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
Brian Motil, Deputy Branch Chief, Fluid Physics and Transport, GRC
John McQuillen, Senior Aerospace Engineer, GRC
SLPS Gravity-Dependent Physical Sciences Research

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

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

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

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

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

**Fundamental Physics**
- Space Optical/Atomic Clocks
- Quantum test of Equivalence Principle
- Cold atom physics
- Critical point phenomena
- Dusty plasmas
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
2. NASA develops CONOPS, performs all associated science activities, and manages payload integration.

2. NASA develops CONOPS, performs all associated science activities, and manages payload integration.

1. Science Definition Team to plan and oversee scientific requirements

3. ISS flight experiment operations

4. Digital Data downlink and sample return for analysis

5. Physical Science Informatics System

Flight Experiments

NRA to perform ground research based on data in informatics

Non-NRA Outside Data Users

CASIS

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

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

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

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
<th>Experiment concept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nucleate Boiling to critical Heat Flux (CHF) and Dry-out (for electrohydrodynamically induced flow)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nucleate Boiling to critical Heat Flux (CHF) and Dry-out for capillary induced flow</td>
<td></td>
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</tbody>
</table>
### Boiling and Condensation

**Continued**

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
<th>Experiment concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film condensation and drop wise condensation.</td>
<td>Film condensation in channels/tubes; partial to full condensation.</td>
<td>Condensation heat transfer coefficient for all flow regimes. Pressure drop for all flow regimes.</td>
</tr>
<tr>
<td></td>
<td>Direct contact condensation on subcooled droplets and agitated liquid-vapor interface.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Film and drop wise condensation on prepared surfaces; contoured and hydrophobic/hydrophilic surfaces.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Condensation pure vapor and vapor gas mixture on porous surfaces and substrates.</td>
<td></td>
</tr>
</tbody>
</table>
**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
**New Concepts**

14 Fluid properties. Refrigerants, 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

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.

ISS Resource Requirements

<table>
<thead>
<tr>
<th>Accommodation (carrier)</th>
<th>Fluid Integrated Rack (FIR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upmass (kg) (w/o packing factor)</td>
<td>225 kg (estimated)</td>
</tr>
<tr>
<td>Volume (m³) (w/o packing factor)</td>
<td>0.3 m³ (estimated)</td>
</tr>
<tr>
<td>Power (kw) (peak)</td>
<td>2500W (estimated)</td>
</tr>
<tr>
<td>Crew Time (hrs) (installation/operations)</td>
<td>TBD</td>
</tr>
<tr>
<td>Autonomous Operation</td>
<td>6 months</td>
</tr>
<tr>
<td>Launch/Increment</td>
<td>12/2017</td>
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</tbody>
</table>

Project Life Cycle Schedule

<table>
<thead>
<tr>
<th>Milestones</th>
<th>SCR</th>
<th>IDR</th>
<th>RDR</th>
<th>PDR</th>
<th>CDR</th>
<th>Ph III Safety</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops complete</th>
<th>Final Report</th>
</tr>
</thead>
</table>

Rev. Date: 8/2014
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.

Rankine Cycle very attractive option for high power systems (> 100 kWe)
• Test Fluid normal – PerFluoroHexane (nPFH)
• Thermophysical Properties

<table>
<thead>
<tr>
<th>Saturated Properties of FC-72</th>
<th>$P_{sat} = 1.0\times10^5 \text{ N/m}^2$ (14.50 psia)</th>
<th>$P_{sat} = 1.5\times10^5 \text{ N/m}^2$ (21.75 psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation temperature, $T_{sat}$ ($^\circ$C)</td>
<td>133.09°F (56.16°C)</td>
<td>68.86</td>
</tr>
<tr>
<td>Liquid density, $\rho_l$ (kg/m$^3$)</td>
<td>1593.42</td>
<td>1560.28</td>
</tr>
<tr>
<td>Vapor density, $\rho_v$ (kg/m$^3$)</td>
<td>13.20</td>
<td>19.52</td>
</tr>
<tr>
<td>Latent heat of vaporization, $h_{fg}$ (J/kg)</td>
<td>94.97x10$^3$</td>
<td>90.71x10$^3$</td>
</tr>
<tr>
<td>Liquid specific heat, $c_{pl}$ (J/kg.K)</td>
<td>1.10x10$^3$</td>
<td>1.12x10$^3$</td>
</tr>
<tr>
<td>Liquid viscosity, $\mu_l$ (kg/m.s)</td>
<td>435.67x10$^{-6}$</td>
<td>381.75x10$^{-6}$</td>
</tr>
<tr>
<td>Vapor viscosity, $\mu_v$ (kg/m.s)</td>
<td>11.56x10$^{-6}$</td>
<td>11.98x10$^{-6}$</td>
</tr>
<tr>
<td>Liquid thermal conductivity, $k_l$ (W/m.K)</td>
<td>53.82x10$^{-3}$</td>
<td>52.43x10$^{-3}$</td>
</tr>
<tr>
<td>Liquid Prandtl number, $Pr_l$</td>
<td>8.91</td>
<td>8.16</td>
</tr>
<tr>
<td>Surface tension, $\sigma$ (N/m)</td>
<td>8.39x10$^{-3}$</td>
<td>7.2x10$^{-3}$</td>
</tr>
</tbody>
</table>

