# Flow Boiling & Condensation Experiment (FBCE): From Initial Concept to Full implementation on the ISS

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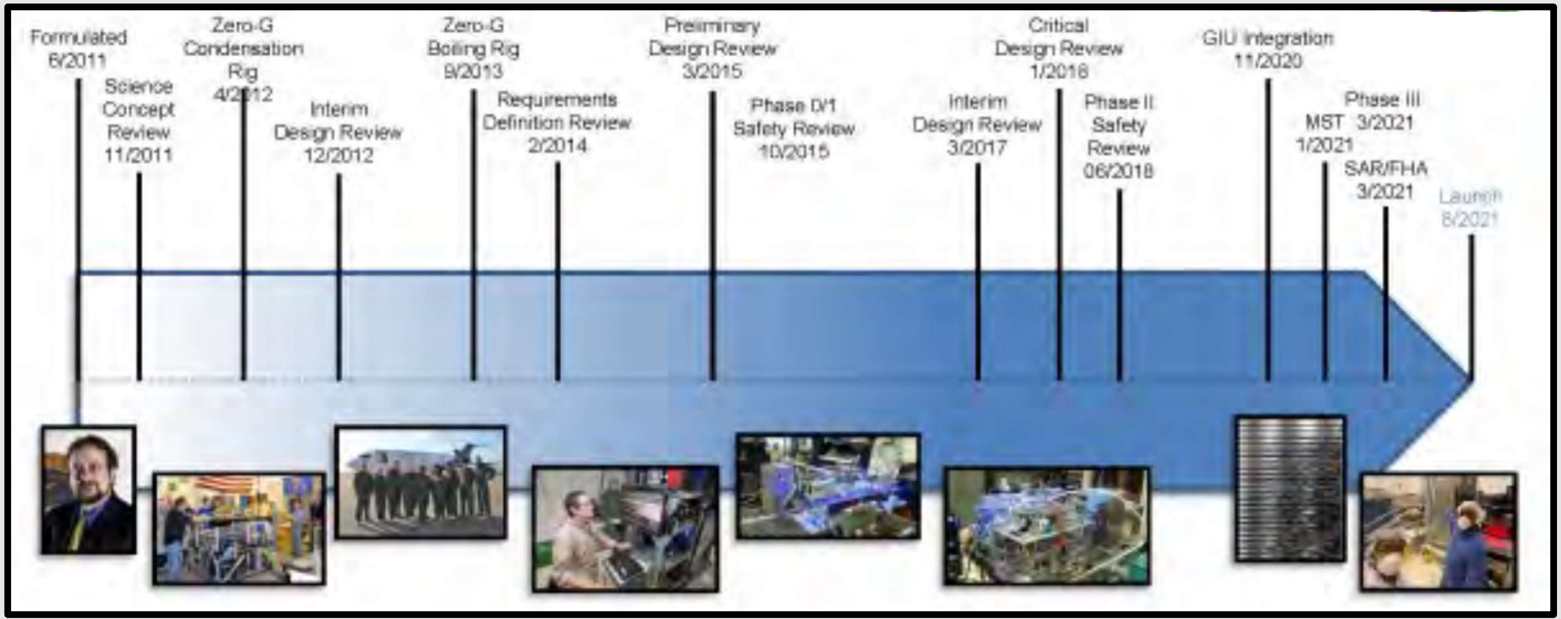
# *History of Purdue's Efforts*

**Culmination of efforts started in the mid-1990s!!**

- **1994 – 1999:** two unsuccessful proposals to NASA; difficulty promoting a shift in microgravity efforts from pool boiling to flow boiling
- **2000 - 2006:** first NASA grant addressing flow boiling in reduced gravity
- **2011:** initial FBCE concept
- **2013:** provided detailed designs to Glenn for:
  - Flow Boiling Module (FBM)
  - Condensation Module for Heat Transfer Measurements (CM-HT)
  - Condensation Module for Flow Visualization (CM-HT)
- **2013:** validated soundness of designs of three modules based on parabolic flight experiments
- **2014-2017:** developed detailed predictions in the form of
  - Empirical correlations for flow boiling and flow condensation in reduced gravity
  - Theoretical models for flow boiling and flow condensation in reduced gravity
- **2017-2021:** Purdue's initiated CFD modeling of flow boiling and flow condensation



# *Overriding Objectives and Applications of FBCE*

## Long Term

The proposed research aims to develop an integrated two-phase flow boiling/ condensation facility for the International Space Station (ISS) to serve as primary platform for entire fluid physics community to obtain two-phase flow and heat transfer data in microgravity.

**Overriding objectives** are to investigate ***the two most fundamental mechanisms*** for phase change in microgravity: **FLOW BOILING and FLOW CONDENSATION.** This includes obtaining ***long-duration*** (1) ***heat transfer data*** and (2) ***video records of interfacial flow structure*** for both.

## Applications

- Nuclear fission/Rankine power cycle for future space missions to the Moon, and Mars and deep space missions
- Vapor compression heat pump for planetary bases (Moon, Mars)
- Thermal control systems and advanced life support systems in spacecraft
- Cryogenic systems: nuclear thermal propulsion, fuel depots, tank chilldown

# *Research Methods*

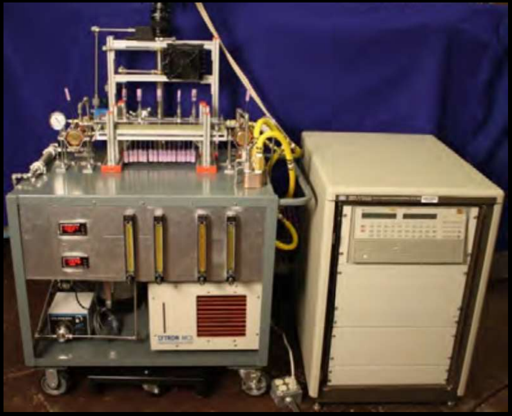
## For both Flow Boiling and Flow Condensation

- Conduct one-$g_e$ experiments at different flow orientations
- Conduct microgravity experiments in parabolic flight aircraft
- Develop empirical correlations applicable to different gravities
- Develop theoretical models applicable to different gravities
- Develop CFD models applicable to different gravities (in progress)
- Refine empirical correlations, theoretical models, and CFD models using ISS data (future)

**ISS will enable obtaining large duration steady state wall temperature measurements and video records of interfacial structure; both are essential for validation purposes!!**

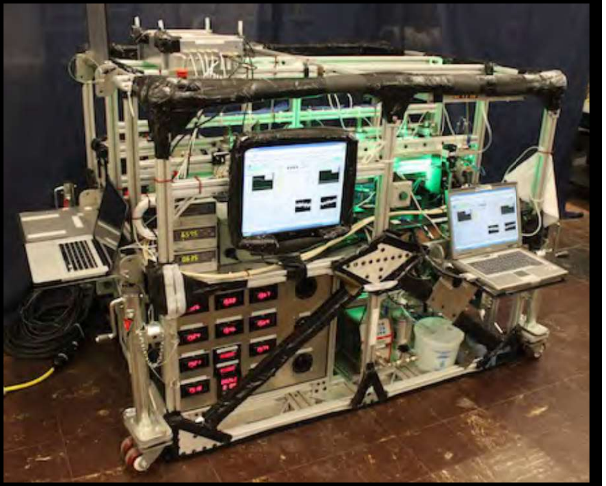
# *Support Facilities at the*
# *Purdue University Boiling & Two-Phase Flow Laboratory (PU-BTPFL)*

