter
L: lens
D: dichroic
GM: galvonmeter mirrors (2)
PMT: photomultiplier tube


Ti:Sapphire Laser
Scan Head
Microscope
Spatial Filter

Fine tuning the optical alignment:

Scan a fluorescent lake sample (e.g., fluorescein in methanol), align scanhead, scope.

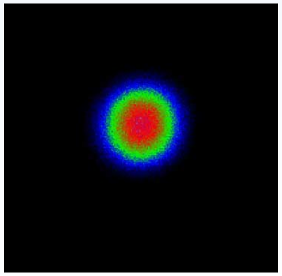


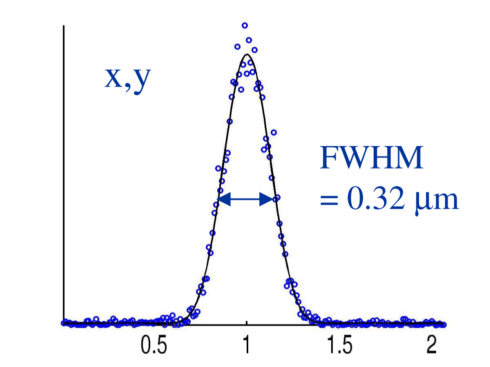
better alignment →

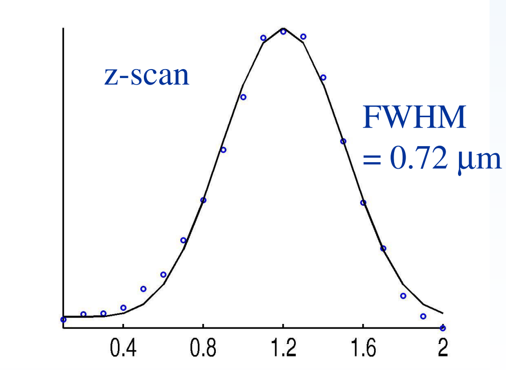
One-color representation

Point-spread-function measurement:

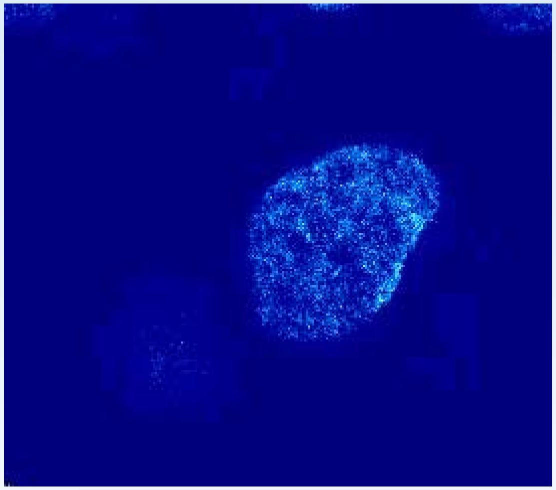
scan 0.093 µm diameter fluorescent microspheres in x,y,z







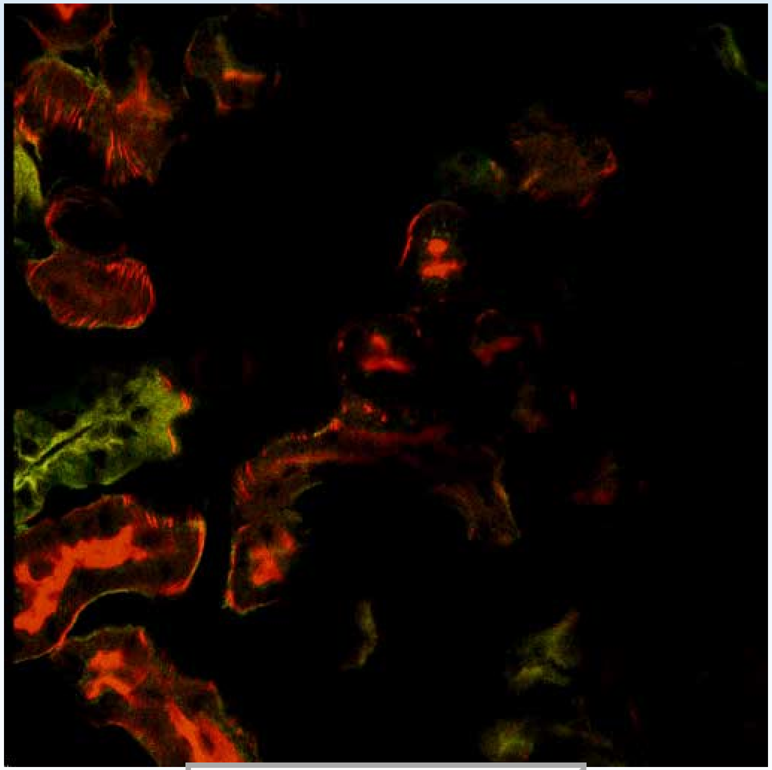
Add micro-incubator for 37 °C , 5% CO$_2$ control:



Click here to play movie

CHO cells expressing YFP;
Time lapse: 2 minutes/frame

Cells provided by Prof. Gabor Forgacs, U. Missouri
and Dr. Rusty Lansford, CalTech

