Microgravity Influence on Physical Systems:

Fluid Physics

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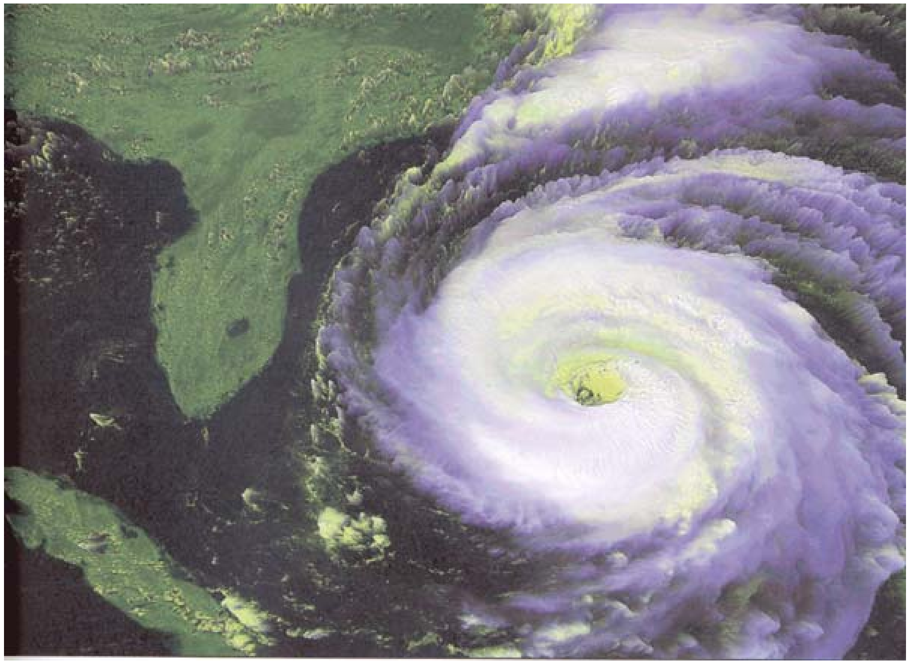

- Fluid physics is the study of the motions of liquids and gases and the associated transport of mass, momentum and energy.
- Studies arise from nature...
  - meteorology
  - oceanography
  - living plants & animals
- and technology.
  - biological
  - chemical/petroleum
  - materials processing
  - mechanical/fluid systems

- The need for a better understanding of fluid phenomena has created a vigorous, multidisciplinary research community whose continuing vitality has been marked by the continuous emergence of new fields of relevance in both basic and applied science.
- Areas of technological and ecological importance such as global atmospheric change, groundwater pollution, oil production, and advanced materials manufacturing often rely for their progress on advances in fluid physics.

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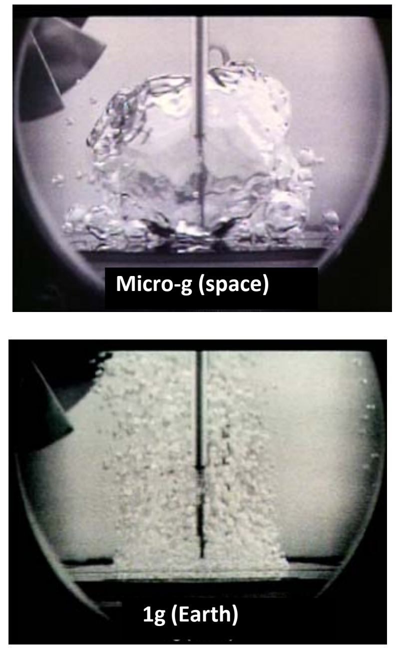

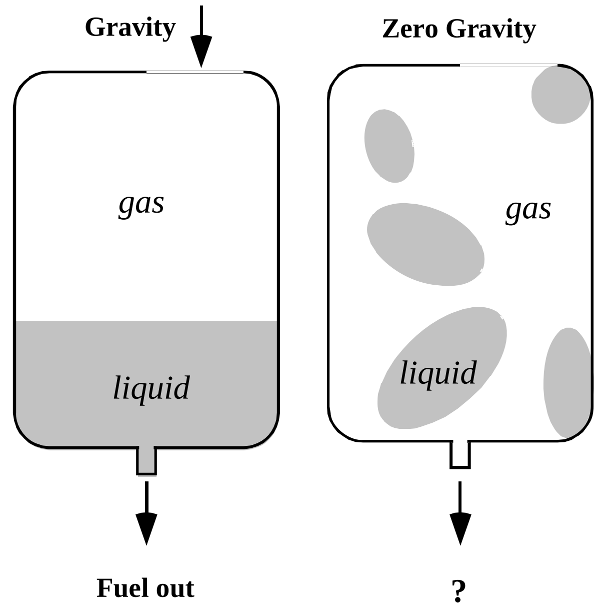

- The near elimination of buoyancy and sedimentation within inhomogeneous fluids in the low-gravity environment provided by the International Space Station (ISS) allows scientists to study the behavior of a whole range of fluids under near weightlessness.