High-Capacity Condensation Facility



Mini/micro-channel Condensation Facility

Falling-Film Heating/Evaporation Facility



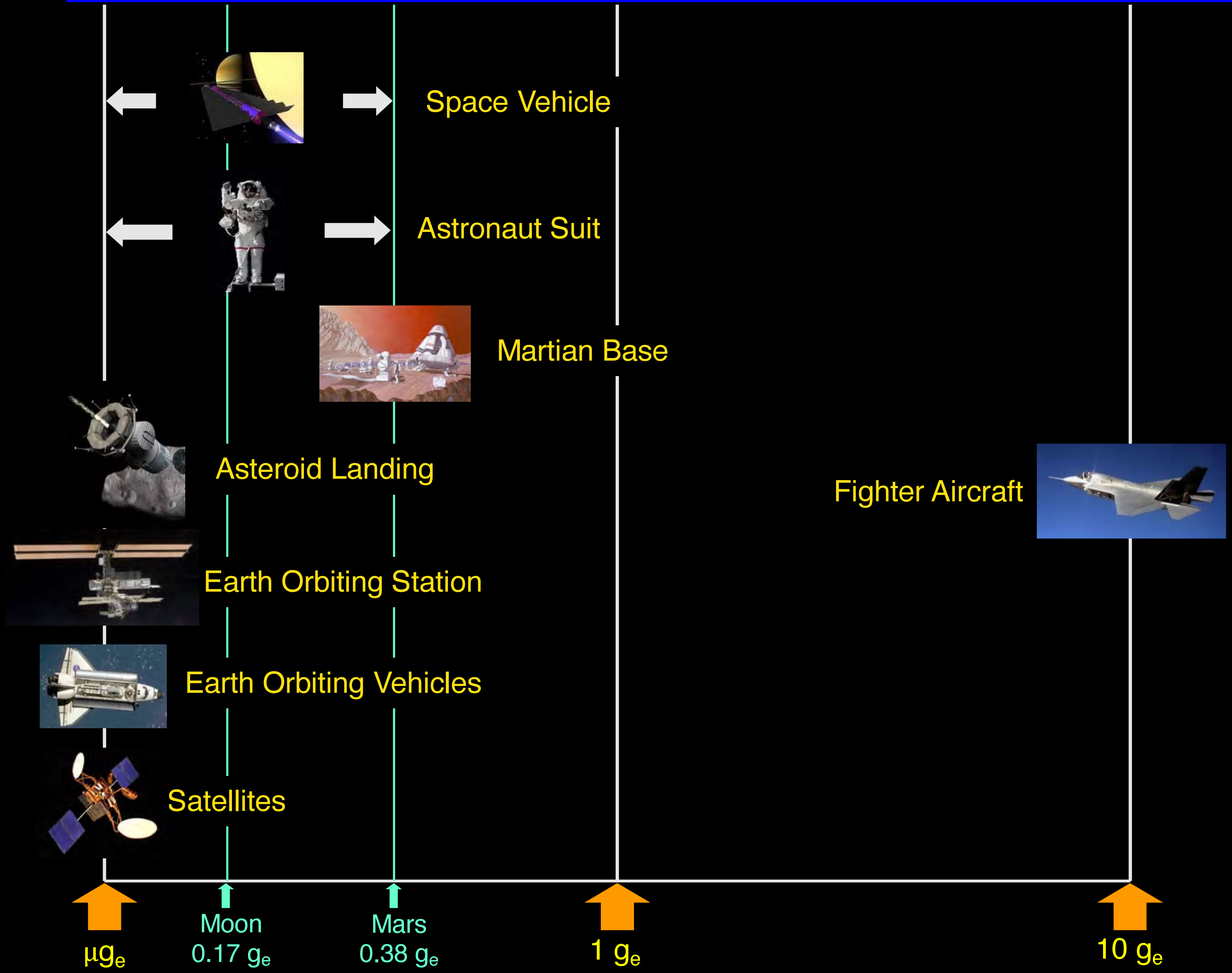
Parabolic Flight Condensation Facility

One-G Flow Boiling Facility

Hybrid Thermal Control System (H-TCS)

Parabolic Flight Flow Boiling Facility

# Examples of Systems Demanding Predictive Models of Effects of Gravity on Two-Phase Flow and Heat Transfer



Space Vehicle

Astronaut Suit

Martian Base

Asteroid Landing

Earth Orbiting Station

Earth Orbiting Vehicles

Satellites

Fighter Aircraft

$\mu g_e$

Moon

$0.17\ g_e$

Mars

$0.38\ g_e$

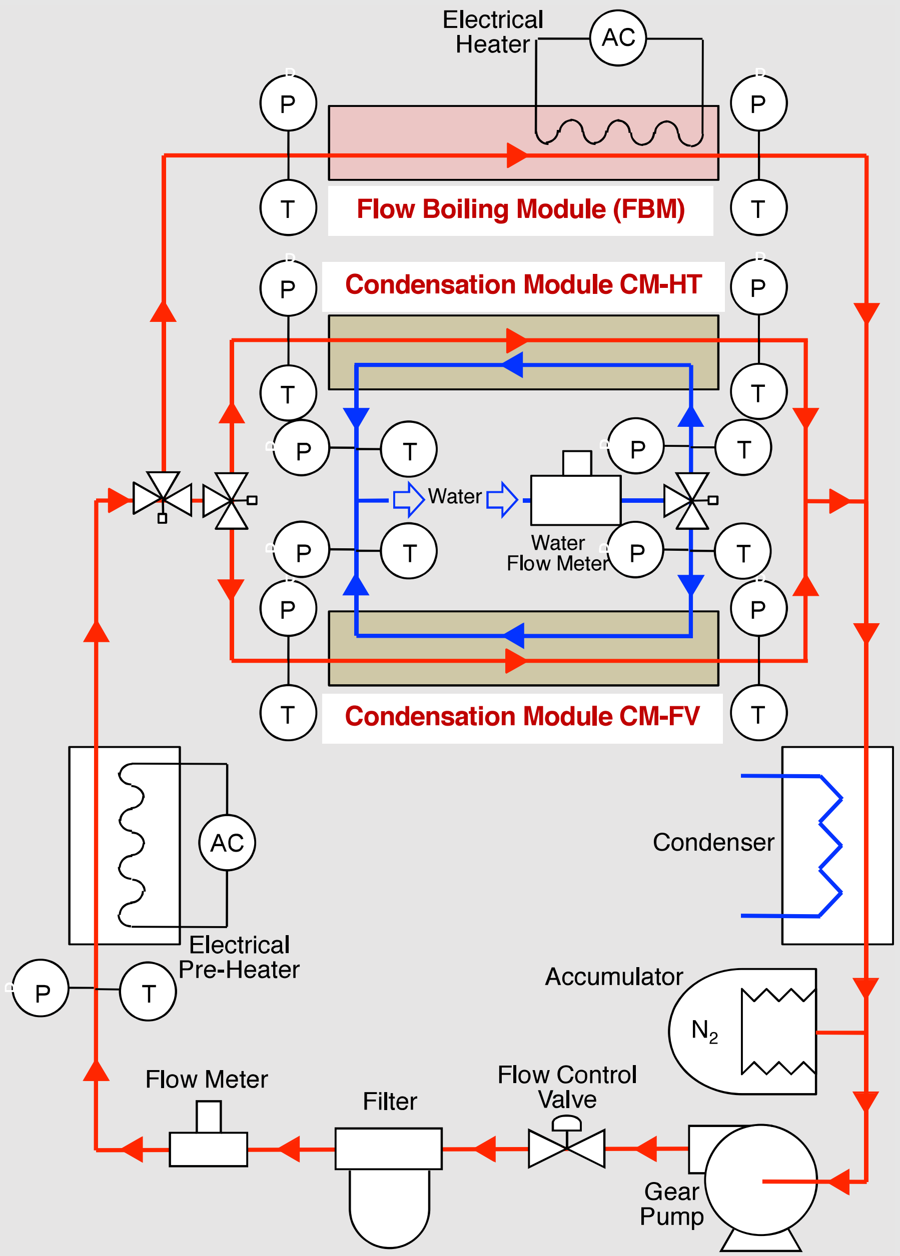
$1\ g_e$

$10\ g_e$

**American Society for Gravitational and Space Research**

**Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)**

# Initial Layout of FBCE



**Consists of:**

- nPFH (normal perfluorohexane, $C_6H_{14}$) sub-loop
- Water sub-loop

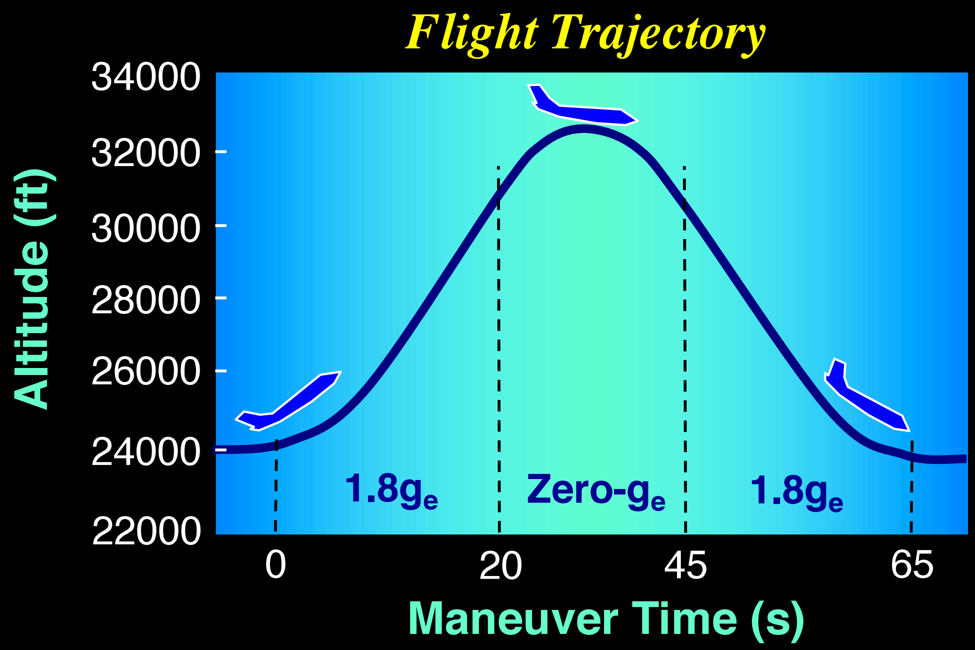
**Three interchangeable test modules:**

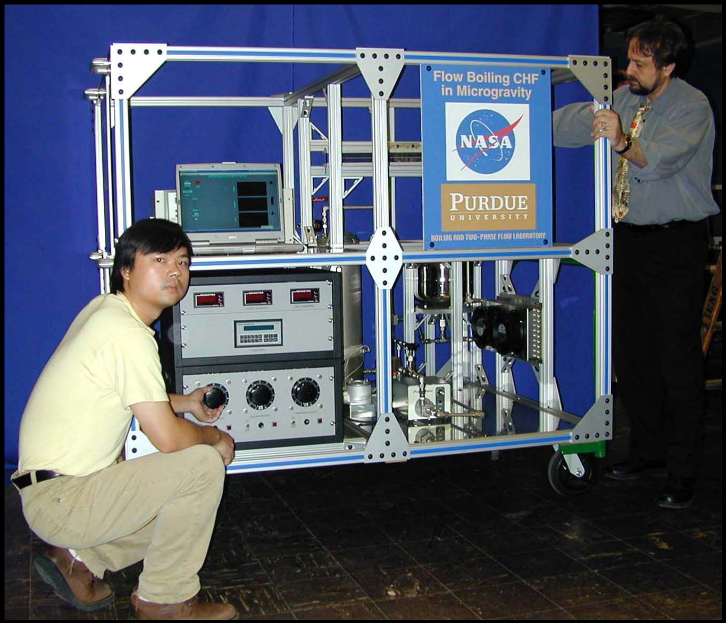
- Flow Boiling Module (FBM)
- Condensation Module for Heat Transfer Measurements (CM-HT)
- Condensation Module for Flow Visualization (CM-FV)

