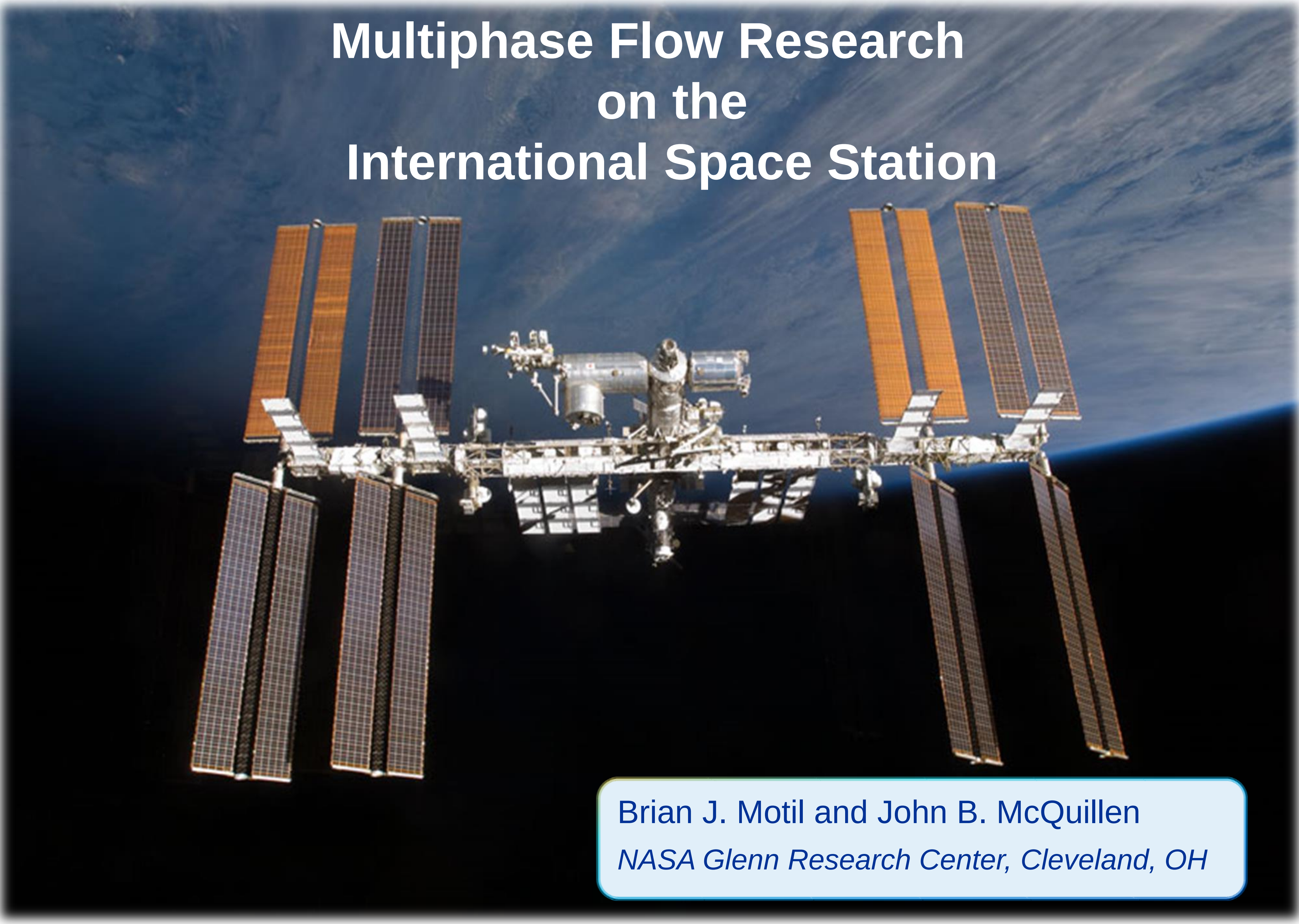
Multiphase Flow Research on the International Space Station



Brian J. Motil and John B. McQuillen

NASA Glenn Research Center, Cleveland, OH

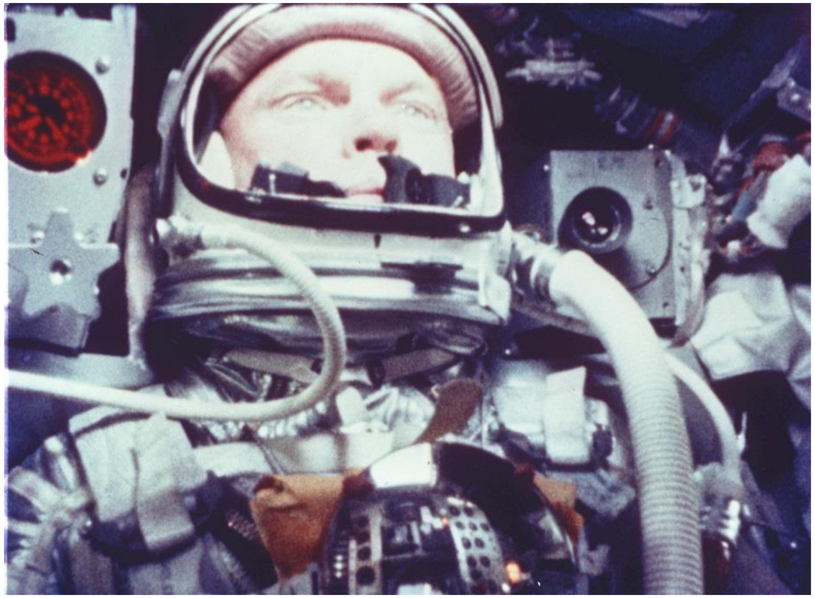
LeRC Developed the First Microgravity Fluid Physics Flight Experiment, on Mercury–Atlas–7 (MA-07)

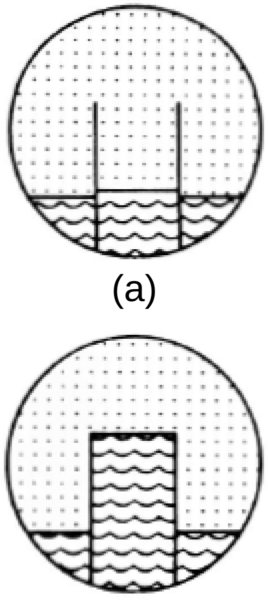
May 24, 1962

Cylindrical baffle in a spherical tank geometry

Experiment H/W Tank: 3.3 in. dia (glass)
Baffle: 1.1 in. dia, 1.9 in. length
Test fluid: distilled water w/ dye, ethyl alcohol

MA-07 commander, Scott Carpenter

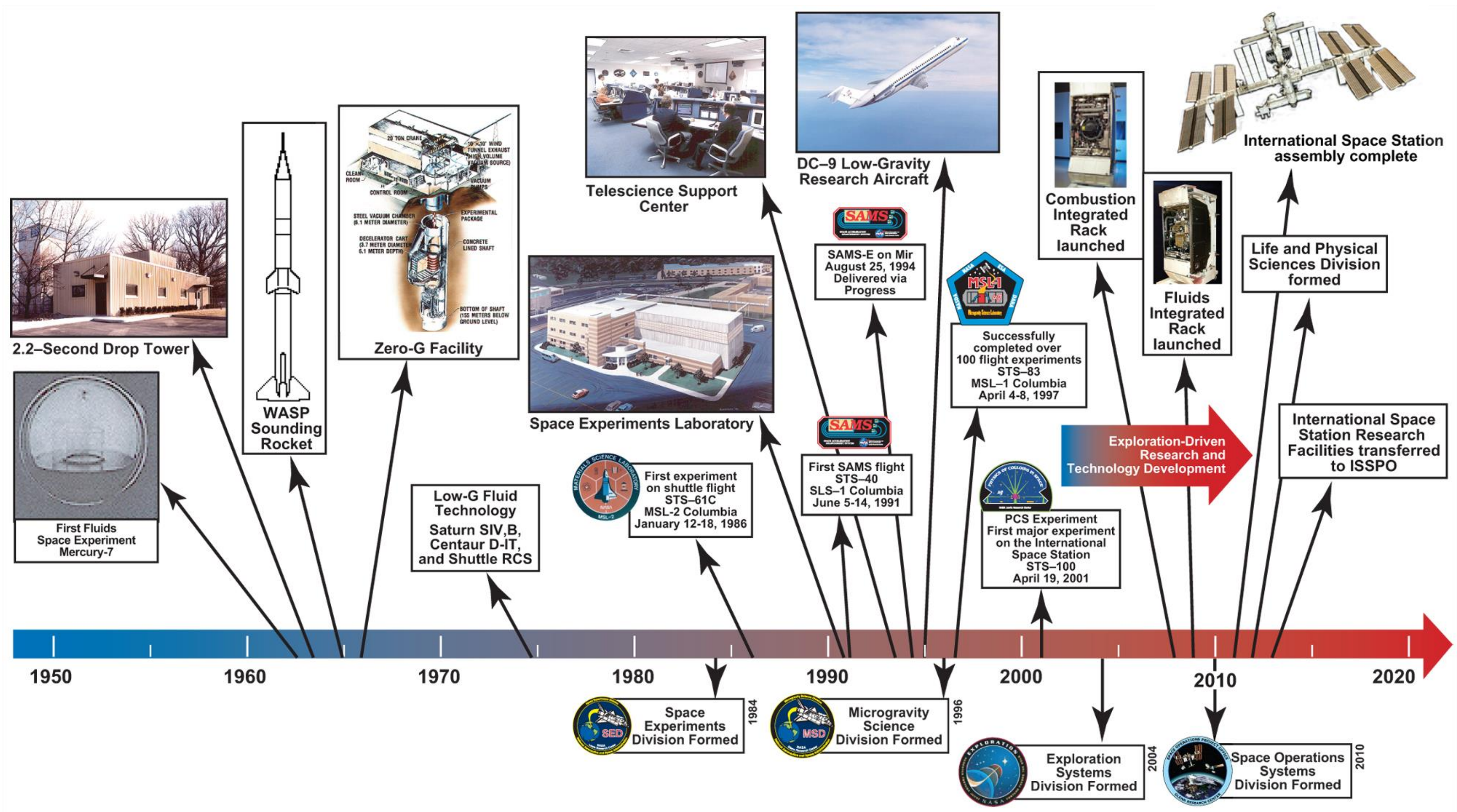




Fluid configuration in spherical tank
a) during a retrofire
b) equilibrium condition in zero g.