- Processes that involve these kinds of fluids are important in many Earth-bound industrial settings, but they also play key roles in the design and operation of many spacecraft systems crucial to the success of human and robotic exploration and exploitation of Space.

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"Many say exploration is part of our destiny, but it's actually our duty to future generations and their quest to ensure the survival of the human species."

- Buzz Aldrin, July 2006

- **One of NASA's primary motives for conducting low-gravity research is to acquire technology-enabling knowledge for Space-based processes and vehicle systems.**
    - **Efficient heat transfer systems (typically involving phase change)**
    - **Life Support systems (two-phase)**
    - **Chemical & Biological Reactors**
    - **Transfer and storage of fluids (cryogen fluids, potable water, etc.)**
    - **Gas-Liquid Separation Systems**

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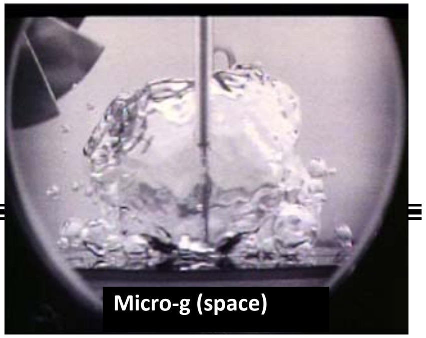

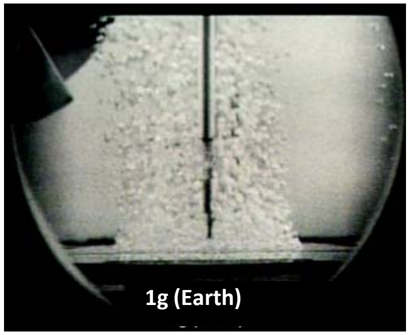

Boiling/Condensation (heat transfer)

- Heat transfer problems in 0-g must consider the combined effects of the lack of buoyancy driven convection (within a single phase) as well as the lack of buoyancy forces between phases.
- Examples include heat pipes (CVB), Pool and Flow Boiling (BXF), and Condensation (FPCE).
- Devices in the next generation of space systems are projected to dissipate heat fluxes that far exceed the capabilities of today's cutting-edge thermal management schemes.
- Critical Heat Flux (CHF) is the most important thermal design parameter for boiling systems involving both heat-flux-controlled devices and intense heat removal. Exceeding CHF can lead to permanent damage, including physical burnout, of the heat-dissipating device.

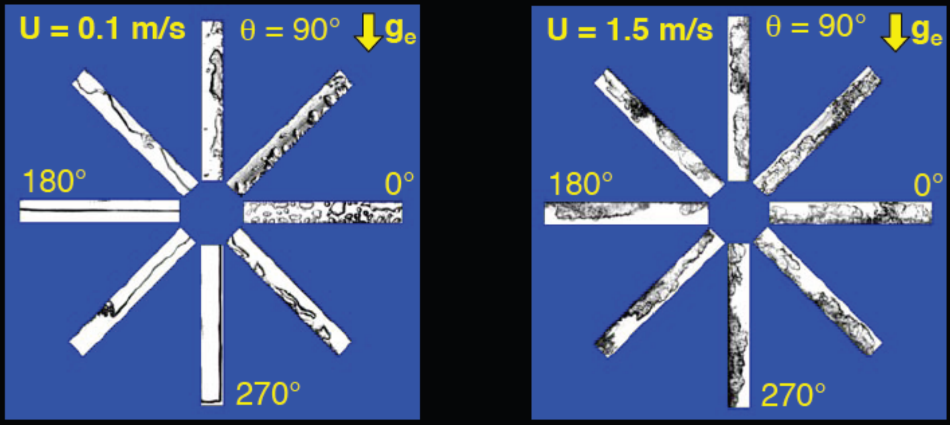

FIG. 6 Vapor behavior just prior to CHF for different orientation at (a) U = 0.1 m/s and (b) U = 1.5 m/s (Zhang, Mudawar and Hasan, 2002).

