NASA Physical Sciences – Presentation to Annual Two Phase Heat Transfer International Topical Team Meeting

Baltimore, MD
September 26, 2014

Francis Chiaramonte, Program Executive for Physical Sciences, NASA HQ

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SLPS Gravity-Dependent Physical Sciences Research

Combustion Science
- Spacecraft fire safety
- Droplets
- Gaseous – Premixed and Non-Premixed
- Solid Fuels
- Supercritical reacting fluids

Biophysics
- Biological macromolecules
- Biomaterials
- Biological physics
- Fluids for Biology

Fluid Physics
- Adiabatic two-phase flow
- Boiling, Condensation
- Capillary Flow
- Interfacial phenomena
- Cryogenics

Materials Science
- Metals
- Semiconductors
- Polymers
- Glasses, Ceramics
- Granular Materials
- Composites
- Organics

Fundamental Physics
- Space Optical/Atomic Clocks
- Quantum test of Equivalence Principle
- Cold atom physics
- Critical point phenomena
- Dusty plasmas

Complex Fluids
- Colloids
- Liquid crystals
- Foams
- Gels
- Granular flows

ISS Facilities for Physical Sciences Research

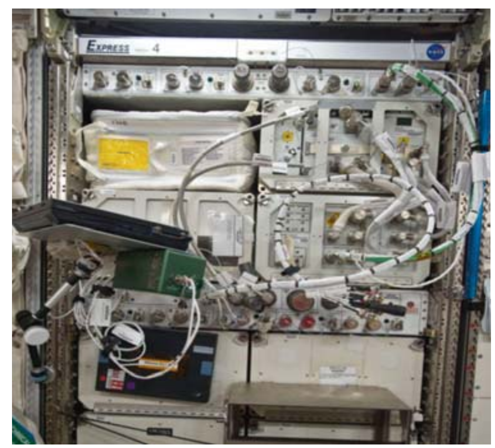
Astronaut Mike Fincke completing install of the CIR/MDCA insert prior to CIR activation in January 2009.

Astronaut Frank DeWinne completing installation in the MSRR prior to on-orbit commissioning October 2009

Astronaut Paolo Nespoli operating the ACE experiment in the FIR/LMM

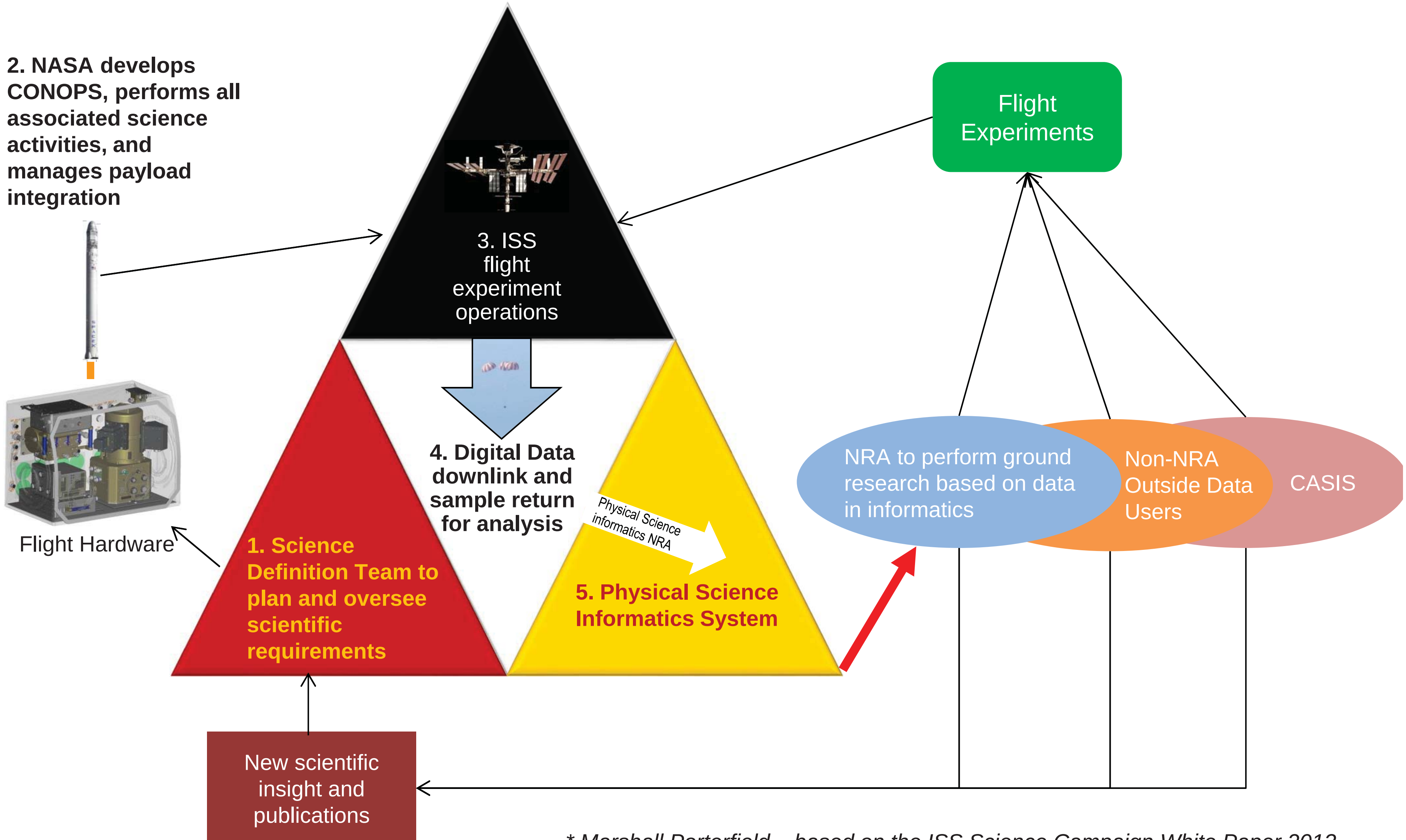
Increment 26 commander Scott Kelly installing CCF in the Microgravity Science Glovebox on ISS

Astronaut Cady Coleman operating the CFE experiment in Maintenance Work Area on the ISS



DECLIC installed in an EXPRESS Rack on board ISS

DATA DISSEMINATION
Physical Sciences Informatics System*



** Marshall Porterfield – based on the ISS Science Campaign White Paper 2013*

FluidsLab Topics

- Adiabatic Two Phase Flow*
- Boiling and Condensation*
- Capillary Flow and Interfacial Phenomena*
- Cryogenic Storage and Transfer**

* Topic to be discussed during ITTW 2014 and ASGSR Conference Oct. 2014

* *Topic only to be discussed during the FluidsLab Workshop at the ASGSR Conference, Oct. 2014

Capillary Flows and Interfacial Phenomena

Category	Sub-Category	Experiment Concept
Capillary Flows	Capillary flow or inbibition, esp. in complex geometries	Capillary flow in idealized but complex pore/wick geometries
	Combined Inertial-capillary driven flows	Combined Inertial-capillary driven flows in complex geometries
	Passive phase separation in capillary flow geometries	Coelescence of bubbles/drops
Interfacial Phenomena	Moving Contact line boundary conditions (esp. with partial or varying wetting)	Contact line dynamics on textured (partially wetting) surfaces
	Heat and Mass transfer effects in capillary flow systems	Capillary flow geometry heat pipe. Capillary flow geometry brine condenser
	Instabilities	Global equilibrium in non-symmetric geometries for liquid management

Adiabatic Two Phase Flow

Category	Sub-Category	Experiment Concept
System Stability	Known Normal Gravity Instabilities	Parallel Channel Instability. Pumped Loop Instability. Mixing or phase Injection. Terrain-Induced Slugging.
	Operational Transients	Startup & Shutdown. Non-Isothermal Gas Phase Contraction/Expansion. Priming. Cavitation.
Flow Regimes	Flow Regime Transitions	Flow Rate Changes. Flow Accelerations (expansions, contractions, bends). Flow Splitting (Tees, separators).
	Channel Geometry	Rectangular Conduit Geometry. Porous Media. Open Channel.
Measurement of Interfacial Structures	Discrete Phases	Measurements of droplets, waves, bubbles. Sprays.
	Flow Evolution	Wave formation, growth and tearoff. Phase Coalescence. Film Growth and/or Rupture.

Capillary Flow and Interfacial Phenomena/ Adiabatic Two-Phase Flow

New Concepts

1. fluid flow in flexible tubing
2. capillary loop with hydrogel
3. changing wettability inside capillary tube
4. working fluid mixture behavior within heat pipes, capillary pumped loop and loop heat pipes.
5. microscale/macroscale interactions
6. structured packing/geometry & spacing of packing
7. heat pipe geometries
8. thermocapillary convection with boiling systems (influence of contact angles)
9. scales with biological systems (leaves) (subdividing of veins)
10. scales of applications

11 astro-sweat (impact on hygiene)
12 capillary flow limits on extremes, critical point, superfluid helium
13 phase separation
14 liquid scavenging
15 improved condensing systems to collect fluid
16 capillary mesh structure with smart materials to evaporate, clean and reuse without external forces
17 phase change materials within a channel geometry, wall materials, microstructure
18 propellant management (LAD)
19 bubble free ice cubes

Boiling and Condensation

Category	Sub-category	Experiment concept
Flow boiling	Nucleate boiling to Critical Heat Flux (CHF) and Dry-out	CHF in channels, tubes as function of mass velocity for subcooled, saturated and two-phase inlet conditions. Effects of dissolve gas on above items. Criteria to predict minimum flow velocity required to ensure gravity independent CHF. Pressure drop for subcooled, saturated and two-phase inlet conditions. Flow boiling heat transfer coefficients for subcooled, saturated and two-phase inlet conditions. Wall temperature and heat flux corresponding to onset of boiling. Entrainment and de-entrainment phenomena. Expansion of liquid in vacuum. Flow of superheated and saturated liquids.
	Nucleate Boiling to critical Heat Flux (CHF) and Dry-out (for electrohydrodynamically induced flow	
	Nucleate Boiling to critical Heat Flux (CHF) and Dry-out for capillary induced flow	

Boiling and Condensation *Continued*

Category	Sub-category	Experiment concept
Film condensation and drop wise condensation.	Film condensation in channels/tubes; partial to full condensation.	Condensation heat transfer coefficient for all flow regimes. Pressure drop for all flow regimes.
	Direct contact condensation on subcooled droplets and agitated liqud-vapor interface.	
	Film and drop wise condensation on prepared surfaces; contoured and hydrophobic/hydrophilicsurfaces.	
	Condensation pure vapor and vapor gas mixture on porous surfaces and subtrates.	
Evaporation from plane and screened surfaces, porous media, at solid-liquid-vapor contact line with and without forced flow.	Heat pipes. Evaporator/ Condenser/ Phase Separator. Porous Media/Screened Surfaces.	