Lewis Research Center's Experiment Principal Investigators:
D. Petrash, R. Nussle, and E. Otto

Glenn Research Center's Role in Gravity-Dependent Research in Space



Fluid Physics and Complex Fluids Today

Fluid Physics

- Two-phase flow
- Phase separation
- Boiling, condensation
- Capillary and interfacial phenomena

Complex Fluids

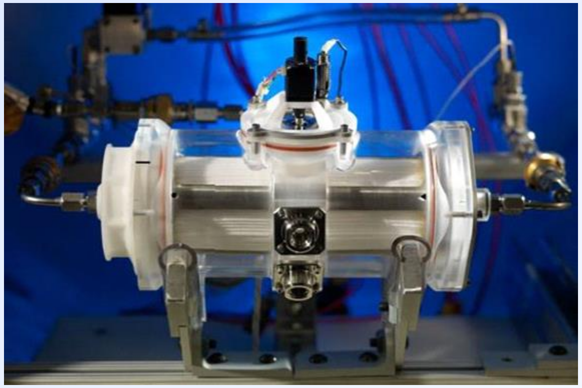
- Colloids
- Liquid crystals
- Foams
- Granular flows

Guiding ISS Research

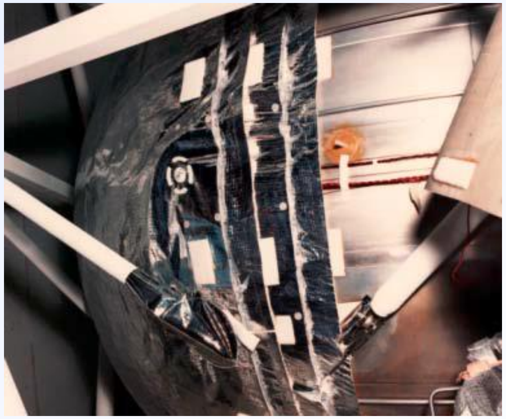
- External teams (FluidsLAB) were formed in 2014 to focus on near-term/ISS research, giving special consideration (when possible) to using existing hardware with minor modifications.
- The overarching goal in fluids should be to develop a sufficient database for future spacecraft designers such that they can select the optimum fluid system in the relevant environment (partial or 0-g).
- Database will establish the basis (closure laws) for CFD models.
- Models/design guidelines then become the basis for AES/STMD led technology development.

"Calculations of gas-liquid flows on earth are not done using "exact" equations but rely rather heavily on empirical models. Hence, prediction of behavior in space is not a matter of turning off the gravity term in the calculations."

ECLSS Water Recovery Rack



Spacesuit Water Membrane Evaporator (SWME)



Cryogen Tank

FluidsLAB Priorities

Multiphase Systems

Without heat transfer

With heat transfer

Adiabatic Two-Phase Flows

#1: Flow Regimes
#2: Instability Phenomena
#3: Bubble and Droplet Dynamics

Capillary Flow and Interfacial Phen.

#1: Multi-User, Multi-Geometry Capillary Science and Technology Facility
#2: Imperfect Wetting Phenomena – Science and Applications
#3: Global Equilibrium in Non-Symmetric/Symmetric Geometries for Liquid Management

Boiling and Condensation

#1: Flow Boiling – Critical Heat Flux and Flow Instabilities.
#2: Flow Condensation in Channels.
#3: Microgravity Issues Relevant to Two Phase Systems

Cryogenic Storage and Handling

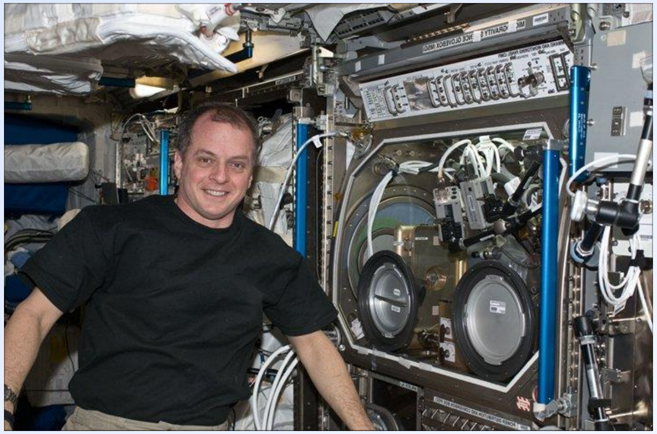
#1: Large scale cryogen storage tank demo.
#2: Active Tank Pressure control & Noncondensable Effects.
#3: Boiling, Turbulence, Impulse Accelerations, Tank Chilldown & Pressurant Injection
#4: Phase Management & Control

Separate reports (4) published in International Journal of Transport Phenomena - IJTP Volume 14, Number 2 (2015)

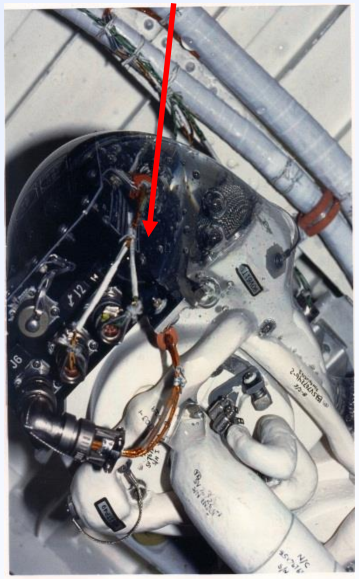
Adiabatic Two-Phase Flow - Applications

2011 Decadal: *"… multiphase systems and thermal transport processes are <u>enabling</u> for proposed human exploration by NASA."*

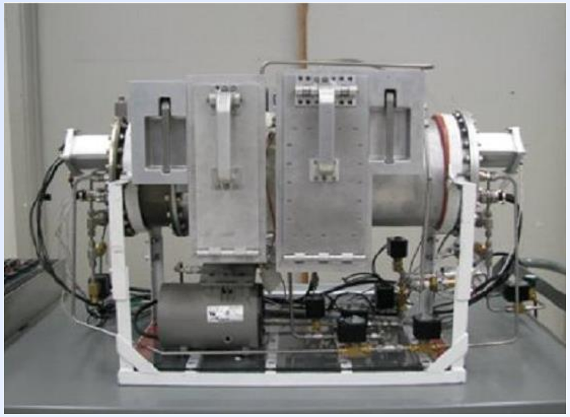
Temperature and Humidity Control for Advanced Plant Habitat



Astronaut T. J. Creamer in front of IVGEN experiment: In-Situ generation of IV-grade fluid



Clogged Rotary Separator on STS 32



Prototype For Heat Melt Compactor Which Squeezes Trash And Recovers Water

ISS Water Recovery System

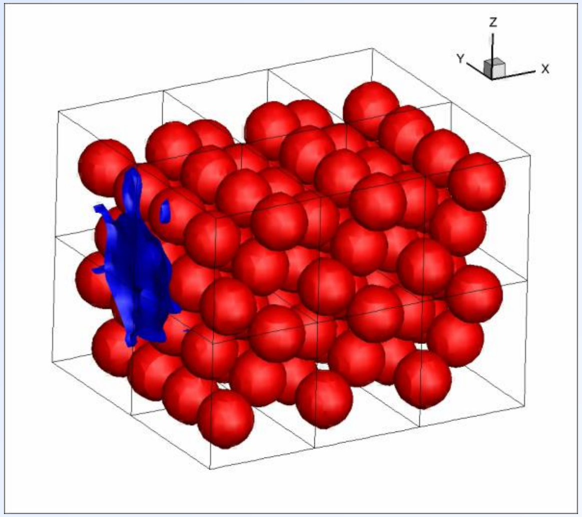
Extravehicular Mobility Unit (EMU) With Water in Helmet During Post-EVA 23 Screening Test

Adiabatic Two Phase Flow

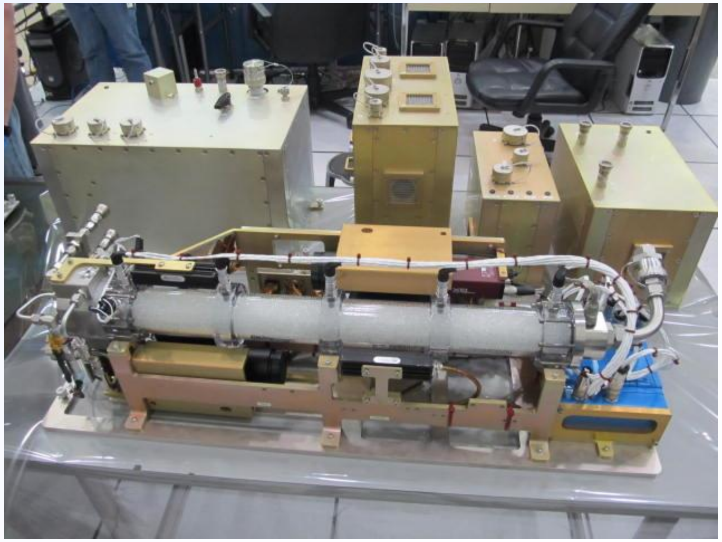
PI: Dr. Brian Motil, NASA GRC
Co-I: Prof. Vemuri Balakotaiah, U. of Houston

Packed Bed Reactor Experiment (PBRE) - 2016 (on-going)

- Investigating the role and effects of gravity on gas-liquid flow through porous media which is a critical component in life-support; thermal control devices; and fuel cells.
- Validate and improve design and operational guidelines for gas-liquid reactors in partial and microgravity conditions.
- Preliminary models predict significantly improved reaction rates in 0-g.
- Models developed from early 0-g aircraft tests led to the successful operation of **IntraVenous fluid GENeration (IVGEN)** in 2010 providing the ability to generate IV fluid from *in situ* resources on the ISS.
- Provides test fixture to test future two-phase flow components.