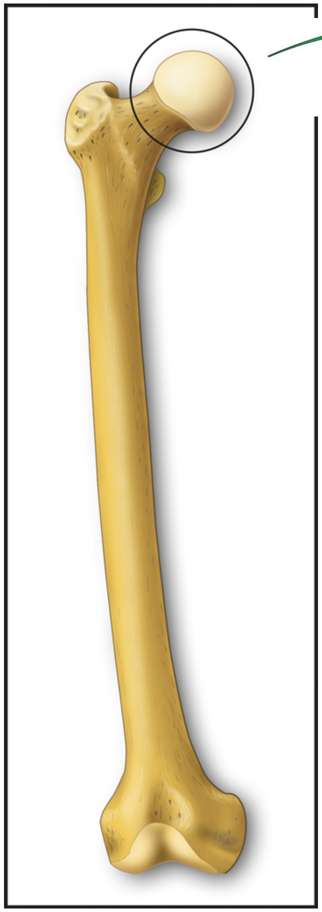


Click here to play movie

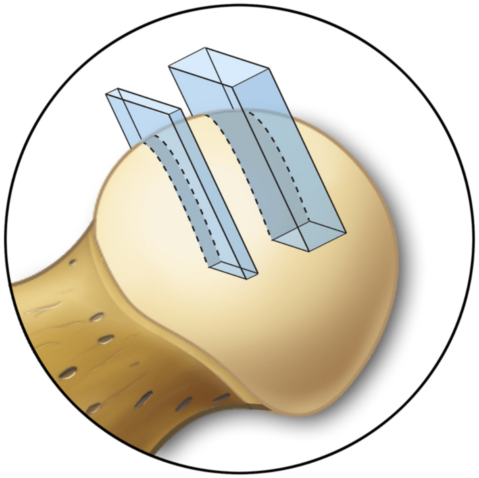
Mouse kidney section: z- scan

Application: Imaging bone tissue

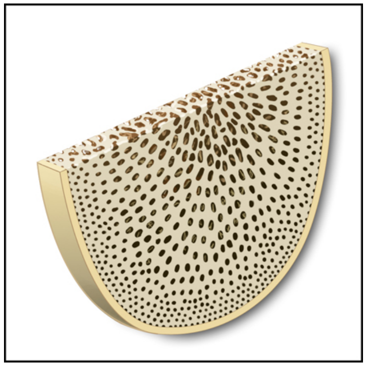
Sample provided by: Melissa Knothe Tate,
Cleveland Clinic Foundation