Flow Boiling and Condensation

New Concepts

1. Discern the important parameters/dimensionless parameters that govern boiling and condensation
2. Manipulation of flow phase distribution in evaporation in 0-g.
3. Manipulation of flow phase distribution in condensation in 0-g.
4. Multiple parallel pipes - flow distribution control
5. Boiling in curved channels
6. Condensation in convergent/divergent channels
7. Passively induced flow for boiling and condensation
8. Partition of heat transfer mechanisms during flow boiling (evaporation, boiling, single phase convection, etc.)
9. How to enhance boiling heat transfer and CHF in microgravity. Fluids (nano, or mixtures), surfaces (chemical or mechanical), EHD.
10. The influence of cavity size distribution on nucleate boiling
11. Two-phase pressure drop across the loop
12. Void fraction distribution in two-phase flow in flow boiling
13. Diagonstics for flow boiling - local temperatures/pressures, local heat transfer coef. Both radial and axial.

Flow Boiling and Condensation (continued)

New Concepts

14 Fluid properties. Refridgerants, water, liquid metals (classes).

15 Effects of geometries - flow geometry, microchannels, tubes, annulus, etc. Flow through conventional channels

16 Multi-component boiling

17 Electric field effect on boiling of water

18 The Effect of Wickability on Boiling and Critical Heat Flux on Micro/Nanostructured Surfaces

Open Science NRA (under consideration)

- Physical Sciences Informatics Ground NRA – 2015

- Fluid Physics, mid 2015, (coordinated solicitation with CASIS)

Flow Boiling and Condensation Experiment (FBCE)

PI: Prof. Issam Mudawar, Purdue University
Co-I: Dr. Mohammad M Hasan, NASA GRC
PS: Dr. David F. Chao, NASA GRC
PM: Nancy R Hall, NASA GRC
Engineering Team: GRC Engineering

Glenn Research Center

Objectives:

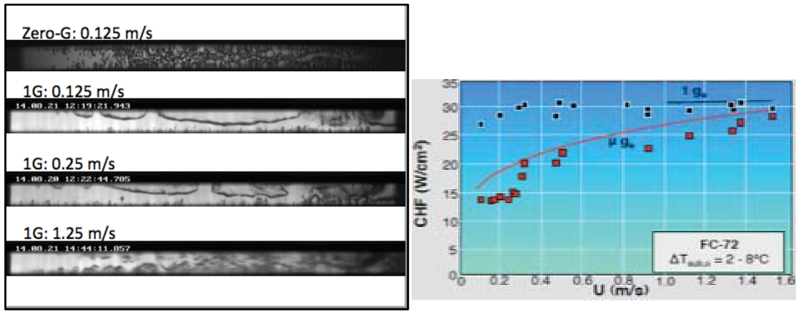
- Develop experimentally validated, gravity independent, mechanistic model for microgravity annular flow condensation and microgravity flow boiling critical heat flux (CHF).

Relevance/Impact:

- Key thermal systems and power generating units must be designed to reduce the size, weight and enhance reliability.
- Two-phase thermal systems utilizing flow boiling and condensation can yield significant enhancement in thermal performance
- Relevant to a wide range of systems:
  - advanced two-phase thermal control system for life support and habitation
  - Rankine cycle, power generation (solar dynamic, nuclear), regenerative fuel cells
  - in space long term storage and transfer of cryogenic propellant

Development Approach:

- To be developed inhouse by GRC Engineering.
- Develop an integrated flow boiling/condensation experiment to serve as a primary platform for obtaining two-phase flow and heat transfer data in microgravity with dielectric fluid, normal-perfluorohexane.
- Engineering models will be used for flight hardware development and flight hardware unit will also be developed.



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

ISS Resource Requirements

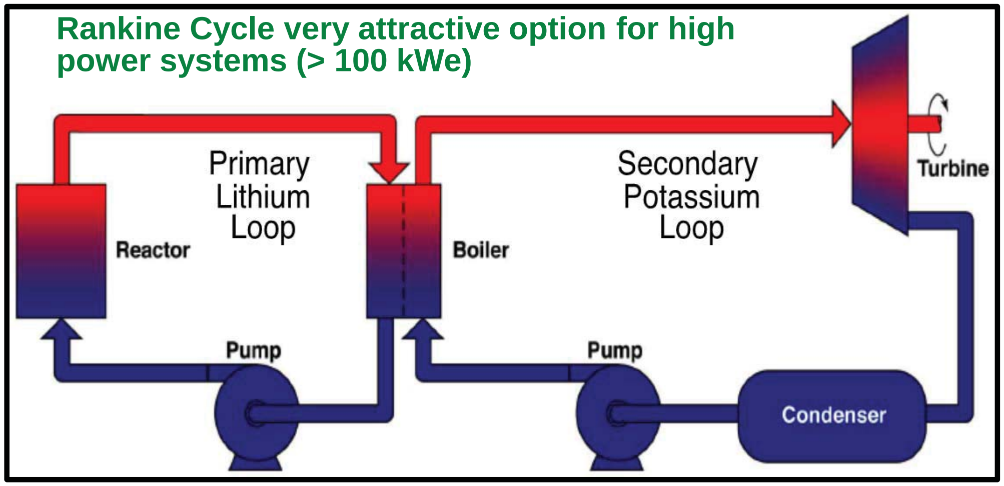
Accommodation (carrier)	Fluid Integrated Rack (FIR)
Upmass (kg) (w/o packing factor)	225 kg (estimated)
Volume (m^3) (w/o packing factor)	0.3 m^3 (estimated)
Power (kw) (peak)	2500W (estimated)
Crew Time (hrs) (installation/operations)	TBD
Autonomous Operation	6 months
Launch/Increment	12/2017

Project Life Cycle Schedule

Milestones	SCR	IDR	RDR	PDR	CDR	Ph III Safety	FHA	Launch	Ops complete	Final Report
FBCE	11/11	12/12	2/2014	3/2015	6/2016	8/2017	9/2017	12/2017	6/2018	12/2019

Flow Boiling and Condensation Experiment (FBCE)

- Thermal management systems responsible for controlling temperature and humidity using Thermal Control System (TCS) consisting of Heat Acquisition, Heat Transport and Heat Rejection hardware.
- Refrigerator/freezer components provide cooling for science experiments and food storage.
- Advanced water recovery systems transfer crew and system wastewater into potable water for crew and system reuse.

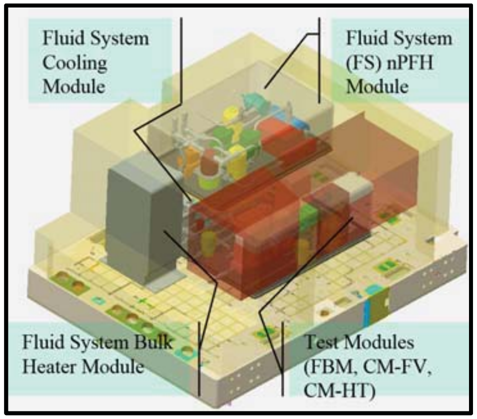


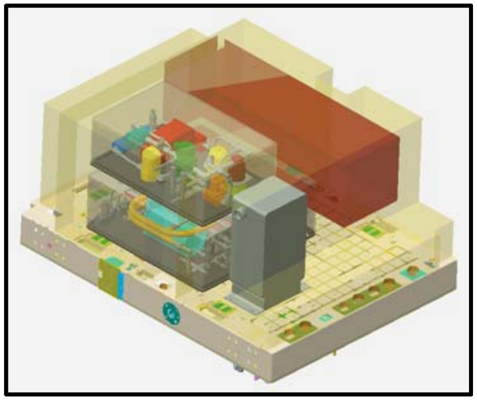
FBCE

- Test Fluid normal – PerFluoroHexane (nPFH)
- Thermophysical Properties

Saturated Properties of FC-72	P_{sat} = 1.0x10^5 N/m^2 (14.50 psia)	P_{sat} = 1.5.0x10^5 N/m^2 (21.75psia)
Saturation temperature, T_{sat} (°C)	133.09°F (56.16°C)	68.86
Liquid density, ρ_f (kg/m^3)	1593.42	1560.28
Vapor density, ρ_g (kg/m^3)	13.20	19.52
Latent heat of vaporization, h_{fg} (J/kg)	94.97x10^3	90.71x10^3
Liquid specific heat, $c_{p,f}$ (J/kg.K)	1.10x10^3	1.12x10^3
Liquid viscosity, μ_f (kg/m)	435.67x10^{-6}	381.75x10^{-6}
Vapor viscosity, μ_g (kg/m.s)	11.56x10^{-6}	11.98x10^{-6}
Liquid thermal conductivity, k_f (W/m.K)	53.82x10^{-3}	52.43x10^{-3}
Liquid Prandtl number, Pr_f	8.91	8.16
Surface tension, σ (N/m)	8.39x10^{-3}	7.2x10^{-3}

- Flow rates 2-40 g/s of nPFH for Boiling, 1-14 g/s for Flow Condensation
- Volume of n-PFH fluid ~ 1.5 liters
- Cooling capability through he ITCS water loop
- Bulk Heater Power on ISS up to 1660 W
- Pressure 100 kPa to 200 kPa Absolute
- Temperature 20 to 120 ºC
- Facility can handle experiments in Flow Boiling with subcooled, saturated, two-phase inlet and Flow Condensation with saturated and two-phase inlet
- Diagnostics
  - Pressure and temperature measurement at different locations of fluid system, on-orbit degassing
  - High speed video data storage and management
  - High speed cameras accommodation





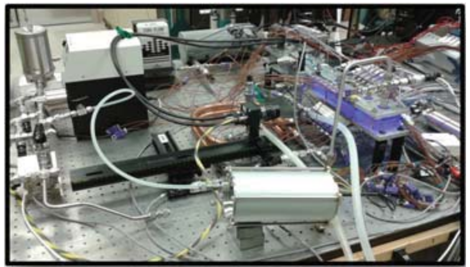
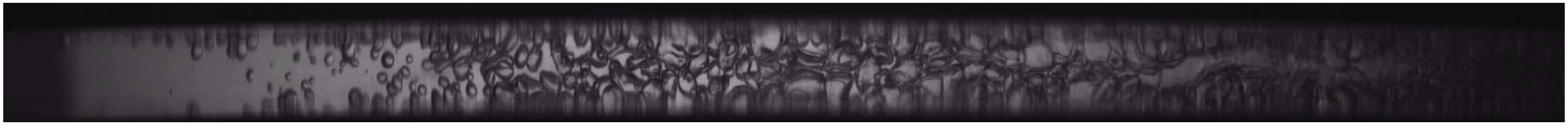


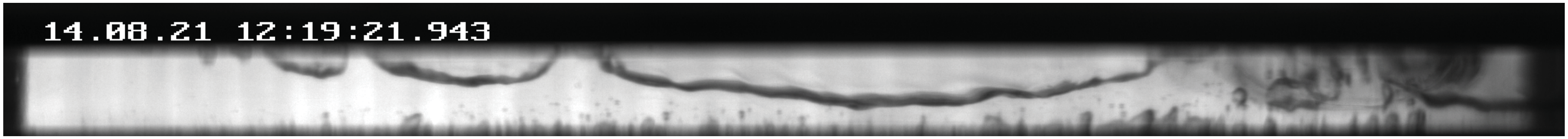
Table-top fluid system and Flow Boiling Module in testing on optics bench