# *Flow Boiling Module (FBM)*

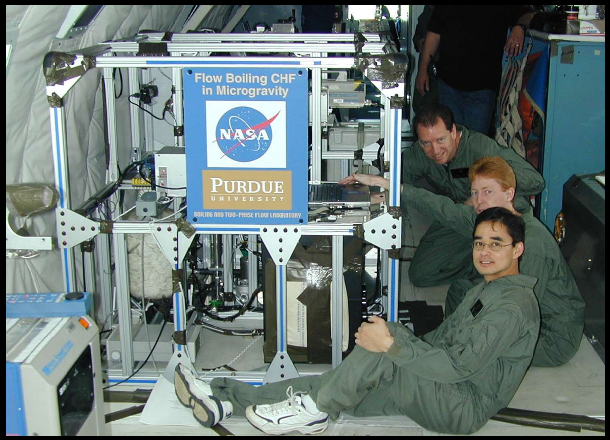
# *Purdue Flow Boiling Parabolic Flight Apparatus*

KC-135 Tests performed at NASA Glenn Research Center

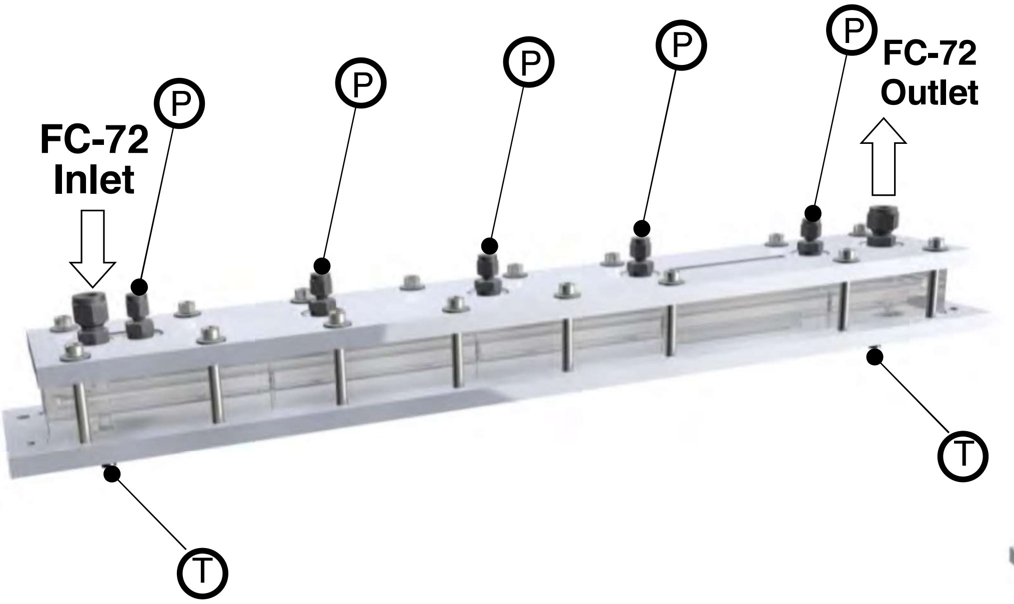


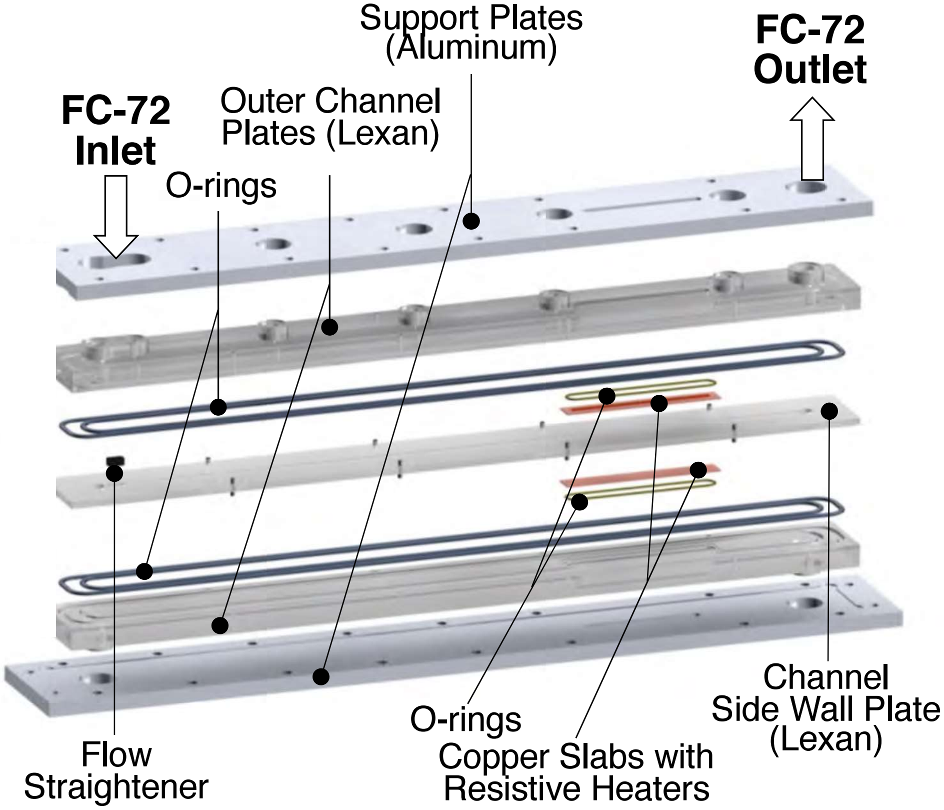


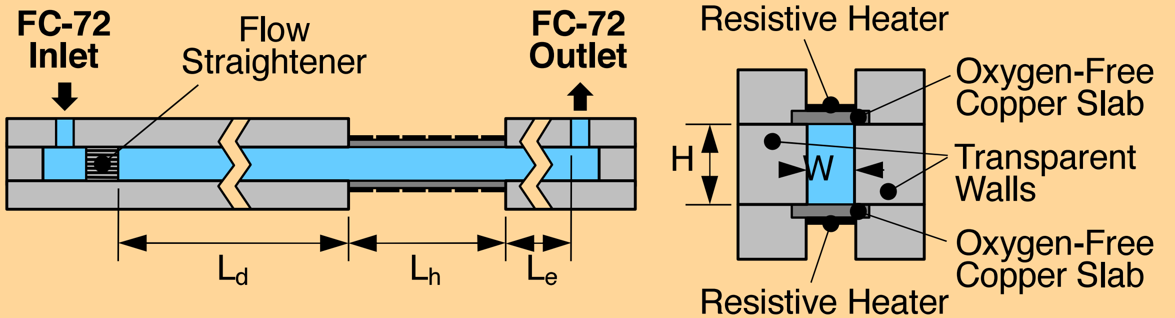
Phase Change Photo Library
(Mudawar, 1984 - 2016)



# Flow Boiling Module (FBM)



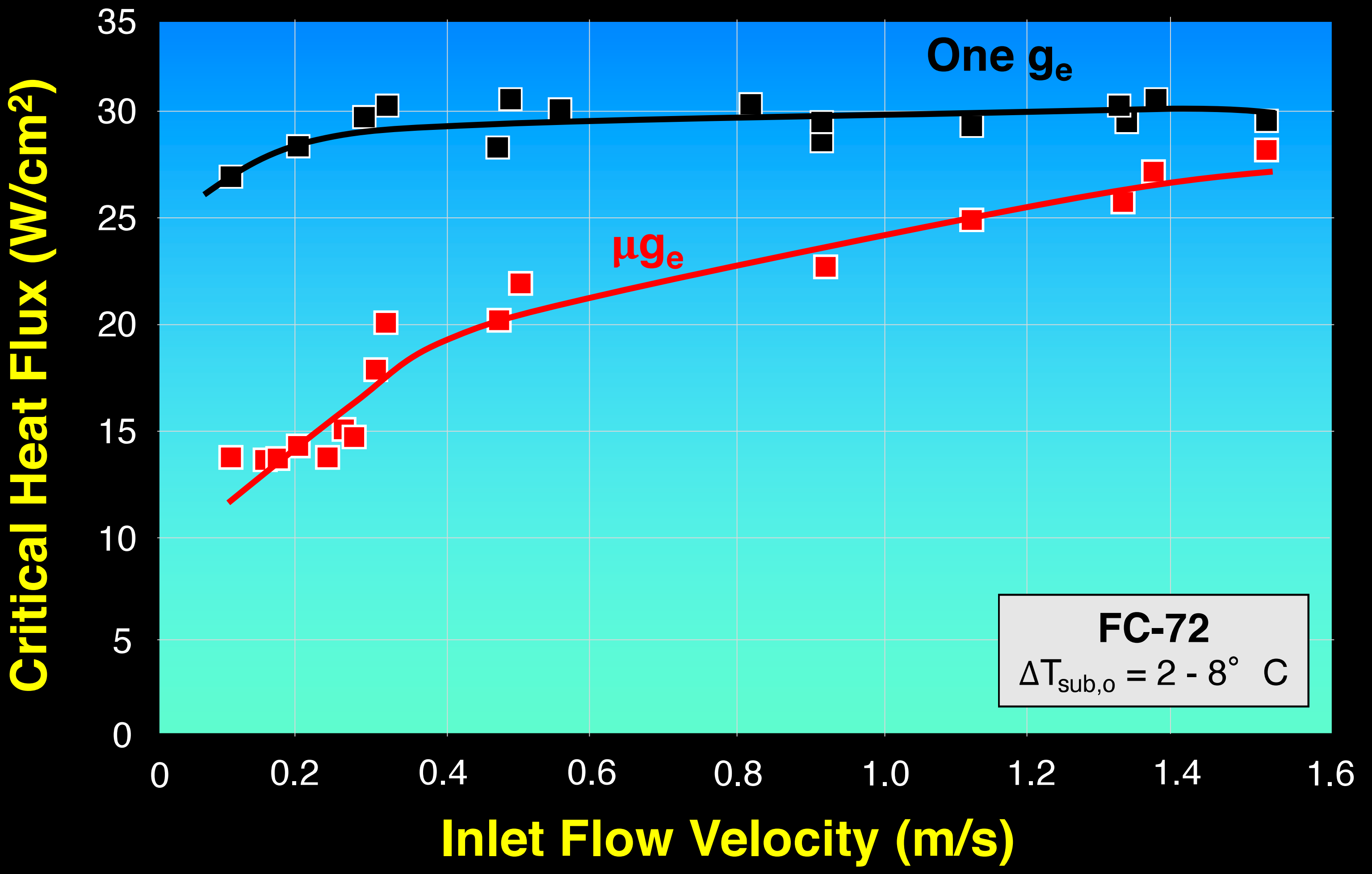




| | |
|---|---|
| Development Length: | $L_d = 327.7$ mm |
| Heated Length: | $L_h = 114.6$ mm |
| Exit Length: | $L_e = 60.7$ mm |