Human femur

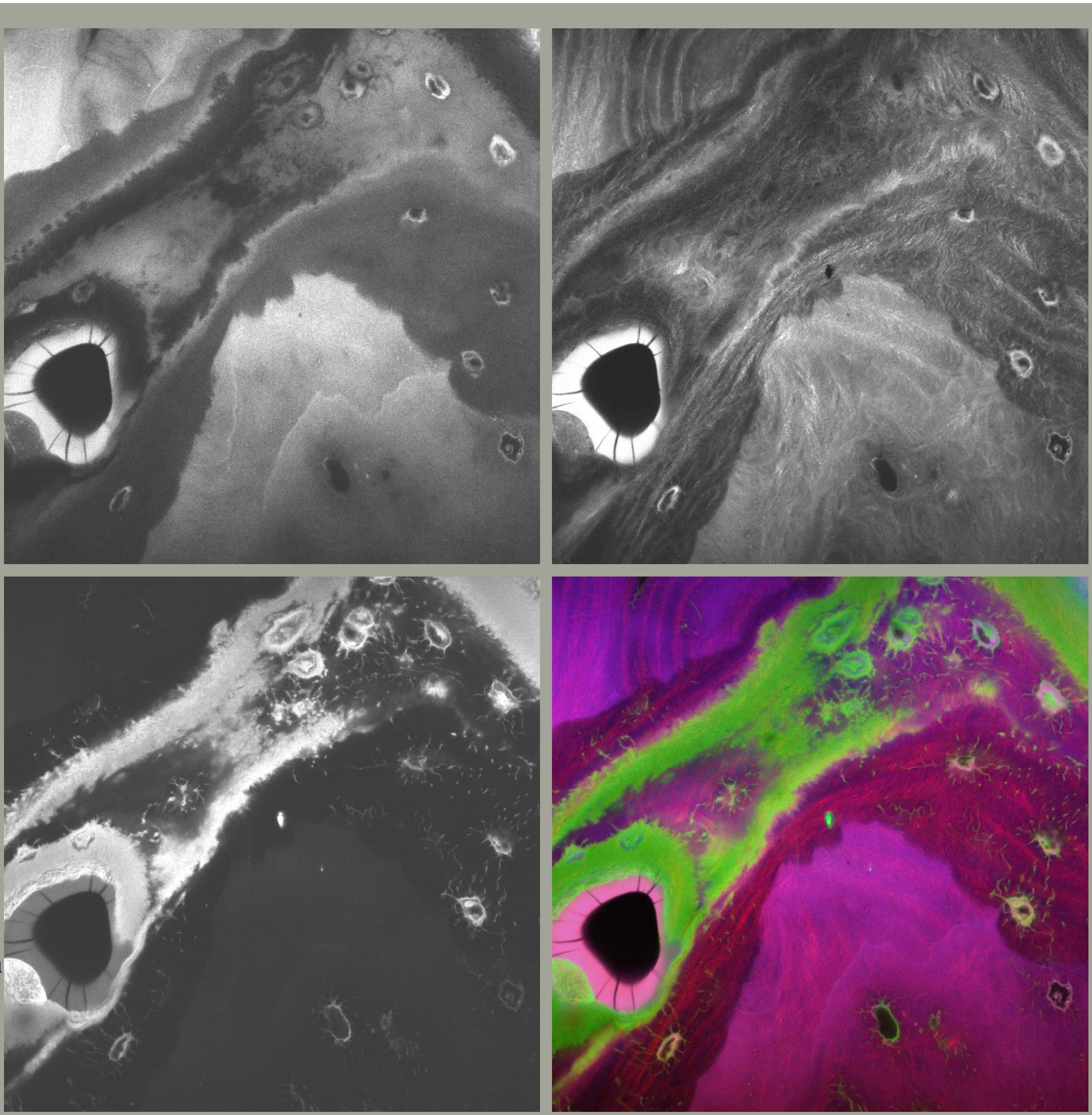


Femoral head



Section from femoral head stained with basic fuschin and embedded in PMMA

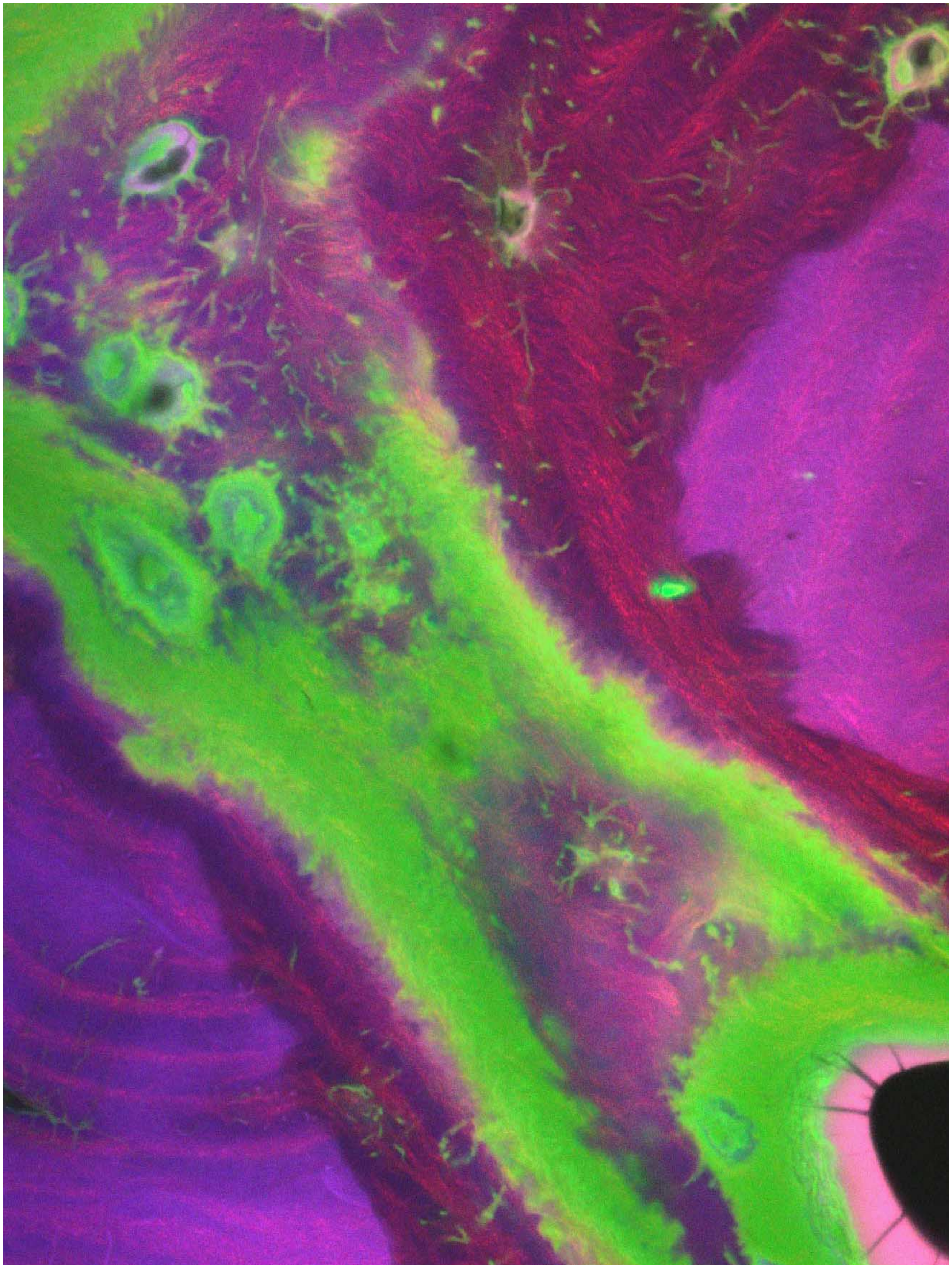
Bone section,
12 μm depth,
$\lambda_{ex.}$: 810 nm

