Plans and Recent Developments for Fluid Physics Experiments Aboard the ISS

John B. McQuillen & Brian J. Motil, *NASA Glenn Research Center, Cleveland, OH*

Experiments

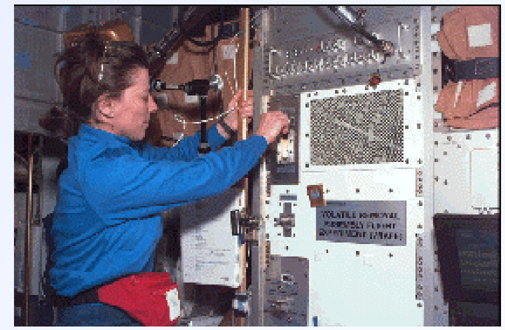
- **Packed Bed Reactor Experiment (PBRE)**
- Two Phase Flow Separator Experiment (TPFSE)
- **Flow Boiling and Condensation Experiment (FBCE)**
- Multiphase Flow and Heat Transfer Experiment (MFHT) aka ESA “Flow Boiling”
- ElectroHydro Dynamic Experiment (EHD)
- **Zero Boil Off Tank (ZBOT) Experiments**

Two-Phase Flow (Adiabatic)

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

Packed Bed Reactor Experiment (PBRE) - 2016

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

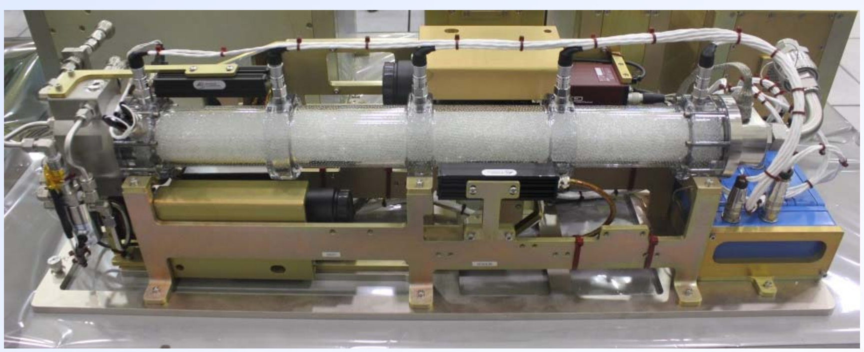


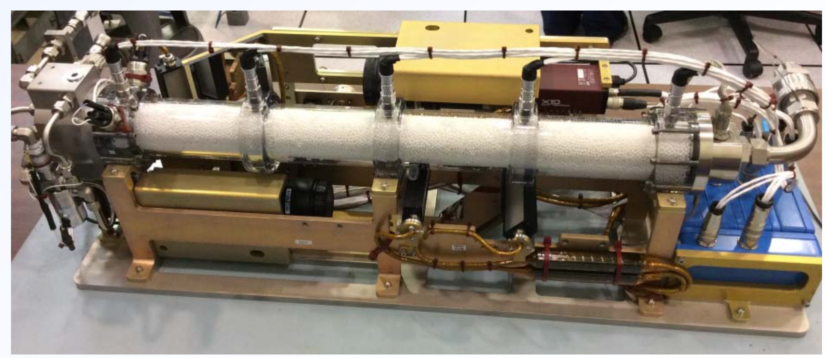
Volatile Reactor Assembly (VRA) on STS 89

Bed	ID, in (cm)	Length, in (cm)	Packing Size, in (cm)	Packing Material
FHS-W	3.0(6.4)	24(61)	0.118 (0.3)	Glass (spheres)
FHS-NW	3.0(6.4)	24(61)	0.118 (0.3)	Teflon (spheres)

IVGEN Deionizing resin bed

Wetting Test Module (glass beads)





Non-Wetting Test Module (Teflon beads)

PBRE Science Requirements

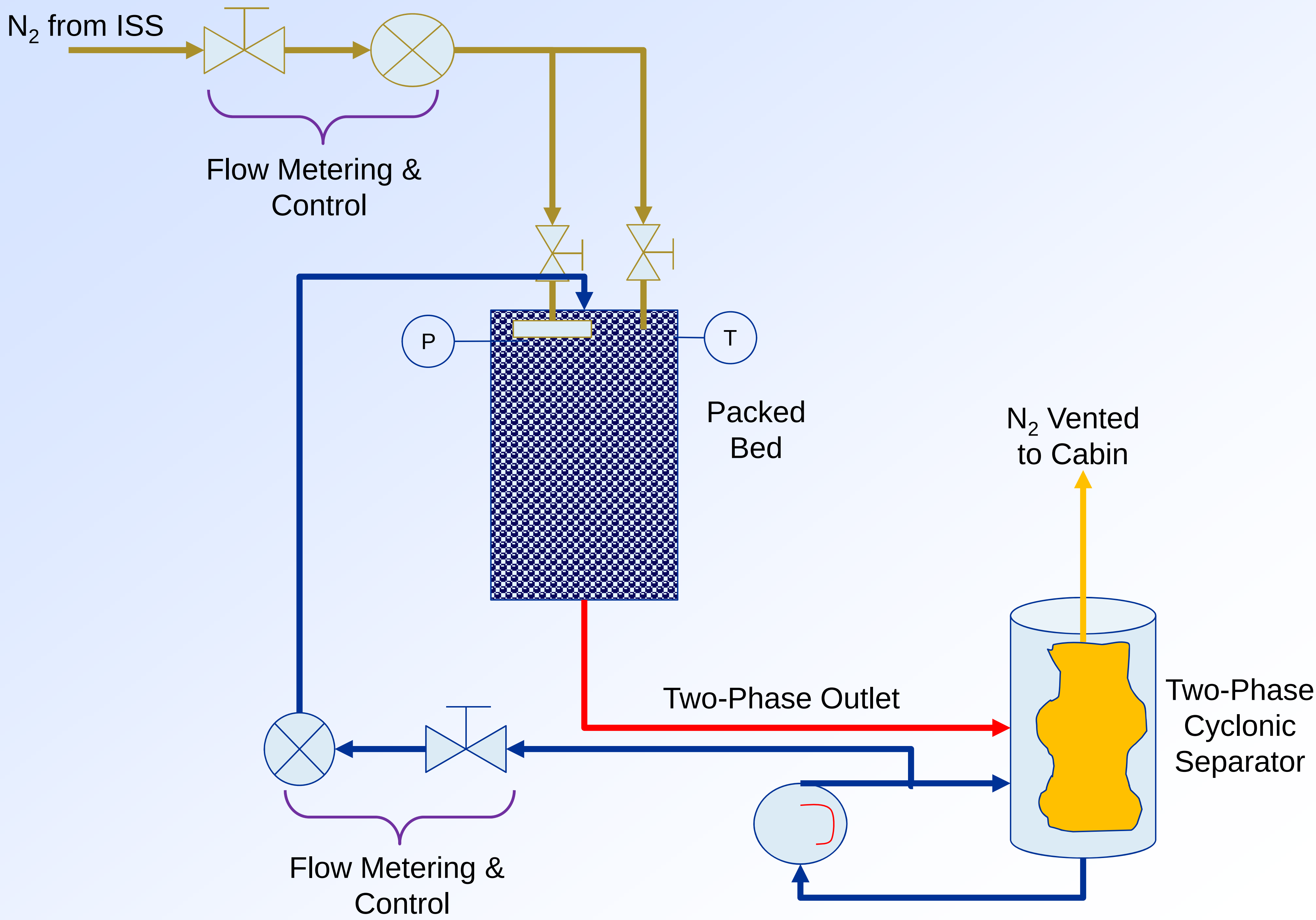
- **Fluid properties:**
  - Water and ISS supplied nitrogen.
  - Surface tension must remain constant (0.065 to 0.072 dyne/cm).
  - No visible foaming or frothing.