Channel Height: H = 5.0 mm
Channel Width: W = 2.5 mm

# *Parabolic Flight Flow Boiling Results*

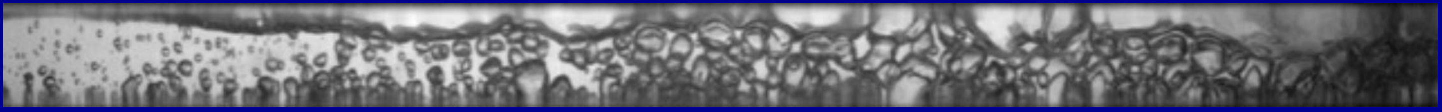


- Critical heat flux (CHF) is the most important design parameter for flow boiling systems, exceeding which can lead to surface overheating or burnout
- Compared to one-$g_e$ CHF data, parabolic flight data show appreciable degradation at low velocities but convergence at high velocities

# *Effects of Velocity on Flow Boiling CHF for Microgravity and One-G*

**CHF for Double-sided Heating: Low U (~ 0.1 m/s)**

Horizontal one $g_e$



Microgravity

**CHF for Double-sided Heating: High U (~ 2 m/s)**

Horizontal one $g_e$

Microgravity

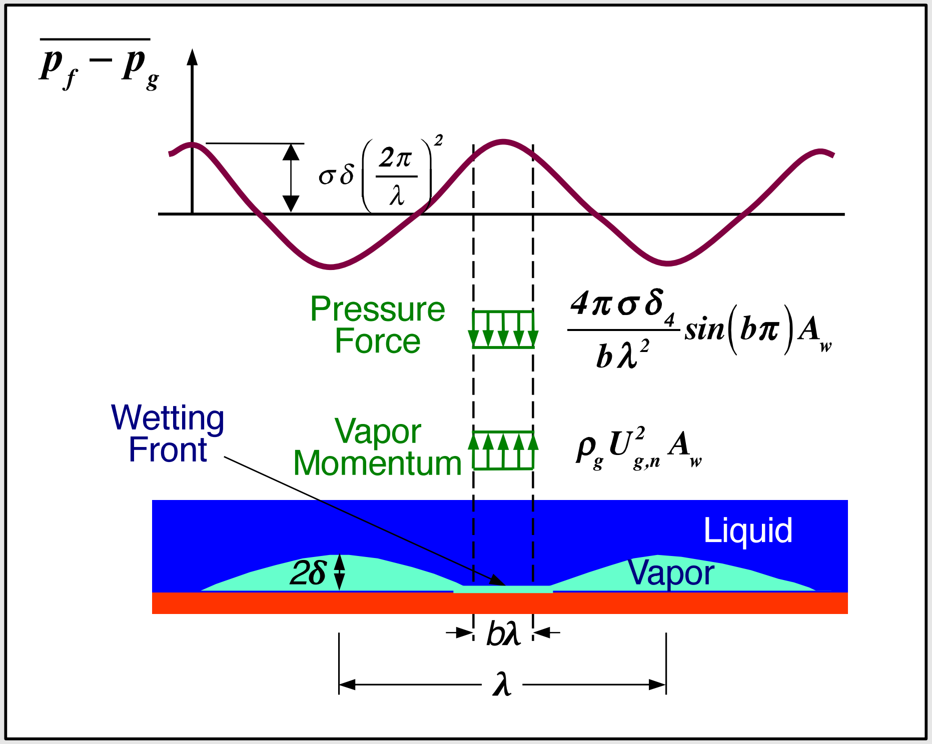
**Low U:**

1. CHF in horizontal one $g_e$ flow is associated with appreciable stratification resulting from strong buoyancy and weak inertia
2. CHF in microgravity at drastically different in interfacial structure compared to one $g_e$

**High U:**

1. CHF in horizontal one $g_e$ flow is no longer stratified as strong inertia dwarfs buoyancy
2. Similar CHF interfacial behavior observed in both microgravity and one $g_e$

# Theoretical Interfacial Lift-off CHF Model



## Use separated flow model to determine axial variations of:

| | |
|---|---|
| $U_{g1}, U_{g2}$ | *Near-wall vapor layer velocities* |
| $U_f$ | *Liquid layer velocity* |
| $\delta_1, \delta_2$ | *Near-wall vapor layer thicknesses* |

## Critical interfacial wavelength

$$k_c = \frac{2\pi}{\lambda_c} = \frac{\rho_f'' \rho_g'' (U_g - U_f)^2}{2\sigma(\rho_f'' + \rho_g'')} + \sqrt{\left[\frac{\rho_f'' \rho_g'' (U_g - U_f)^2}{2\sigma(\rho_f'' + \rho_g'')}\right]^2 + \frac{(\rho_f - \rho_g) g_n}{\sigma}}$$

*where* $\rho_f'' = \rho_f\, coth(2\pi H_f / \lambda_c)$ *and* $\rho_g'' = \rho_g\, coth(2\pi H_g / \lambda_c)$

**Earth Gravity:** $g_{n,1} = g_e \cos\theta$ *and* $g_{n,2} = g_e \cos(\theta + \pi) = -g_e \cos\theta$

**Microgravity:** $g_{n,1} = g_{n,2} = \mu g_e \cong 0$ ➡ $\lambda_c = \frac{2\pi\sigma(\rho_f'' + \rho_g'')}{\rho_f'' \rho_g'' (U_g - U_f)^2}$

## Mean pressure difference across wetting front

$$\overline{p_f - p_g} = \frac{4\pi\sigma\delta}{b\lambda_c^2} sin(b\pi)$$

*where b = 0.20 is ratio of wetting front length to wavelength*

## Interfacial lift-off criterion

$$\overline{p_f - p_g} = \rho_g \left[\frac{q_w''}{\rho_g h_{fg}}\right]^2$$

## Surface energy balance

$$q_m'' = b\, q_w''$$

## Critical heat flux

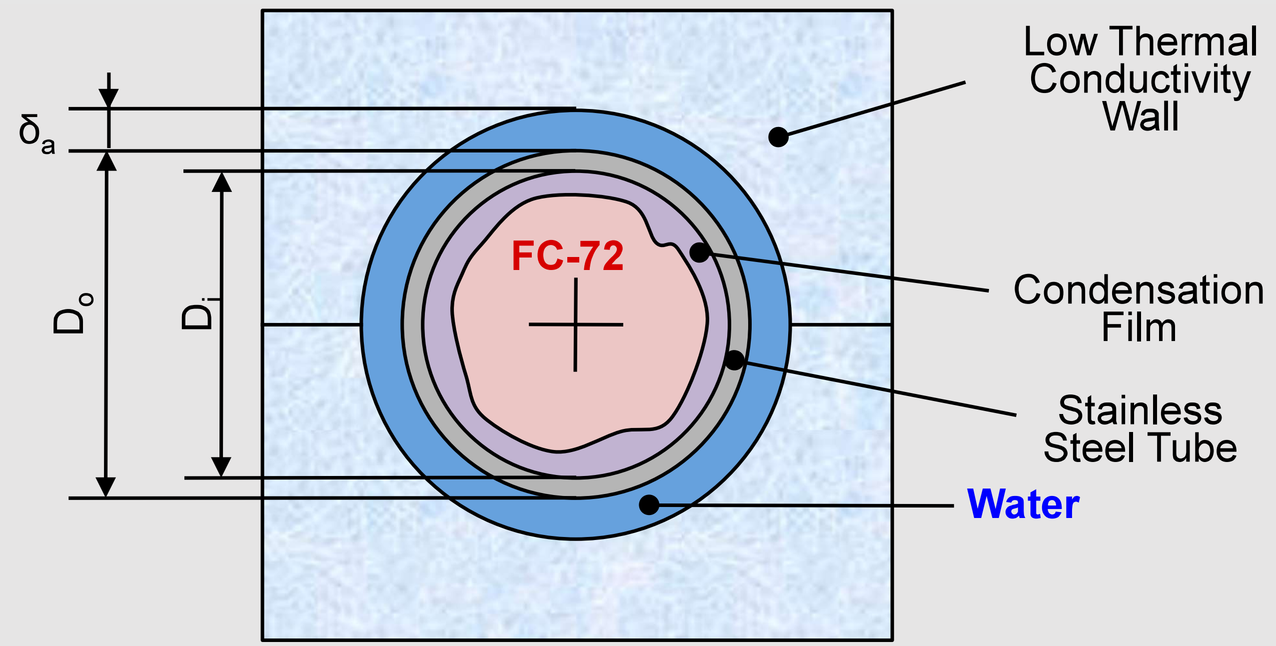
$$\boxed{q_m'' = \rho_g \left(c_{p,f} \Delta T_{sub,in} + h_{fg}\right) \left[\frac{4\pi\sigma b\, sin(b\pi)}{\rho_g}\right]^{1/2} \left.\frac{\delta^{1/2}}{\lambda_c}\right|_{z^*}}$$