FBCE Flow Boiling Module Videos

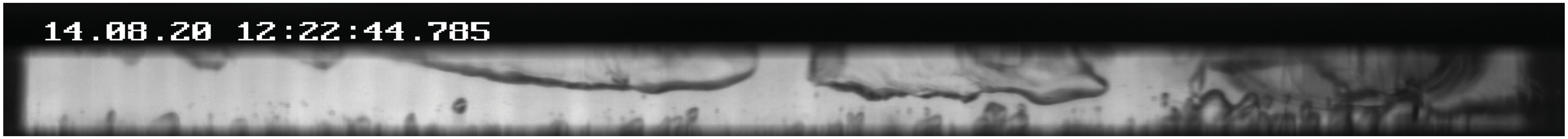
Zero-G: 0.125 m/s



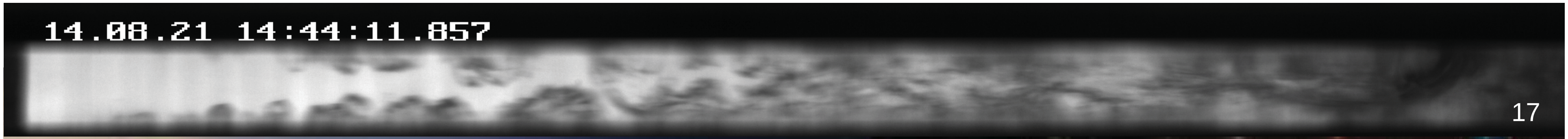
1G: 0.125 m/s



1G: 0.25 m/s



1G: 1.25 m/s



ElectroHydrodynamic (EHD) Thin Film Boiling Experiment

Glenn Research Center

PI: Prof. Jamal Seyed-Yagoobi, Worcester Polytechnic Institute
Co-I: Jeffrey Didion, NASA GSFC
PS: Dr. Mojib Hasan, NASA GRC
PM: *Nancy R. Hall,* NASA GRC
Engineering Team: ZIN Technology

Objective:

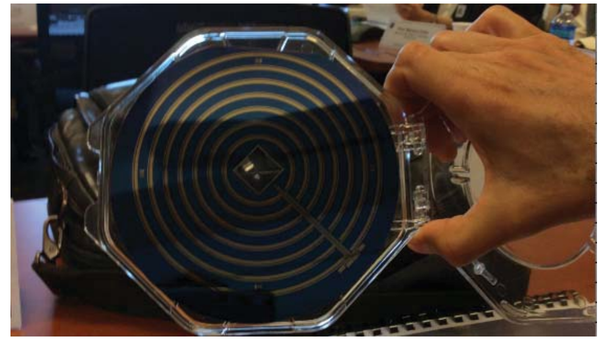
- Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to:
  - The effects of microgravity on the electrically generated two-phase flow.
  - The effects of microgravity on electrically driven liquid film boiling (includes extreme heat fluxes).
- Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.

Relevance/Impact:

- Provides phenomenological foundation for the development of electric field based two-phase thermal management systems leveraging EHD, permitting optimization of heat transfer surface area to volume ratios as well as achievement of high heat transfer coefficients thus resulting in system mass and volume savings.
- EHD replaces buoyancy or flow driven bubble removal from heated surface.

Development Approach:

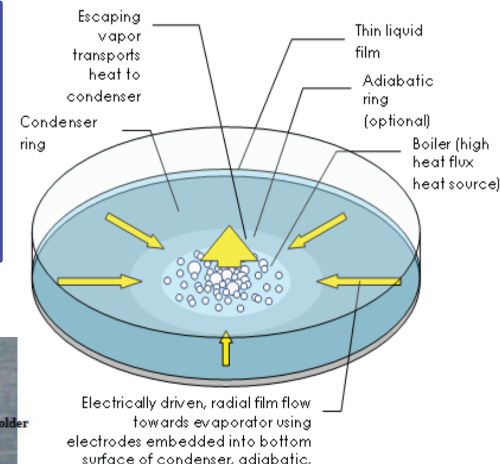
- Conduct preliminary experiments in low gravity and ground-based facilities to refine technique and obtain preliminary data for model development.
- ISS environment required to characterize electro-wetting effect on nucleate boiling and CHF in the absence of gravity.
- Will operate in the Microgravity Science Glovebox.

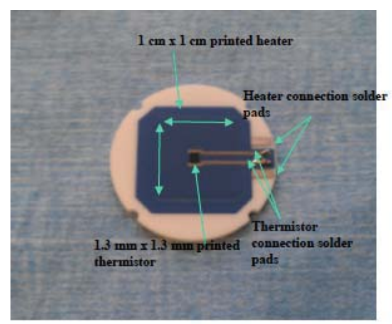


Top: Silicon wafer manufactured by GSFC.

Right: Schematic of silicon wafer.

Bottom: EHD heater





Project Life Cycle Schedule

Milestones	SCR	RDR	PDR	CDR	FHA	Launch	Ops Complete	Final Report
Baseline	6/14	9/17	9/18	10/19	9/20	12/20	3/21	4/21

Revision Date: 03/2015

Zero Boil-Off Tank (ZBOT) Experiment: Fluid Mixing

Glenn Research Center

PI: Dr. Mohammad Kassemi, NCSER/GRC
Co-I: Dr. David Chato, NASA GRC
PS: John McQuillen, NASA GRC
PM: William Sheredy, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Objective:

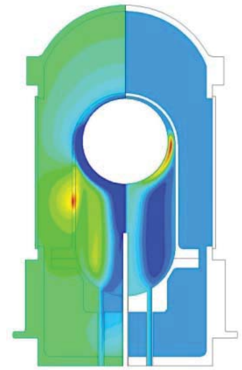
- Develop a small-scale simulant-fluid ISS flight experiment to study storage tank pressurization & pressure reduction through fluid mixing in microgravity.
- Gather high fidelity microgravity data under known/controlled conditions for verification & validation of storage tank CFD models.
- Formulate much-needed microgravity empirical correlations for thermal stratification, pressurization, liquid mixing, pressure reduction, and interfacial heat and mass transfer.
- Assess the engineering feasibility of dynamic Zero-Boil-Off (ZBO) pressure control for microgravity applications.

Relevance/Impact:

- ***Reduce propellant launch mass*** (cost) and ***decrease risks*** for future space missions by aiding the development of dynamic pressure control schemes for long-term storage of cryogenic fluids.
- ***Increase design reliability*** by providing archival data for benchmarking and improving CFD models/codes used by the Cryogenic Fluids Management Community (CFM) and the Aerospace Companies for future (ground-tested-only) tank designs.

Development Approach:

- Ground Phase: Develop ground-based experiment and obtain 1-g data for tank pressurization and pressure reduction.
- Flight Phase: Develop ISS experiment/hardware and obtain microgravity data for tank pressurization and pressure reduction.
- Modeling: Develop a state-of-the art two-phase CFD model for tank pressurization and pressure control.
- Validation: Validate and Verify the CFD model with microgravity and 1g data.
- Scale-Up: Use the validated CFD model and empirical correlations derived from the 1g and microgravity data for scale-up tank design.



CFD Model Prediction: Temp & Flow Fields in Microgravity

ZBOT Engineering Model in the MSG Work Volume Mockup

ISS Resource Requirements

Accommodation (carrier)	Microgravity Science Glovebox (MSG)
Upmass (kg) (w/o packing factor)	114 kg
Volume (m^3) (w/o packing factor)	0.23 m^3
Power (kw) (peak)	0.445 kw (0.314 kw max continuous)
Crew Time (hrs) (installation/operations)	13 hrs. total
Launch/Increment	Launch: SPX-7/45 & 46 (Ops)

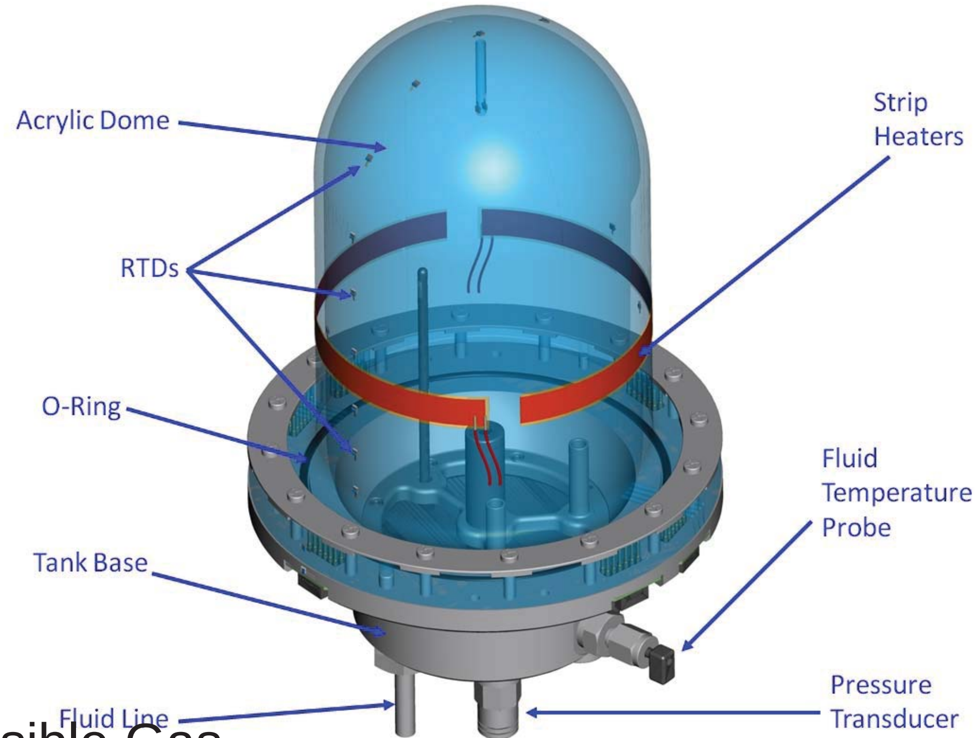
Project Life Cycle Schedule

Milestones	SCR	RDR	PDR	CDR	VRR	Phase III Safety	FHA	Launch	Ops	Return	Final Report
Actual/ Baseline	7/06	6/08	2/10	12/12	3/14	11/14	3/15	6/15	10/15 – 2/16	TBD	2/17

Revision Date: 8/12/14

Test Fluid: Perfluoro-normal-Pentane
- Density ~ 1.6 g/ml
- Viscosity ~ 0.4 cP
- Surface Tension ~ 15 dynes/cP
- Normal Boiling Pt: 30 °C