Boiling and Two-Phase Flow Laboratory *Purdue University*

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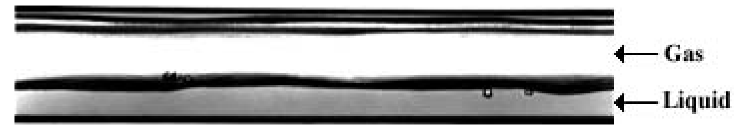
Gas-liquid phase distribution (no heat transfer)

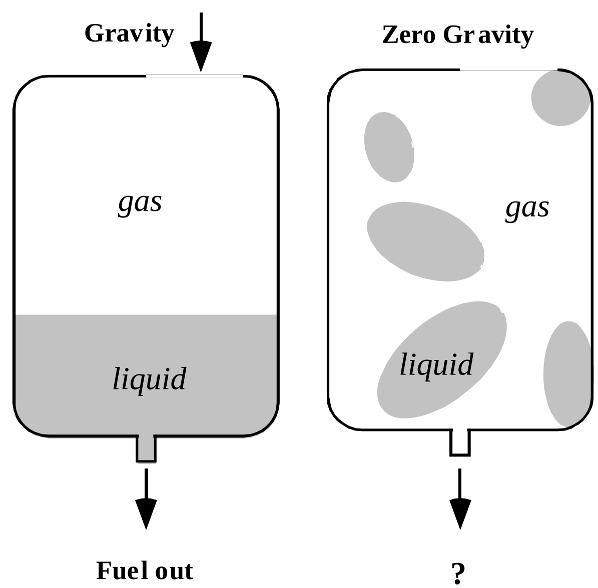
- "Multiphase" flows are commonly found aboard spacecraft in both propulsion and life-support systems
- On Earth the two phases often stratify with the more dense liquid underlying the less dense gas. In the absence of gravity, the fluids become more intermingled, forming a core-annular flow.
- Another example is low mass liquid-management systems under isothermal conditions (partially filled fuel tank). If situated on Earth and gravity is vertical, fuel can be removed from below. If gravity is absent, the body of fuel might no longer be adjacent to the exit or even constitute a contiguous mass.



Horizontal pipe on Earth.

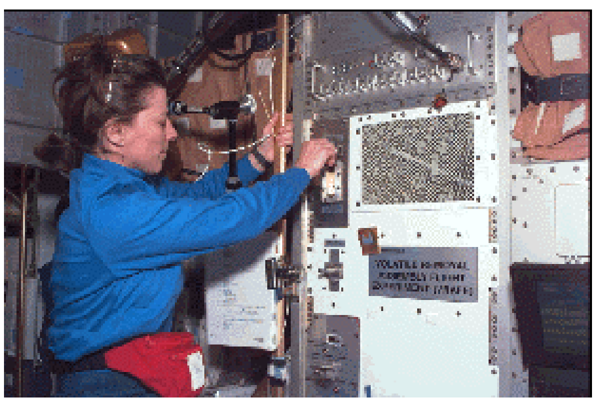
Aboard the Space Shuttle.

The radically different flow morphologies require different theoretical models in order to be able to predict these flows.

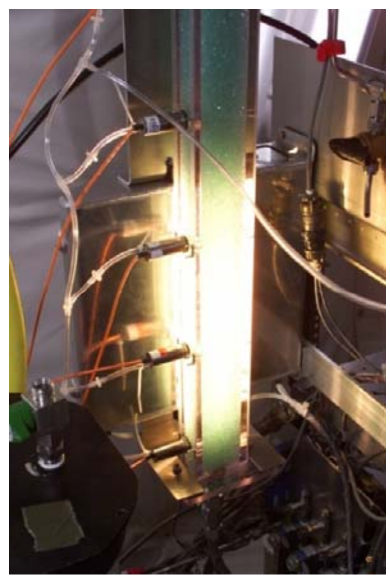


Multiphase Reactors (chemical and biological)

- **Advantages of porous media components include higher throughputs, compact design, operational flexibility and minimal power consumption.**
- **Porous media are critical components in life support systems; thermal control devices; fuel cells; and biological and chemical reactors.**
- **Start up (transients)**
- **Effects of wetting & non-wetting packing material)**
- **Pressure drop**
- **Liquid holdup**