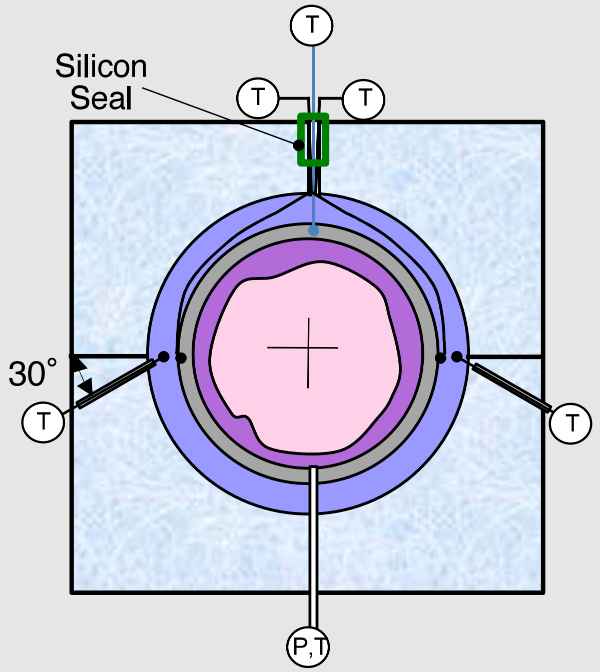
# Condensation Module for Heat Transfer Measurements (CM-HT)

# &

# Condensation Module for Flow Visualization (CM-FV)

# *Condensation Module for Heat Transfer Measurements (CM-HT)*



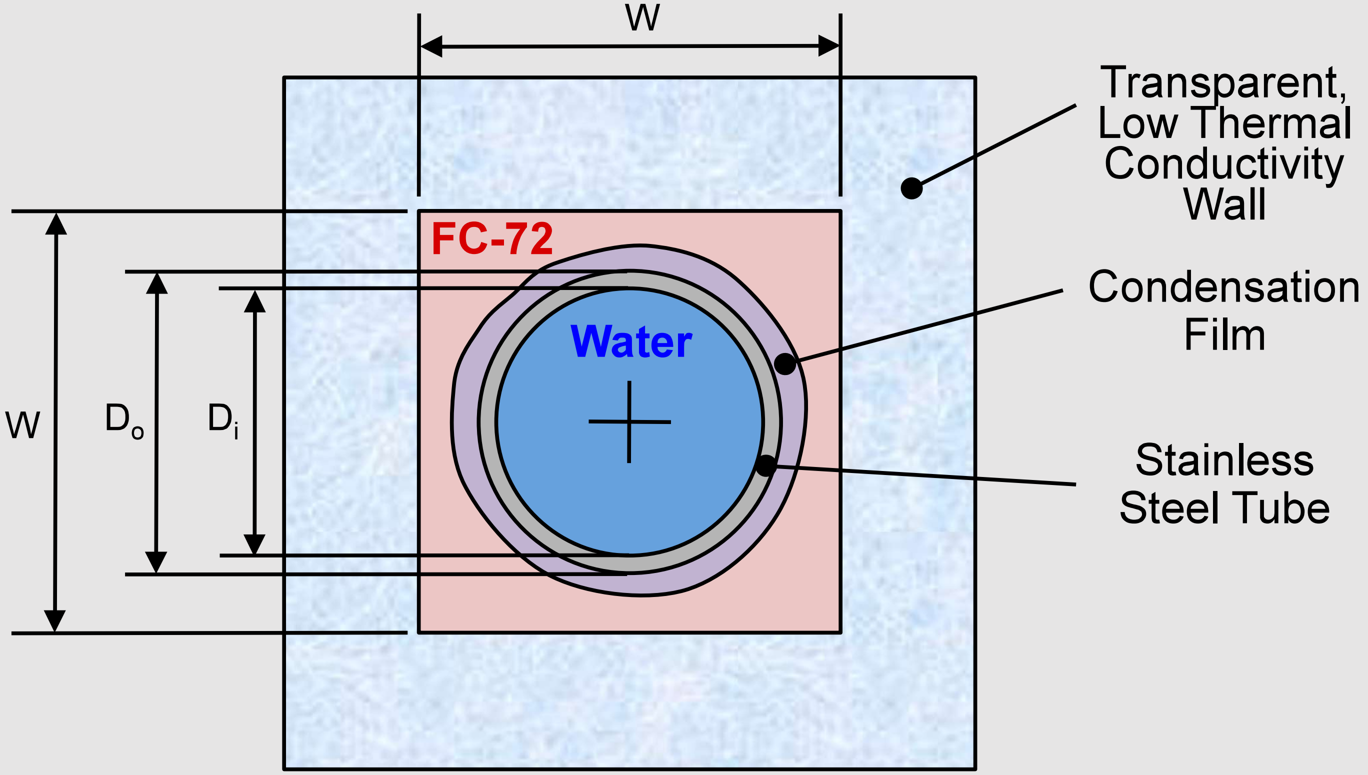


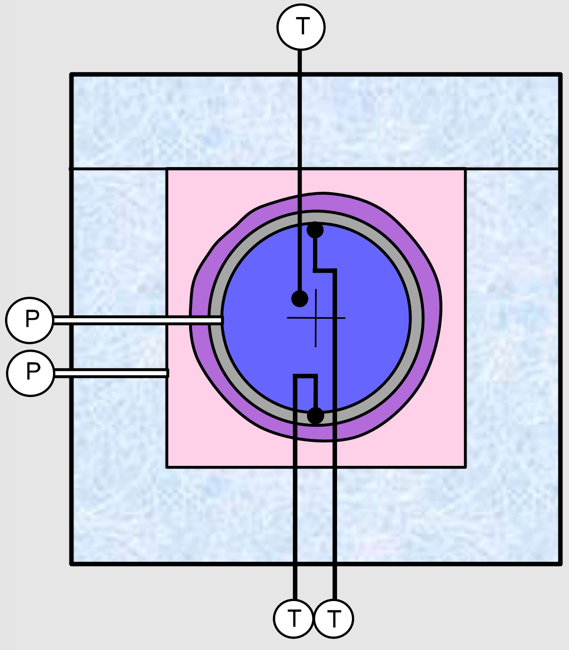
**Temperature Instrumentation**

| FC-72 side: | Water side: |
|---|---|
| $D_i$ = 7.12 mm | $\delta_a$ = 2.38 mm |
| $t_{wall}$ = 0.41 mm | |
| L = 574.6 mm | |

- CM-HT is designed to simulate flow condensation occurring naturally within actual condensation tubes
- FC-72 vapor supplied at inlet rejects heat to external water flow and condenses into gradually thickening annular liquid film
- Wall temperature measurements available externally on water side to avoid disrupting liquid film motion; this allows installing large number of thermocouples spanning entire condensation length
- Metal condensation tube precludes video access to interfacial structure of condensation film.

# *Condensation Module for Flow Visualization (CM-FV)*





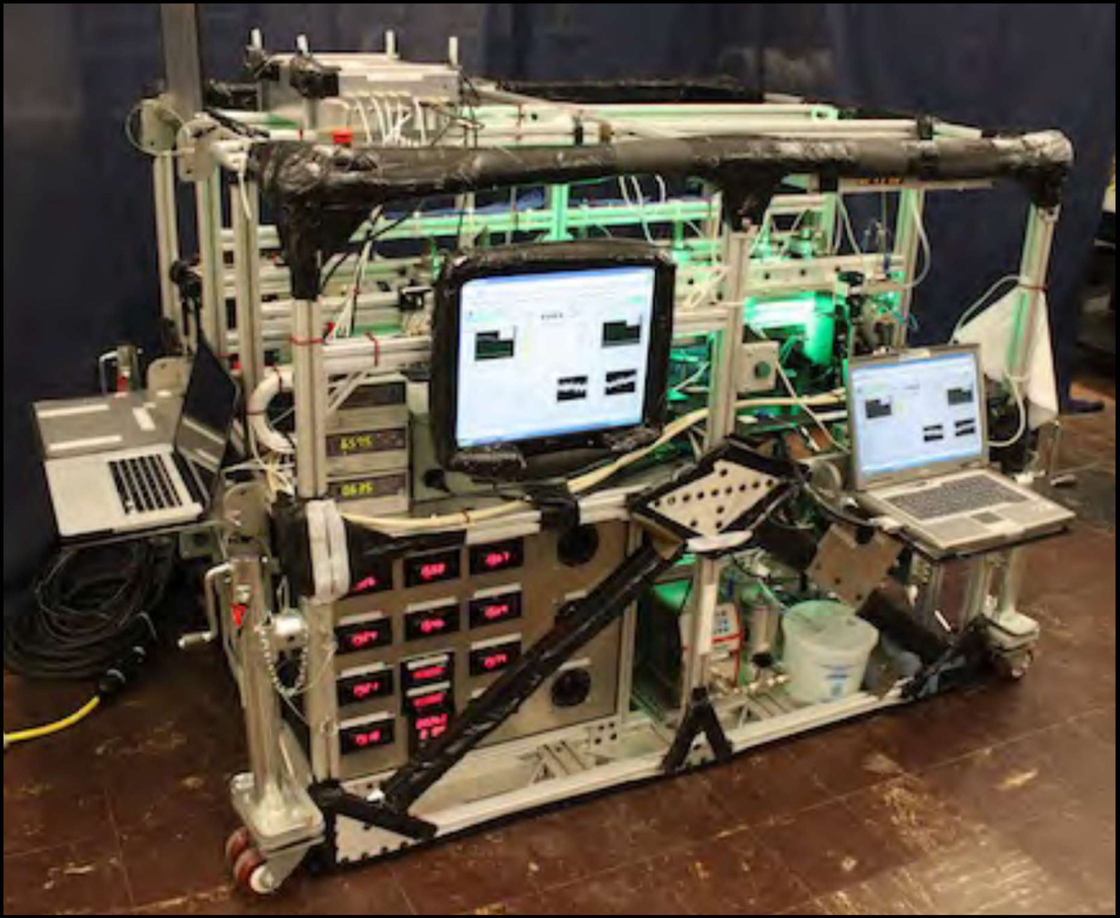
**Instrumentation**

| FC-72 side: | Water side: |
|---|---|
| W = 11.13 m | $D_i$ = 7.14 mm |
| L = 587 mm | $t_{wall}$ = 0.406 mm |