Jet Flow Rates: 0.4 to 3 ml/s
Strip Heater Power: 0 to 1 W
Pressure: 60 - 200 kPa
Temperature 25 - 50 °C
Fill Levels 70 to 90%
Ullage bubble: Vapor &/or Noncondensible Gas
Diagnostics
- Pressure Sensor ±0.34 kPa
- Several RTD's ±0.1°C in fluid, on inside and outside tank wall
- High Resolution Camera and Visible light backlight
- Laser and Particle Imaging Velocimetry



Test Tank
10 cm Diameter
20 cm Long
Hemispherical Cap
1.3 L total Volume

Zero Boil-Off Tank-2 (ZBOT-2) Experiment: Noncondensable Gas Effects

Glenn Research Center

PI: Dr. Mohammad Kassemi, NCSER/GRC
Co-I: Dr. David Chato, NASA GRC
PS: John McQuillen, NASA GRC
PM: William Sheredy, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Objective:

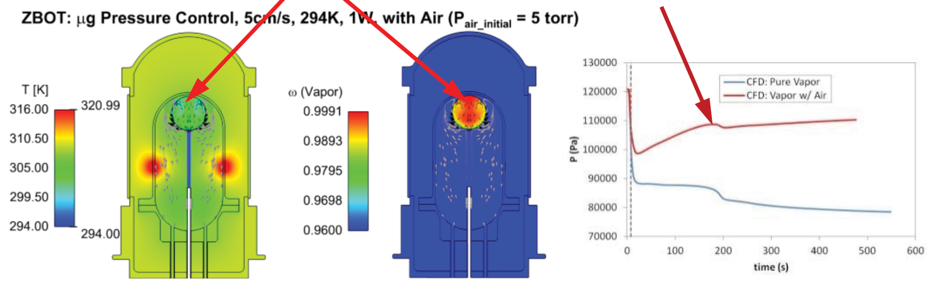
- Noncondensable gases can significantly affect Zero-Boil-Off (ZBO) storage tank pressurization and pressure reduction, especially, in microgravity with the danger of deteriorating tank pressure control
- There are currently no microgravity data on the effect of Non-condensable on evaporation/condensation rates in microgravity.
- This research will investigate three important effects of non-condensable gases on the transport and phase change phenomena that control tank pressure. These effects can be best studied when they are readily unmasked in microgravity:
  - The transport barrier created by non-condensable in the ullage during microgravity pressurization and pressure control.
  - The creation of thermocapillary convection induced by non-condensable and its effect on mixing, stratification and destratification in the liquid.
  - The penetration of noncondensbles into the Knudsen layer and its impact on condensation during microgravity pressure control.

Development Approach:

- Flight Experiment: ***Modify*** the ZBOT-1 hardware and diagnostics for non-condensable gas studies. Obtain microgravity data to determine the effect of the noncondensables on tank pressurization, thermal de-stratification, and pressure reduction through mixing/cooling in microgravity.
- Theoretical Work: ***Expand*** the existing ZBOT-1 two-phase CFD model by incorporating the non-condensable gas kinetics, species transport, and Marangoni convection submodels. ***Validate*** the expanded two-phase CFD model and submodels.

Residual noncondensable forms transport barrier for vapor condensation

NonCondensable gas impedes pressure reduction in space



Hand-in-Hand Microgravity & 1G Experimentation & Computational Modeling

ISS Resource Requirements

Accommodation (carrier)	Microgravity Science Glovebox
Upmass (kg) (w/o packing factor)	50 Kg*
Volume (m^3) (w/o packing factor)	0.1 m^3*
Power (kw) (peak)	0.445 kw (0.314 kw max continuous)
Crew Time (hrs) (installation/operations)	13 hrs. total
Launch/Increment	Launch: 2020

*ZBOT-2 new hardware only

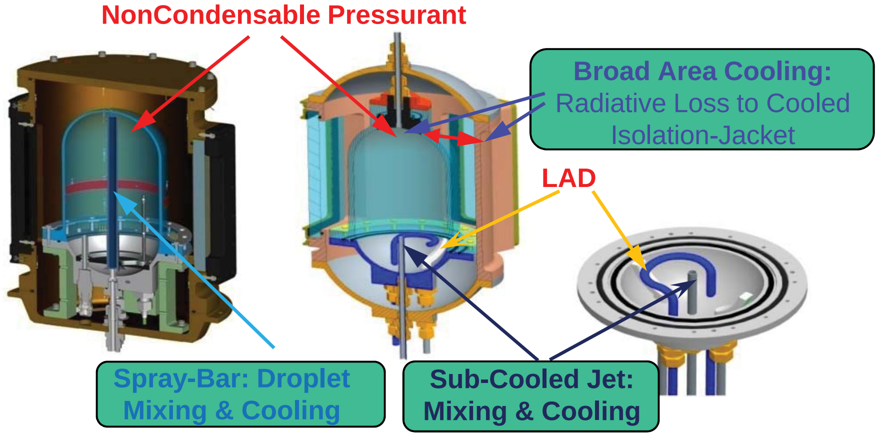
Project Life Cycle Schedule

Milestones	Kickoff	SCR/RDR	PDR	CDR/VRR	Phase III Safety	FHA	Launch	Ops Complete	Final Report
Actual/ Baseline	10/15	9/16	9/17	9/18	7/19	9/19	1/20	3/20	3/21

Zero Boil-Off Tank-3 (ZBOT-3) Experiment: Active Cooling

Glenn Research Center

PI: Dr. Mohammad Kassemi, NCSER/GRC
Co-I: Dr. David Chato, NASA GRC
PS: John McQuillen, NASA GRC
PM: William Sheredy, NASA GRC
Engineering Team: ZIN Technologies, Inc.



Objective:

- The Spray-Bar-Droplet and Jet-Mixing active cooling pressure control mechanism have not been tested in microgravity.
- There are no microgravity data on droplet dispersion, transport, and phase change although all of these phenomena are strongly gravity-dependent.
- This experiment will perform temperature, pressure and non-intrusive velocity measurements and phase and droplet visualization to:
  - examine the break-up and heat & mass transport characteristics of droplets in microgravity
  - record the residence time of the droplets in the ullage in microgravity
  - compare the thermal de-stratification and pressure reduction time constants of spray-bar and jet mixing mechanisms at different fill-levels, heat inputs, and jet velocities in presence and absence of non-condensables.

Development Approach:

- Flight Experiment: ***Modify*** the ZBOT-1/2 hardware to incorporate spray bar and broad area cooling technologies and diagnostics for these studies. Obtain microgravity data to determine the effectiveness of the different active pressure control strategies in microgravity.
- Theoretical Work: ***Expand*** the existing ZBOT-1/2 two-phase CFD model by incorporating spray-bar Lagrangian/Eulerian droplet phase change submodels. ***Validate*** the expanded two-phase CFD model and submodels.

ISS Resource Requirements

Accommodation (carrier)	Microgravity Science Glovebox
Upmass (kg) (w/o packing factor)	50 Kg*
Volume (m^3) (w/o packing factor)	0.1 m^{3}*
Power (kw) (peak)	0.445 kw (0.314 kw max continuous)
Crew Time (hrs) (installation/operations)	13 hrs. total
Launch/Increment	Launch: 2023

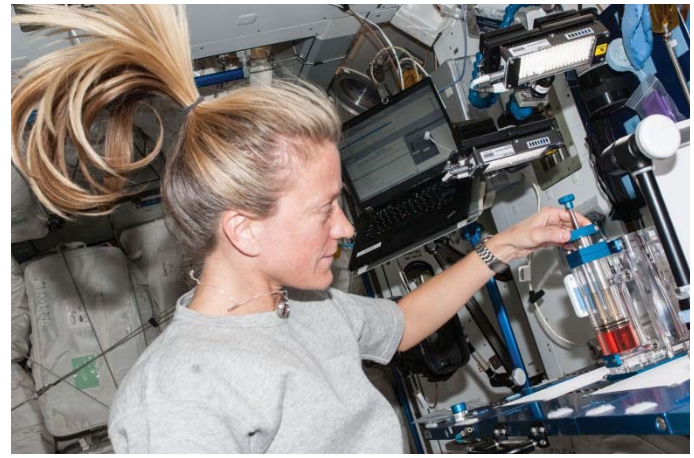
*ZBOT-3 new hardware only

Project Life Cycle Schedule

Milestones	Kickoff	SCR/RDR	PDR	CDR/VRR	Phase III Safety	FHA	Launch	Ops Complete	Final Report
Actual/ Baseline	10/18	9/19	9/20	9/21	7/22	9/22	1/23	3/23	3/24

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

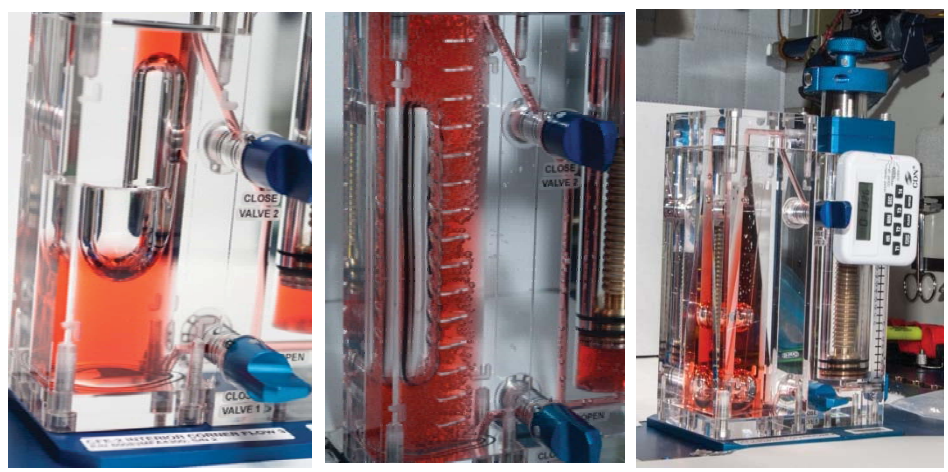
- Series of handheld vessels with various test chamber geometries to investigate the behavior of capillary flow phenomena in wicking structures such as interior corners and small gaps created by a vane and the test chamber wall.
- The working fluid is silicone oil of various viscosities, depending on 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.



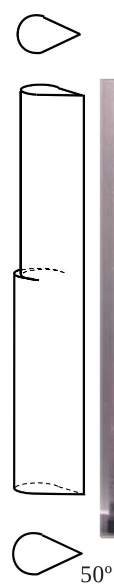
Interior Corner Flow Modules (ICF3, ICF 8 and ICF9)

PI: Prof. Mark Weislogel, Portland State University

Capillary Flow Experiments-2 (CFE-2) Science Summary

- **Summary:** CFE-2 currently has 11 CFE-2 vessels on board the International Space Station. The CFE-2 vessels are hand-held experiments and operated one-at-a-time in the Maintenance Work Area (MWA). Each vessel contains a unique geometry to study capillary flow.
- **Description:** The CFE-2 objective is to investigate the role of capillary forces in the transport and storage of fluid systems in space. Capillary forces can be exploited to control fluid orientation and enable predictable performance for large mission critical systems involving fluids.
- **Space Application:** Technologies in space use capillary forces to position and transport fluid. CFE-2 provides improved design knowledge in the storage and transport of liquids in space thereby increasing system reliability, decreasing system mass, and reducing overall system complexity. Results from these experiments will guide the design of capillary devices such as 3D vane networks and tapered screen geometries for bubble-free collection and positioning of fuels, cryogens, and water for waste water treatment, and air revitalization
- **Earth Application:** CFE-2 results will also enhance performance and design strategies of fluid systems on Earth such as lab-on-chip technologies, and in-line passive phase separators.