- **Test Section:**
  - On orbit replaceable test section (operate one at a time).
  - Envelope must allow for 12.5 cm diameter x 61 cm long

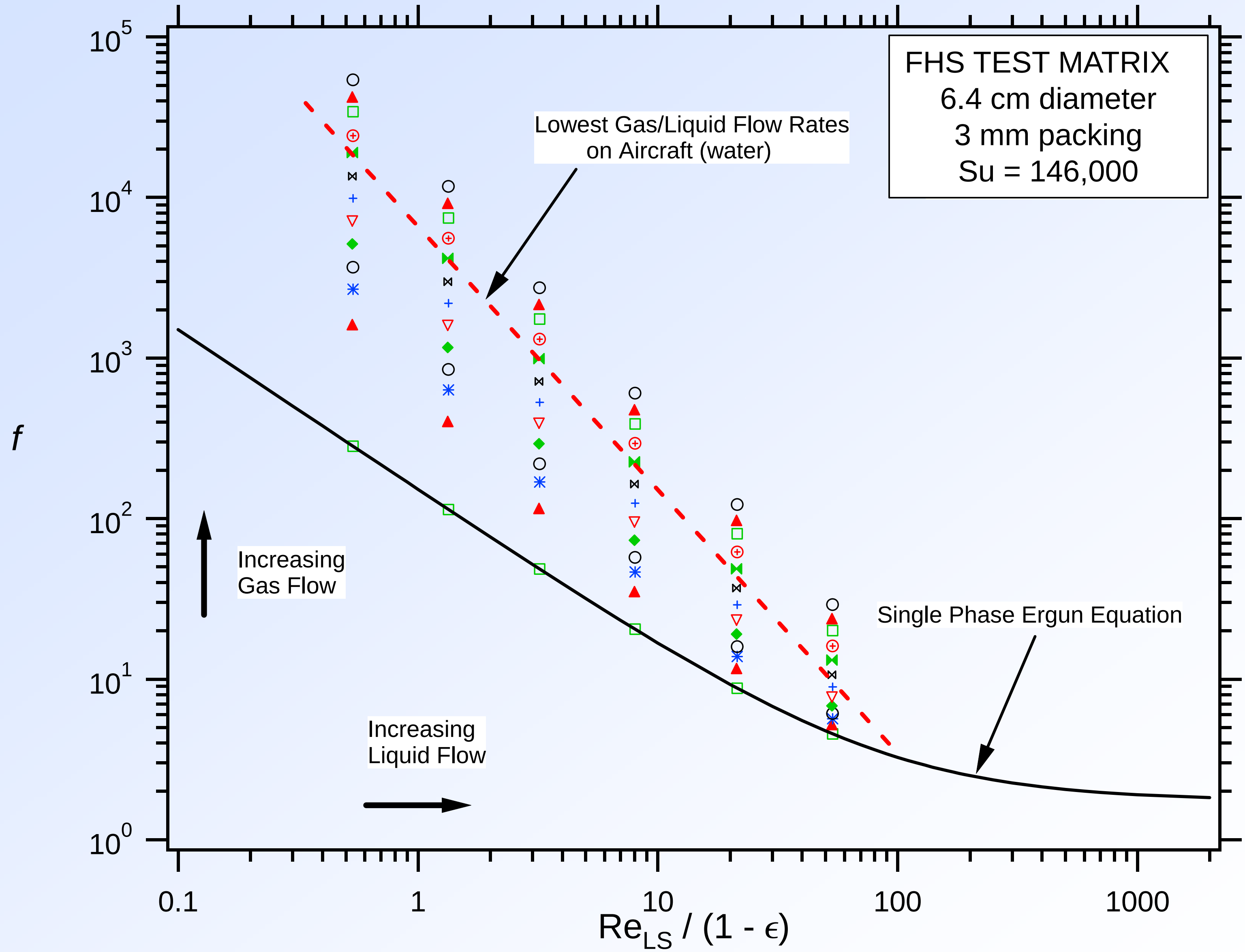
- **Flow rates:**
  - Liquid flow: 0-150 liters/hr.
  - Gas flow: 0-3 kg/hr
  - Require tight control within test run, even for very low flow rates.
  - Require ability for step change in flow rates in unsteady tests.
  - Require discrete bubbles on order of packing size for low flow rates.

- **Pressure and Temperature Control:**
  - Maintain steady average pressure during test run (average over pulse).
  - Actively control absolute pressure within test run to +/- 13 kPa
  - Active temperature control not required but Delta over test run must be < 2 deg C.

PBRE Simplified Flow Schematic



PBRE Test Matrix



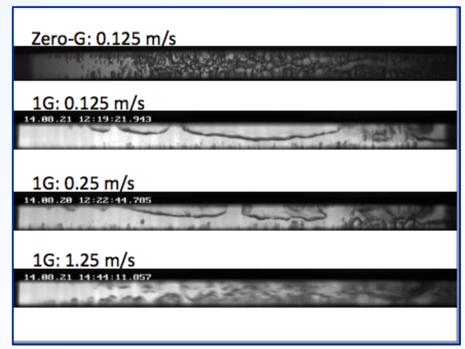
PBRE Summary of First Ops

- PBRE completed flight ops on the first (of two) test sections. The first test section is filled with glass beads (wetting packing), the second is filled with Teflon beads (non-wetting) – all other aspects are identical.
- Only pressure and flow data was down linked. High speed video was saved on hard drives that were returned in late August, but not available to the PI team yet.
- Pressure data indicates models correctly predict transition from pulse to bubble flow.
- Pressure drop models appear to deviate from experimental at lower flow rates.
  - May indicate unexpected gas-continuous phase.

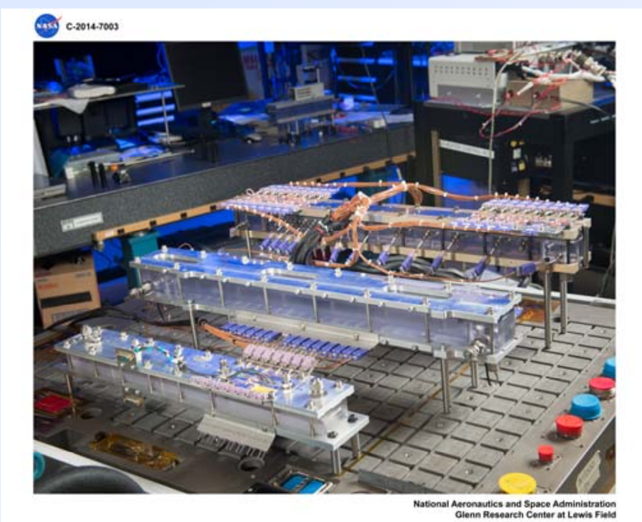
Second Ops Tentatively Scheduled for late 2016 into early 2017

Flow Boiling and Condensation Experiment (FBCE) – 2019

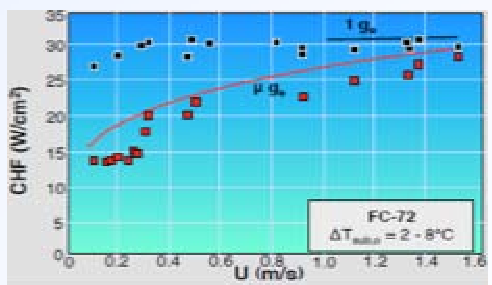
- Will develop mechanistic models for microgravity flow boiling Critical Heat Flux (CHF) and dimensionless criteria to predict the minimum flow velocities required to ensure gravity-independent CHF along with boiling heat transfer coefficients and pressure data correlations.
- Will develop mechanistic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



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



FBCE Test Module



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

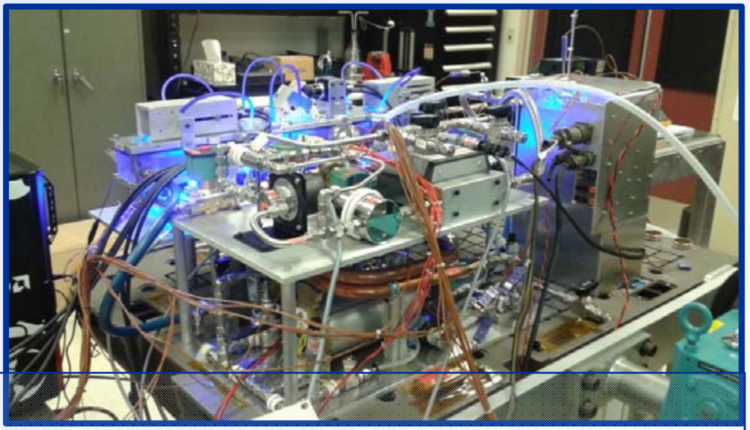
Fluid & Hardware

Test Fluid:

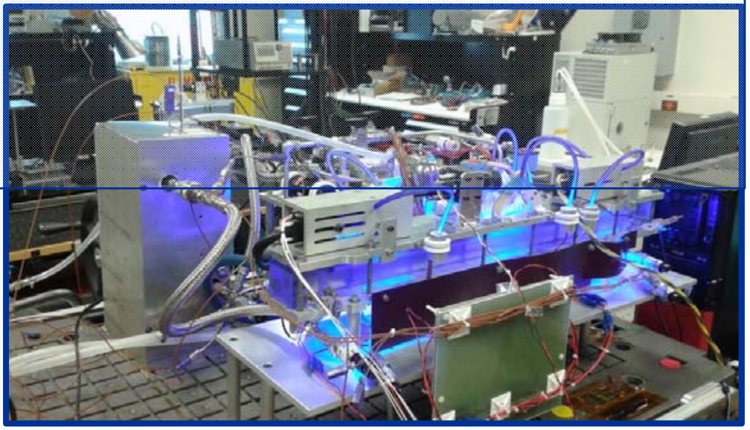
Perfluoro-*normal*-hexane

PFnH (C_6F_{14}).