• 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 the ITCS water loop
• Bulk Heater Power on ISS up to 1660 W
• Pressure 100 kPa to 200 kPa Absolute
• Temperature 20 to 120 °C
• 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
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

**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.

**Project Life Cycle Schedule**

<table>
<thead>
<tr>
<th>Milestones</th>
<th>SCR</th>
<th>RDR</th>
<th>PDR</th>
<th>CDR</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops Complete</th>
<th>Final Report</th>
</tr>
</thead>
</table>

Revision Date: 03/2015
Zero Boil-Off Tank (ZBOT) Experiment: Fluid Mixing

**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.

**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.

<table>
<thead>
<tr>
<th>Accommodation (carrier)</th>
<th>Microgravity Science Glovebox (MSG)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upmass (kg)</strong></td>
<td>114 kg</td>
</tr>
<tr>
<td>(w/o packing factor)</td>
<td></td>
</tr>
<tr>
<td><strong>Volume (m³)</strong></td>
<td>0.23 m³</td>
</tr>
<tr>
<td>(w/o packing factor)</td>
<td></td>
</tr>
<tr>
<td><strong>Power (kw)</strong></td>
<td>0.445 kw (0.314 kw max continuous)</td>
</tr>
<tr>
<td>(peak)</td>
<td></td>
</tr>
<tr>
<td><strong>Crew Time (hrs)</strong></td>
<td>13 hrs. total</td>
</tr>
<tr>
<td>(installation/operations)</td>
<td></td>
</tr>
<tr>
<td><strong>Launch/Increment</strong></td>
<td>Launch: SPX-7/45 &amp; 46 (Ops)</td>
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</tbody>
</table>

**Project Life Cycle Schedule**

<table>
<thead>
<tr>
<th>Milestones</th>
<th>SCR</th>
<th>RDR</th>
<th>PDR</th>
<th>CDR</th>
<th>VRR</th>
<th>Phase III Safety</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops</th>
<th>Return</th>
<th>Final Report</th>
</tr>
</thead>
</table>

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

**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 noncondensables 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.

**Accommodation (carrier)**
- Microgravity Science Glovebox

<table>
<thead>
<tr>
<th>Accommodation (carrier)</th>
<th>Microgravity Science Glovebox</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upmass (kg)</strong></td>
<td>50 Kg*</td>
</tr>
<tr>
<td>(w/o packing factor)</td>
<td></td>
</tr>
<tr>
<td><strong>Volume (m³)</strong></td>
<td>0.1 m³*</td>
</tr>
<tr>
<td>(w/o packing factor)</td>
<td></td>
</tr>
<tr>
<td><strong>Power (kw)</strong></td>
<td>0.445 kw (0.314 kw max continuous)</td>
</tr>
<tr>
<td>(peak)</td>
<td></td>
</tr>
<tr>
<td><strong>Crew Time (hrs)</strong></td>
<td>13 hrs. total</td>
</tr>
<tr>
<td>(installation/operations)</td>
<td></td>
</tr>
</tbody>
</table>

**Launch/Increment**
- Launch: 2020

**ISS Resource Requirements**

**Revision Date: 8/12/14**

**Hands-On**

**NonCondensable gas impedes pressure reduction in space**

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

**Project Life Cycle Schedule**

<table>
<thead>
<tr>
<th>Milestones</th>
<th>Kickoff</th>
<th>SCR/RDR</th>
<th>PDR</th>
<th>CDR/VRR</th>
<th>Phase III Safety</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops Complete</th>
<th>Final Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual/ Baseline</td>
<td>10/15</td>
<td>9/16</td>
<td>9/17</td>
<td>9/18</td>
<td>7/19</td>
<td>9/19</td>
<td>1/20</td>
<td>3/20</td>
<td>3/21</td>
</tr>
</tbody>
</table>