CFE-2 Vane Gap: *A progression of increasing vane angles reduces the gap between the vane and the chamber wall. When the dial is aligned with the critical angle, capillary wetting occurs and the fluid is transported to the top of the test chamber.*



Interior Corner Flow 4 (ICF4): *The snow-cone shaped test chamber includes a step change in radius along the axial direction of the test chamber. When the bubble spans the step, a pressure difference develops causing the bubble to move from the top to bottom.*

Two-Phase Flow Separator Experiment (TPFSE)

Glenn Research Center

PI: Dr. Georges Chahine, DYNAFLOW, Inc.
PI: Prof. Yasuhiro Kamotani, Case Western Reserve University
Co-I: Prof. Jaikrishnan Kadambi, Case Western Reserve University
PS: Lauren Sharp, NASA GRC
PM: Nang Pham, NASA GRC

Objectives:

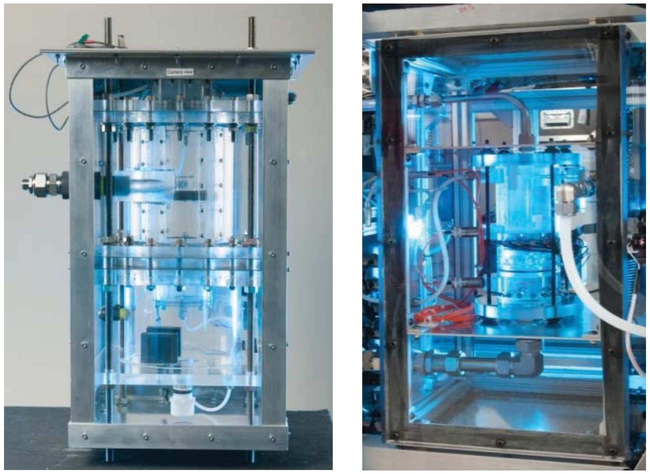
- Develop and evaluate the performance of a gas-liquid phase separator suitable for space applications including the transient and steady-state instability behavior
- Utilize DYNAFLOW's DYNASWIRL® technology to generate high intensity swirl flow with no moving parts
- Operate close to cavitation inception in the core of the vortex line for efficient separation at low void fractions (DYNAFLOW)
- Validate and verify the multiphase CFD modeling approaches that have been developed to simulate the complicated two-phase transport processes associated with phase separation in microgravity. (CWRU)

Relevance/Impact:

- Gas-liquid separators are a critical component in Active Thermal Control Systems (ATCS) and Environmental Control and Life Support Systems (ECLSS) applications.
- Requiring no moving parts, cyclonic phase separation improves performance, increases component life, and significantly reduces cost and weight while improving reliability.

Development Approach:

- TPFSE is a joint investigation to study cyclonic phase separation with two different design concepts. The DYNAFLOW concept includes an inner chamber with tangential slots. The CWRU concept includes a movable baffle plate and interchangeable injection nozzle.



The TPFSE test sections, DYNAFLOW (left) and CWRU (right), with containment for integration in a test rig for testing

ISS Resource Requirements

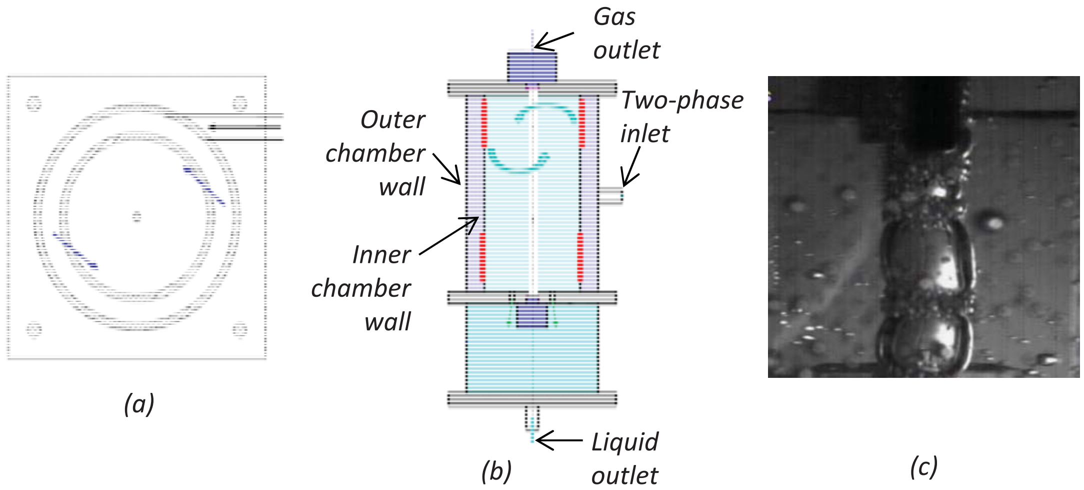
Accommodation (carrier)	Fluids Integrated Rack (FIR)
Upmass (kg) (w/o packing factor)	210 (prelim est.)
Volume (m^3) (w/o packing factor)	0.247 (prelim est.)
Power (kw) (peak)	2.1 (prelim est.)
Crew Time (hrs) (installation/operations)	10hrs (prelim est. – 5hrs setup & 5hrs disassemble; 3hrs (prelim est. - Test Section, Diagnostic Module & SSDs swap out; 200hrs (prelim est. - autonomous ops)
Launch/Increment	TBD

Milestones	SCR	RDR	PDR	CDR	Phase III Safety	FHA	Launch	Ops complete	Final Report
	5/2013	9/2016	10/2017	12/2018	5/2020	8/2020	1/2021	2021	Return +12mo

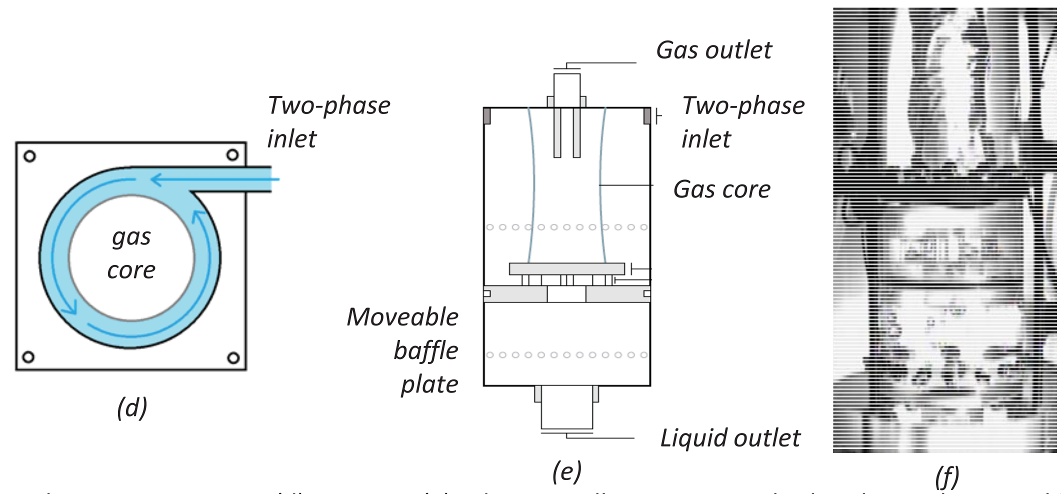
Two-Phase Flow Separator Experiment (TPFSE)

Science Summary:

- The DYNAFLOW and CWRU concepts both utilize inertia from a tangentially injected two-phase flow to separate the liquid from the gas phase.
- These cyclonic two-phase separator concepts were tested during flights on the reduced gravity aircraft in September 2013.
- During low-g operation in the reduced gravity aircraft:
  - A gas-liquid mixture entered the test section through the injection port.
  - The liquid (denser) phase accumulated to form a layer along the chamber wall, while the gas (less dense) formed a vortex core in the center of the chamber.
  - Large gas bubbles coalesced and formed a gas core.
  - Successful phase separation was observed as liquid and gas were extracted at opposite ends of each test section.
- Test parameters, including liquid flow rate, gas flow rate, were varied during the reduced gravity aircraft campaign to understand the performance and operability limits of each phase separator.



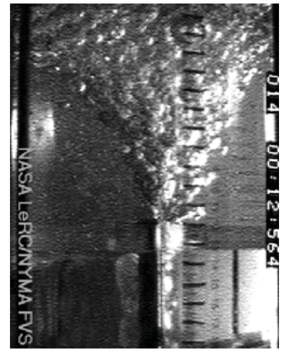
The DYNAFLOW concept – (a) top view, (b) side view – illustrates the inner and outer chambers along with the two-phase inlet and gas/liquid outlets. A science image (c) – an enlarged view of the gas core within the inner chamber shows coalescence during a low-g aircraft flight.



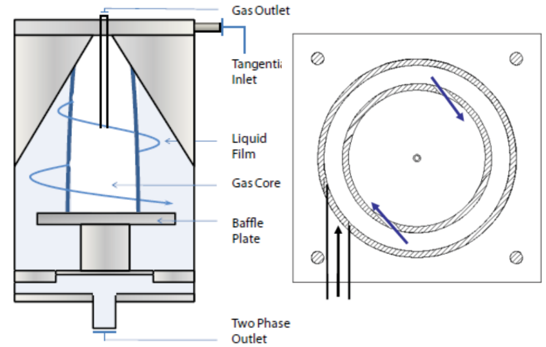
The CWRU concept – (d) top view, (e) side view – illustrates a single chamber with a movable baffle plate, the two-phase injection port, and the gas/liquid outlets. A science image (f) of the gas core during a low-g aircraft flight. The baffle plate bounds the gas core to ensure no gas enters the liquid outlet.

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) – 2018

- Two PI Teams will share common test hardware to study different aspects.
- Will address the design and performance of passive two-phase flow separator technologies.
- Determine range of flow rates for acceptable performance.
- Quantify the effect of fluid properties and separator geometry.
- Determine separator response and stability envelope to startup, shutdown and liquid slugging conditions.
- Passive separation is critical to high reliability and low power gas-liquid systems for used in thermal control and life support.