Volatile Reactor Assembly (VRA) on STS 89

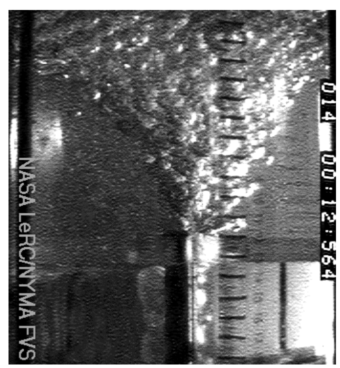


Packed Bed test in low-g Aircraft

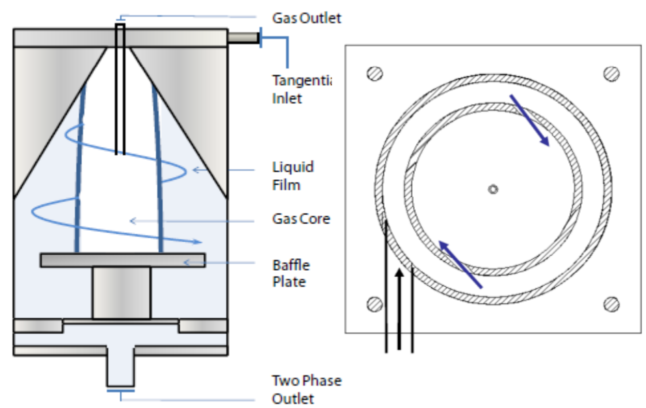
Biological Reactors →

Gas-liquid Separation Devices

- **Gas-liquid separators are targeted for use in Active Thermal Control Systems (ATCS) and Advanced Life Support (ALS) applications**
- **Prevent degraded performance or shortened life for components that accept a single phase input, i.e., centrifugal pumps and compressors.**
- **Promote enhanced phase change by removing second phase and to promote contact with heat transfer surface.**



Reduced Gravity Bubble Vortex



Cyclonic Concepts

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- Equally important is the use of ISS and other microgravity platforms as a test bed for the improvement of life on the planet and the advancement of science. We will require continuing advances in fundamental and applied fluid physics.
  - Interfacial or Capillary Phenomena
  - Coalescence and Aggregation
  - Granular Flows
  - Electrostatics of Granular Materials
  - Colloids
  - Non-Newtonian Fluids

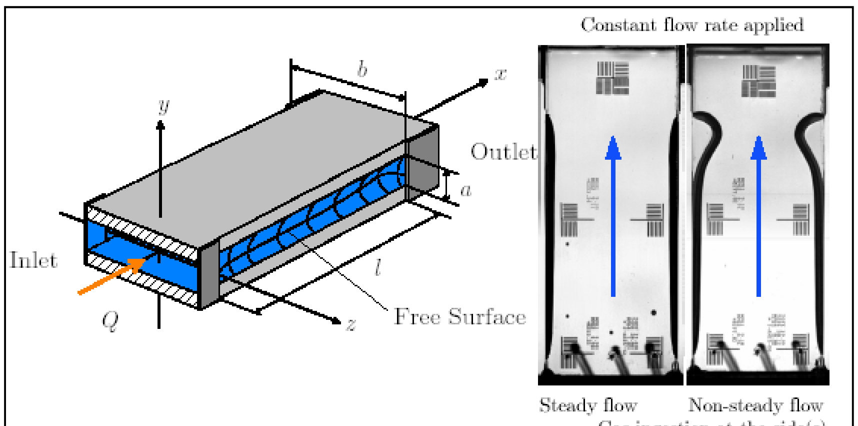
"When the influence of gravity on fluid behavior is diminished or removed, other forces, otherwise of small significance, can assume paramount roles."

- NRC Report to NASA, 2003

Interfacial or Capillary Phenomena

- **Cross-cutting and of interest to NASA in the management of liquids in 0-g environments, but also pertains to problems encountered in terrestrial environments.**
- **The dynamics of moving contact lines is an important but poorly understood aspect of wetting and is critical to thin films, coating flows, and drying process.**
- **Current work looks at new geometries to provide a more fundamental understanding of capillary effects in porous media, such as heat pipe wicks and water uptake in soils.**

Astronaut Jeffrey Williams performs one of multiple tests of the Capillary Flow Experiment Investigation



Example of a capillary channel
Liquid withdrawn at the outlet, liquid provided at the inlet

45° vane angle in microgravity.

45° vane angle in earth gravity.