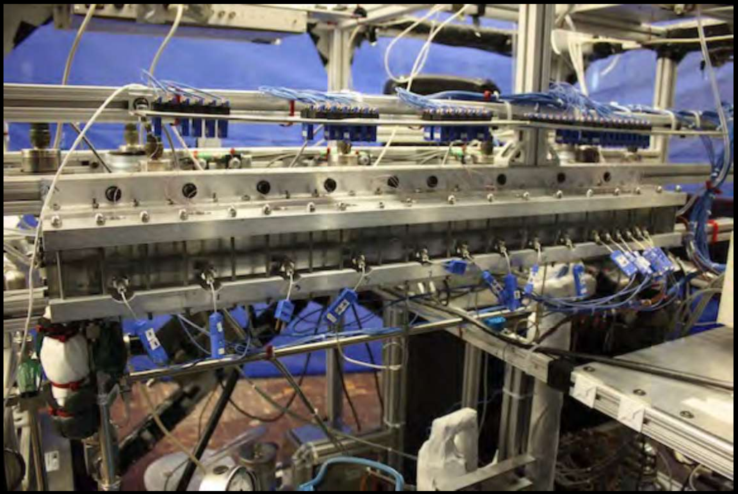
- CM-FV is designed to facilitate video access to interfacial flow structure of condensation film
- Dimensions are based on equivalency of condensation length between CM-FV and CM-HT, with nPFH vapor superficial velocity ratio in CM-FV to that in CM-HT of 0.48
- Condensation occurs on tube outside as FC-72 vapor condenses into gradually thickening liquid film
- Wall temperature measurements available internally on water side to avoid disrupting liquid film motion
- Small inner diameter limits number of thermocouples for wall temperature measurements
- Primary function of CM-FV is to capture interfacial flow structure rather than detailed wall temperature measurements

# *Purdue Flow Condensation Parabolic Flight Apparatus*

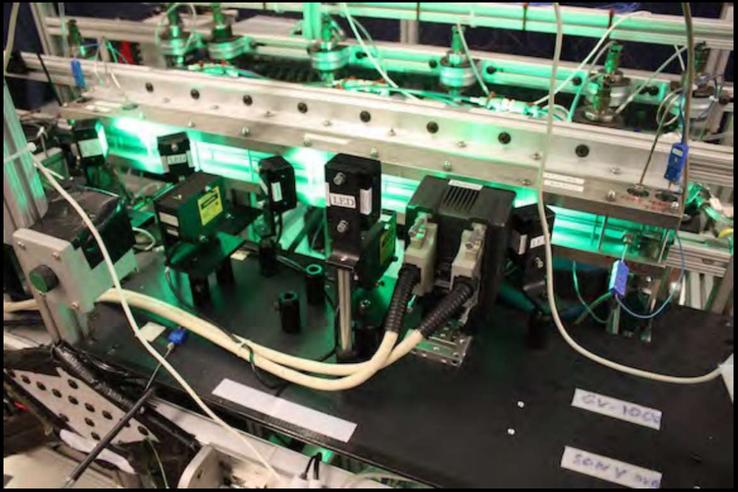
## Condensation Rig



CM-HT and CM-FV were successfully tested in parabolic flight

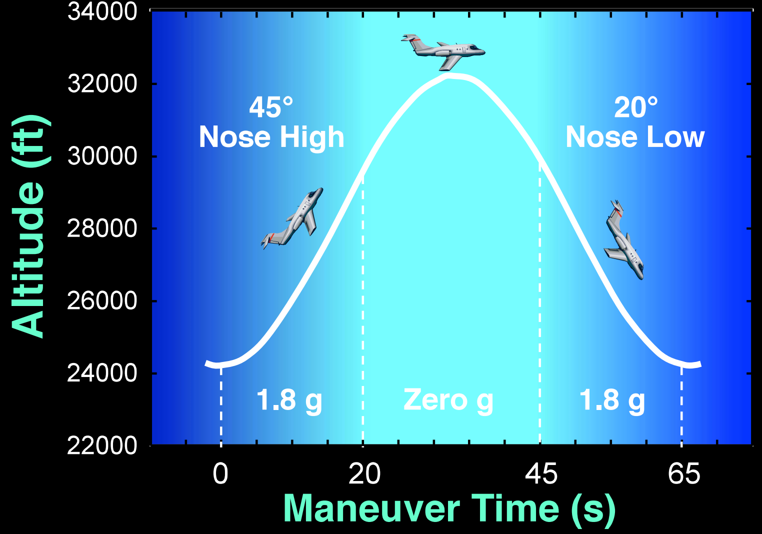


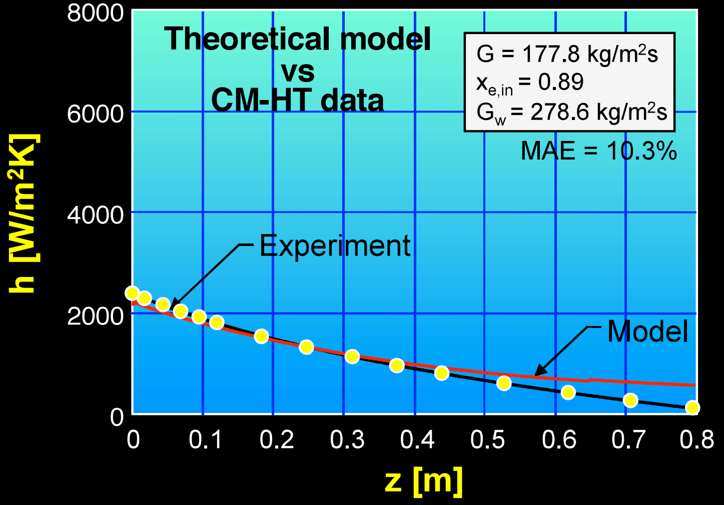
CM-HT:  Condensation Module for Heat Transfer Measurements



CM-FV:  Condensation Module for Flow Visualization

# *Heat Transfer in Annular Condensation in Microgravity*





**Key limitation of both condensation modules is difficulty achieving steady state during parabolas**

**CM-FV interfacial flow structure video**

**Microgravity**

**G = 90.2 kg/m²s**

($x_{e,in} = 0.73$, $G_w = 678$ kg/m²s)