Pulse Flow CFD Model (Dr. Y. Lian)

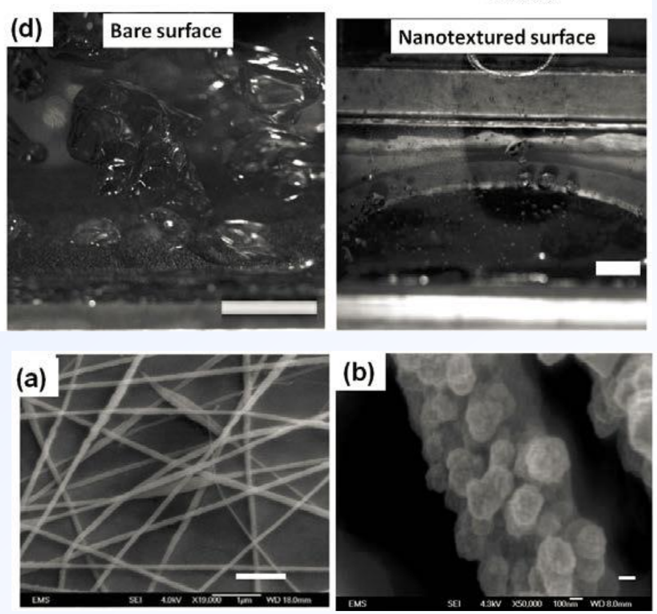

PBRE Flight Hardware

Adiabatic Two Phase Flow

US Co-I: Prof. Alexander Yarin, University of Chicago
ESA PI: Prof. Cameron Tropea, Institute of Fluid Mechanics and Aerodynamics (SLA) Technische Universität Darmstadt

Dynamics of Liquid Film/ Complex Wall Interaction (DOLFIN II) - 2019

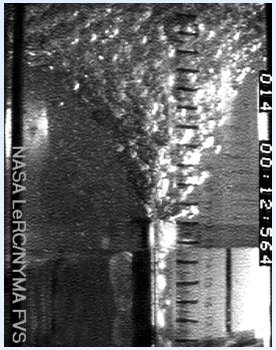
- ESA led experiment to develop continuum models to describe interactions between spreading fluids and chemically and/or morphologically complex surfaces in 0-g.
- Ability to manipulate surface flows in microgravity is a key to thermal management solutions in space exploration.
- US PI (Yarin) will perform experiments on spray cooling over specially patterned surfaces.
- Recently developed numerical model to detail physical mechanisms of pool-boiling.
- Boiling curves measured on nano-textured surfaces revealed heat fluxes 2-7 times higher than those on the bare surfaces, also increasing the CHF.
- Polymer nanofiber mats significantly increase heat transfer in pool boiling in channel flows (this part was conducted together with the group of the Technical University of Darmstadt, Germany).



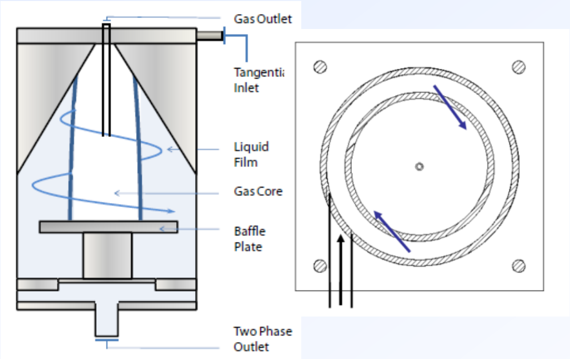
Nanofibers (a) are plated with copper (b) to form a mat that greatly alters nucleation patterns leading to much higher heat flux (d)

Gas-Liquid Separation Devices

Pumped Separator for PBRE



Reduced Gravity Bubble Vortex



Cyclonic Concepts

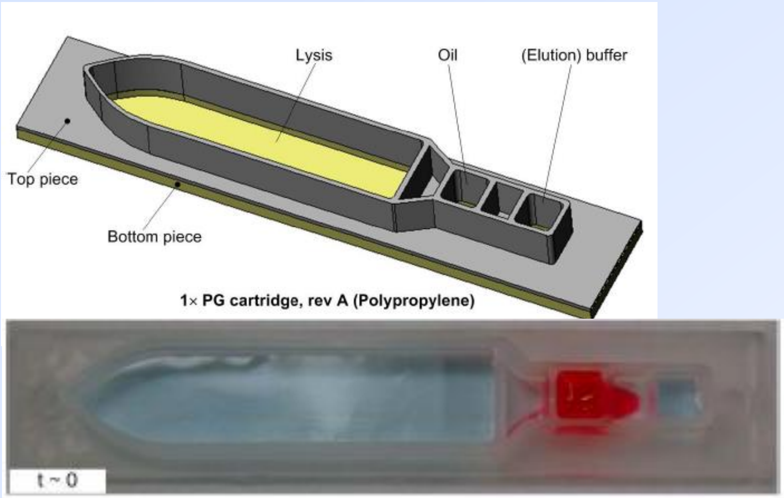
PI: Dr**.** Georges Chahine and Xiongjun Wu, DynaFlow, Inc.
PI: Prof**.** Yasuhiro Kamotani, Case Western Reserve University
Co-I: Prof. Jaikrishnan Kadambi, Case Western Reserve University

Two-Phase Flow Separator Experiment (TPFSE) – 2021

- Two PI Teams will share common test hardware to study different aspects.
- Experiments will determine separator performance at extreme gas/liquid mixtures and flow rates.
- Determine separator stability envelope to startup, shutdown and liquid slugging conditions.
- TPFSE facility can accommodate additional experimental test sections of future investigators.
- Advanced separation technology is critical to high reliability, audibly quiet, and low power gas-liquid systems for use in astronaut life support, fluid degassing, and power generation.

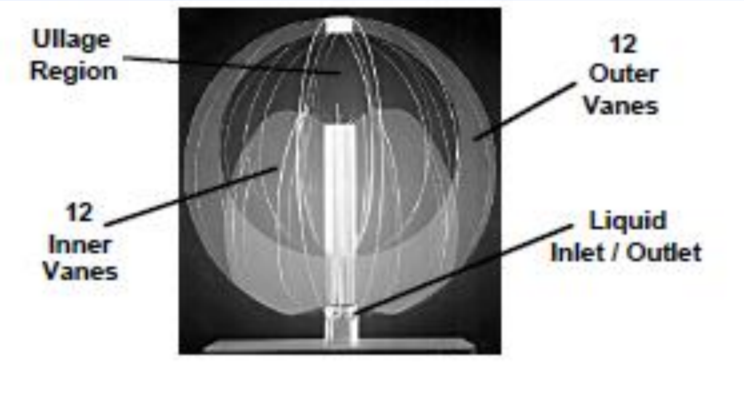
Capillary Flow and Interfacial Phenomena - Applications

When asked to name one of the biggest challenges to living in space, Astronaut Suni Williams replied that it is removing and dealing with bubbles in fluids systems.



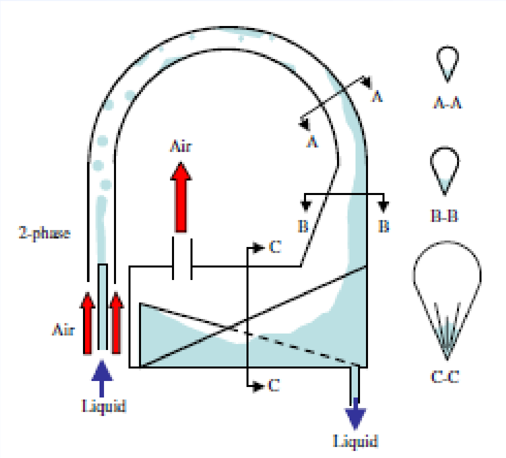
A fluid cartridge to detect infectious diseases developed through collaboration with NASA PI (CFE)

The evolution of the “coffee cup” designed for partially wetting teas and coffees in microgravity



Vented Tank Resupply Experiment (VTRE) Vane Type Propellant Management Device (PMD)

Chato, David, and Timothy Martin. “Vented Tank Resupply Experiment – Flight Test Results.” NASA Technical Memorandum 107498 (1997).



A diagram of the device for urine collection or other gas/liquid separations in low or zero gravity conditions

E.A. Thomas, M.M. Weislogel, D.M. Klaus, Design Considerations for Sustainable Spacecraft Water Management Systems, *Adv. Space Res.*, Vol. 46, pp. 761-767, 2010

Capillary and Interfacial Phenomena

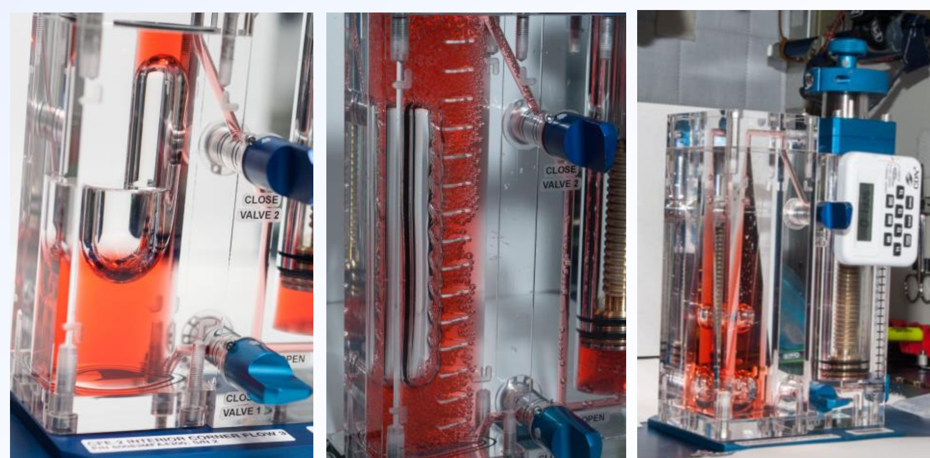
The Capillary Flow Experiment (CFE 1&2) -2004 - 2014

- Series of handheld vessels with various test chamber geometries to investigate the behavior of capillary flow phenomena in wicking structures such as interior corners and small gaps created by a vane and the test chamber wall.
- The working fluid is silicone oil of various viscosities, depending on the individual unit geometry.
- The results of CFE have applications in propellant management for fluid storage tanks, thermal control systems, and advanced life support systems for spacecraft.
- Critical wetting vane angles have been determined to within 0.5 degrees for Vane Gap 1 and 2 experiments.
- A bulk shift phenomena has been characterized that has implications for tank designs.