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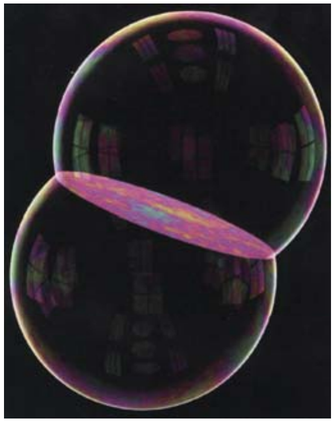
Coalescence and Aggregation



- **Phase separation is the act of isolating a solid, liquid or gas (or all three) from the liquid or gas in which it is (they are) dispersed, for example, separating an oil/water emulsion or the removal of bubbles or solid particles from a liquid.**

- **Numerous fluid/fluid phase-separation processes rely on coalescence or aggregation of dispersed phases to form continuous phases, e.g. droplet condensation, boiling, condensation, and foam drainage. Relative motions caused by gravity, thermocapillary (due to the temperature dependence of surface tension) and intermolecular forces all contribute to foam drainage and film rupture, which can be either advantageous or disadvantageous, depending on the application.**

- **In some cases, coalescence may be undesirable. New methods have recently been discovered for suppressing coalescence of liquid bodies and wetting of solid surfaces which have anticipated application both on Earth and in Space.**

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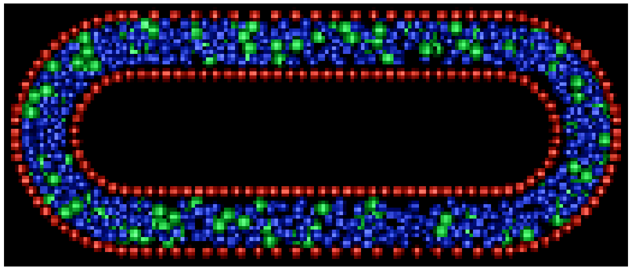
Granular Mechanics and Flows

- **Granular mechanics and flows arise in a wide range of Industries ($1 trillion/year) Pharmaceutical, Food, Chemical, Detergents, Agricultural, Metallurgy, Plastics, Cement, Mining, etc.**
- **They affect human life and the environment. From snow/mud avalanches, desertification (through aeolian dune transport), and earthquakes.**
- **Safer granular storage/transport (e. g. prevent silo explosions)**
- **Huge dollar savings potential through improved design and control of granular processes saves money through improved efficiency and environment-friendliness**
- **Experimentation in a reduced-gravity or microgravity environment could allow one to isolate and understand the forces of non-gravitational origin and to eliminate density-gradients associated with gravity.**

Potential Applications:

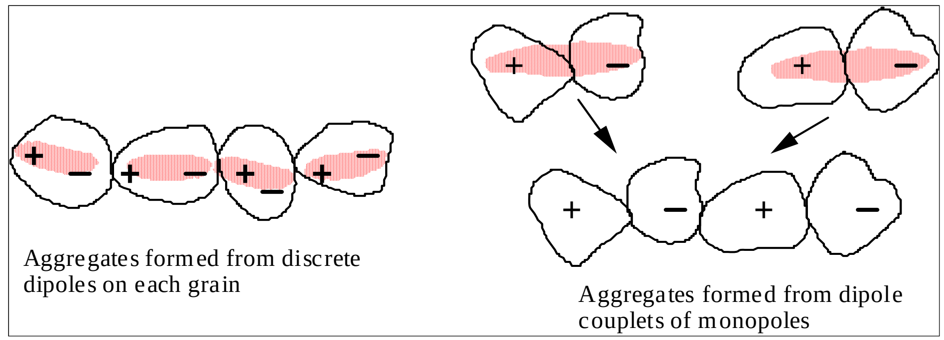
- Earthquake engineering
- Soil mechanics and foundation engineering
- Planetary vehicle engineering
- Powder technology
- Terrestrial and Planetary geology
- Mars exploration
- Erosion processes