*ZBOT-2 new hardware only*
Zero Boil-Off Tank-3 (ZBOT-3) Experiment: Active Cooling

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

<table>
<thead>
<tr>
<th>Accommodation (carrier)</th>
<th>Microgravity Science Glovebox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upmass (kg) (w/o packing factor)</td>
<td>50 Kg*</td>
</tr>
<tr>
<td>Volume (m³) (w/o packing factor)</td>
<td>0.1 m³*</td>
</tr>
<tr>
<td>Power (kw) (peak)</td>
<td>0.445 kw (0.314 kw max continuous)</td>
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<tr>
<td>Crew Time (hrs) (installation/operations)</td>
<td>13 hrs. total</td>
</tr>
<tr>
<td>Launch/Increment</td>
<td>Launch: 2023</td>
</tr>
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</table>

*ZBOT-3 new hardware only

Project Life Cycle Schedule

<table>
<thead>
<tr>
<th>Milestones</th>
<th>Kickoff</th>
<th>SCR/RDR</th>
<th>PDR</th>
<th>CDR/VRR</th>
<th>Phase III Safety</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops Complete</th>
<th>Final Report</th>
</tr>
</thead>
</table>

Revision Date: 8/12/14
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.

PI: Prof. Mark Weislogel, Portland State University

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

Pl: 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.

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<th>Milestones</th>
<th>SCR</th>
<th>RDR</th>
<th>PDR</th>
<th>CDR</th>
<th>Phase III Safety</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops complete</th>
<th>Final Report</th>
</tr>
</thead>
</table>
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.
Gas-Liquid Separation Devices

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.

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

Pumped Separator for PBRE

Reduced Gravity Bubble Vortex

Cyclonic Concepts
Packed Bed Reactor Experiment (PBRE)

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.

Project Life Cycle Schedule

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<tr>
<th>Milestones</th>
<th>SCR</th>
<th>RDR</th>
<th>PDR</th>
<th>CDR</th>
<th>FHA</th>
<th>Launch</th>
<th>Ops</th>
<th>Final Report</th>
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ISS Resource Requirements

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<th>Accommodation (carrier)</th>
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<td>Upmass (w/o packing factor)</td>
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<tr>
<td>Volume (w/o packing factor)</td>
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<td>Peak Power</td>
<td>0.75 kW</td>
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<td>Crew Time</td>
<td>8 hours (4hrs setup; 4hrs disassemble) 2 hours (Test Module and SSDs change-out)</td>
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<tr>
<td>Autonomous Ops</td>
<td>200 hours</td>
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<tr>
<td>Launch/Increment</td>
<td>SPACEX8/Inc 44</td>
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</table>
Packed Bed Reactor Experiment (PBRE)

Packed Bed Overview

- 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

**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)

**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
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.

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.

Project Life Cycle Schedule

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<th>Milestones</th>
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<th>RDR</th>
<th>PDR</th>
<th>CDR</th>
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</table>

ISS Resource Requirements

- Accommodation (carrier) Flows Integrated Rack (FIR)/LMM
- Upmass (kg) (w/o packing factor) 6 Kg for CVB-2
- Volume (m³) (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
Heat Pipe Experiment - Loop (HPE-L)  (Proposed)

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 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.

Project Life Cycle Schedule

<table>
<thead>
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<th>Milestones</th>
<th>SCR</th>
<th>RDR</th>
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</table>

Concept drawing from: NIAC Proposal
NNH14ZOA001N-14NIAC (Plawsky, Motil, Chao)

Loop heat pipe configuration

Fluids used: pentane/isoctane mixtures, water/isopropanol mixtures
**Objective:**
- Develop a mechanistic understanding of flow regime characteristics affecting 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**

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<tr>
<td>Volume (m³)</td>
<td>(w/o packing factor)</td>
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<tr>
<td>Power (kw)</td>
<td>(peak)</td>
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**Project Life Cycle Schedule**

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**Revision Date:** 08/22/2014
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.