Astronaut Karen Nyberg adjusting the liquid volume during a CFE-2 Interior Corner Flow 9 (ICF9) experiment on ISS (June 15, 2013)

45°vane angle in earth gravity.

45°vane angle in microgravity.



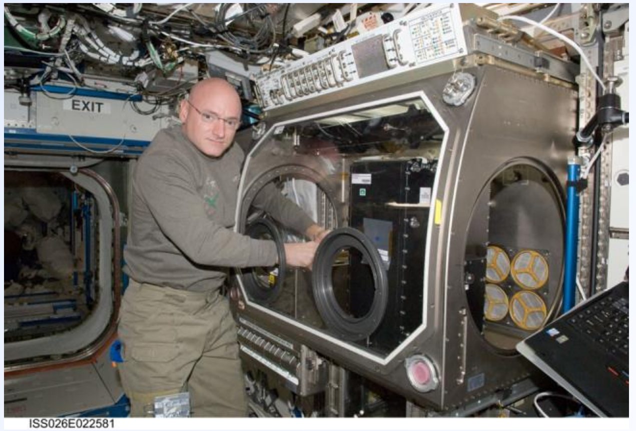
Interior Corner Flow Modules (ICF3, ICF 8 and ICF9)

PI: Prof. Mark Weislogel, Portland State University

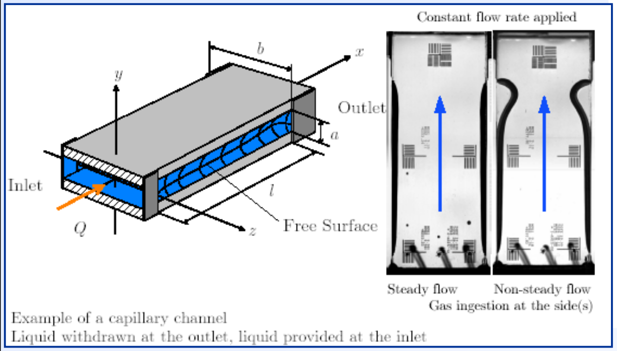
Capillary and Interfacial Phenomena

The Capillary Channel Flow (CCF) Experiment 2011–2014

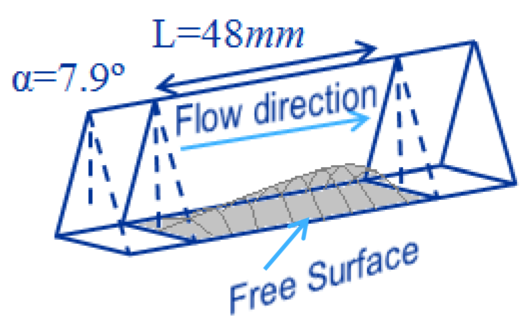
- Led by the German Space Agency (DLR) with a US/NASA Co-Investigator.
- Study of open channel capillary flow in microgravity.
  - The cross section of the flow path is partly confined by free surfaces.
- Experiment has led to high fidelity models that accurately predict maximum flow rates for an open capillary channel
- Research is critical to on-orbit fuel transfers and in space propulsion systems that utilize capillary vanes.
  - Current design of spacecraft fuel tanks rely on additional reservoirs (higher mass) to prevent the ingestion of gas into the engines during firing.



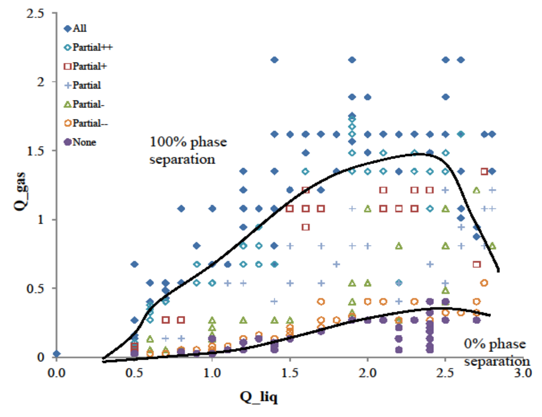
Astronaut Scott Kelly installing CCF in MSG in Dec 2010.



Capillary Channel Flow Test Unit 1 (flat plate and groove geometries)



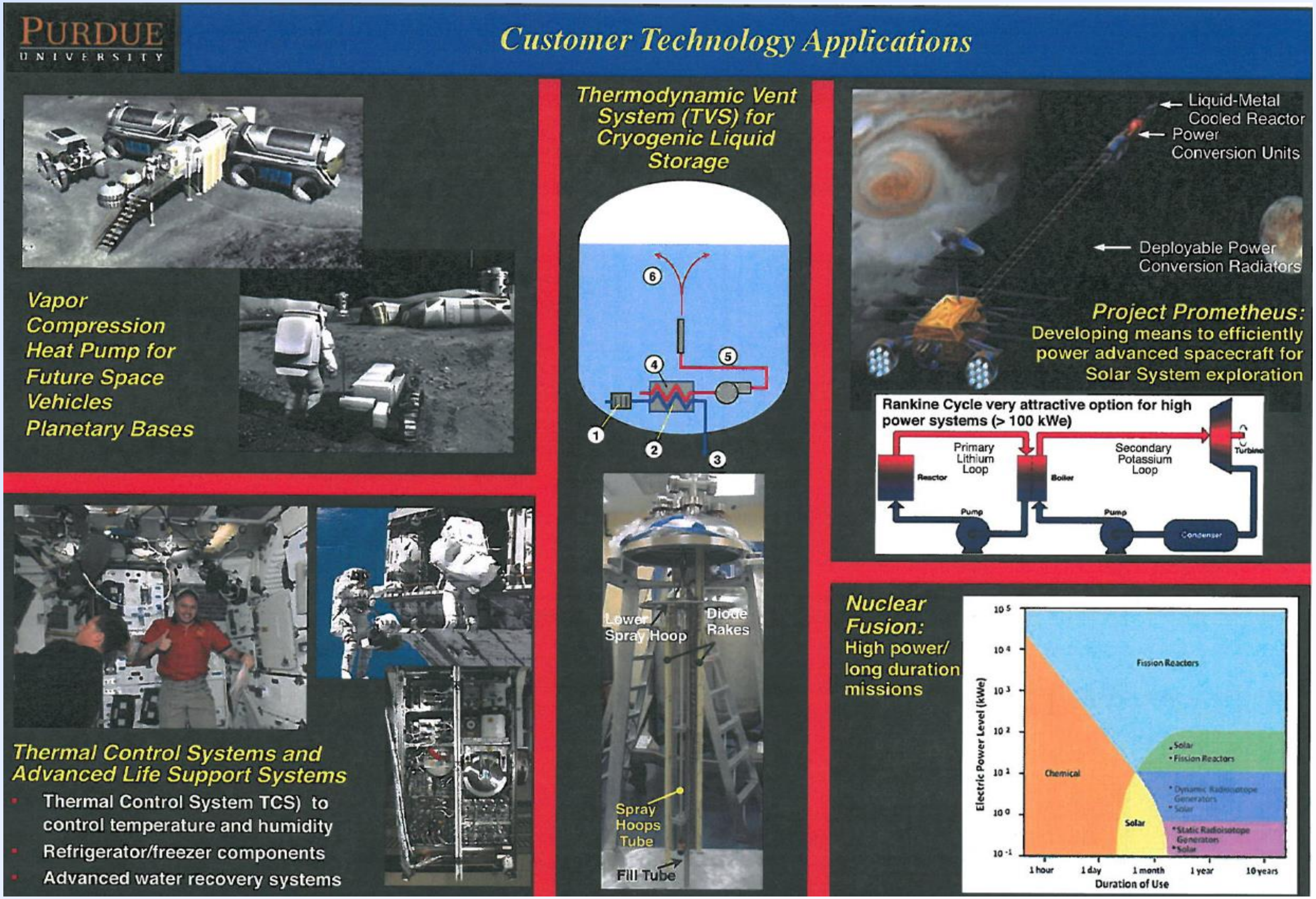
Capillary Channel Flow Test Unit 2 (interior corner (wedge) geometry)



Gas-Liquid Phase Separation Flow Regime Map

PI: Prof. Michael Dreyer, ZARM
US Co-I: Prof. Mark Weislogel, Portland State University

Boiling and Condensation - Applications

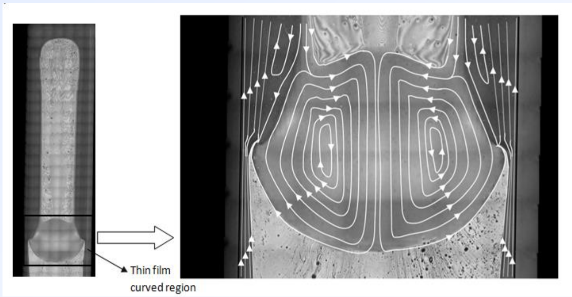


2011 Decadal: ***"Research literature, unfortunately, contains only very limited data on pool boiling in reduced gravity. Thus, <u>available correlations and models are unable to provide reliable data</u> on nucleate boiling and critical heat flux in reduced gravity."***

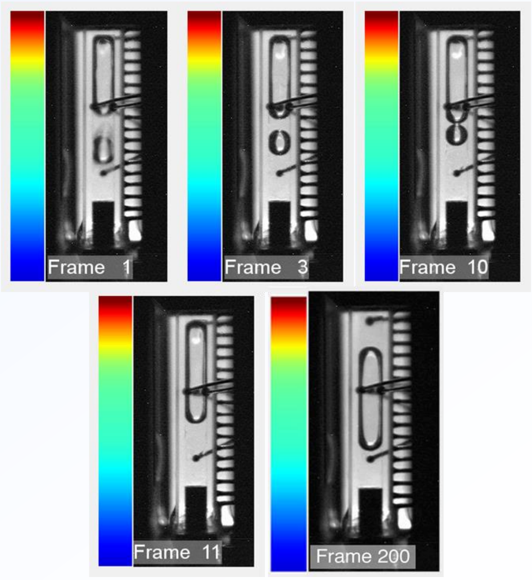
Boiling (Evaporation) and Condensation

Constrained Vapor Bubble (CVB) Experiment – 2009 & 2013

- Prototype for a wickless heat pipe in microgravity – based on corner flows.
- Used pure Pentane as operating fluid for first set of experiments.
- Provided fundamental transport data including the overall stability, flow characteristics, average heat transfer coefficient in the evaporator, and heat conductance as a function of heat flow rate and vapor volume.
- Interferometry technique obtained direct measurements of fluid curvature and thickness.
- Visualized film stability and shape of dry out regions with a microscope in detail never obtained before in microgravity.
- CVB-2 (2013) extended data to a *binary mixture* rather than a pure fluid (Pentane – Isohexane).
- Discovered a new limit for heat pipe operation: Marangoni or Flooding limit.
  - First performance limitation is flooding, not dryout of the heater end.
  - Wickless designs can pump more than enough liquid to the heater end.
- Flooding limitation can be broken by the addition of a second, liquid, component. This may be the origin of reported enhancements using mixtures.
- Unexpected phenomena were observed and enhanced in microgravity including meniscus oscillations, autophobic droplet formation, and controlled single bubble nucleation phenomena (a hybrid pool/flow boiling experiment not accessible in 1-g environments).