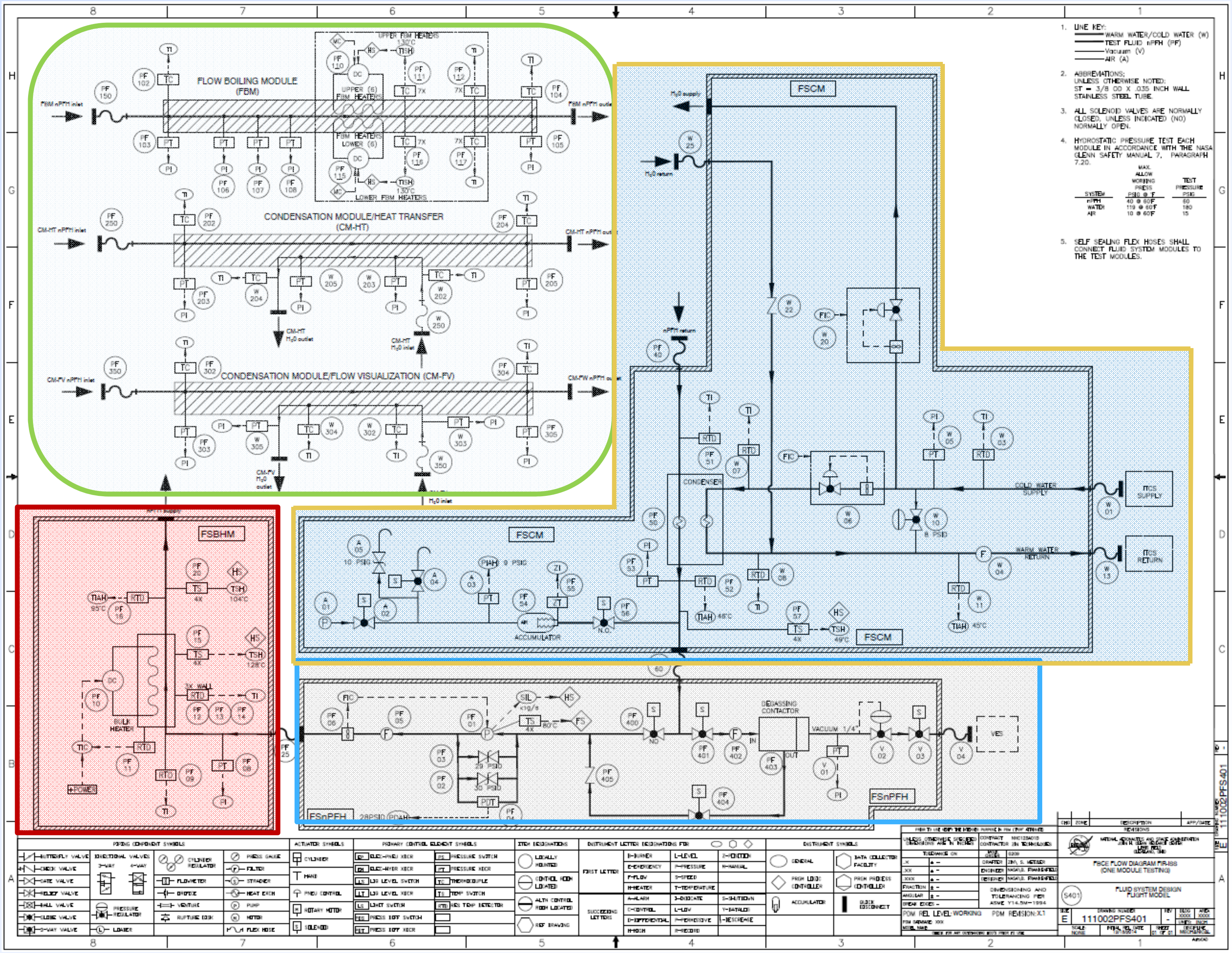
Molecular Weight	338
Boiling Point (1 atm)	56 °C
Latent Heat of Vaporization (at normal boiling point)	88 J/g
Liquid Density	1.68 g/ml
Absolute Viscosity	0.64 centipoise
Liquid Specific Heat	1.05 J/(g * °C)
Liquid Thermal Conductivity	0.057 W/(m * °C)
Surface Tension	12 dynes/cm