z = 58 mm, 4000 fps

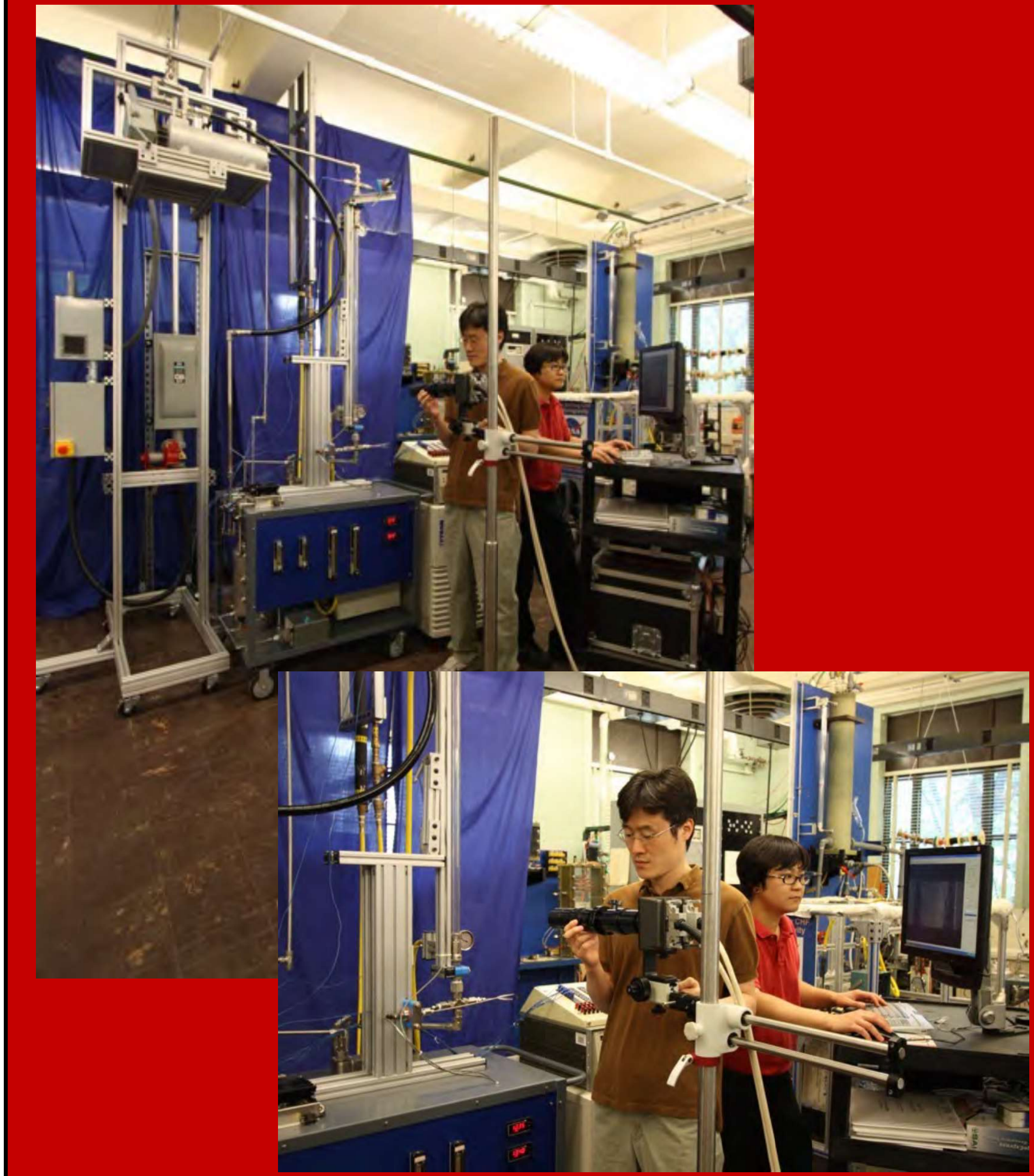
**Hyper-G**

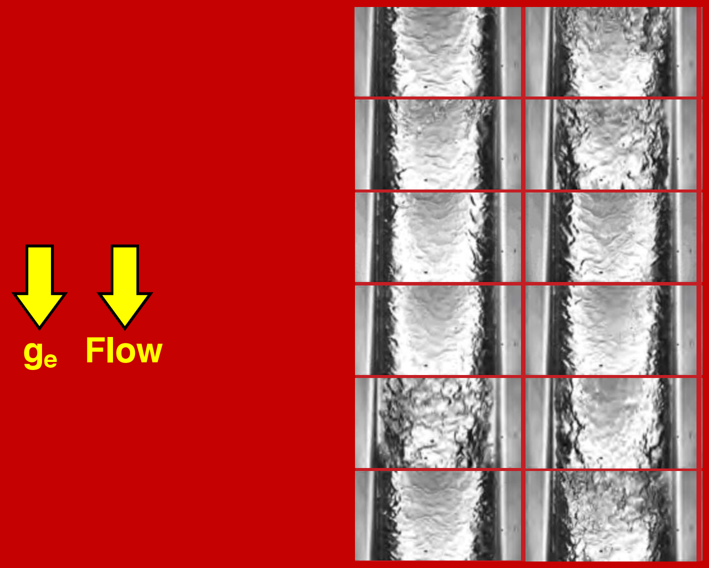
**G = 68.0 kg/m²s**

($x_{e,in} = 0.4$, $G_w = 601$ kg/m²s)

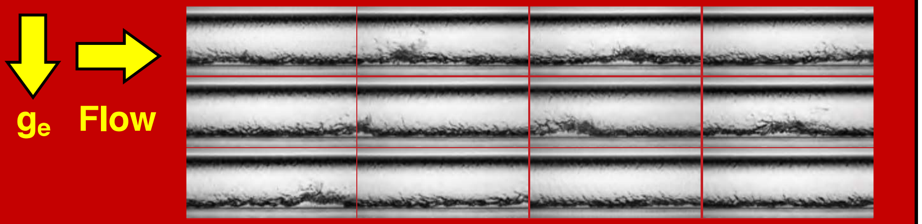
z = 351 mm, 4000 fps

# *Heat Transfer in Annular Condensation at One-G*

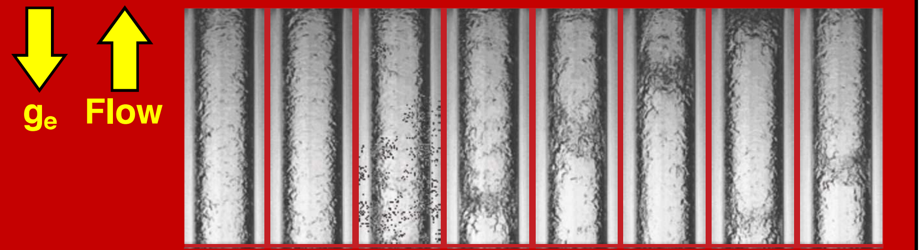




Vertical Downflow



Horizontal Flow



Vertical Upflow

## *Ultimate Goal:*

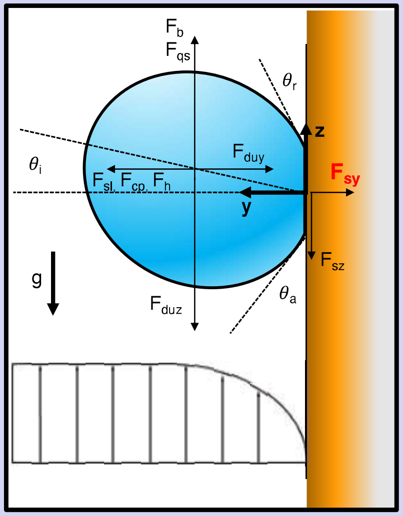
***Develop experimentally validated correlations, theoretical models, and CFD models for both flow boiling and flow condensation***

# CFD Methodology for FBM

## Computational Models used:

- ☐ ***Volume-of-fluid (VOF) model***
  Tracks interface between liquid and vapor, involves interface shape reconstruction
- ☐ ***Shear-stress transport (SST) k-ω model***
  Accounts for turbulent effects including interfacial damping
- ☐ ***Lee model***
  Predicts interfacial mass and heat transfer resulting from phase change, evaporation and condensation
- ☐ ***Continuum surface force (CSF) model***
  Incorporates surface tension in VOF calculation, considering the pressure jump across the surface

### Forces Acting Bubble:



**Forces parallel to surface**

$$\sum F_z = F_{s,z} + F_{du,z} + F_{qs} + F_b = \rho_g V_b \frac{du_z}{dt}$$

**Forces normal to surface**

$$\sum F_y = F_{s,y} + F_{du,y} + F_{sl} + F_h + F_{cp} = \rho_g V_b \frac{du_y}{dt}$$

**Shear-lift coefficient**

$$C_L = \frac{F_{sl}}{\frac{1}{2}\rho_f U_r^2 \pi a^2} = 3.877 G_s^{1/2} \times \left[\mathrm{Re}_b^{-m/2} + \left(0.344 G_s^{1/2}\right)^m\right]^{1/m}$$

**Dimensionless shear rate**

$$G_s = \left|\frac{dU_r}{dy}\right| \frac{a}{U_r} \quad , a=d_b/2$$

## Governing Equations:

- ☐ ***Continuity of volume fraction***

$$\frac{\partial \alpha_f}{\partial t} + \nabla \bullet \left(\alpha_f \vec{u}_f\right) = \frac{1}{\rho_f} \sum \left(\dot{m}_{gf} - \dot{m}_{fg}\right)$$

$$\frac{\partial \alpha_g}{\partial t} + \nabla \bullet \left(\alpha_g \vec{u}_g\right) = \frac{1}{\rho_g} \sum \left(\dot{m}_{fg} - \dot{m}_{gf}\right)$$

- ☐ ***Momentum***

$$\frac{\partial}{\partial t}\left(\rho \vec{u}\right) + \nabla \bullet \left(\rho \vec{u}\vec{u}\right) = -\nabla P + \nabla \bullet \left[\mu\left(\nabla \vec{u} + \nabla \vec{u}^T\right)\right] + \vec{F}$$

- ☐ ***Energy***

$$\frac{\partial}{\partial t}\left(\rho E\right) + \nabla \bullet \left(\vec{u}\left(\rho E + P\right)\right) = \nabla \bullet \left(k_{eff} \nabla T\right) + S_h$$

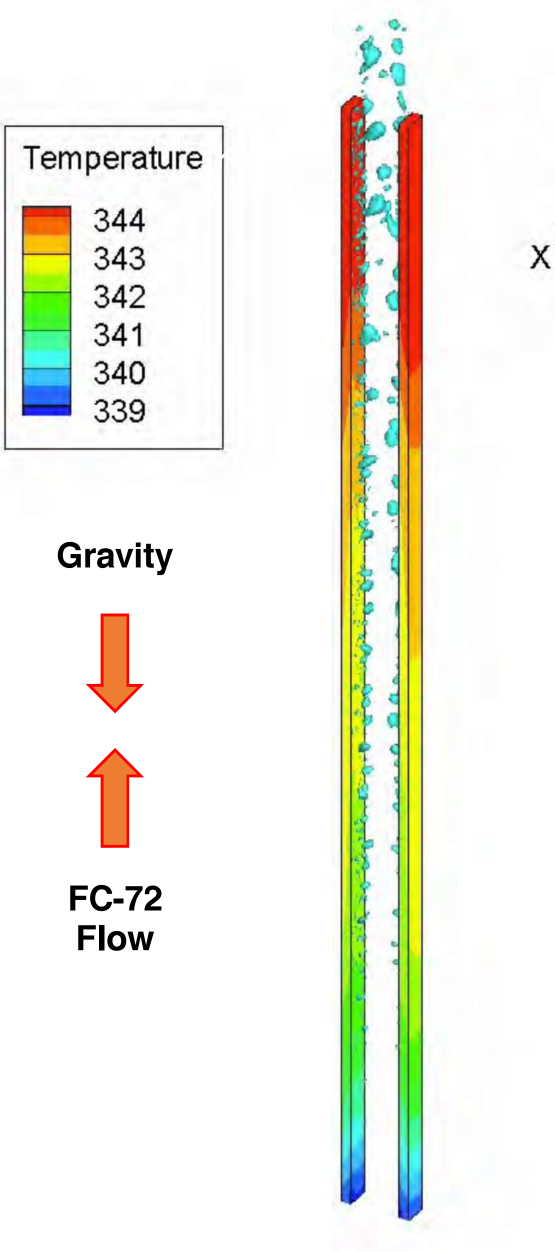
- ☐ ***Turbulent kinetic energy and dissipation transport***

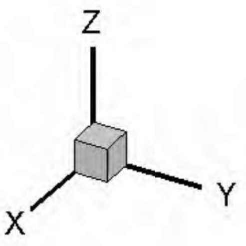
$$\frac{\partial}{\partial t}\left(\rho k\right) + \nabla \bullet \left(\rho k \vec{u}\right) = \nabla \bullet \left(\Gamma_k \nabla k\right) + \widetilde{G_k} - Y_k + S_k$$