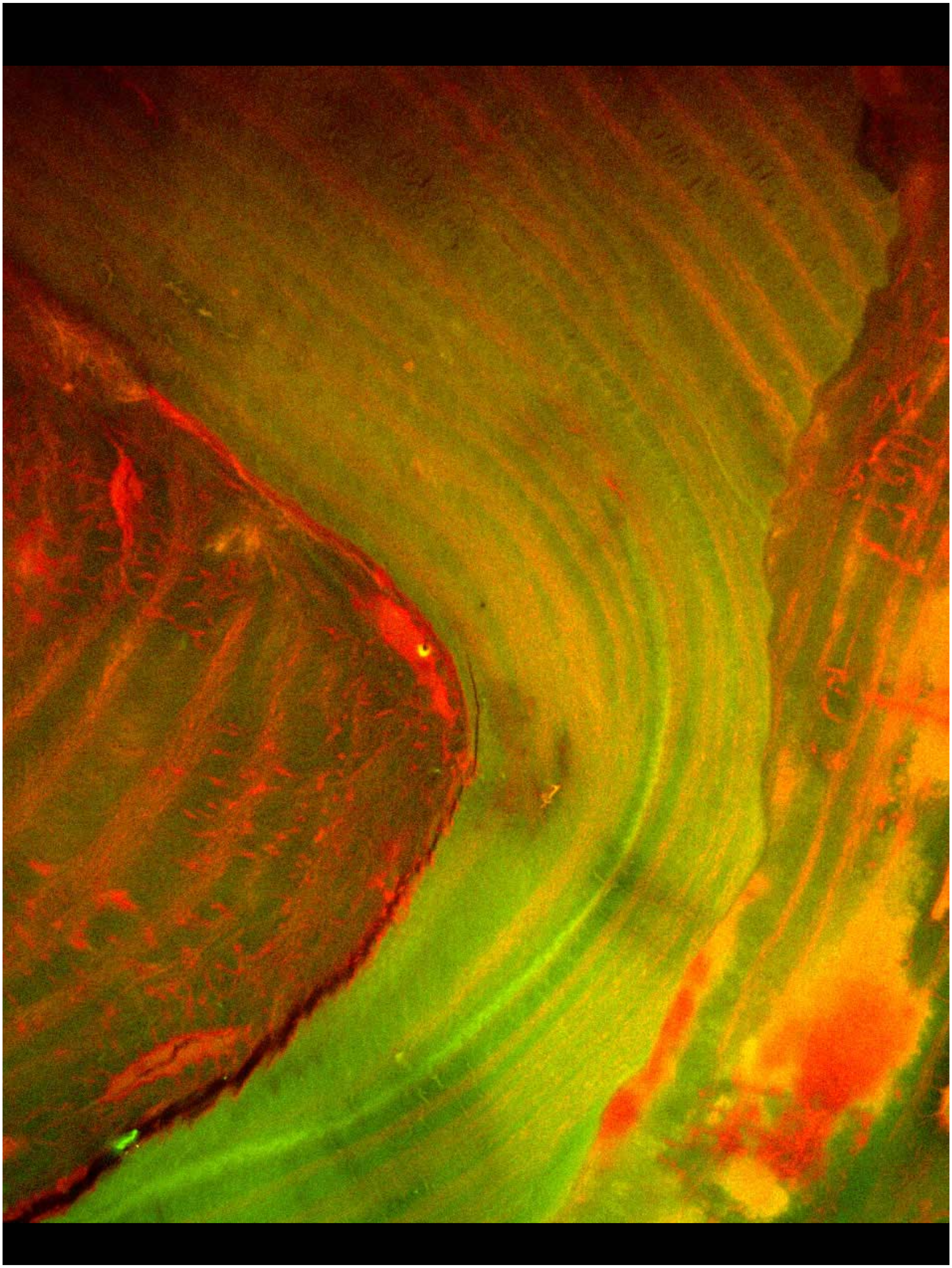


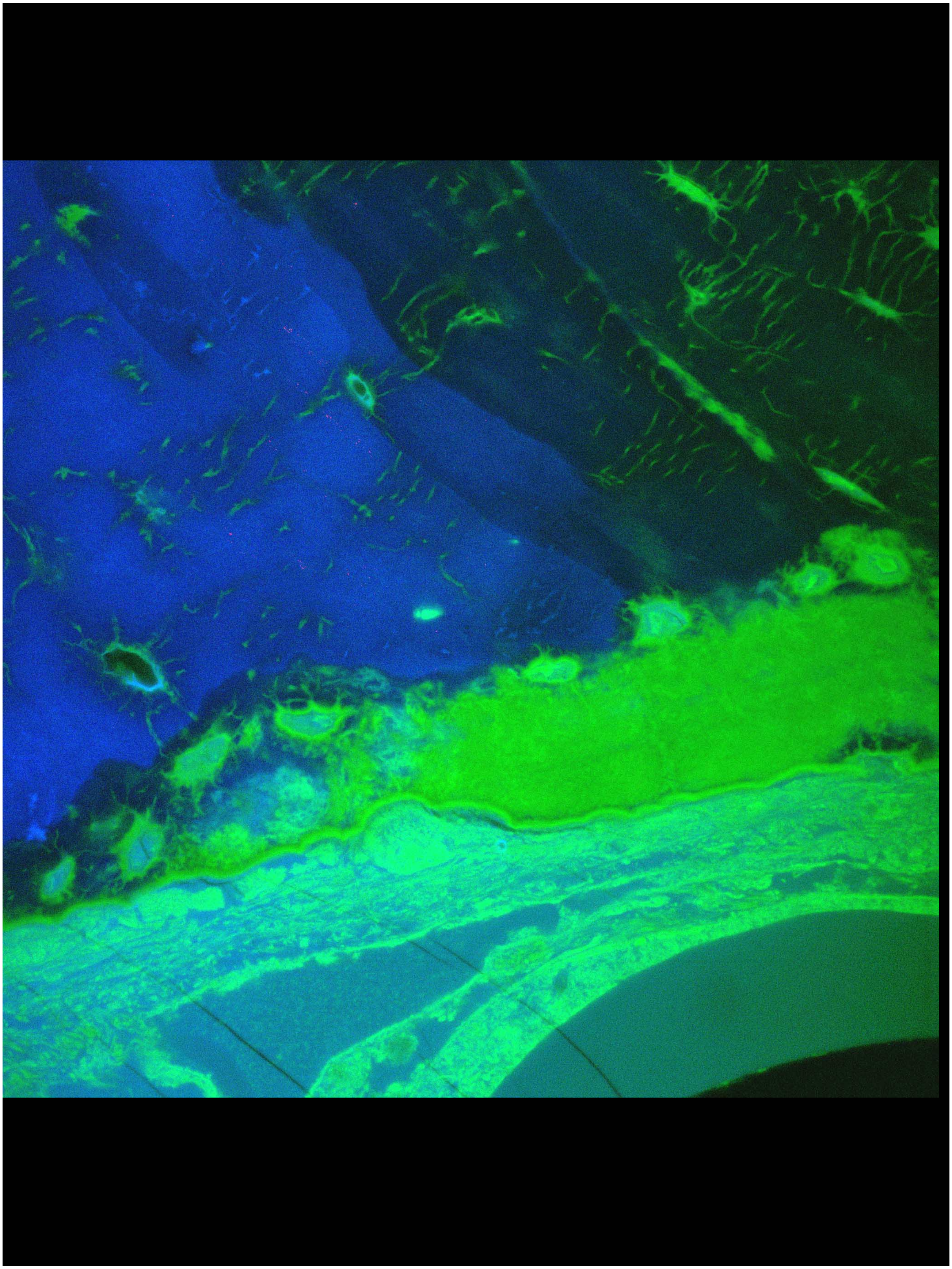
435-485 nm
Autofluorescence