Packed Bed Reactor Experiment (PBRE)

Glenn Research Center

PI: Dr. Brian Motil, NASA GRC
Co-Is: Prof. Vemuri Balakotaiah, University of Houston
& Julie L Mitchell (JSC)
PS: Dr. Enrique Ramé, NCSER-NASA GRC
PM: Nang Pham, NASA, GRC

Objectives:

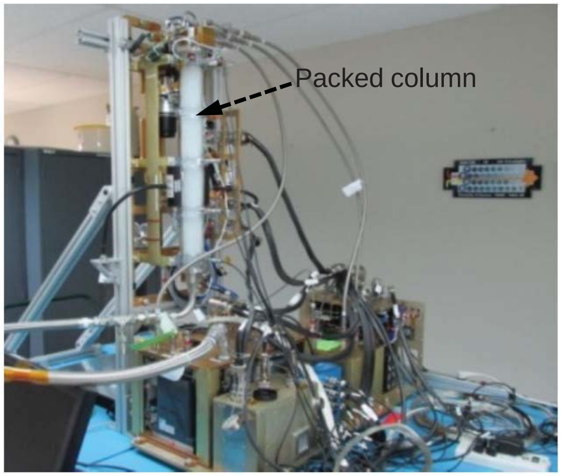
- Investigate role and effects of gravity on hydrodynamics of gas-liquid flow through porous media.
- Develop/validate scaling laws and design tools for future packed bed reactors in 0-g and partial-g environments, including start up and transient operations.
- Identify strategies to recover single-phase beds from undesired trapped gas bubbles.

Relevance/Impact:

- Directly aligns with high priorities from the NRC Decadal survey on Biological and Physical Sciences (1) and the NRC 2000 report on Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies (2):
  - AP-2: Provides a study of a critical multiphase flow component for life support systems (1)
  - TSES-6: Provides a fundamental study in porous media under microgravity conditions (1)
  - T-6: Lack of understanding of partial g on life support systems (1)
  - T-22: lack of closed loop water recovery (1)
  - Multiphase flow and heat transfer: Recomm. #1, 2 & 7 p. 181 (2)
- Two-phase components are critical to life support and thermal control systems.

Development Approach:

- Completed extensive (but time-limited) low-G aircraft tests.
- Two packing types: wetting and non-wetting to probe wettability effects.
- Engineering model hardware and Proto-flight unit.
- Develop on-orbit replaceable test section to extend experiment capabilities for future development of two-phase components/devices.



PBRE Engineering Model Unit. The column is packed with 3mm glass beads

ISS Resource Requirements

Accommodation (carrier)	Microgravity Science Glovebox
Upmass (w/o packing factor)	125 kg
Volume (w/o packing factor)	0.150 m^3
Peak Power	0.75 kW
Crew Time	8 hours (4hrs setup; 4hrs disassemble) 2 hours (Test Module and SSDs change-out)
Autonomous Ops	200 hours
Launch/Increment	SPACEX8/Inc 44

Project Life Cycle Schedule

Milestones	SCR	RDR	PDR	CDR	FHA	Launch	Ops	Final Report
	6/2005	2/2011	12/2011	3/2013	3/2015	8/2015	Inc. 47	Return +12mo

Packed Bed Overview

Engineering Model column packed with 3-mm Teflon beads in the ZIN fabrication area. An identical column is packed with 3-mm glass beads.

- Pressure drop for 2-phase flow in micro-g drastically different from 1-g
- Flow regime boundaries in micro-g fundamentally different from 1-g:
  - Bubbly-to-Pulse Flow regime boundary exists only in micro-g
  - For similar gas and liquid flows, the 1-g flow regime boundary is trickle-to-pulse
- Pressure drop and Flow Regime boundary correlations need to be recreated in micro-g before reliable design methods for 2-phase flow in packed beds can be developed

Packed Bed Reactor Experiment - Applied: PBRE-A (proposed)

PI: TBD from MSFC (2 PIs)
Co-I: Dr. Brian Motil, NASA, GRC
PS: Dr. Enrique Ramé, NCSER-NASA GRC
PM: Nang Pham, NASA, GRC

Objectives:

- Study the role and effects of gravity on hydrodynamics of gas-liquid flow through realistic packed beds

One of the packed columns used in the Biological Water Processors (in development)

Selected Applications:

- Aqueous-Phase Catalytic Oxidation (APCO) System
  - Prototype catalytic oxidation system (post-processor for water recovery systems)
- Microbial Check Valve (MCV)
  - Potable water with 2 ppm iodine to prevent microbial growth
- Activated Carbon/Ion Exchange (ACTEX)
  - Removes iodine from potable water before crew consumption
- Ion Exchange for Calcium Removal (in development)
  - Removes Ca++ ions from urine to prevent calcium sulfate precipitation in the ISS Urine Processor Assy
- Volatile Removal Assembly (VRA)
  - A catalytic oxidation system for water treatment
- IntraVenous Fluid GENeration (IVGEN)
  - A deionizing resin bed to remove contaminants to standards of the United States Pharmacopeia (USP)

IVGEN packed column

Development Approach:

- Utilize PBRE hardware capability to replace test sections to expand testing to more realistic packed beds
- Develop test sections with realistic packing used in current or future space applications

BACK - UP

Constrained Vapor Bubble-2 (CVB-2)

WBS: 904211.04.02.20.06

Glenn Research Center

PI: Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute
Co-I: Prof. Peter C. Wayner, Jr., Rensselaer Polytechnic Institute
PS: Dr. David F. Chao, NASA GRC
PM: Ronald Sicker, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Objective:

- Determine the fundamental transport in a prototype wickless heat pipe 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 for a complex (~94% Pentane/ 6% Iso-Hexane) binary fluid in microgravity.

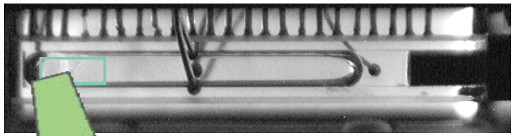
Relevance/Impact:

- Results will lead to optimally designed heat pipes (for ground and space) that will operate at full capacity and provide significant weight savings.
- CVB-2 will provide the understanding of the maximum achievable performance of simplified heat pipes based on corner flows using a complex fluid.
- 22 papers and publications from original CVB, exceeded science and engineering objectives. Results in Chemical Engineering Textbook "Transport Phenomena Fundamentals", Joel Plawsky, 2010 and Second edition 2013.

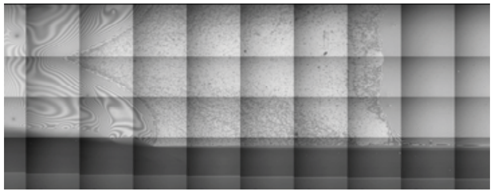
Development Approach:

- The CVB/LMM is designed for autonomous ground operation. Crew time is required for initial installation and check out in the FIR) sample change out, and removal from FIR.
- Re-fly CVB 30mm module with binary mixture.

Astronaut T. J. Creamer installing the first CVB Module on March 20, 2010.



(Top) 30mm CVB pentane module full scale. (Bottom) 10x images of the condensation and vapor region.



ISS Resource Requirements

Accommodation (carrier)	Fluids Integrated Rack (FIR)/LMM
Upmass (kg) (w/o packing factor)	6 Kg for CVB-2
Volume (m^3) (w/o packing factor)	0.009 CVB-2
Power (kw) (peak)	0.5kw for CVB/LMM 1.1 kw for FIR/CVB/LMM
Crew Time (hrs) (installation/operations)	5 Hours
Autonomous Operations	250 hrs/module
Launch/Increment	ATV4/Increment 35-36, OPS – 35-36

Project Life Cycle Schedule

Milestones	SCR	RDR	PDR	CDR	VRR	Safety	FHA	Launch	Ops	Return	Final Report
Actual/ Baseline	9/97 CVB	8/12 CVB-2	2/02 LMM/CVB	12/03 LMM/CVB	8/04 LMM/CVB	Phase III 11/12	1/13	6/13	Inc 35-38	10/2014	2015

Heat Pipe Experiment - Loop (HPE-L) (Proposed)

PI: Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute
Co-I: Dr. David F. Chao, NASA GRC, Dr. Brian J. Motil, NASA GRC
Project Scientist: Eric Golliher, NASA GRC
PM: Ronald Sicker, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Concept drawing from: NIAC Proposal NNH14ZOAOO1N-14NIAC (Plawsky, Motil, Chao)

Objective:

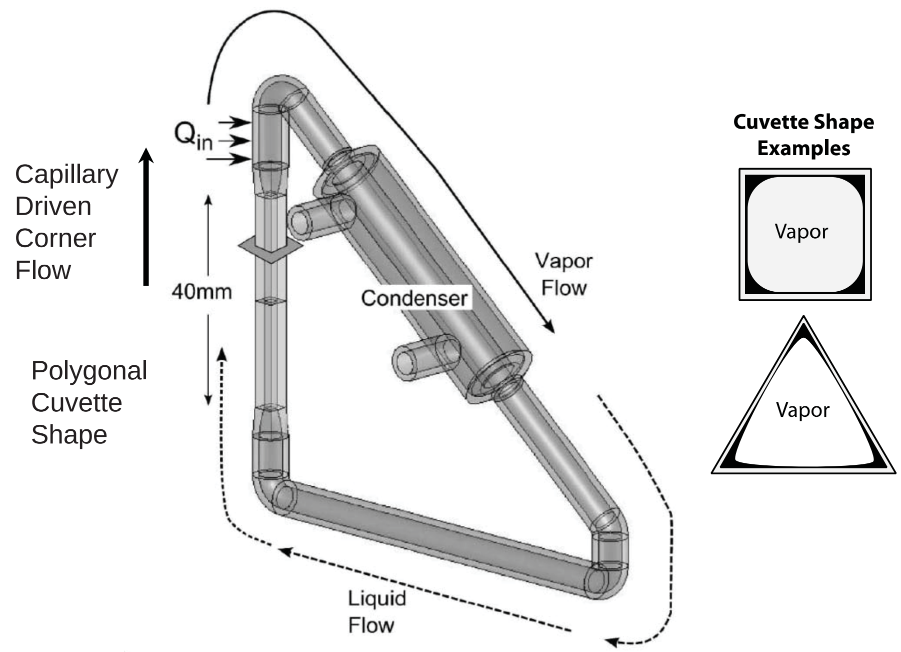
- Development and spaceflight test of a prototype loop heat pipe facility that would be used to cool critical electronic and life support systems aboard spacecraft.
- Novel design based on the Constrained Vapor Bubble that provides for complete control of the vapor-liquid interface using wickless, channel geometry designs, capillary flow, and complex fluid mixtures to eliminate the need for wicks and minimize Marangoni stresses.

Relevance/Impact:

- Contains no moving parts to fail and can be made lightweight.
- Offers improved performance, reliability, and operability, especially in microgravity.
- Is directly applicable for cooling critical civilian and military components.
- Designed to to manipulate the vapor-liquid interface using specially designed cross sectional shapes and Marangoni forces driven by the heater and condenser sections.
- Producing paper claiming discovery of new limit to heat pipe operation called the Marangoni limit

Development Approach:

- The CVB/LMM is designed for autonomous operation through scripts and ground commands.
- Crew time is required for initial installation and check out in the Fluids Integrated Rack (FIR), sample change out, and removal from FIR.