Engineering Model of FBCE on FIR Plate Mockup



FBCE Fluid System Architecture



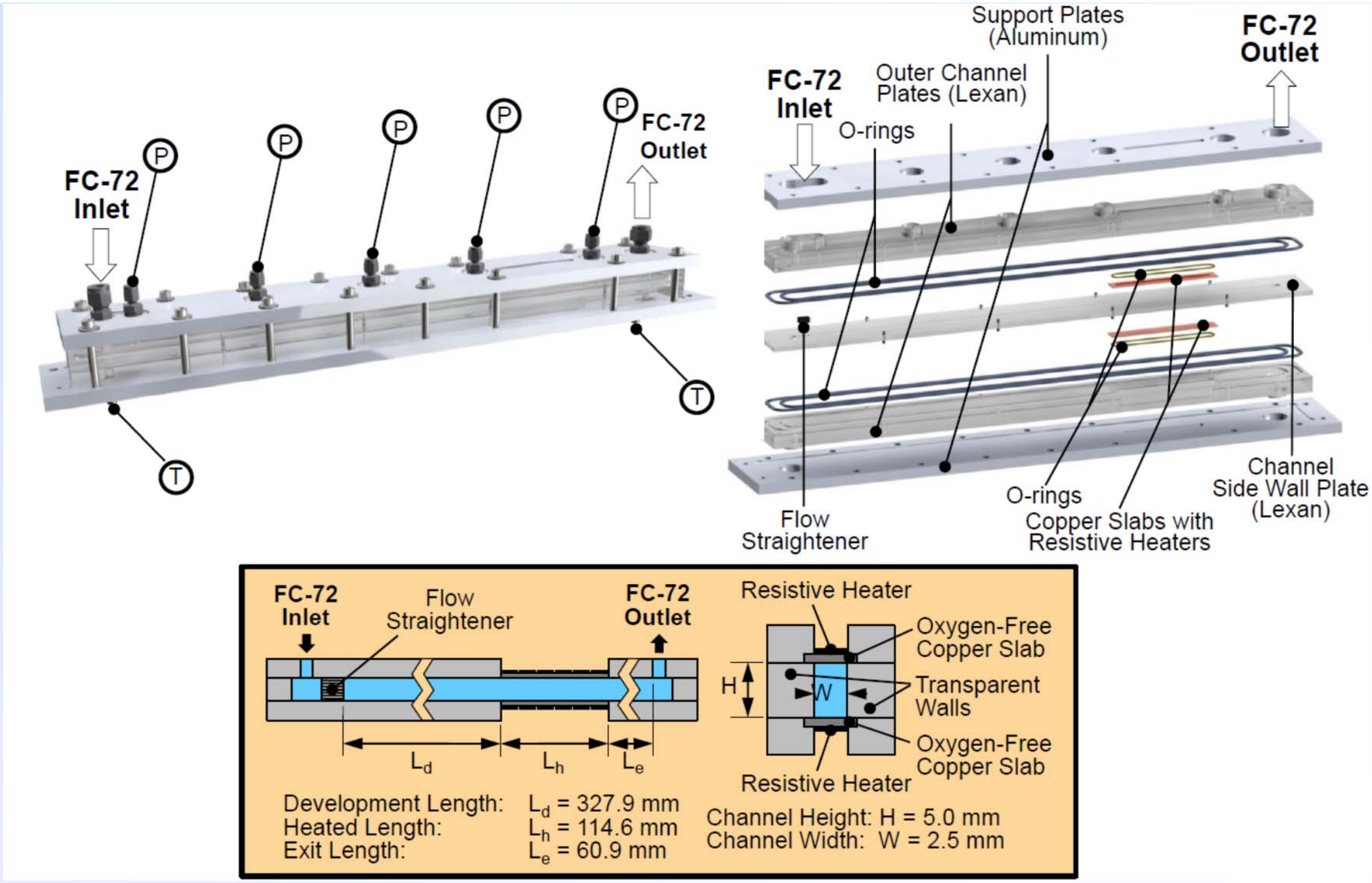
Test Modules

FS-BHM

FS-CM

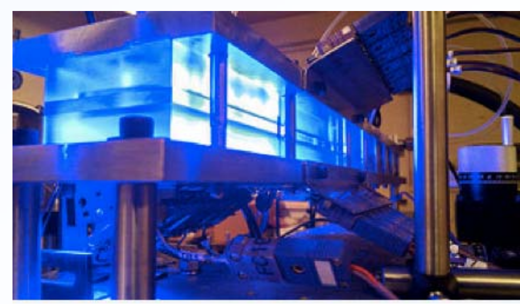
FS-nPFHM

FBCE Boiling Test Section

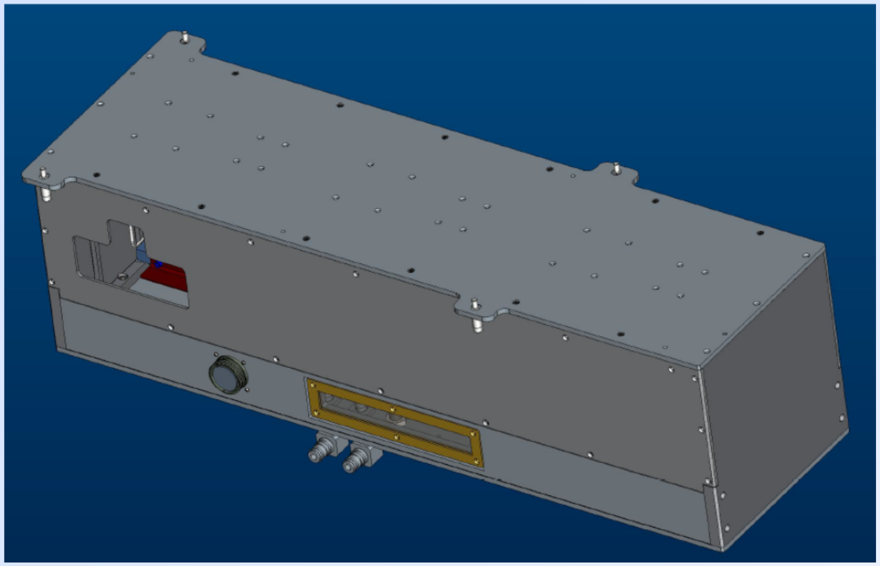


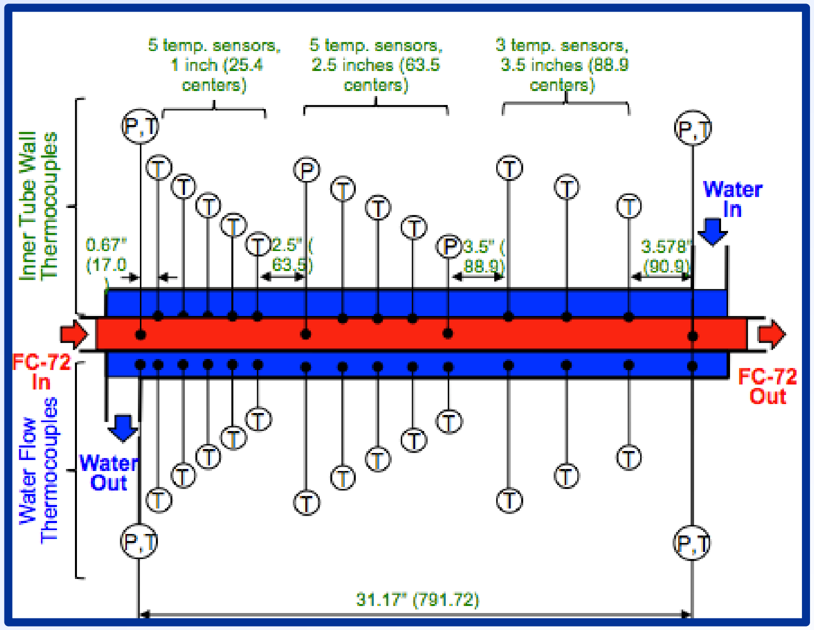
Thermocouples on FBM

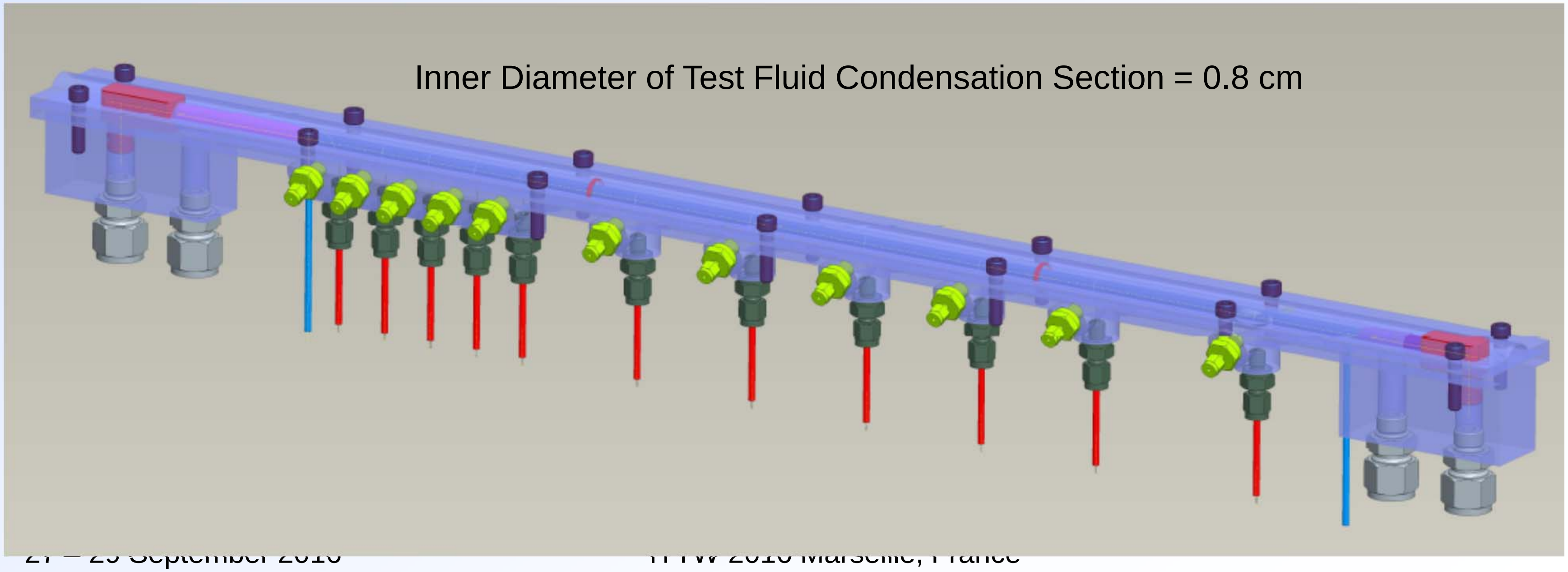
Flow Boiling Module



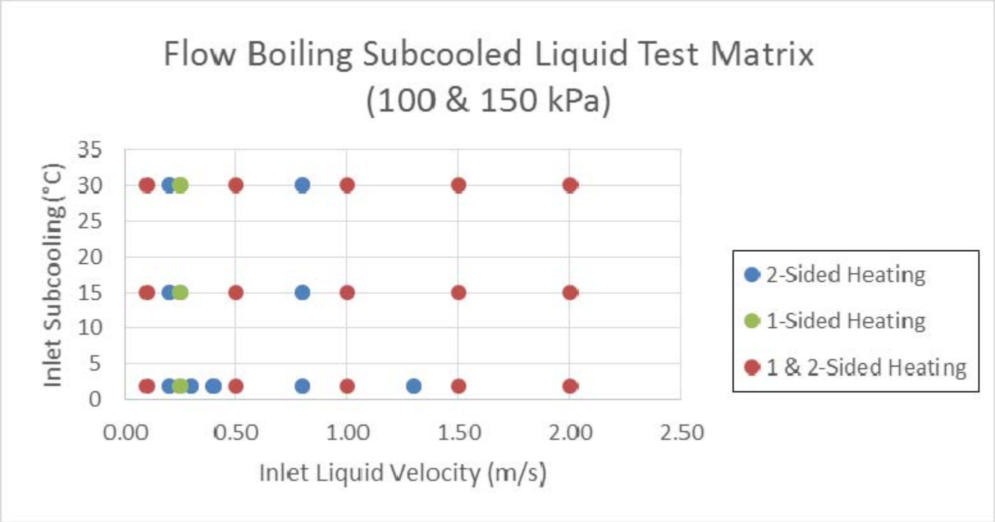
FBCE Condensation Test Section



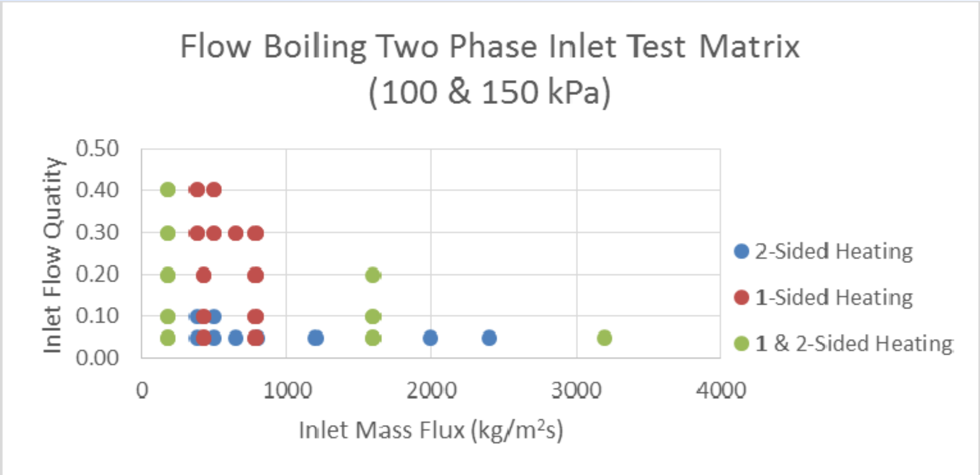


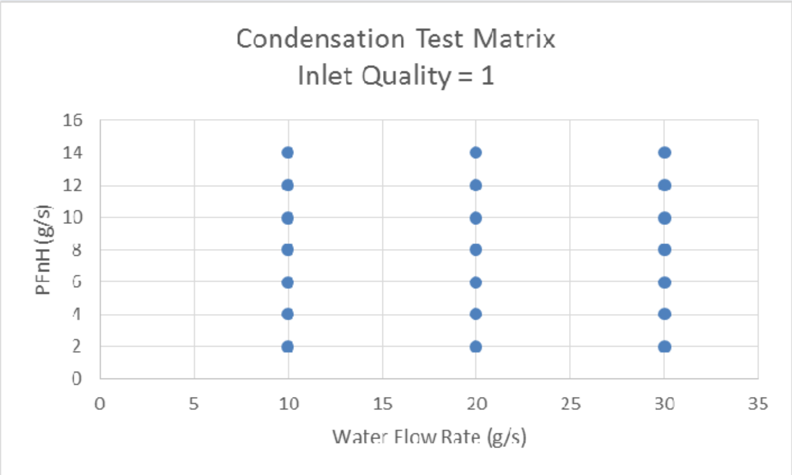


Tentative FBCE Test Matrices



1.0 m/s ≅ 21 g/s ≅ 1700 kg/(m^2*s)

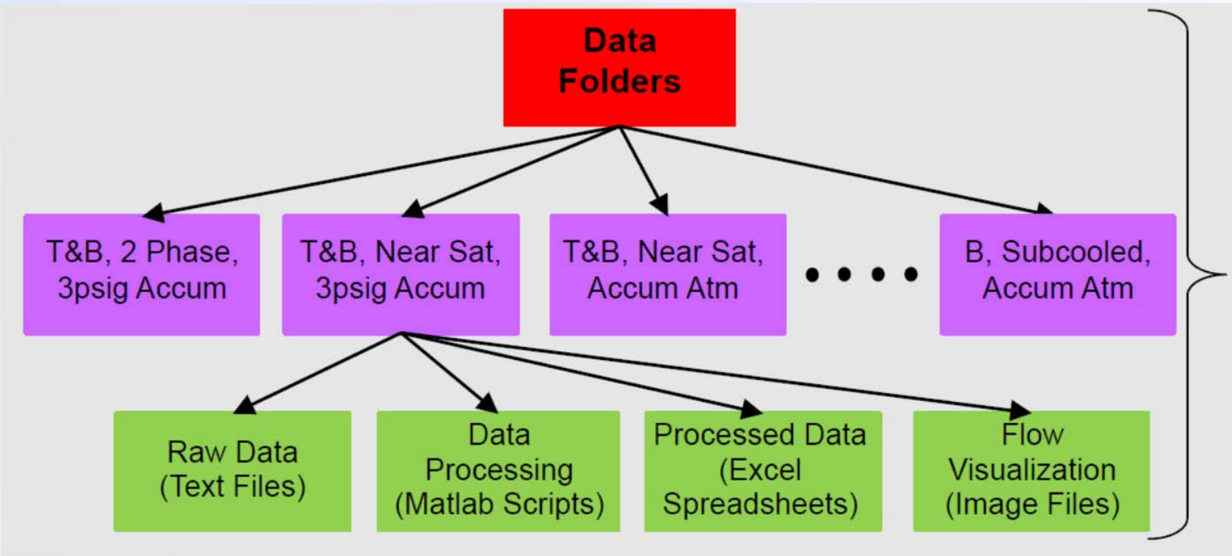