Mineralized matrix ?

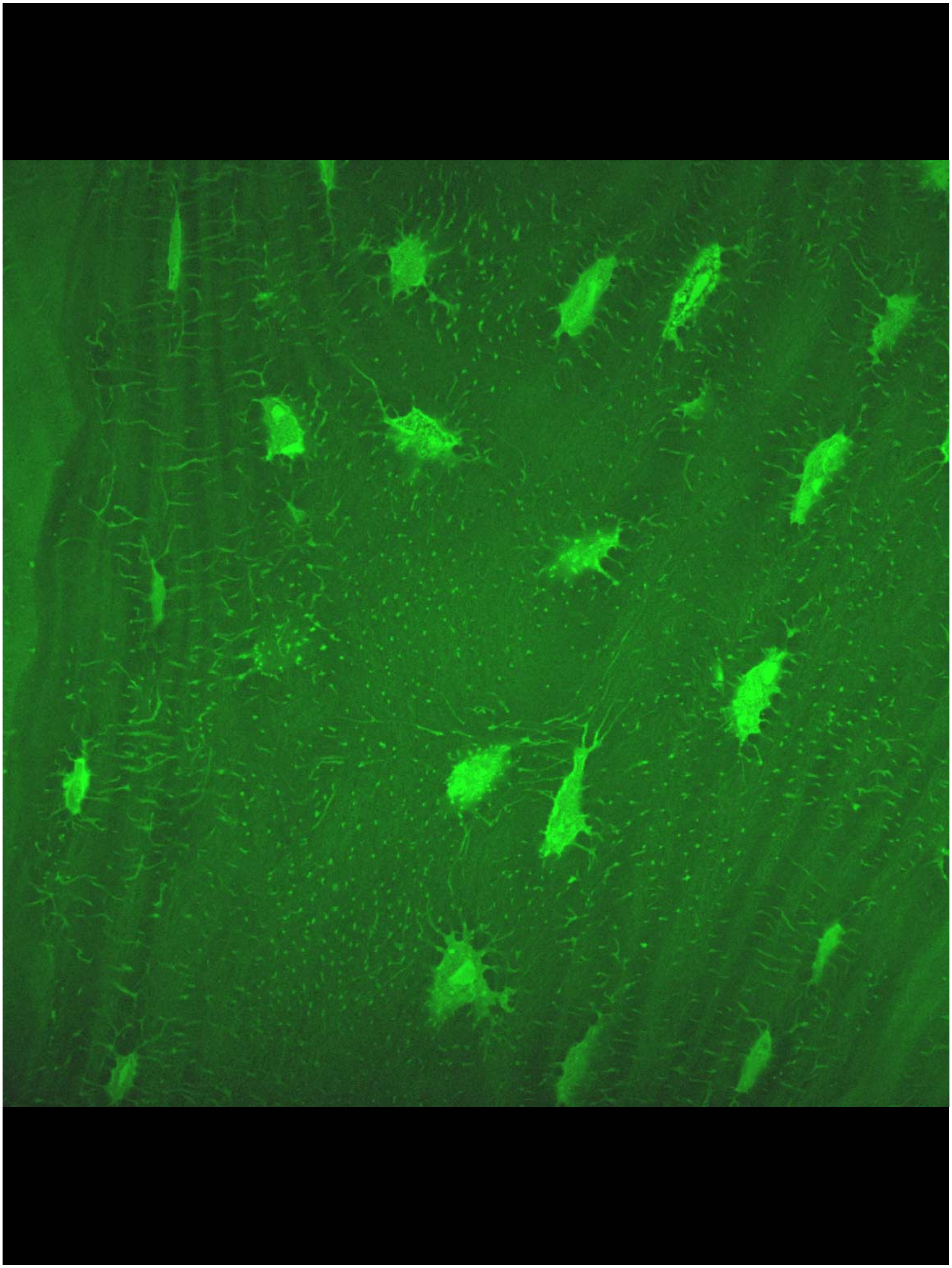
640-700 nm
Autofluorescence
Collagen matrix