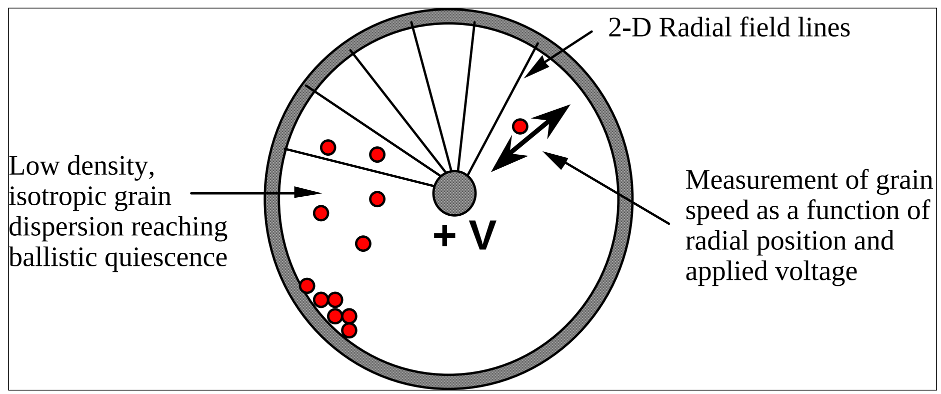


Study of granular particles size segregation driven by mechanisms other than gravity in a binary mixture (green/blue) of spheres

Electrostatics of Granular Materials

- **Gain insight into powerful electrostatic adhesion forces hypothesized to be caused by “always attractive” dipole attractions.**





Electrostatic manipulation of the grains in microgravity will expose the forces at work between particles

Potential Applications:

- Reduce dust contamination of space suits for use on the Moon or Mars
- Design more efficient dust filter systems
- Enhance dust removal in clean rooms
- Improve inkjet and laser printing processes
- Applying pesticides to agricultural crops
- Provide a fundamental understanding of the role of electrostatic forces that cause adhesion, cohesion in granular systems.

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Colloids

- By studying colloids in microgravity, you can:

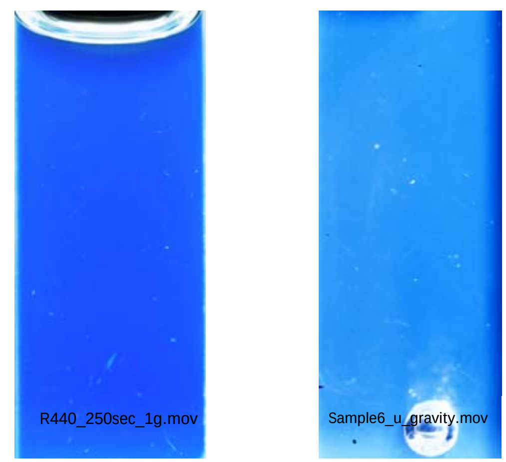
- Measure phase separation rates in microgravity to develop underlying theory for predicting product shelf-life (P & G). Collapse [irreversible separation] occurs on Earth and must be mitigated with expensive particle additives. The BCAT-6 experiment is looking at the effects of polydispersity on depletion attraction. (Matthew Lynch, P&G).

- See and control how structures form. Colloidal engineering is now possible. (David Weitz, Harvard).

- For the nano-revolution to come to fruition we need self-replication, that is, the ability to produce ~10^{12} structures from 1 model. For example, picture LOTS of little nano-pumps created by self-replication.

- The technology now exists to create lock-and-key reactions with the possibility of creating self-replicating non-biological structures from nanoscale building blocks using colloidal self-assembly. These studies lay the foundation for this process. (Paul Chaikin, NYU)

BCAT-5 colloid experiment presently on the International Space Station (ISS).



Movies of phase separation
Same sample on Earth and in space
David Weitz / Peter Lu (Harvard)

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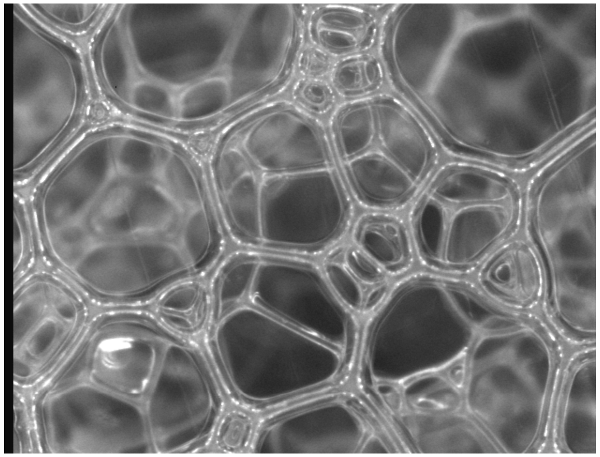
Non-Newtonian Fluids