FBCE Data Organization

- **Contain four filetypes:**
- ***Text Files* containing raw sensor data output by data acquisition system**
- ***MatlabScripts* for processing raw data**
- ***Excel Spreadsheets* containing all relevant parameters (*e.g.,* pressure drop, heat transfer coefficient, CHF) output by processing script**
- ***Image Files* for flow visualization**

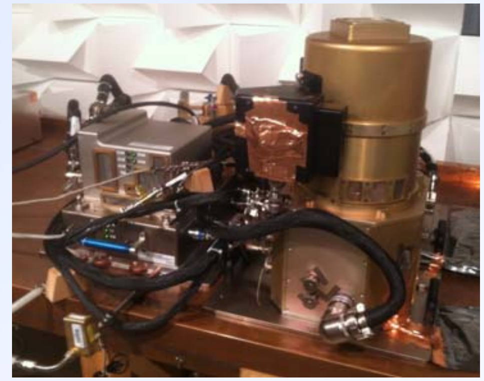
With subfolders used to group data by operating conditions



Full description of file paths and data file structures found in "Organizational Documents" folder

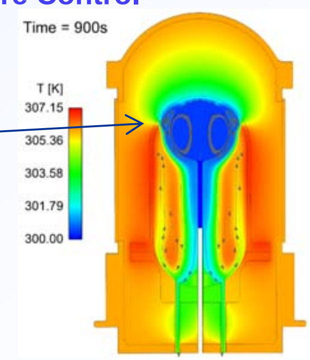
Zero Boil-Off Tank Experiment (ZBOT) - 2017