Marangoni limit and flooding of heater end with flow streamlines.



Unexpected Explosive Nucleation in 0-g.

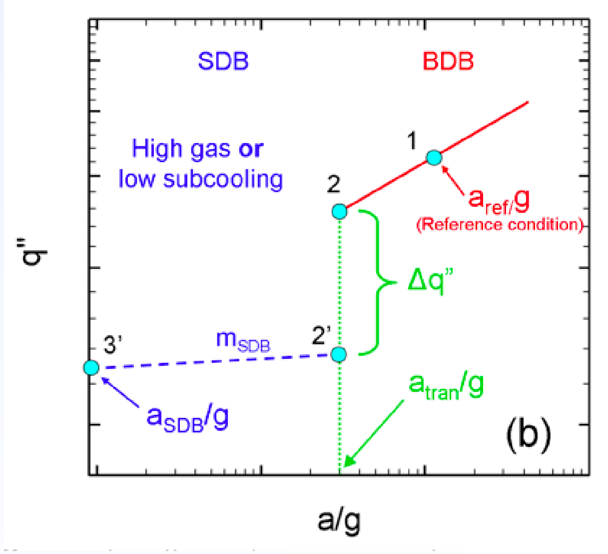
PI: Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute
Co-I: Prof. Peter C. Wayner, Jr., Rensselaer Polytechnic Institute

PI: Prof. Jungho Kim, University of Maryland
PI: Prof. Vijay K. Dhir, University of California, LA

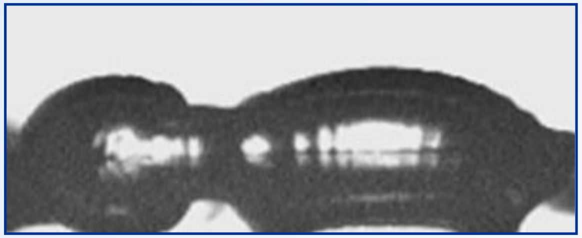
Boiling eXperiment Facility (BXF) – 2011

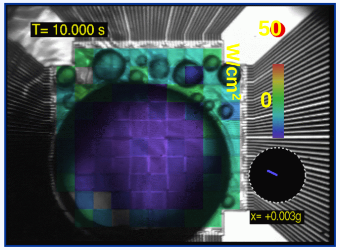
- BXF included two separate pool boiling investigations:
  - **Microheater Array Boiling Experiment (MABE)**
  - **Nucleate Pool Boiling Experiment (NPBX)**.
- Advanced understanding of local boiling heat transfer mechanisms & critical heat flux in microgravity for nucleate and transition pool boiling.
- Detailed measurements of bubble growth, detachment and subsequent motion of single and merged (larger) bubbles.
- Developed a criteria for Boiling Transition
  - Buoyancy Dominated Regime (BDB)
    - Heat transfer by bubble growth and departure
    - Heat flux increases with gravity
  - Surface Tension Dominated Regime (SDB)
    - Dominated by the presence of a non-departing primary bubble
    - Effect of residual gravity is very small
  - Transition Criteria based on Capillary Length

Paulo Nespoli installing BXF in MSG.



Transition of boiling Heat Flux as a function of acceleration.





(Left) *Coalescence of vapor bubbles on NPBX wafer.*

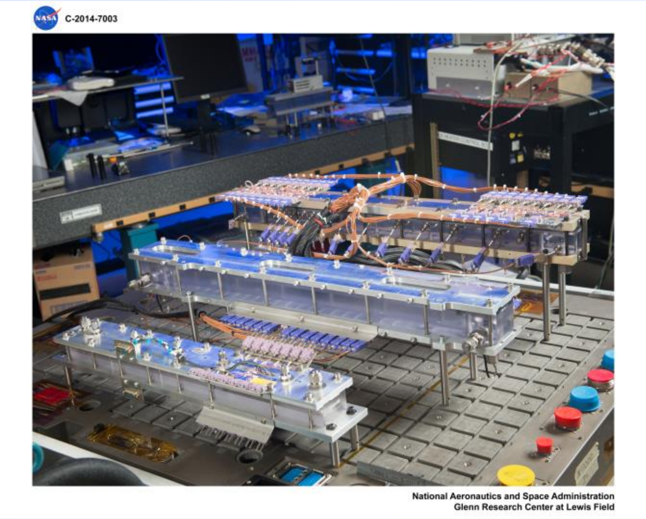
(Right) *Subcooled nucleate boiling in μg. The MABE microheater array is colorized with actual heat flux data.*

Boiling and Condensation

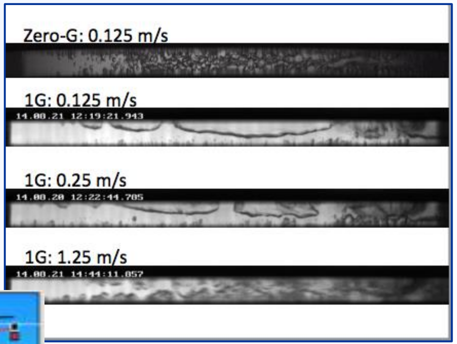
Flow Boiling and Condensation Experiment (FBCE) – 2019

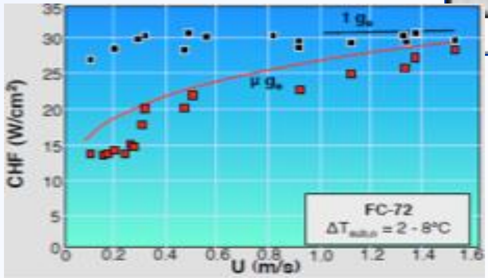
- Will develop mechanistic models for microgravity flow boiling Critical Heat Flux (CHF) and dimensionless criteria to predict the minimum flow velocities required to ensure gravity-independent CHF along with boiling heat transfer coefficients and pressure data correlations.
- Will develop mechanistic model for microgravity annular condensation and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent annular condensation; also develop correlations for other condensation regimes in microgravity.
- Recently completed an axisymmetric 2-D computational model developed to predict variations of void fraction, condensation heat transfer coefficient, wall temperature and temperature profile across the liquid film.

PI: Prof. Issam Mudawar, Purdue University
Co-I: Dr. Mojib Hasan, NASA GRC



FBCE Test Module





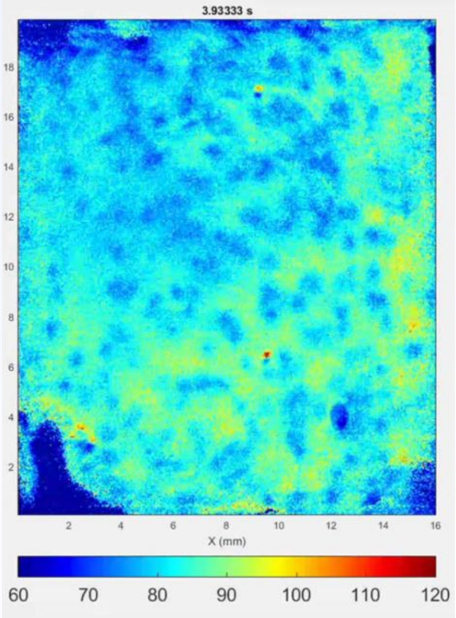
Critical Heat Flux (CHF) data and model predictions for microgravity and Earth gravity for flow boiling.

Boiling and Condensation

PI: Prof. Jungho Kim, University of Maryland
ESA PI: Catherine Colin, Institut de Mécanique des Fluides de Toulouse

Multiphase Flow and Heat Transfer Experiment (MFHT) - 2019

- Will develop models that incorporate two-phase flow regimes and fluid conditions to predict local heat transfer coefficients from subcooled nucleate boiling through critical heat flux (CHF) and dryout.
- Will obtain local measurements of the wall heat transfer coefficient with high temporal and spatial resolution using an infrared video (IR) camera.
- ESA to provide carrier and facility: (Fluid Science Laboratory (FSL) Thermal Platform
- ESA will build and develop flight hardware/insert.
- NASA will design, build and test prototype insert.