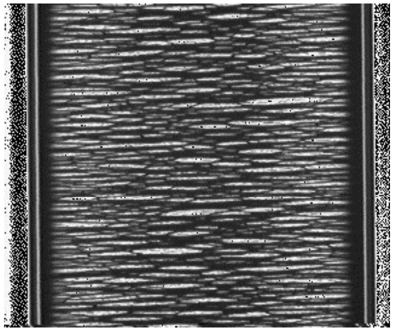
e.g. Foams

- **Foam products comprise a multibillion-dollar industry.**
- **Benefits include improved consumer products and new lightweight materials.**
- **We rely on foam products for safety (fire extinguishers) and comfort (seat cushions, shaving cream, etc.)**
- **Water-based foams are an exciting example of *complex fluids*; they share properties of solids, liquids, and gases... all-in-one!**



e.g., Magnetorheological Fluids

- **MR fluids are a class of smart materials capable of changing visco-elastic properties. Microgravity data of the internal particle structure and dynamics will provide an assessment of the viscous-elastic properties of these fluids. The results may improve limb and dextrous motion in robotic components and human-robotic interfaces for EVA suits.**



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Mapping to NRC Reports

FIGURES ES.1, ES.2, and ES.3:

Only subjects already considered by the committee to be of high priority in at least one discipline are included in this analysis, and therefore the magnitude scale ranges only from important to very important (or critical). A subject may not have a high impact in every category and therefore may not appear in every figure. Numbers inside the same circle should be considered to occupy approximately the same position in the figure. The numbers in the figures represent the research topics as follows:

1. Multiphase flow and heat transfer;
2. Complex fluids: (a) self-assembly and crystallization, (b) complex fluid rheologies;
3. Interfacial processes: (a) wetting and spreading, (b) capillary-driven flows and equilibria, (c) coalescence and aggregation (liquid phase);
4. Biofluid dynamics: (a) cellular biotechnology, (b) physiological flows;
5. Turbulent combustion;
6. Chemical kinetics;
7. Soot and radiation;
8. Smoldering combustion;
9. Development of computer simulations of fire dynamics on spacecraft;
10. Oxygen systems fire safety;
11. Ignition, flame spread, and screening techniques for engineering materials;
12. Antimatter search/measurements;
13. Elemental composition survey;
14. Complete the current set of fundamental physics ISS experiments: (a) low-temperature experiments, (b) relativity and precision clock experiments, (c) other NASA clock application experiments;
15. Nucleation process within, and the properties of, undercooled liquids;
16. Dynamics of microstructural development during solidification;
17. Morphological evolution of multiphase systems;
18. Computational materials science;
19. Collection of thermophysical data of liquid state in microgravity.

NRC Report "Assessment of Directions in Microgravity and Physical Sciences Research at NASA", report released 2003

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8 *ASSESSMENT OF DIRECTIONS IN MICROGRAVITY AND PHYSICAL SCIENCES RESEARCH AT NASA*

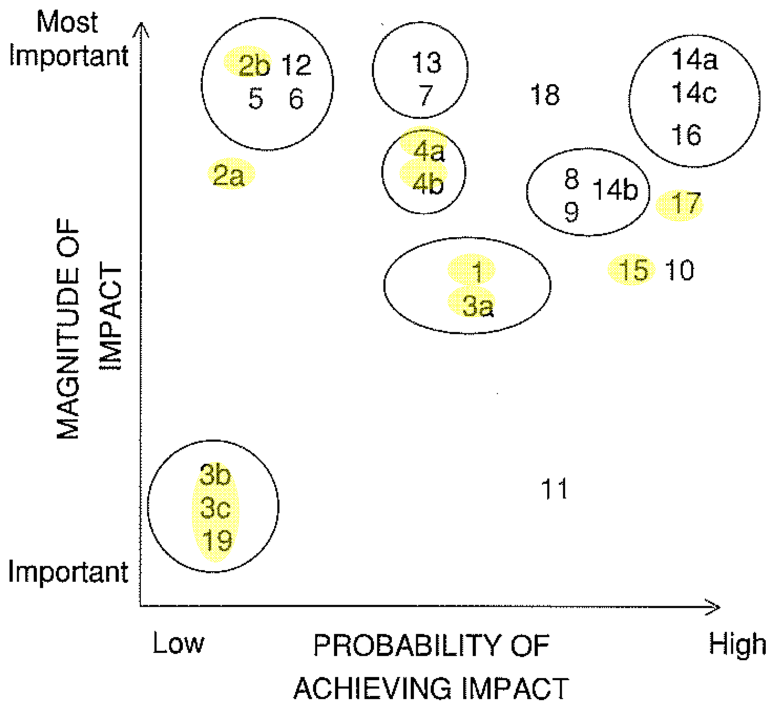

FIGURE ES.1 Assessment of research topics in terms of their likely impact on scientific knowledge and understanding.