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

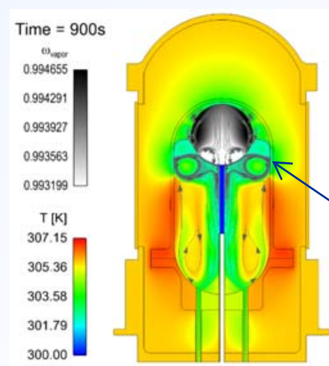


ZBOT EU

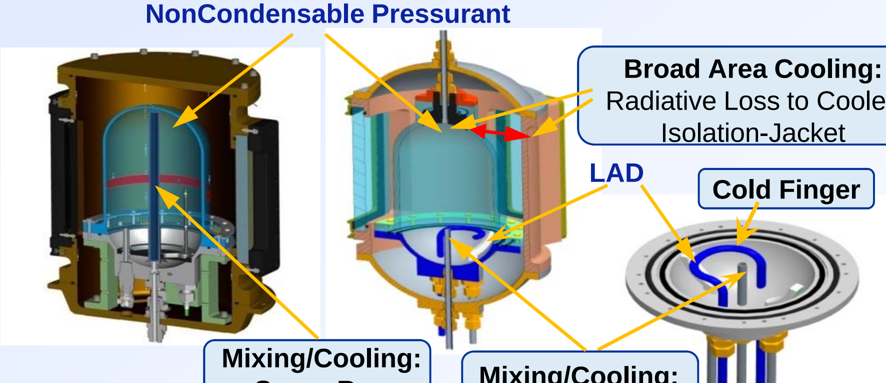
Effect of Noncondensable on Flow and Temperature Fields during Jet cooling Pressure Control



Pure Vapor - Cool Jet envelopes the Ullage



Marangoni Flow Due to Noncondensable Impedes Penetration of Cool jet around the Ullage



PI: Dr. Mohammad Kassemi, NCSER
Co-I: Dr. David Chato, NASA, GRC

ZBOT in MSG Simulator at NASA MSFC

Data Acquisition and Control Unit (DACU)

Camera Package

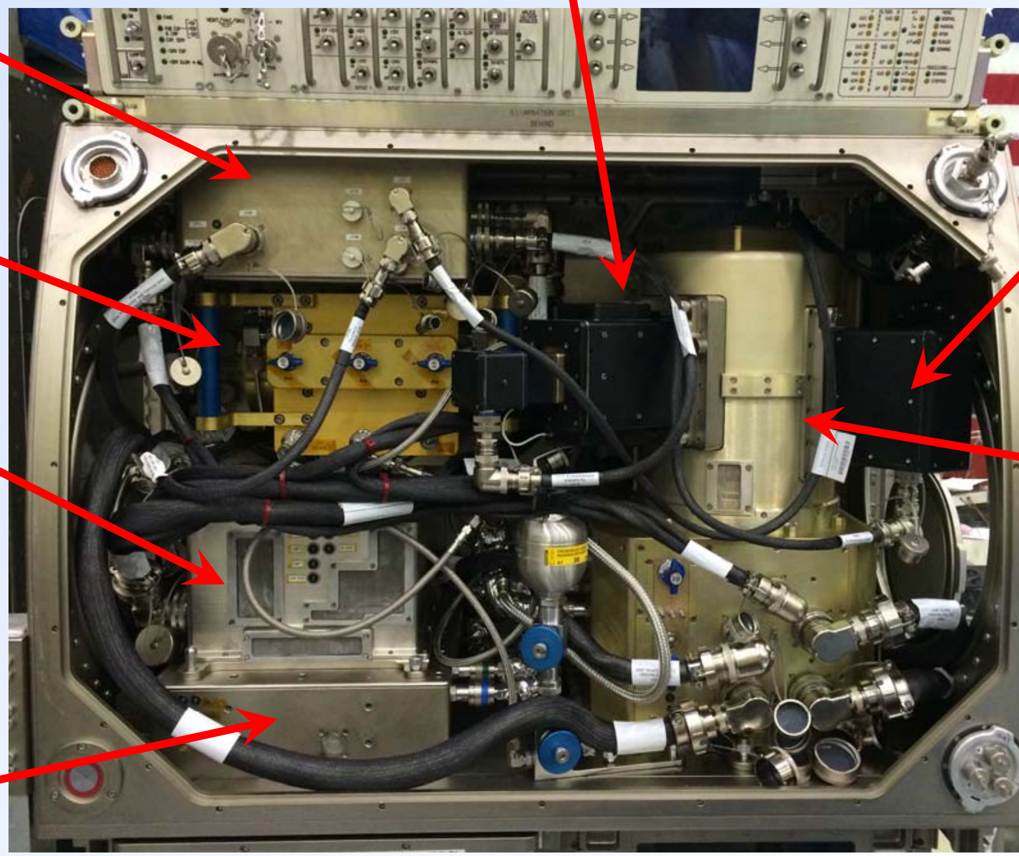
Fluid Reservoir

Illumination Package

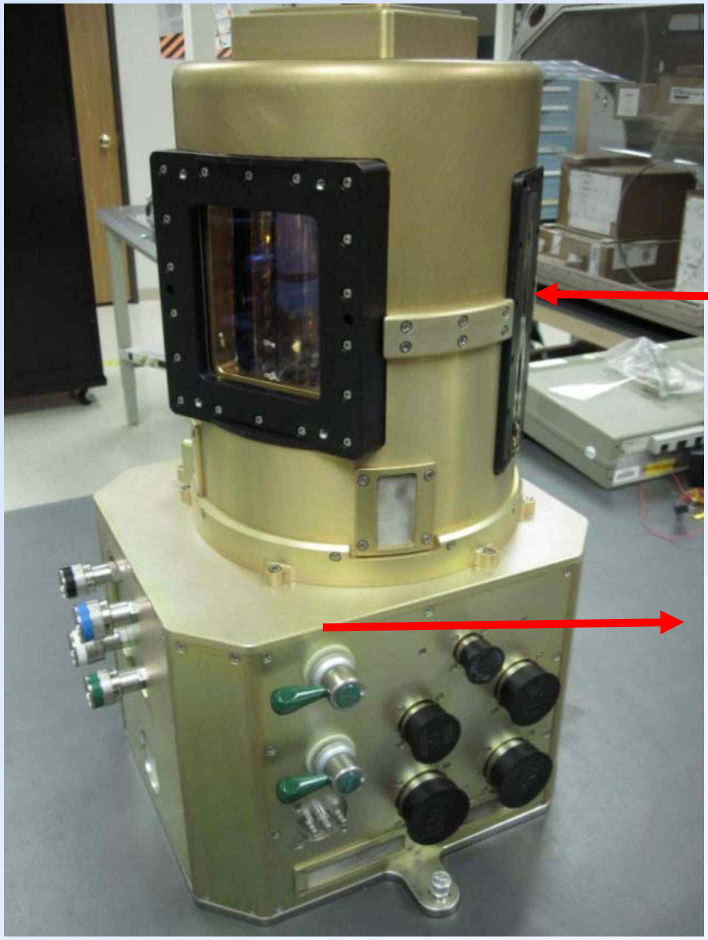
Thermal Control Unit (TCU)

Test Section

Cold Plate Package (CPP)



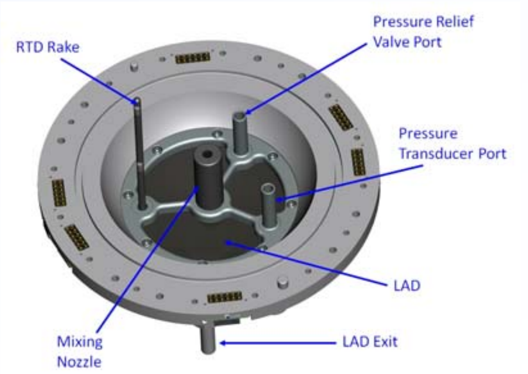
ZBOT Test Section



Test Section Subassembly (includes the Test Tank, Vacuum Jacket and Cooling Jacket)

Fluids Support Unit (FSU)

Test Tank Base



- Test Fluid – Perfluoro-*normal*-Pentane (PnP)