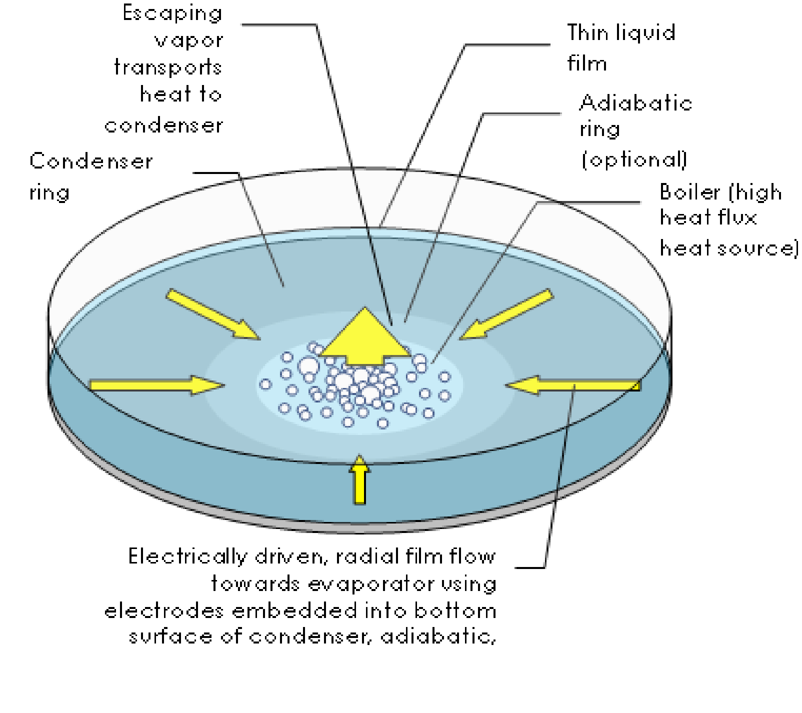


Snapshot of pool boiling data using quantum dots to measure temperature

Boiling and Condensation

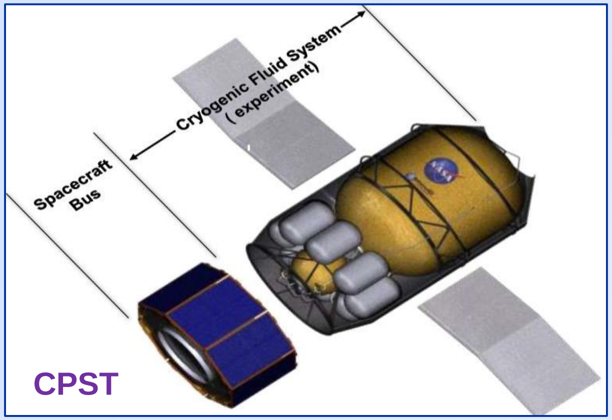
Electro-Hydrodynamic Device (EHD) – 2021

- Uses a dielectric fluid to electrically drive liquid to the heated area – forcing the bubbles away from the nucleation sites.
- Will develop fundamental understanding and physical models to characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change.
- Will characterize electrowetting effect on boiling and CHF in the absence of gravity.
- Micro-scale devices have extremely high heat fluxes due to the small heat transfer surface area.
- Provides a robust, non-mechanical, lightweight, low-noise and low-vibration device.

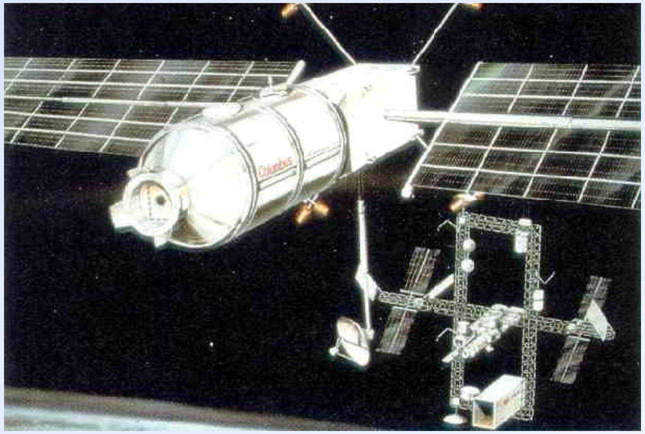


PI: Prof. Jamal Seyed-Yagoobi, Worcester Polytechnic Institute
Co-I: Jeffrey Didion, NASA GSFC

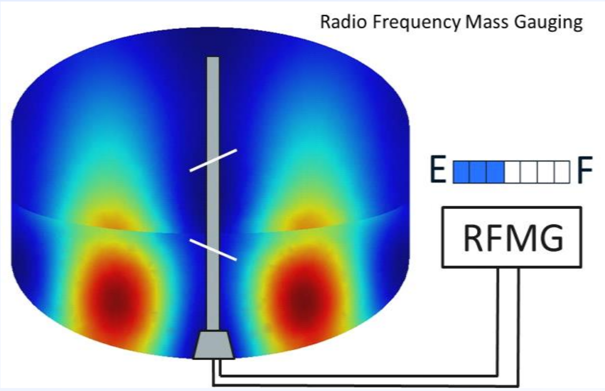
Cryogenic Storage & Handling - Applications



Cryogenic Propellant Storage & Transfer



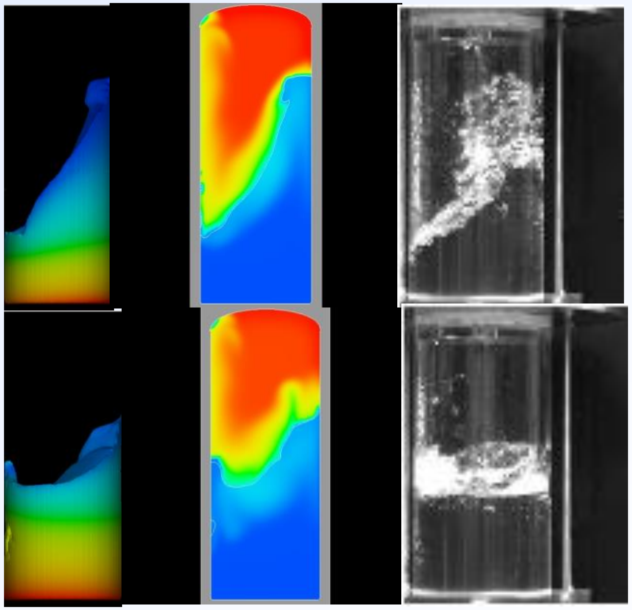
ESA Columbus Free Flyer



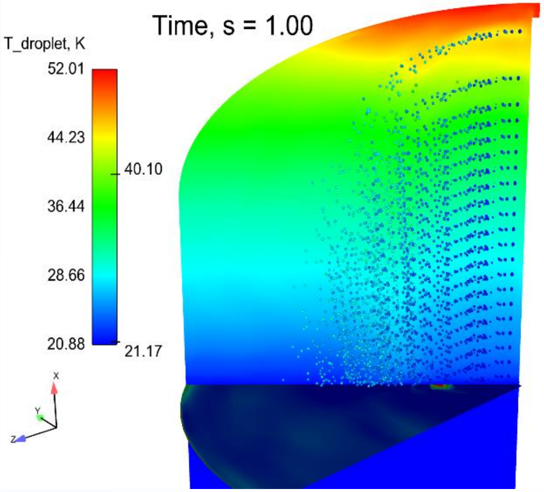
Radio-frequency Mass Gauging

"The data obtained from these highly controlled and instrumented experiments in the microgravity environment will be critical for validating models that will be used to design integrated low- and zero-boil-off cryogenic fluid storage and utilization concepts for a wide range of missions."

Jeffrey Sheehy,
Senior Technical Officer, STMD



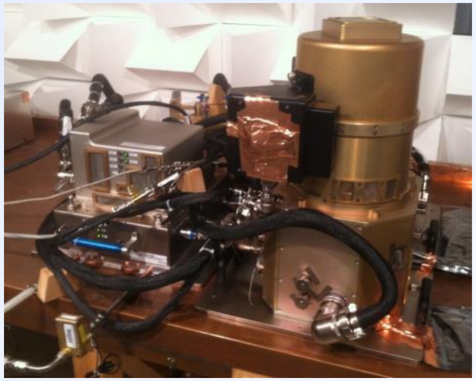
Capturing Liquid Slosh Dynamics



Model Validation: Tank Spray Droplet Pressure Control

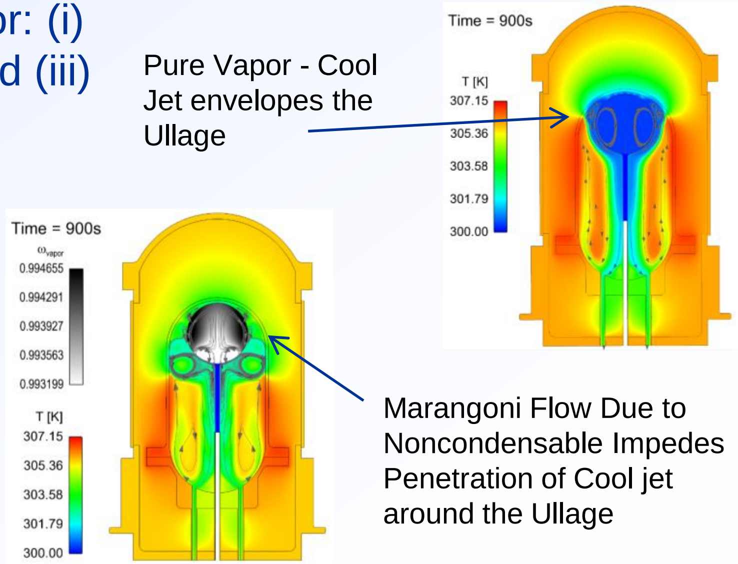
Zero Boil-Off Tank Experiment (ZBOT) - 2016

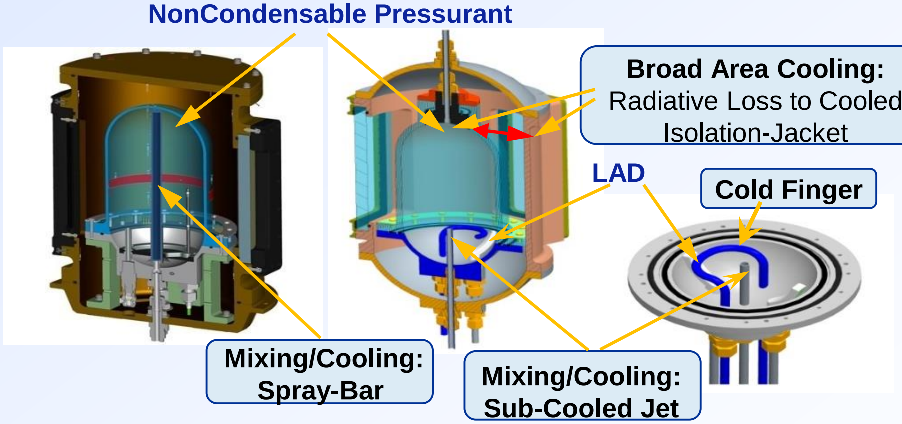
- Will study storage tank pressurization & pressure reduction through fluid mixing in microgravity (ZBOT-1).
- Add the effects of non-condensable gasses (ZBOT-2). The presence of non-condensables produces barriers to the transport of vapor to and from the interface creating gradients of the gaseous concentrations along the interface may give rise to Marangoni convection. This changes the pressurization and pressure reduction rates.
- ZBOT-3 will characterize tank thermal destratification and pressure reduction through active cooling schemes for: (i) sub-cooled jet mixing (ii) droplet spray-bar mixing; and (iii) broad area cooling with intermittent mixing.
- ZBOT provides an instrumented test section with controllable BCs; velocimetry; and flow visualization.