NRC Report "Assessment of Directions in Microgravity and Physical Sciences Research at NASA", report released 2003

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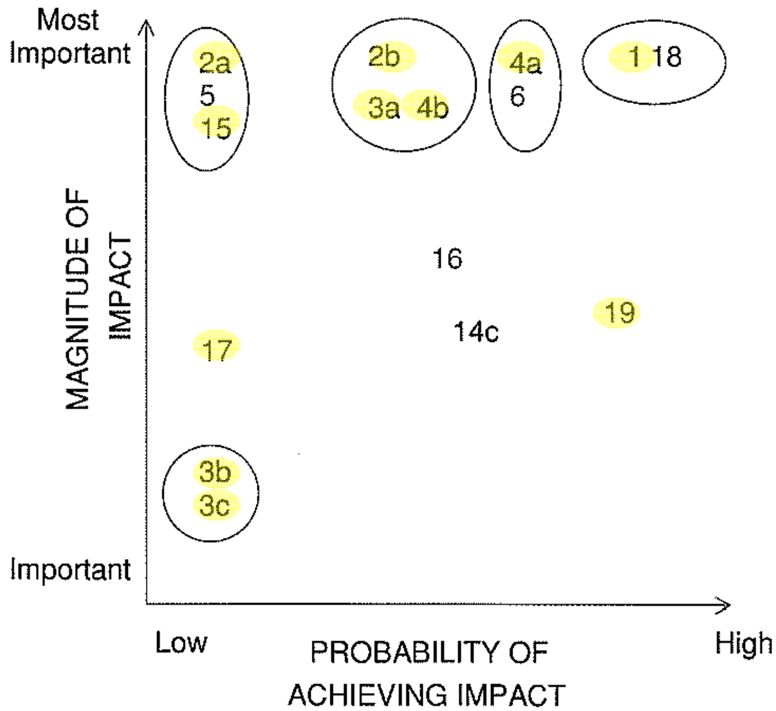

FIGURE ES.2 Assessment of research topics in terms of their likely impact on terrestrial applications such as industry's technology needs.

NRC Report "Assessment of Directions in Microgravity and Physical Sciences Research at NASA", report released 2003

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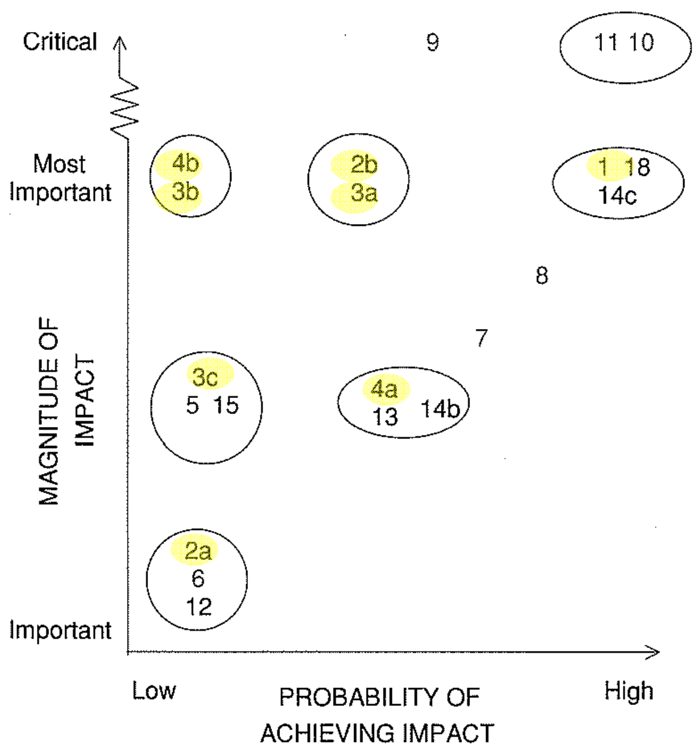

FIGURE ES.3 Assessment of research topics in terms of their likely impact on NASA's technology needs.

NRC Report "Assessment of Directions in Microgravity and Physical Sciences Research at NASA", report released 2003

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Gravity masks the effects of many important fluid flow phenomena.

There are many areas that can provide new and important insights via experiments on the ISS.

Gravitationally induced convection or sedimentation make it very difficult to study the physics that underlie processes common on earth.