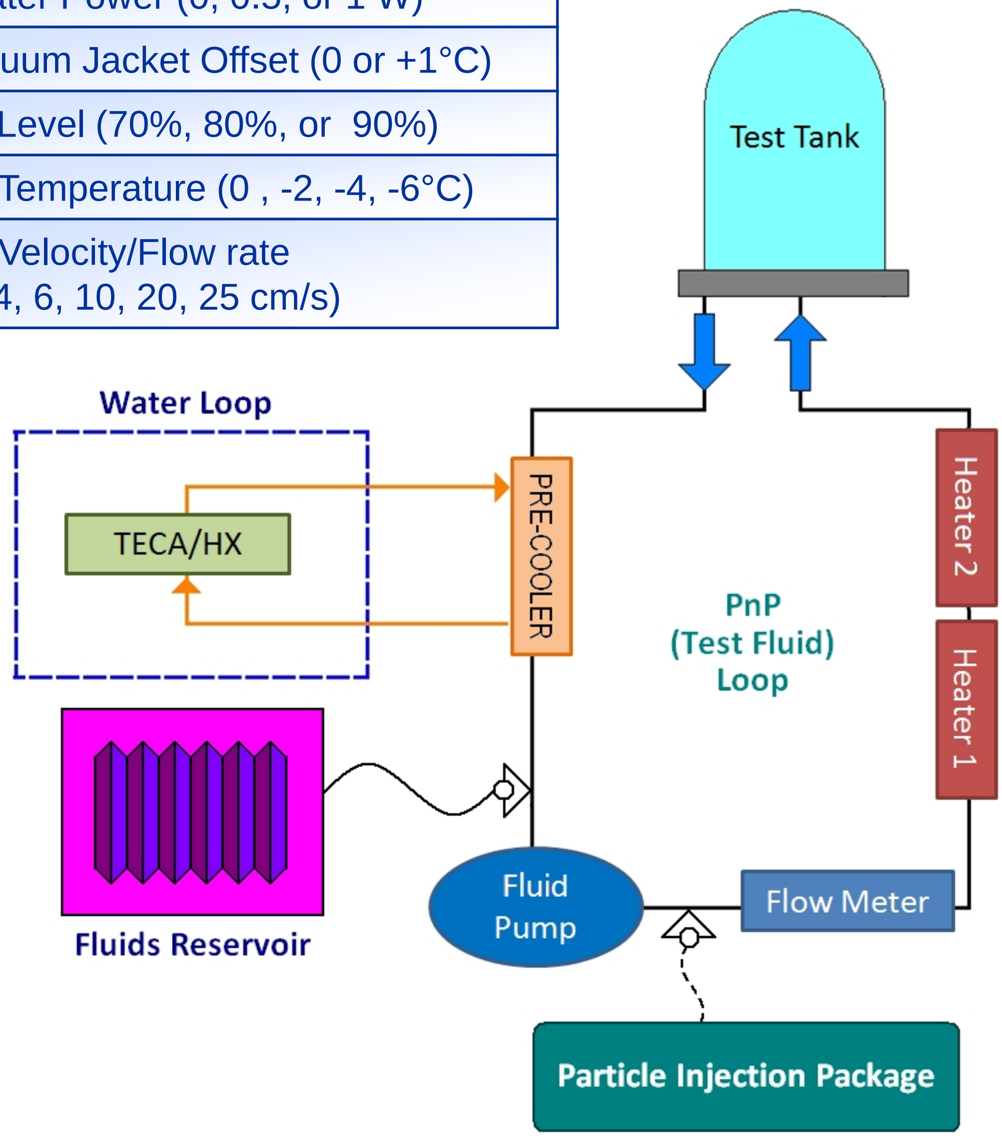
Molecular Weight	288
Boiling Point (1 atm)	30 °C
Latent Heat of Vaporization (at normal boiling point)	88 J/g
Liquid Density	1.63 g/ml
Absolute Viscosity	0.44 centipoise
Liquid Specific Heat	1.09 J/(g * °C)
Liquid Thermal Conductivity	0.056 W/(m * °C)
Surface Tension	9 dynes/cm

ZBOT Measurements & Data

Type of Test	Method & Mode
Pressurization	Heater Strip
	Vacuum Jacket Heating
	Heater and Vacuum Jacket
Mixing Only	Uniform Temperature
	After Self-Pressurization
Subcooled Mixing	Uniform Temperature
	After Self-Pressurization

Input Variables
Heater Power (0, 0.5, or 1 W)
Vacuum Jacket Offset (0 or +1°C)
Fill Level (70%, 80%, or 90%)
Jet Temperature (0 , -2, -4, -6°C)
Jet Velocity/Flow rate (2, 4, 6, 10, 20, 25 cm/s)

Outputs vs Time Evolution
Pressure
Fluid Temperature (6 locations)
Wall Temperature (17 locations)
Jacket Temperature (21 locations)
Jet Penetration Depth I (imaging)
DPIV Velocity/Flow Structures (Tech Demo)



ZBOT Test Matrix

Self Pressurization					
Fill level (%)	**Tank heater (W)**	**Vacuum jacket**	**$T_{initial}$ after precond-itioning (°C)**	**Jet Speed (cm/s)**	**Duration of Test**
70 + 80 + 90	0	$T_{VJ} = T_{tank} + 1°C$	$T_0 = 34$	N/A	12 hrs
70 + 80 + 90	0.5	$T_{VJ} = T_{tank}$	$T_0 = 34$	N/A	12 hrs
90	0.5	$T_{VJ} = T_{tank} + 1°C$	$T_0 = 34$	N/A	8 hrs
90	0.75	$T_{VJ} = T_{tank}$	$T_0 = 34$	N/A	5 hrs
90	1	$T_{VJ} = T_{tank}$	$T_0 = 34$	N/A	3.5 hrs
90	1	$T_{VJ} = T_{tank}$	$T_0 = 34$	N/A	3.5 hrs

ZBOT Test Matrix

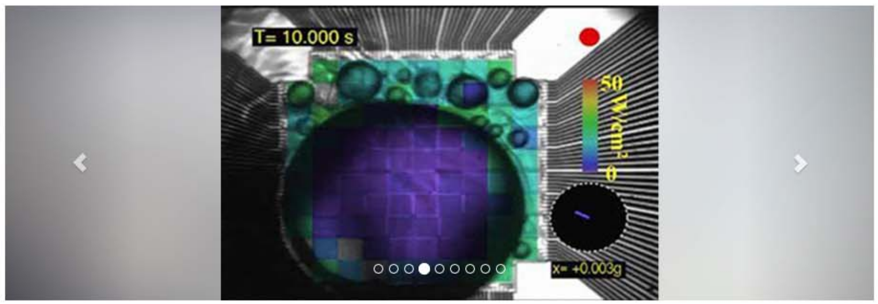
Jet Mixing						
Fill level (%)	**Tank heater (W)**	**Vacuum jacket**	**$T_{initial}$ after precond-itioning (°C)**	**Jet Speed (cm/s)**	**T_{jet} (°C)**	**Duration of Test**
70 & 90	0	$T_{VJ} = T_{tank}$	T_0 = 38 & 34	2	T_{outlet}	10 min
70, 80 & 90	0	$T_{VJ} = T_{tank}$	T_0 = 38	4	T_{outlet}	10 min
70	0	$T_{VJ} = T_{tank}$	T_0 = 38	4	T_{outlet}	10 min
70 & 90	0	$T_{VJ} = T_{tank}$	T_0 = 38	6	T_{outlet}	10 & 30 min
70, 80 & 90	0	$T_{VJ} = T_{tank}$	T_0 = 38	10, 20 & 25	T_{outlet}	10 min
80	0	$T_{VJ} = T_{tank}$	N/A	6	T_{outlet}	0.5 hrs