ZBOT EU

Effect of Noncondensable on Flow and Temperature Fields during Jet cooling Pressure Control





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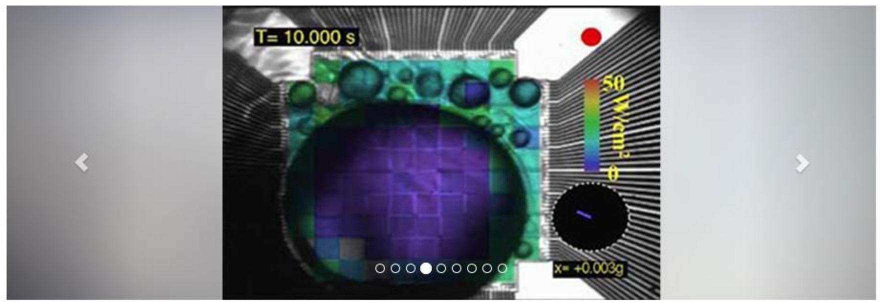
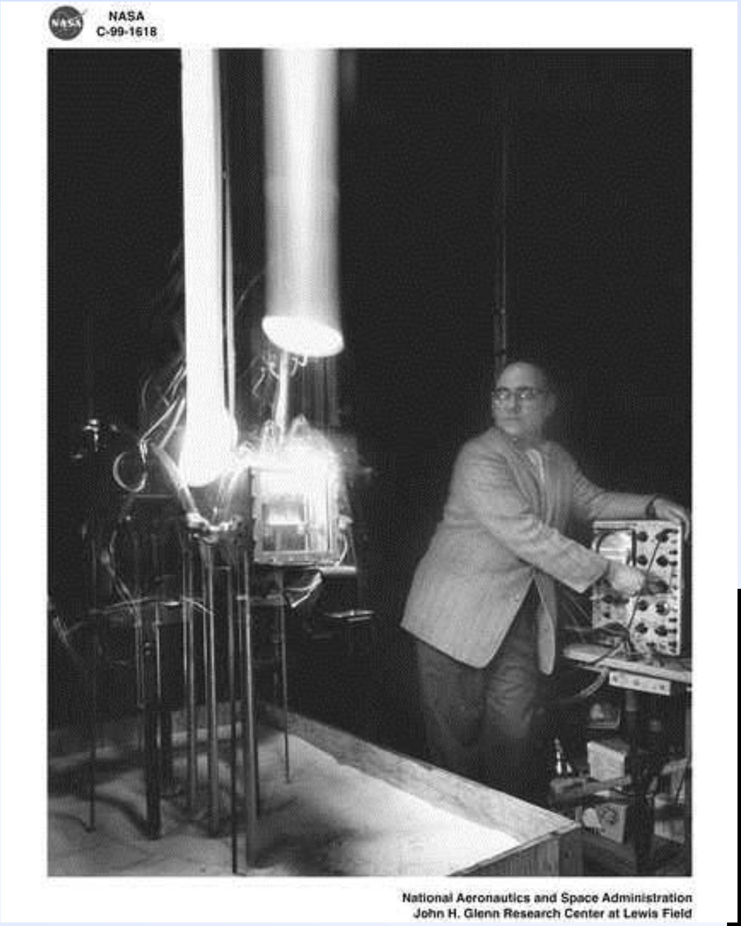


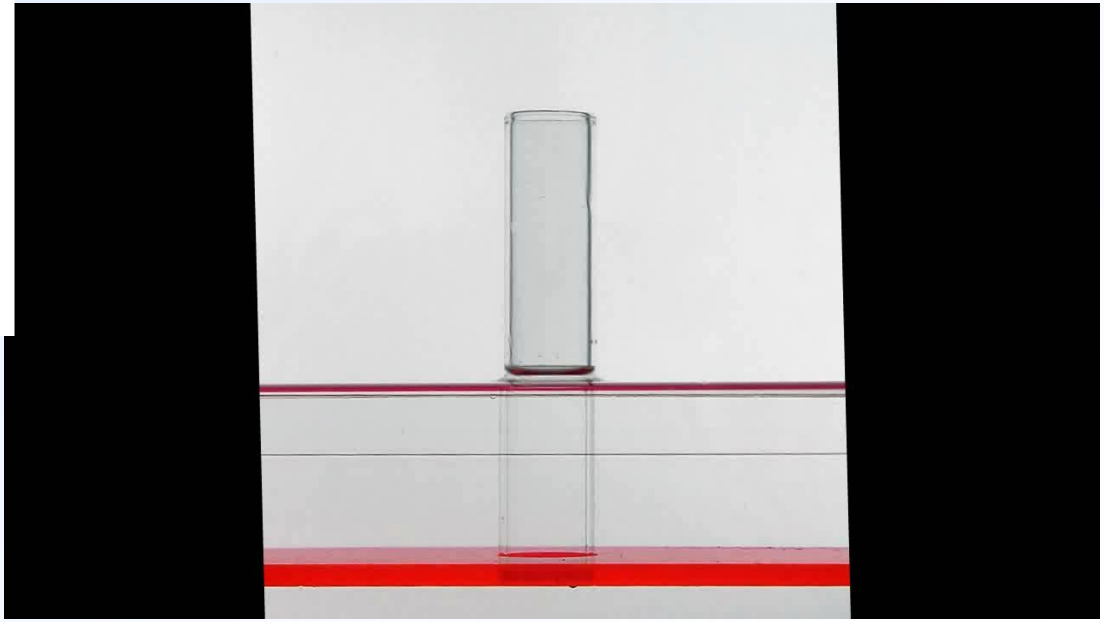
At NASA, we are excited to announce the roll-out of the Physical Science Informatics (PSI) data repository for physical science experiments performed on the International Space Station (ISS). The PSI system is now accessible and open to the public. This will be a resource for researchers to data mine the PSI system and expand upon the valuable research performed on the ISS using it as a research tool to further science, while also fulfilling the President's Open Data Policy.

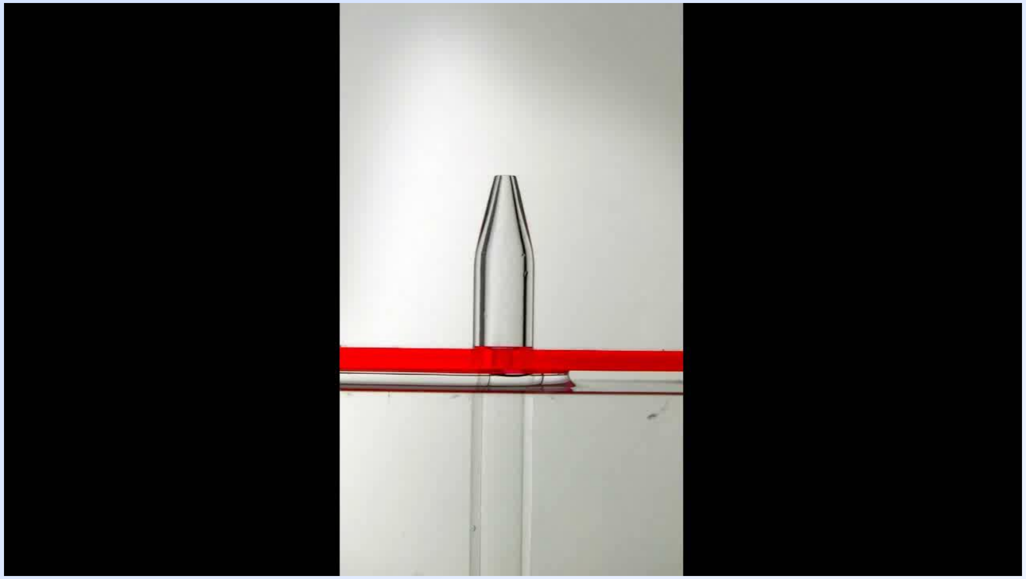
Fluid Physics Investigations

Acronym	Title	Research Area	Completion Status	NRA Eligibility
CCF	Capillary Channel Flow	Fluid Physics	Complete	Yes
CFE	Capillary Flow Experiment	Fluid Physics	Complete	Yes
CVB	Constrained Vapor Bubble	Fluid Physics	Complete	Yes
CVB-2	Constrained Vapor Bubble-2	Fluid Physics	Completed 2016	No
MABE	Microheater Array Heater Boiling Experiment	Fluid Physics	Completed 2016	Yes
NPBX	Nucleate Pool Boiling Experiment	Fluid Physics	Complete	Yes

BACKUP SLIDES


NASA
C-99-1618
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field





Priorities for Adiabatic Two-Phase Flows

Low Gravity Bubbly Flow Through Sudden Expansion that fills expanded area

Low Gravity Bubbly Flow Through Sudden Expansion resulting in two-phase bubbly jet

Priority # 1:

Utilize ISS to develop fundamental tools to predict phase location and flow dynamics in two-phase systems to discern the effects of gravity.