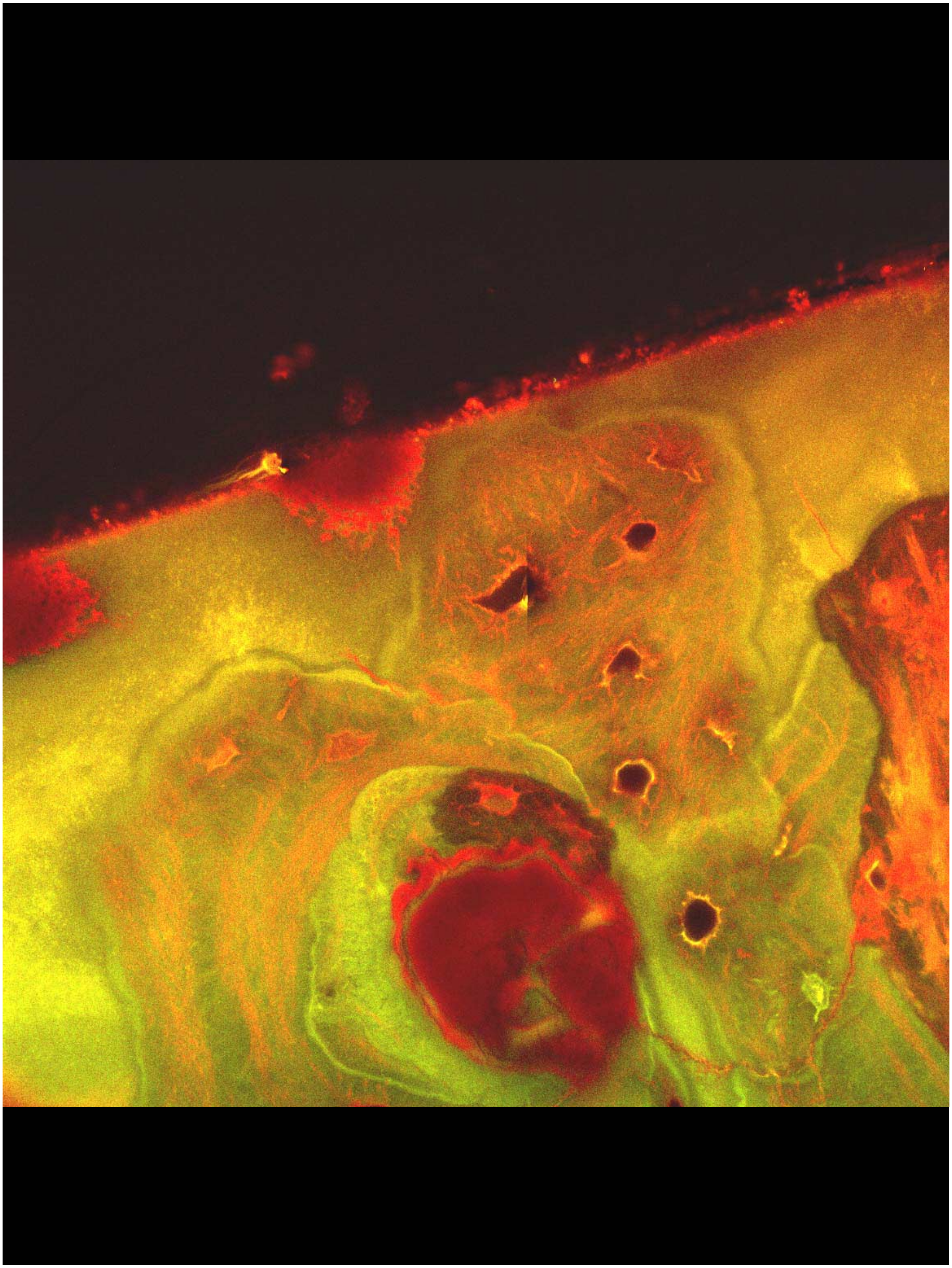
590-640 nm
Basic fuschin stain

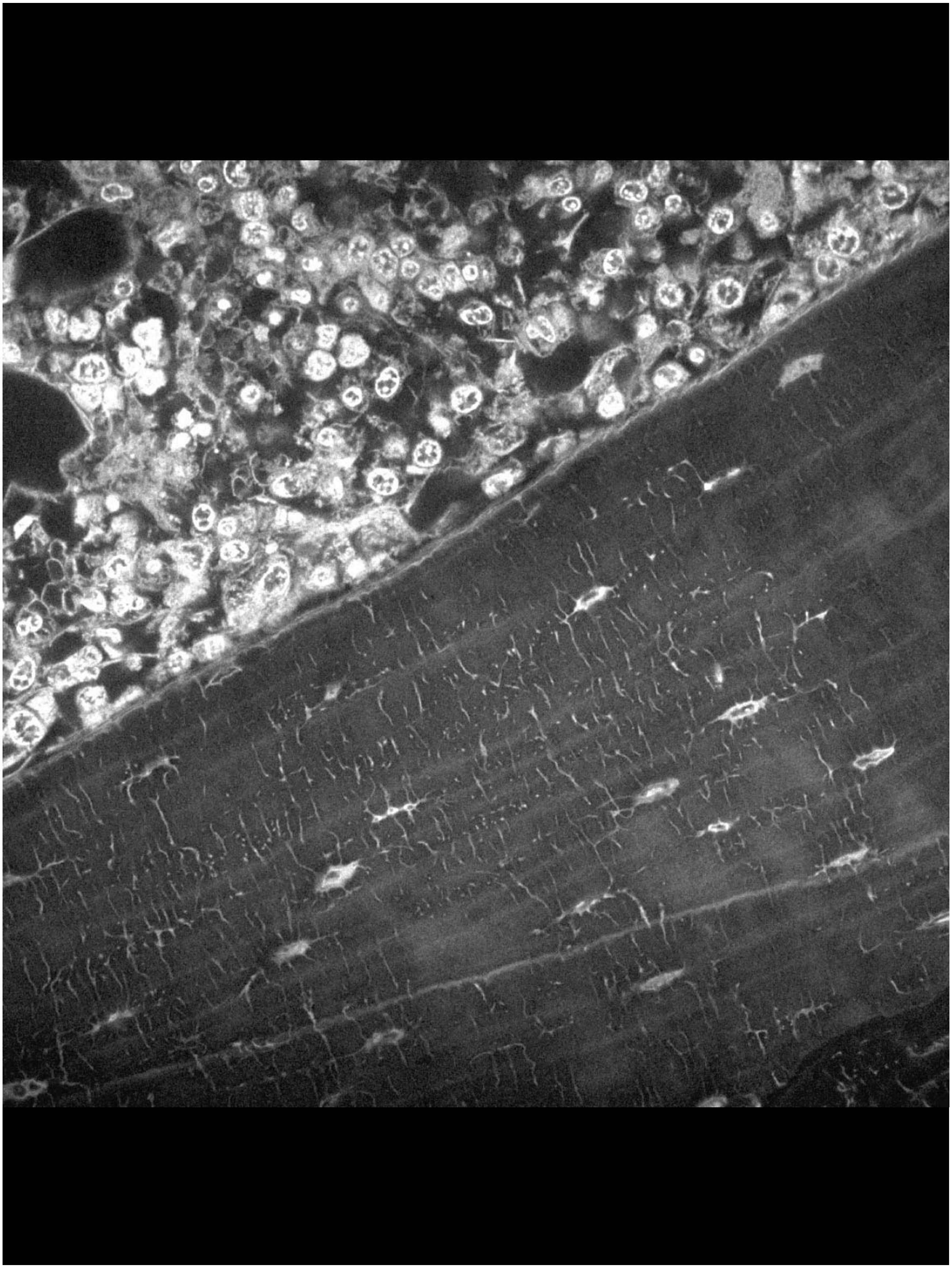




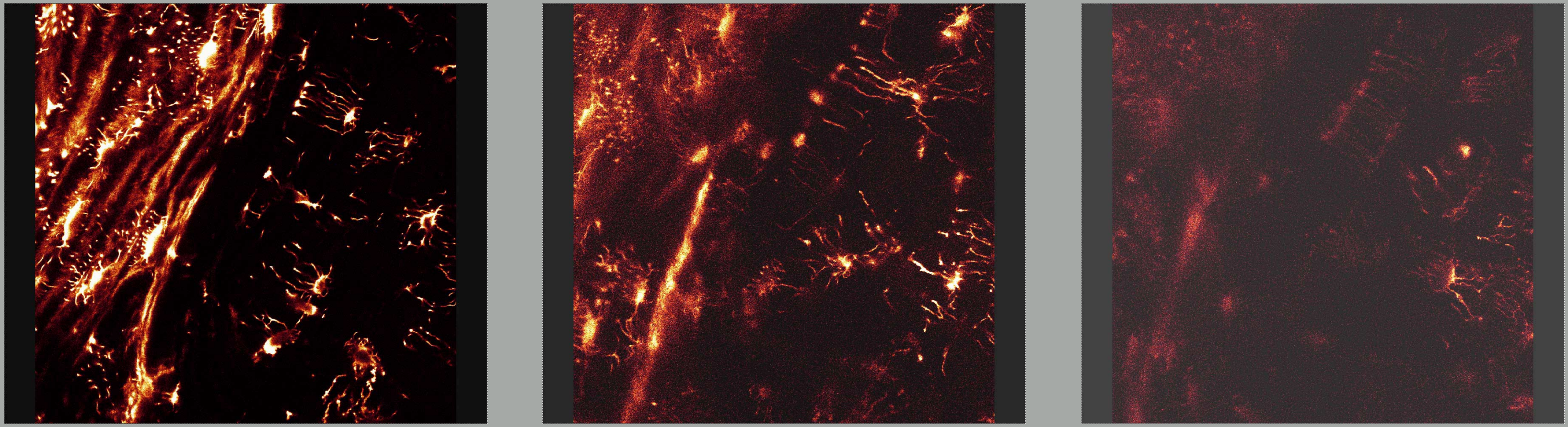




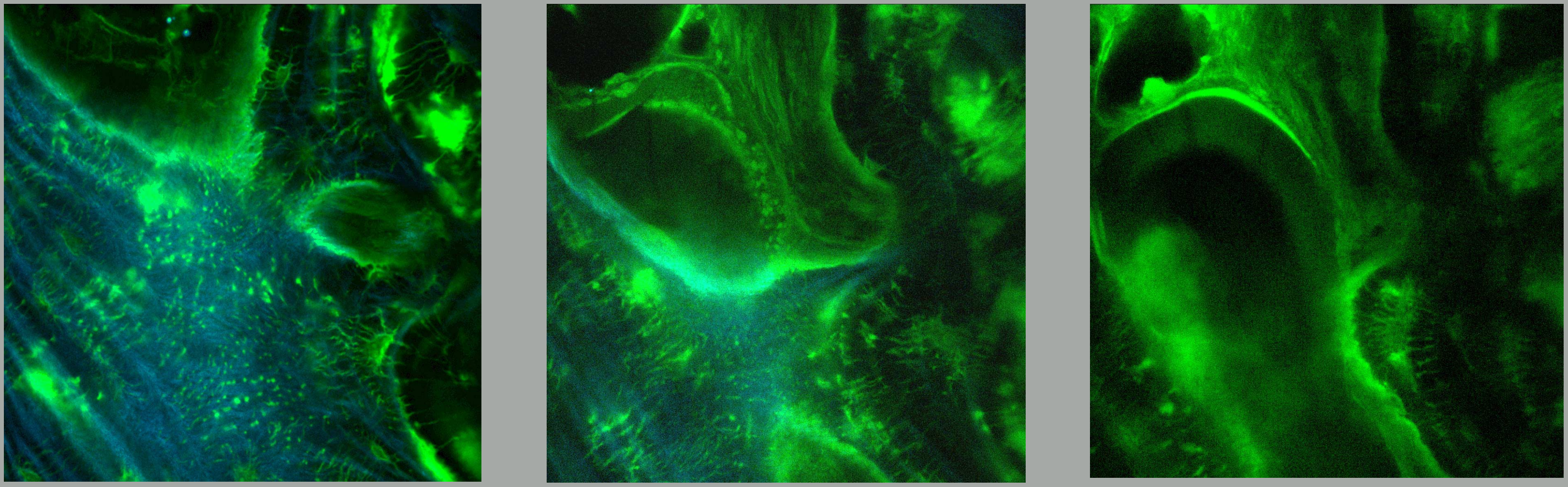




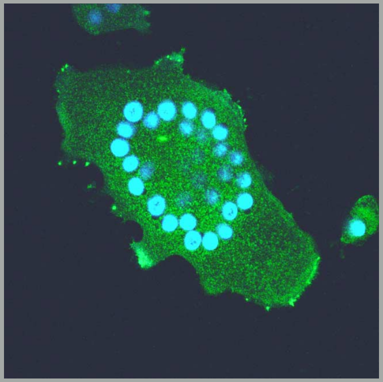
Confocal (top, 568 nm) versus Two-photon (bottom, 910 nm)



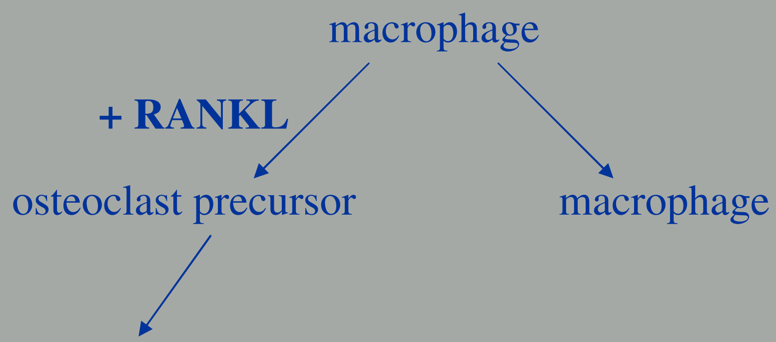
20 micron depth 50 micron depth 70 micron depth



Cortical bone (femur)



Producing osteoclasts in-vitro:



macrophage

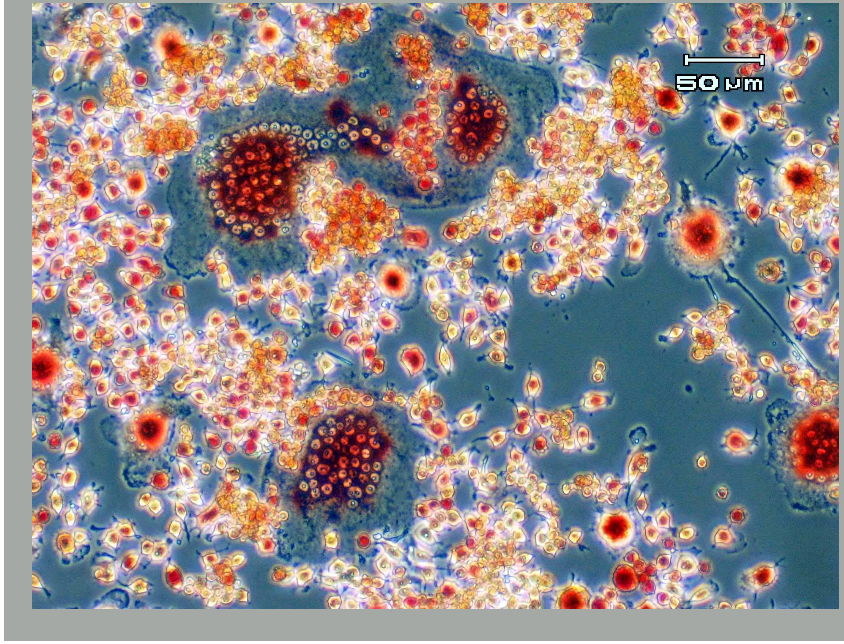
+ RANKL

osteoclast precursor

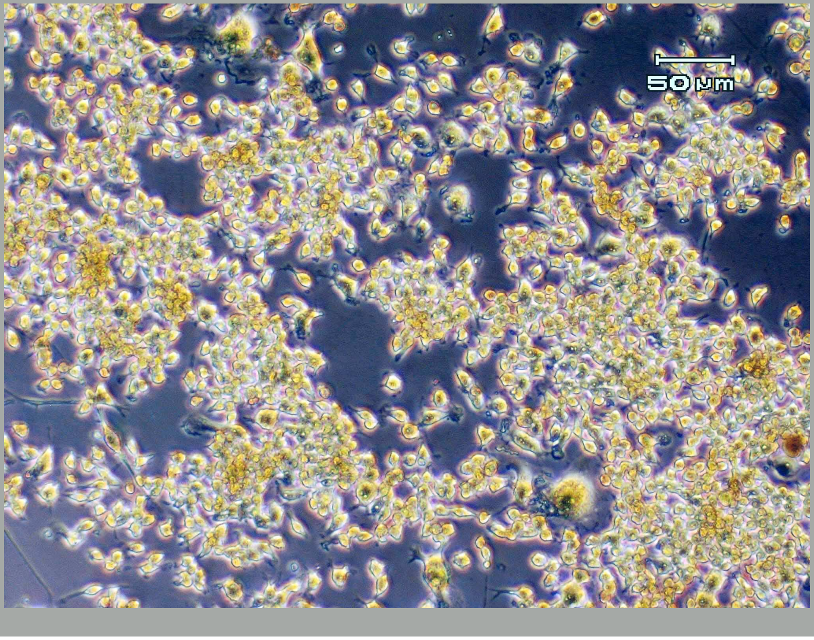
macrophage

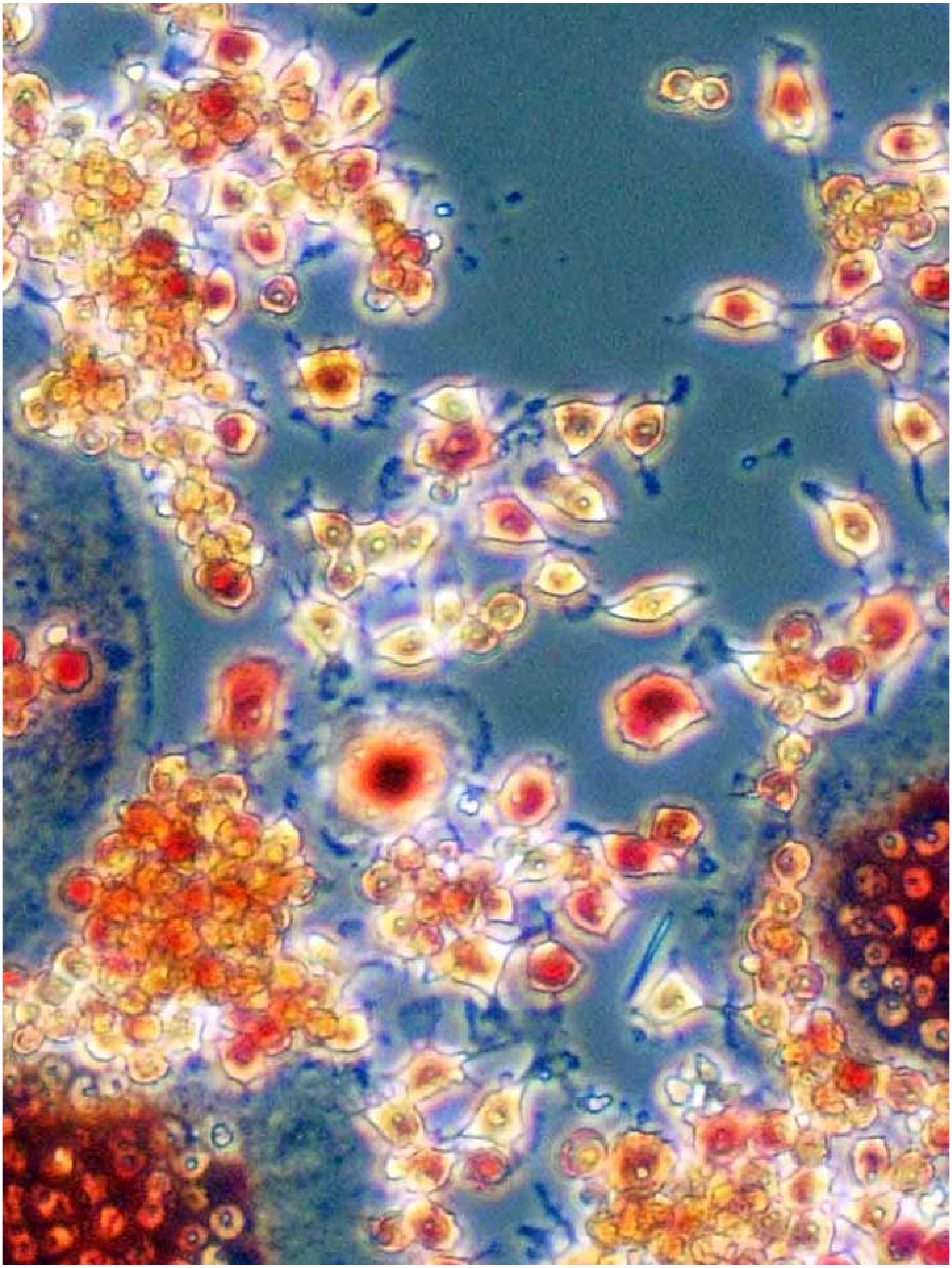
multinucleated osteoclast

TRAP+



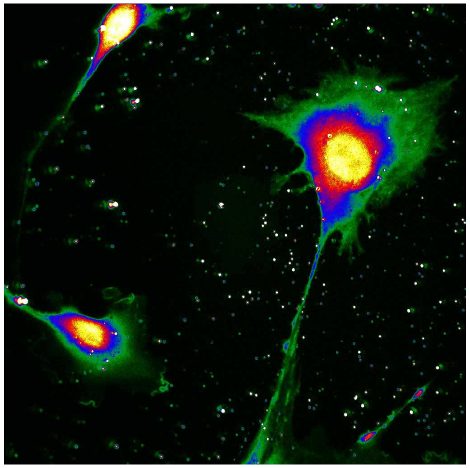
TRAP- **(no RANKL treatment)**





Fluorescence Lifetime Imaging Microscopy (FLIM)

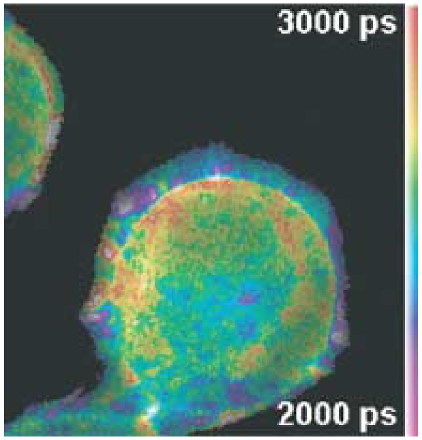
- Presently adding FLIM capability to the microscope



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 $\tau = \dfrac{1}{\Gamma + k}$

Γ, 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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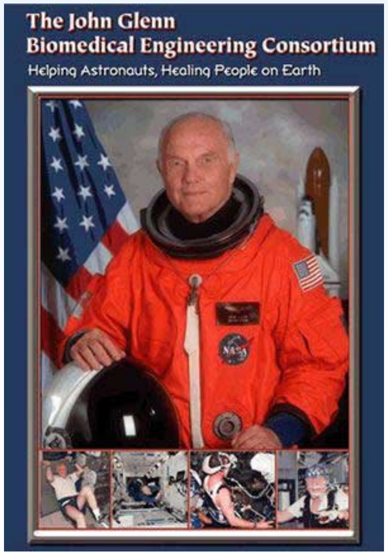
NASA John Glenn Biomedical
Engineering Consortium

… for financial support!



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