Loop heat pipe configuration

Fluids used: pentane/isohexane mixtures, water/isopropanol mixtures

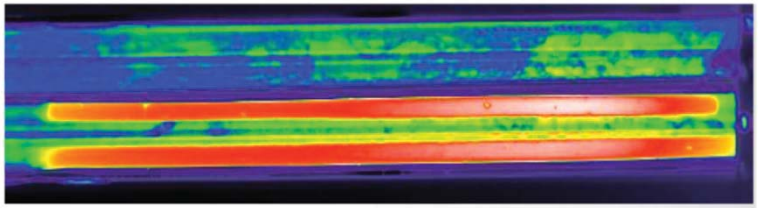
Project Life Cycle Schedule

Milestones	SCR	RDR	PDR	CDR	FHA	Launch	Ops complete	Final Report
Actual/ Baseline	2/2018	11/2018	11/2019	11/2020	12/2021	3/2022	6/2023	6/2024

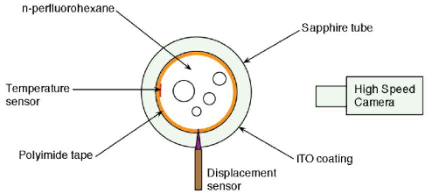
Multiphase Flow and Heat Transfer (MFHT)

ESA PI: Catherine Colin, Institut de Mécanique des Fluides de Toulouse
NASA PI: Prof. Jungho Kim, University of Maryland
PS: John McQuillen, NASA GRC
PM: Nancy Hall, NASA GRC
Engineering Team: NASA, GRC

Glenn Research Center



Flow boiling Image within a silicon tube visualized using an IR camera.



Concept of Experimental Technique.

Objective:

- Develop a mechanistic understanding of flow regime characteristics affect heat transfer coefficients
- Provide local heat transfer measurements with much higher temporal and spatial resolution than currently available to elucidate heat transfer mechanisms for various flow regimes.
- Determine mass flow limits of gravity influence on heat transfer and pressure drop

Relevance/Impact:

- Next generation spacecraft require the advantages of flow boiling heat transfer (isothermal, high heat flux), but lack the full understanding of the heat transfer mechanisms in microgravity.
- Enhance the development of two-phase thermal management systems, which provide isothermal control. By reducing the temperature difference between the heat source and radiator, the higher operating temperature for the radiator significantly reduces the area and weight of the radiator.

Development Approach:

- High speed thermography will measure local heat transfer to investigate effect of gravity and tube size on flow boiling.
- Utilize ESA Fluid Science Laboratory (FSL) Thermal Platform.
- NASA will design, build and test prototype insert to be installed in ESA FSL Thermal Platform.

ISS Resource Requirements

Accommodation (carrier)	Microgravity Science Glovebox
Upmass (kg) (w/o packing factor)	TBD
Volume (m^3) (w/o packing factor)	TBD
Power (kw) (peak)	TBD
Crew Time (hrs) (installation/operations)	TBD
Autonomous Ops Time (hrs)	TBD
Launch/Increment	1/2021

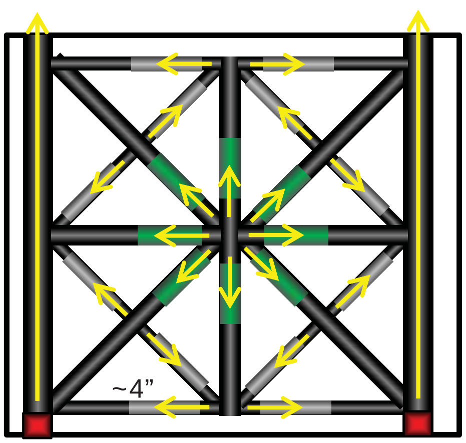
Project Life Cycle Schedule

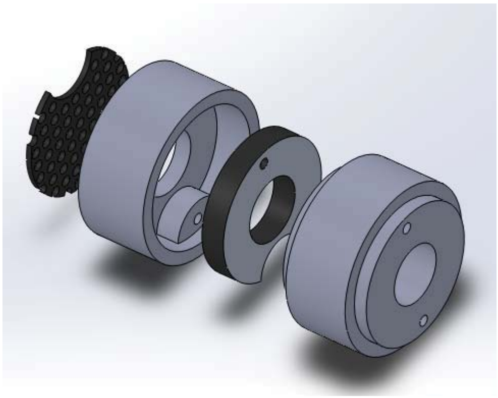
Milestones	SCR	RDR	PDR	CDR	Safety	PSR	FHA	Launch	Ops complete	Final Report
Planned	9/2016	9/2017	9/2018	9/2019	8/2020	9/2020	9/2020	1/2021	6/2022	6/2023

Revision Date: 08/22/2014

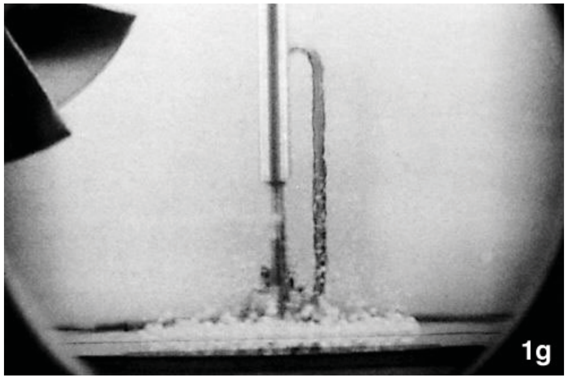
EHD Technology Applications

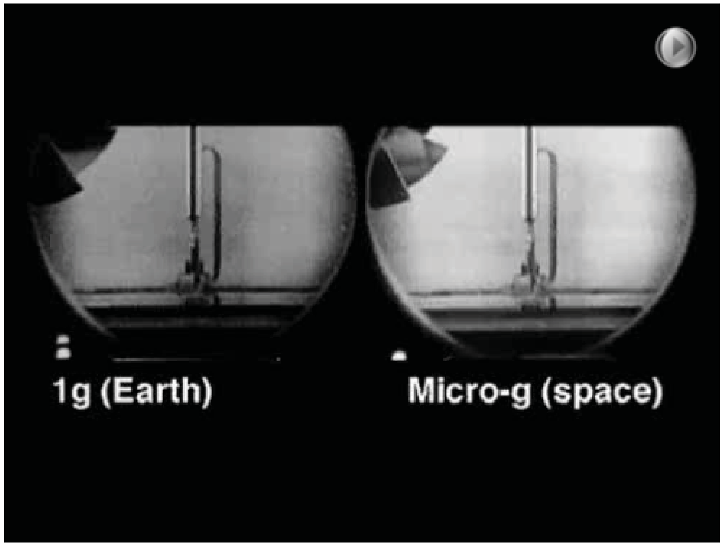
- CubeSats and nano-satellite class missions are gaining significant traction within NASA and the commercial space industry. Embedded thermal systems, such as EHD based devices investigated herein, provide significant Size, Weight and Power (SWaP) engineering advances.
- When combined with advanced small-scale manufacturing, embedded thermal control systems can take advantage of high temperature heat acquisition (lower thermal resistance), optimized heat transfer surface area and inherently high heat transfer coefficients yielded by the EHD technique.
- The PI and Co-I are simultaneously exploring a prototype single phase EHD based, bio-inspired multi-functional structural thermal device for the United States Air Force Research Laboratory Space Vehicles Directorate.

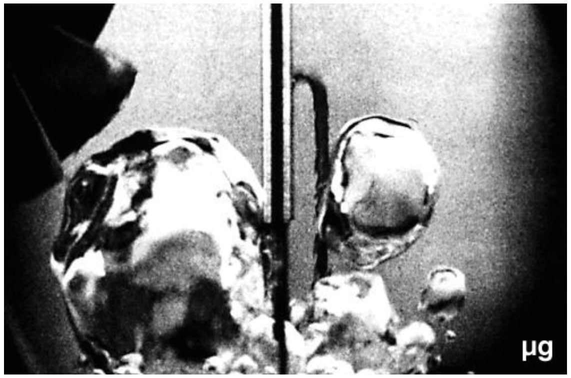




Pool Boiling (for EHD justification)



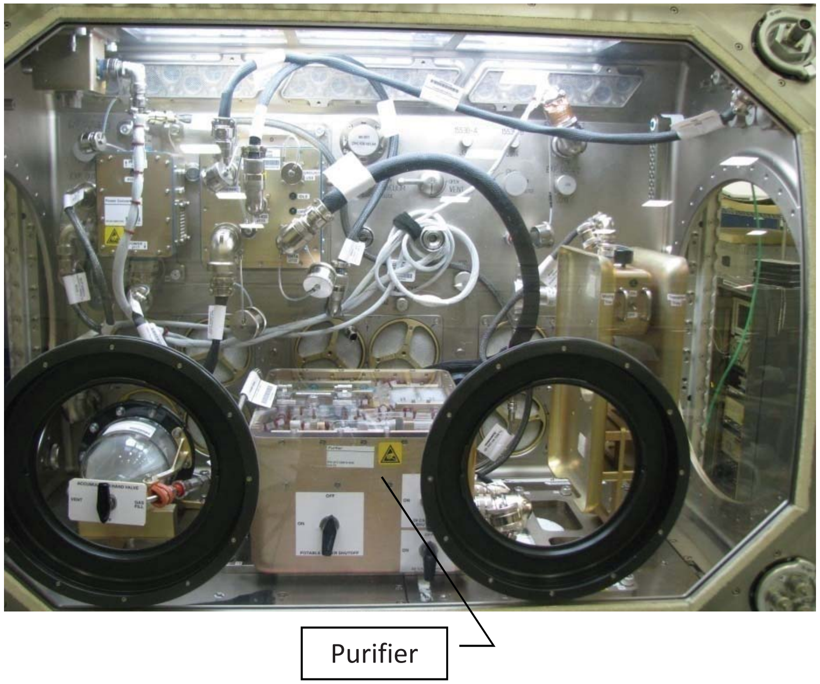




- This figure illustrates remarkable differences in pool boiling between normal gravity and microgravity conditions.
  - In normal gravity the heater surface is covered with a large number of small bubbles that rise due to buoyancy.
  - In microgravity a large bubble of vapor appears at the top of the heater. Small bubbles merge into the large one at the heater surface.
  - These difference give rise to significant changes in heat transfer coefficient and critical or buoyant heat flux.

Space Technology Applications (for Packed Beds)

- IntraVenous Fluid GENeration (IVGEN): demonstrated a microgravity compatible water purification and pharmaceutical mixing system.
- Successfully flown in March, 2010.
- Deionizing resin bed:
  - Remove contaminants from feedstock water
  - Meet purity level standards of the United States Pharmacopeia (USP)
- Required minimal liquid velocity to clear bubbles from packed bed and minimal flow rate to meet purified water production requirements.
- Model was used for:
  - ~6" packed bed
  - 5/8" inner diameter
  - 0.4 to 0.5 diameter packing
  - Actual flow rate: 28 ml/min
  - "Equivalent flow": 15.8 liter/min



International Cooperation: NASA Physical Sciences Research

- Multilateral Engagement: International Microgravity Strategic Planning Group (IMSPG)
  - Coordinate the development and use of ISS research among microgravity research programs in areas of common interest to maximize the productivity of microgravity research internationally.
  - Meets once a year on the margins of the annual meeting of the American Society for Gravitational and Space-Research
  - Members: ASI, CNES, CSA, ESA, DLR, JAXA, NASA and Roscosmos
  - Priority Areas for International Coordination Include:
    - All disciplines within Physical Sciences
    - Sharing facilities, experiment-specific hardware, data, etc.