ZBOT Test Matrix

Subcooled Jet						
Fill level (%)	Tank heater (W)	Vacuum jacket	$T_{initial}$ after precond-itioning (°C)	Jet Speed (cm/s)	T_{jet} (°C)	Duration of Test
70	0	$T_{VJ} = T_{tank}$	$T_0 = 38$	2	T_0-2	0.5 hrs
70	0	$T_{VJ} = T_{tank}$	$T_0 = 38$	2	T_0-4	0.5 hrs
70 & 90	0	$T_{VJ} = T_{tank}$	$T_0 = 38$	2	T_0-6	0.5 hrs
70 & 90	0	$T_{VJ} = T_{tank} + 1$°C	N/A	4	T_0-2	0.5 hrs
70, 80 & 90	0.5	$T_{VJ} = T_{tank}$	N/A	4	T_0-2	0.5 hrs
90	1	$T_{VJ} = T_{tank}$	N/A	6	T_0-2	0.5 hrs

http://psi.nasa.gov

Home | About | Investigations | Awarded Research | Register | Sign In



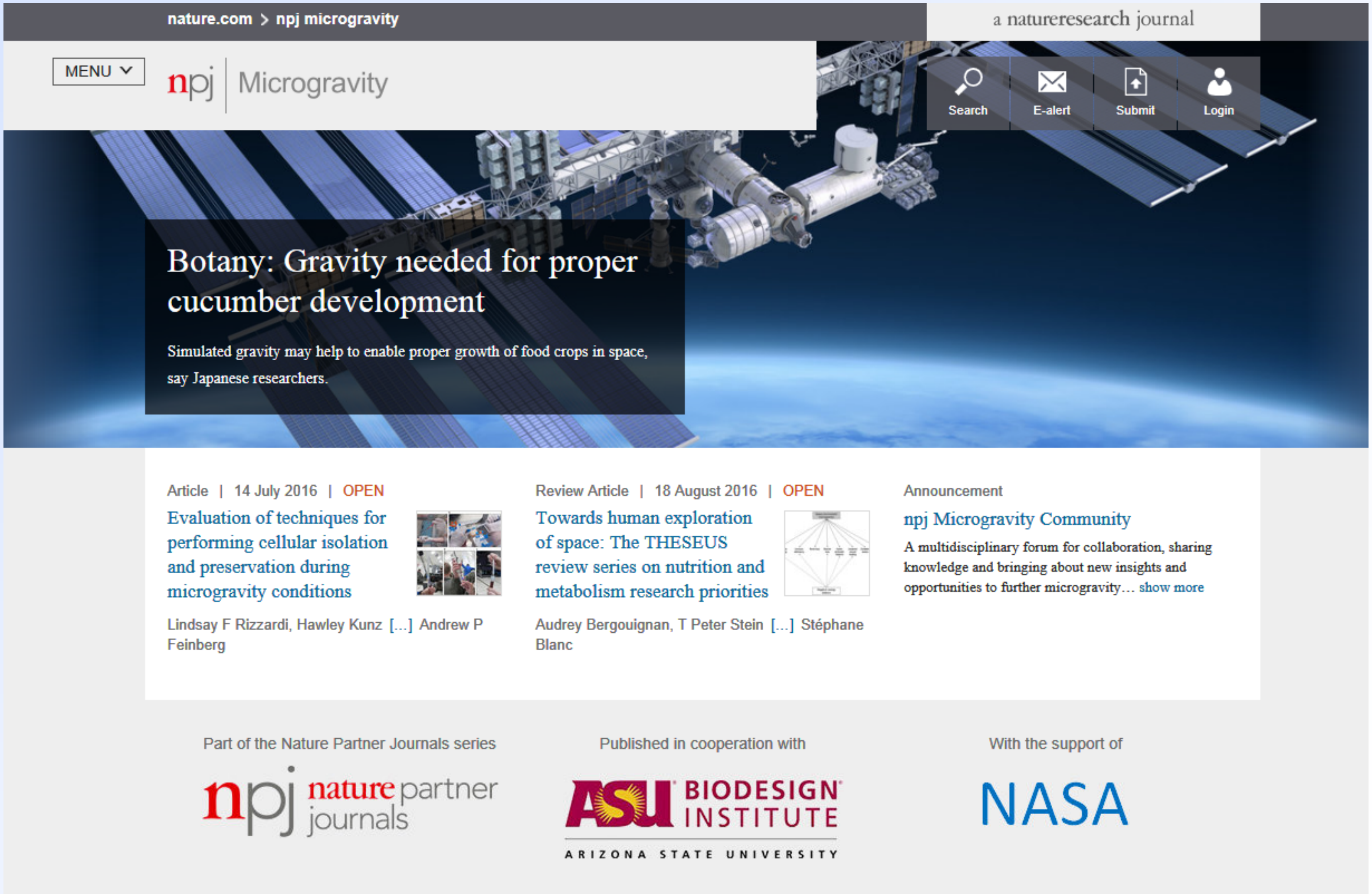
At NASA, we are excited to announce the roll-out of the Physical Science Informatics (PSI) data repository for physical science experiments performed on the International Space Station (ISS). The PSI system is now accessible and open to the public. This will be a resource for researchers to data mine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

Fluid Physics Investigations

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

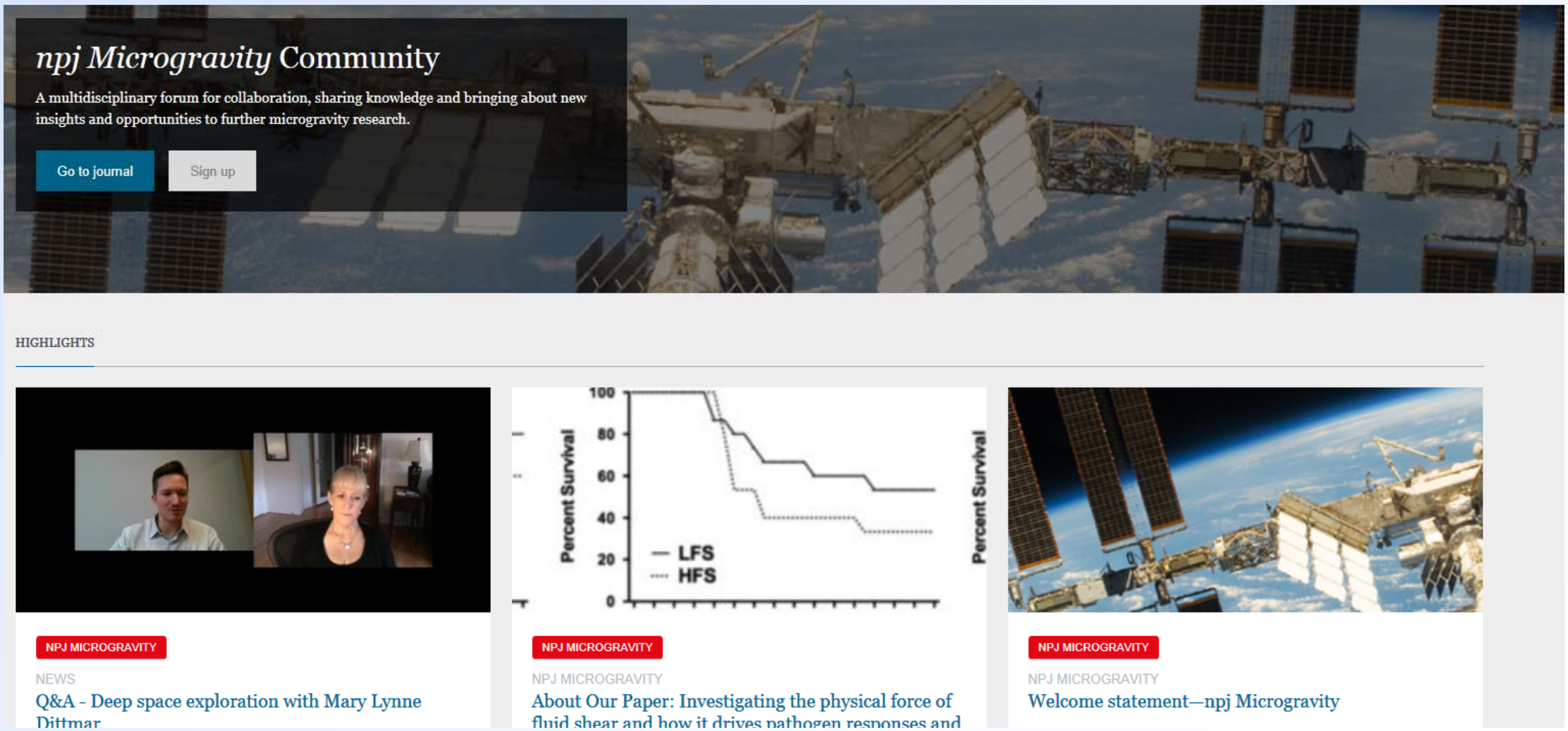
http://www.nature.com/npjmgrav/

On-line, open access journal published by Springer Nature to highlight important scientific advances in the life sciences, physical sciences and engineering fields that are facilitated by spaceflight and analogue platforms.



https://npjmicrogravitycommunity.nature.com/

Community is now up and running to provide a multidisciplinary forum for international collaboration, sharing knowledge and bringing about new insights and opportunities to further microgravity research.



Questions?