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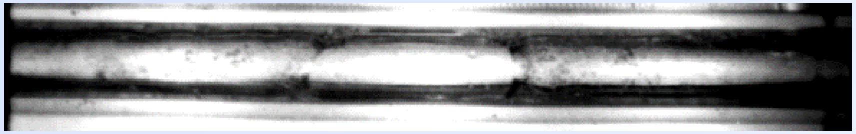


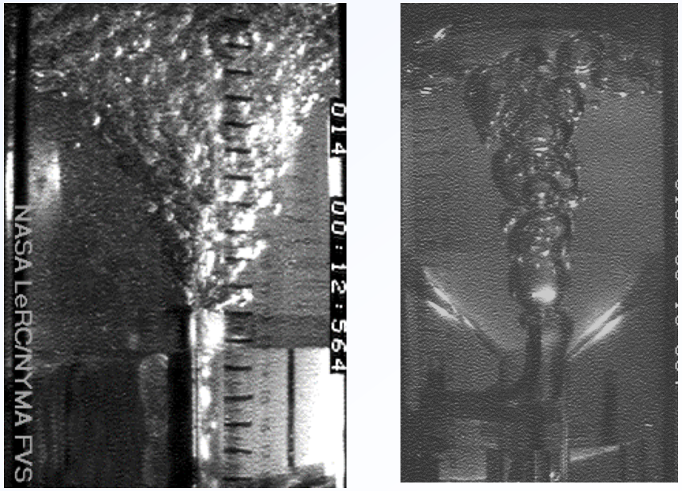
Rupture of Liquid Film in Slug Flow due to Instability

Priority # 2:

Predict and understand two-phase closed-loop system behavior with a focus on transients, oscillations and the evolution of phase distribution to ensure safe and reliable operations.

Priority # 3:

Predict and understand the mechanisms for bubble and droplet coalescence, interactions and dynamics.

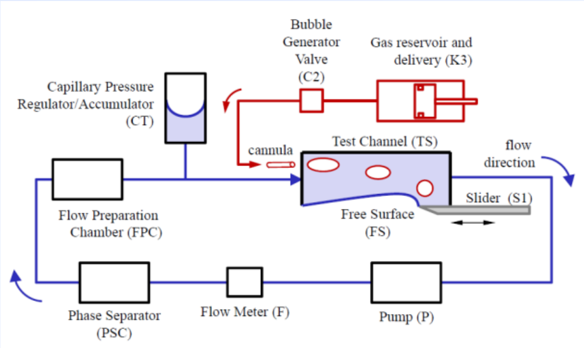


Bubble Flow Coalescence in Cyclonic Separator

Priorities for Capillary Flow and Interfacial Phen.

Priority # 1:

To create the ability for many users to simply and rapidly perform numerous capillary flow studies, from simple to complex, on ISS.



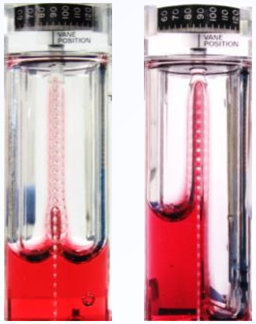
CFE Contact Line for partially wetting conditions. Pinning edge (right) vs smooth cylinder (left).

Priority # 2:

Determine moving contact line boundary conditions (perfect, partial or varying wetting, non-wetting) due to contaminants, surfactants, surface finish, and particulates and, investigate advancing/receding contact lines (e.g. hysteresis at the contact line) in a variety of capillary flow sensitive geometries.

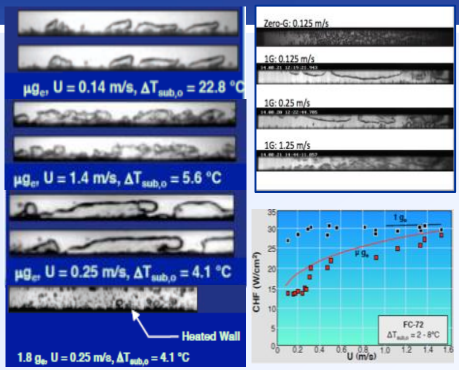
Priority # 3:

Determine global equilibrium criteria in non-symmetric and symmetric geometries for liquid management. There are often many possibilities for static liquid positioning. Additional theoretical work is critical in determining when to expect problems in various geometries of interest.



Two different global equilibrium points for the same test chamber geometry.

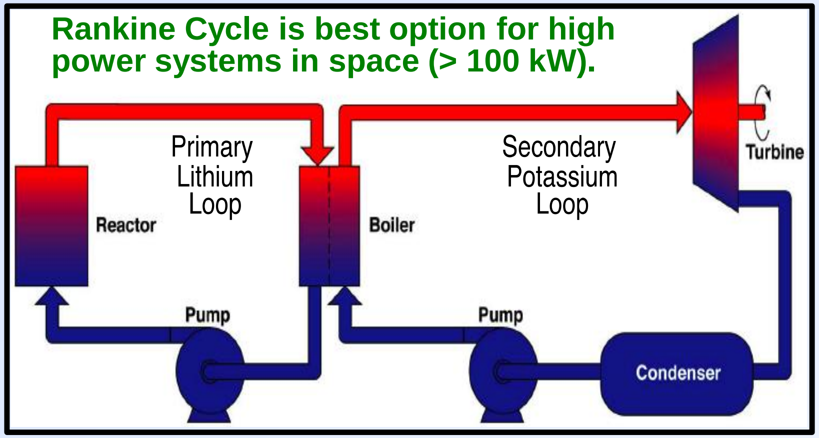
Priorities Boiling and Condensation



Critical Heat Flux (CHF) data and model predictions for microgravity and Earth gravity for flow boiling.

Priority # 1:

Develop approaches to enhance boiling heat transfer, delay CHF, predict the onset of boiling, and develop and validate predictive models. Significantly advance our understanding of the physics of flow boiling CHF and instabilities in microgravity.

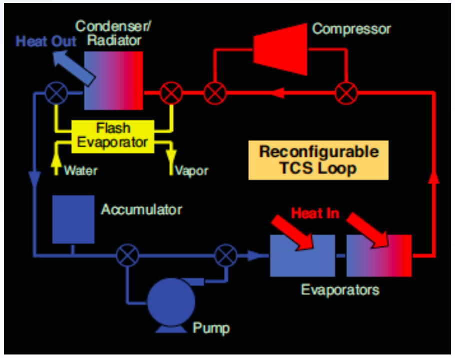


Priority # 2:

Develop capabilities to predict flow condensation heat transfer performance in microgravity. Factors to be addressed include: non-condensable gas, wave effects, inlet superheat / subcooled outlet effects, enhancement techniques, tapered channels, flow passage effects, capillary enhancement techniques, surface modification, drop-wise condensation.

Priority # 3:

Develop understanding of instabilities (multichannel flow reversals, flooding, etc.), transients (start-up, loss of coolant, load variation), evaporator / condenser phase separator, NCG separation - removal - isolation, and loop sensing and feedback control strategies.



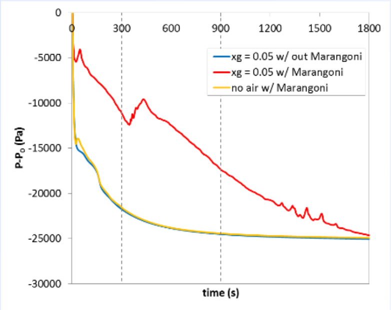
Reconfigurable Thermal Control System

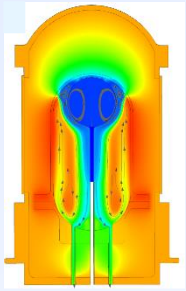
Priorities Cryogenic Storage & Handling

Priority # 1:

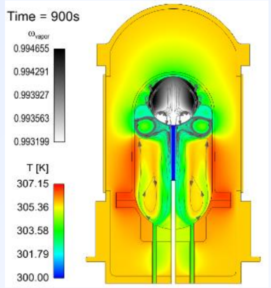
Understand the impact of noncondensables gases on tank pressurization and pressure control in microgravity.

Establish a microgravity science & engineering foundation for comparison and optimization of axial-jet and spray-droplet tank pressure control designs.

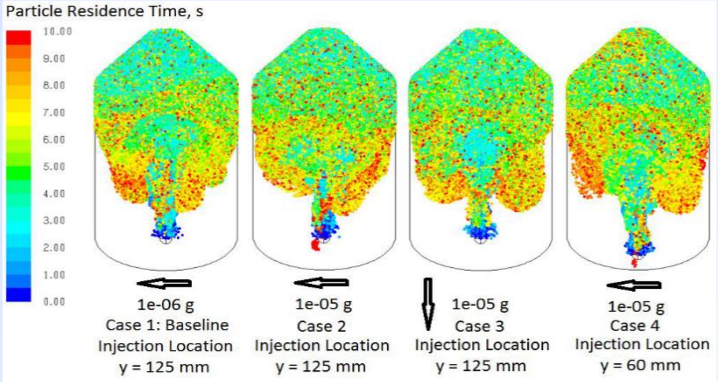




Pure Vapor



Non-Condensable



Simulation of Tank Chilldown in Space

Priority # 2:

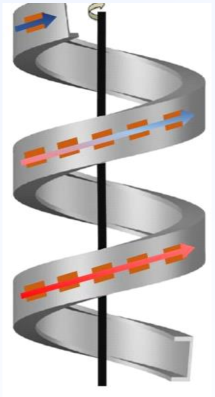
Understand the impact of microgravity boiling, interfacial turbulence and curvature, and impulse accelerations on tank pressurization.

Study tank chill down and tank pressurization using submerged and non-submerged injectors – logical extension to ZBOT series.

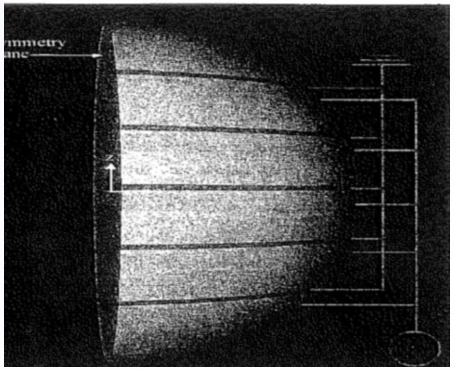
Priority # 3:

Understand different aspects of storage tank phase management and phase control in microgravity using different devices:

- Capillary fluid dynamics – extends CCF work
- Hydrophobic materials
- Dielectrophoretic forces
- Radio-Frequency mass gauging



Large Scale Capillary Devices



Dielectrophoretic Phase Management