International Cooperation:
NASA Physical Sciences Research

- Bilateral Engagement: NASA works directly with other space agencies or research institutions - especially the ISS partner agencies (examples):
  - ESA: Collaborative research in the ESA Material Science Laboratory (MSL) furnaces using ESA-developed cartridges and supporting development of NASA cartridges, Electro Magnetic Levitation (EML) facility and Microwave Ground link stations for the Atomic Clock Ensemble in Space Experiment. (common and unilateral objectives)
  - ASI: Collaboration to study Biofuels using the NASA Combustion Integrated Rack
  - CNES: Joint use of a CNES DECLIC hardware for joint investigations in fluid physics and/or solidification of transparent materials.
  - JAXA: Cooperation on the combustion of fuel droplets using NASA's Combustion Integrated Rack (CIR) and JAXA's Group Combustion Experiment Module (GCEM) hardware to perform experiments (common and unilateral objectives).
  - Russia: OASIS – Scientists' protocol and ISS Program protocol – study the unique behavior of liquid crystals in microgravity using the NASA Microgravity Sciences Glovebox

Benefits of International Cooperation on ISS Research

- The ISS laboratory has reached a mature configuration including many unique research facilities provided by each International Partner.
- To maximize the utilization of these facilities, the partners are pursuing cooperative arrangements where partners perform investigations in each other's facilities and utilize each others on-orbit (and ground) resources.
- Benefits:
  - Allows access to more researchers from more countries
  - Fosters cooperative research objectives between partners
  - Allows complementary research to be performed in multiple facilities
  - Facilitates wide distribution of research data
  - Avoids duplication of facilities/capabilities in the severely limited volume of the ISS
  - Reduces crew training and operations planning by re-using existing facilities/capabilities
  - Reduces overall cost of research
  - Maximizes the return on investment for each facility

International Collaboration

- International Collaboration for each Physical Sciences Discipline:
  - Biophysics
  - Combustion Science
  - Complex Fluids
  - Fluid Physics
  - Fundamental Physics
  - Materials Science

NASA's International Cooperation in Physical Sciences on ISS

Theme	Acronym	Experiment	International Partners							
			ESA	JAXA	CSA	ROS COS MOS	CNES	DLR	ASI	KARI
Biophysics	PROTEIN	Protein Nucleation and Growth Kinetics Experiment (Vekilov)	S							
	Nano Step-2	Solution Crystallization Observation Facility, (SCOF), Suzuki, (Vekilov)		S						
	Delucas	Effect of Macromolecular Transport on Protein Crystillization						P		
	Vekilov	Solution Convection and Nucleation Precursors in Protein Crystallization								
	Snell	Growth Rate Dispersion of Biological Crystal Samples								
	Hirsa	Amyloid Fibril Formation in Microgravity								

Blue Print: Experiment Acronyms in Blue are Sponsored by non-NASA Agency
S: Sponsor
P: Participant

NASA's International Cooperation in Physical Sciences on ISS

Theme	Acronym	Experiment	International Partners							
			ESA	JAXA	CSA	ROSCOSMOS	CNES	DLR	ASI	KARI
Combustion Science	SOFIE	Solid FLAmabiity of Materials Experiment								
	BASS-2	Burning and Suppression of Solids								
	FLEX-2	Flame Extinguishment Experiment–2								
	FLEX-2J	Flame Extinguishment experiment– with JAXA		P						
	SCE	Solid Combustion Expt. - 2012 JAXA AO, Fujita,Olsen..(2015, MSPR)		S						
	GCE	Group Combustion Experiment - 2D droplet array		S						
	FLEX-ICE	Flame Extinguishment experiment–Italian Combustion Experiment							P	
	ISFSS	Int'l Standard of Fire Safety in Space – 2012 JAXA AO, Fujita,Olsen,etal (2016,MSPR)		S						
	ACME	Advanced Combustion via Microgravity Experiments (Gaseous)								
	SCWO (planned)	Super Critical Water Oxidation	P				P			
	SCWM	Super Critical Salt Water Mixture Experiment					S			

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Theme	Acronym	Experiment	International Partners							
			ESA	JAXA	CSA	ROS COS MOS	CNES	DLR	ASI	KARI
Complex Fluids	ACE	Advanced Colloids Experiment	P							P
	COLLOID	Colloidal Solids Experiment	S							
	PASTA-LIFT	PArticle STAbilized Emulsions and Foams–Liquid Film Tensiometer	S							
	Soft Matter Dynamics (formerly FOAM-C)	Foam Optics and Mechanics–Coarsening	S							
	BCAT-C1	Binary Colloidal Alloy Test-Canada 1			S					
	InSPACE-3+	Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions-3+								
	OASIS	Observation and Analysis of Smectic Islands in Space				P		P		
	VIPGRAN (COMPGRAN)	Compaction and Sound Transmission in Dense Granular Media	S							

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Theme	Acronym	Experiment	International Partners							
			ESA	JAXA	CSA	ROS COS MOS	CNES	DLR	ASI	KARI
Fluid Physics	FBCE	Flow Boiling and Condensation Experiment								
	RUBI	Reference mUltiscale Boiling Investigation	S							
	MFHT	Multiphase Flow with Heat Transfer	S							
	ZBOT	Zero Boiloff Experiment								
	ZBOT-2	Zero Boiloff Experiment–2								
	CCF	Capillary Channel Flow						S		
	CFE-2	Capillary Flow Experiment–2								
	DOLFIN II	Dynamics of Liquid Film/ Complex Wall Interaction	S							
	CVB-2	Constrained Vapor Bubble–2								
	EHD	Electro-hydrodynamic flow								
	PBRE	Packed Bed Reactor Experiment								
	TPFSE	Two Phase Flow Separator Experiment								
	JEREMI	JAXA Marangoni Flow Experiment (Narayanan, Kamotani)		S						
	VIPIL-Faraday (Planned)	ESA Vibration in Liquids experiment, planning stages (Narayanan)	S							

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Theme	Acronym	Experiment	International Partners							
			ESA	JAXA	CSA	ROS COS MOS	CNES	DLR	ASI	KARI
Fundamental Physics	ACES	Atomic Clock Ensemble in Space	S							
	SOC	Space Optical Clock	S							
	QTEST (planned)	Quantum Weak Equivalence Principle	P							
	CAL	Cold Atom Laboratory								
	PK-4	Plasma Kristall–4	S							
	PLASMALAB (planned)	Kinetic studies of strongly coupled systems: Interdisciplinary Research with Complex Plasmas	S							
	ALI-R	Alice Like Insert - reflight					S			

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Theme	Acronym	Experiment	International Partners							
			ESA	JAXA	CSA	ROS COS MOS	CNES	DLR	ASI	KARI
Materials Science	CSLM-4	Coarsening of Dendritic Solid-Liquid Mixtures-4								
	DSI-R/SPADES	Spatiotemporal Evolution of Three-Dimensional Dendritic Array Structures					S			
	MICAST	Microstructure Formation in Castings	S							
	CETSOL	Columnar to Equiaxed Transition in Solidification Processing	S							
	SETA	Solidification along an Eutectic path in Ternary Alloys	S							
	METCOMP	Metastable solidification of Composites	S							
	SISSI	Silicon ISS Investigation	S							
	RDGS	Reduction of Defects in Germanium Silicon	S							
	CGTS	Crystal Growth of Ternary Compound Semiconductors	S							
	IE-ELF	Interfacial Energy- Electrostatic Levitator Furnace – 2012 JAXA AO, Watanabe, Heyers, et al. (2017, ELF)		S						
	GEDS	Gravitational Effects in Distortion in Sintering								
	FAMIS	Formation of Amorphous Metallics In Space								
	FOG	Formation of Gasarities								
	THERMOLAB	Thermophysical Properties of Liquid Metallic Alloys	S							
	ICOPROSOL	Thermophysical properties and solidification behavior of undercooled Ti-Zr-Ni liquids showing in icosahedral short-range order	S							
	PARSEC	Peritectic Alloy Rapid Solidification with Electromagnetic Convection	S							

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MAPPING
Physical Sciences Research to Space Technology Roadmaps

- TA02: In-Space Propulsion Systems*
  - Propellant Storage, Transfer & Gauging Liquid
    - Zero Boiloff: ZBOT > ZBOT-2 > ZBOT-3, (TSES – 2***)
    - Fluid Management: CFE > CFE-2, CCF, (AP2)
- TA03: Space Power & Energy Storage
  - Power Generation: FBCE (AP1)
- TA05: Communication and Navigation: ACES (FP -2)
- TA06: Human Health, Life Support and Habitation Systems
  - Environmental Control and Life Support Systems and Habitation Systems
    - Air Revitalization, and Water Recovery & Management: PBRE > PBRE-A** > PBRR** (TSES- 6)
      - Liquid-Gas Phase Separation: CFE-2, TFPSE (AP1)
    - Waste Management: SCWM > SCWM-2 > SCWO** (TSES-6)
  - Environmental Monitoring, Safety and Emergency Response
    - Fire Prevention, Detection and Suppression
      - Materials Flammability: BASS-2 > SoFIE > MWT-FS** (NASA STD 6001 Test 1) (AP6, TSES – 8)
- TA12: Materials, Structures, Mechanical Systems and Manufacturing: FAMIS, MVCS (AP10)
- TA14: Thermal Management Systems
  - Heat Pipes: CVB > CVB-2 > CVB-3** > HPE-L** (AP1)
  - Two-Phase Pumped Loop Systems: FBCE, MFHT, EHD (AP1, TSES - 1)

** OCT Space Technology Roadmaps, 2014 (blue), ** proposed experiment, ***Decadal Survey Identifier*

Experiment Acronyms

ACES	Atomic Clock Ensemble in Space
BASS	Burning and Suppression of Solids
CFE	Capillary Flow Experiment
CCF	Capillary Channel Flow
CVB	Constrained Vapor Bubble
EHD	ElectroHydroDynamic flow experiment
HPE-L	Heat Pipe Experiment - Loop
FAMIS	Formulation of Amorphous Metals in Space
FBCE	Flow Boiling and Condensation Experiment

MsFHT	Multiphase Flow And Heat Transfer Experiment
MVCS	Morphological study in Variable Cross Section
MWT-FS	Microgravity Wind Tunnel - Fire Safety
PBRE	Packed Bed Reactor Experiment
PBRE-A	Packed Bed Reactor Experiment - Applied
PBRR	Packed Bed Reaction Rate Experiment
SoFIE	Solid Fuel Ignition and Extinction
TPFSE	Two Phase Flow Separator Experiment
ZBOT	Zero Boil-off Tank Experiment