~4"
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 differences give rise to significant changes in heat transfer coefficient and critical or buoyant heat flux.
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 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

## Biophysics

<table>
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<th>Acronym</th>
<th>Experiment</th>
<th>International Partners</th>
</tr>
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<tr>
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<td>PROTEIN</td>
<td>Protein Nucleation and Growth Kinetics Experiment (Vekilov)</td>
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<td>Nano Step-2</td>
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<td>Delucas</td>
<td>Effect of Macromolecular Transport on Protein Crystallization</td>
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<td>Vekilov</td>
<td>Solution Convection and Nucleation Precursors in Protein Crystallization</td>
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<td>Snell</td>
<td>Growth Rate Dispersion of Biological Crystal Samples</td>
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<td>Hirsa</td>
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<td>BASS-2</td>
<td>Burning and Suppression of Solids</td>
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<td>FLEX-2</td>
<td>Flame Extinguishment Experiment–2</td>
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<td>FLEX-2J</td>
<td>Flame Extinguishment experiment– with JAXA</td>
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## Complex Fluids

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<td>Binary Colloidal Alloy Test-Canada 1</td>
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<td>InSPACE-3+</td>
<td>Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions-3+</td>
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## Fluid Physics

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<td>Flow Boiling and Condensation Experiment</td>
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<td>JAXA Marangoni Flow Experiment (Narayanan, Kamotani)</td>
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<td><strong>VIPIL-Faraday (Planned)</strong></td>
<td>ESA Vibration in Liquids experiment, planning stages (Narayanan)</td>
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# NASA’s International Cooperation in Physical Sciences on ISS

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<th>Experiment</th>
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<tr>
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<td>QTEST (planned)</td>
<td>Quantum Weak Equivalence Principle</td>
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*Blue Print*: Experiment Acronyms in Blue are Sponsored by non-NASA Agency

S: Sponsor  
P: Participant
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## Materials Science

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<td>MICAST</td>
<td>Microstructure Formation in Castings</td>
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<td>CETSO</td>
<td>Columnar to Equiaxed Transition in Solidification Processing</td>
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<td>SETA</td>
<td>Solidification along an Eutectic path in Ternary Alloys</td>
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<td>METCOMP</td>
<td>Metastable solidification of Composites</td>
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<td>SISSI</td>
<td>Silicon ISS Investigation</td>
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<td>RDGS</td>
<td>Reduction of Defects in Germanium Silicon</td>
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<td>CGTS</td>
<td>Crystal Growth of Ternary Compound Semiconductors</td>
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<td>GEDS</td>
<td>Gravitational Effects in Distortion in Sintering</td>
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<td>FAMIS</td>
<td>Formation of Amorphous Metallics In Space</td>
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<td>FOG</td>
<td>Formation of Gasarities</td>
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<td>THERMOLAB</td>
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<td>ICOPROSOL</td>
<td>Thermophysical properties and solidification behavior of undercooled Ti-Zr-Ni liquids showing in icosahedral short-range order</td>
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<td>PARSEC</td>
<td>Peritectic Alloy Rapid Solidification with Electromagnetic Convection</td>
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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

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>ACES</td>
<td>Atomic Clock Ensemble in Space</td>
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<tr>
<td>BASS</td>
<td>Burning and Suppression of Solids</td>
</tr>
<tr>
<td>CFE</td>
<td>Capillary Flow Experiment</td>
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<tr>
<td>CCF</td>
<td>Capillary Channel Flow</td>
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<tr>
<td>CVB</td>
<td>Constrained Vapor Bubble</td>
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<tr>
<td>EHD</td>
<td>ElectroHydroDynamic flow experiment</td>
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<tr>
<td>HPE-L</td>
<td>Heat Pipe Experiment - Loop</td>
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<tr>
<td>FAMIS</td>
<td>Formulation of Amorphous Metals in Space</td>
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<tr>
<td>FBCE</td>
<td>Flow Boiling and Condensation Experiment</td>
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<tr>
<td>MsFHT</td>
<td>Multiphase Flow And Heat Transfer Experiment</td>
</tr>
<tr>
<td>MVCS</td>
<td>Morphological study in Variable Cross Section</td>
</tr>
<tr>
<td>MVCS</td>
<td>Morphological study in Variable Cross Section</td>
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<tr>
<td>MWT-FS</td>
<td>Microgravity Wind Tunnel - Fire Safety</td>
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<tr>
<td>PBRE</td>
<td>Packed Bed Reactor Experiment</td>
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<td>PBRE-A</td>
<td>Packed Bed Reactor Experiment - Applied</td>
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<td>PBRR</td>
<td>Packed Bed Reaction Rate Experiment</td>
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<tr>
<td>SoFIE</td>
<td>Solid Fuel Ignition and Extinction</td>
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<td>TPFSE</td>
<td>Two Phase Flow Separator Experiment</td>
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<tr>
<td>ZBOT</td>
<td>Zero Boil-off Tank Experiment</td>
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