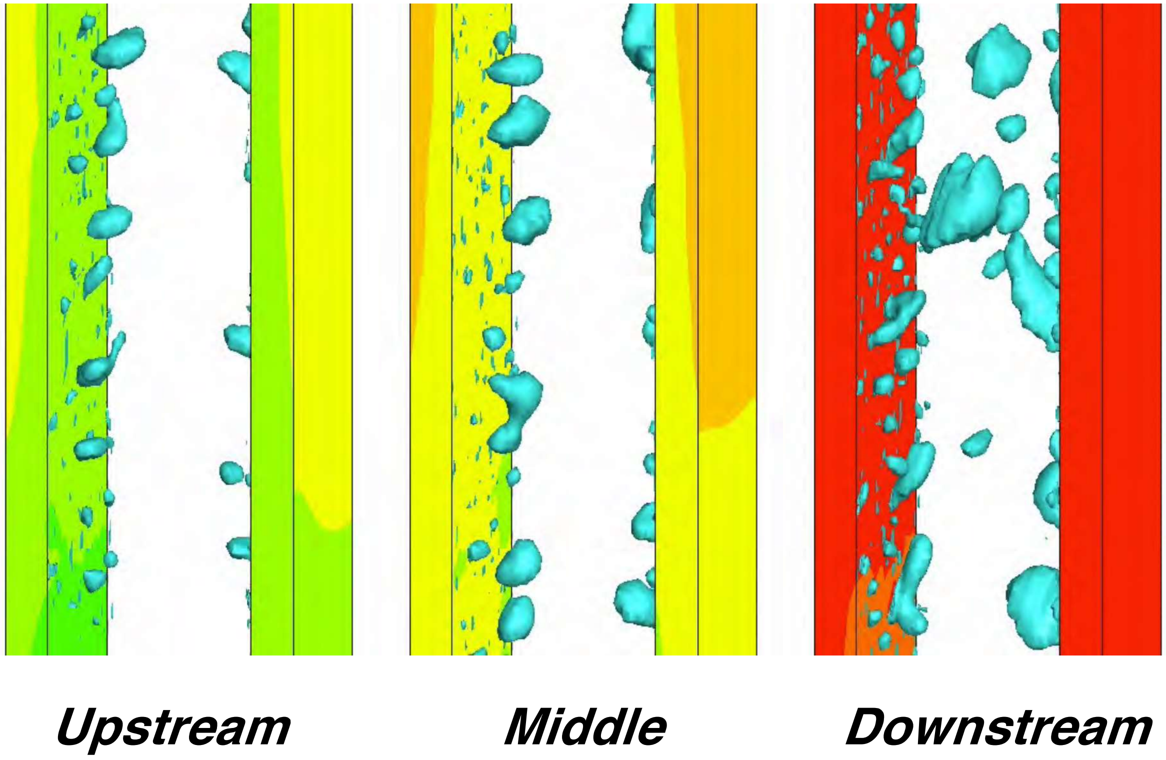
$$\frac{\partial}{\partial t}\left(\rho \omega\right) + \nabla \bullet \left(\rho \omega \vec{u}\right) = \nabla \bullet \left(\Gamma_\omega \nabla \omega\right) + G_\omega - Y_\omega + D_\omega + S_\omega$$

# *CFD Validation of FBM Wall Temperature Measurements and Interfacial flow Structure*

G = 445.75 kg/m²s
q″ = 143 kW/m²
$\Delta T_{sub}$ = 30.81°C
Vertical upflow
One-G

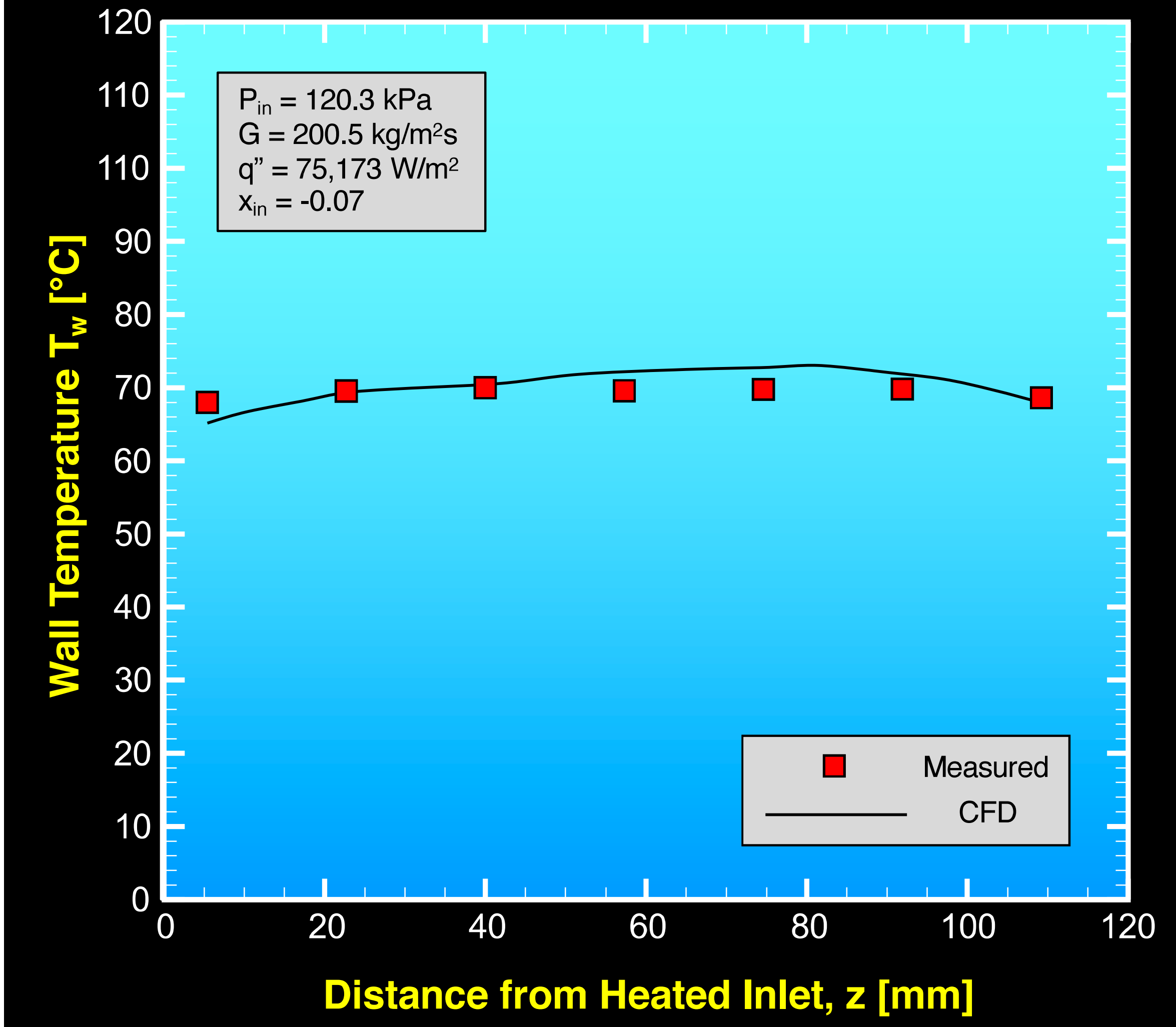


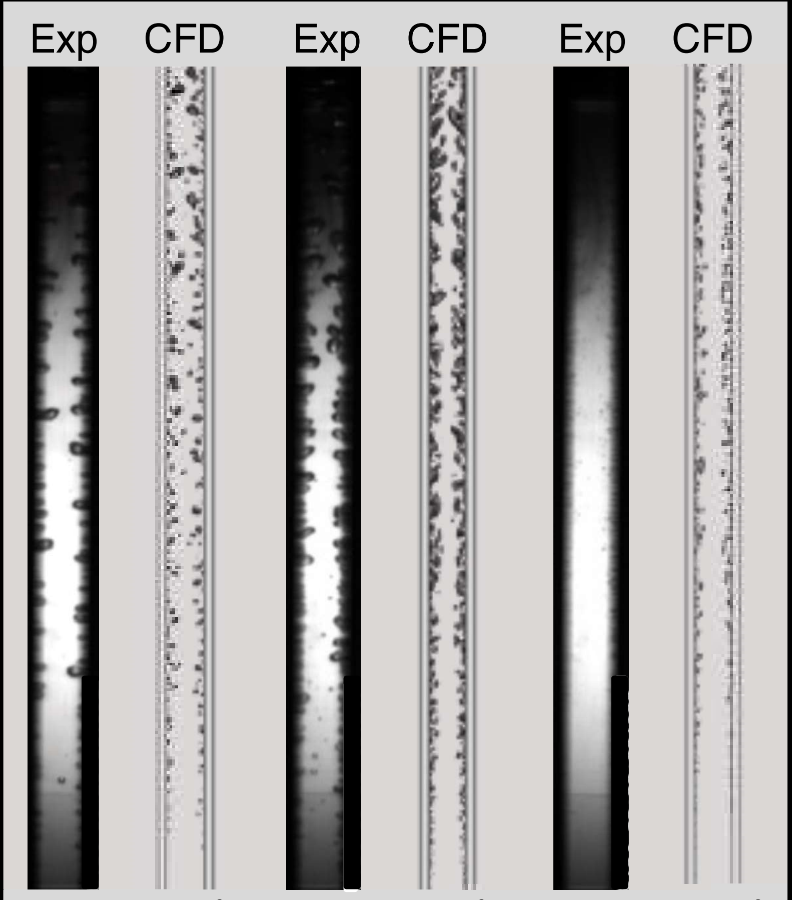




Video frame rate is 5 fps
Individual images in sequence separated by 1 ms

# CFD Validation against FBM Data





G = 445.75 kg/m$^2$s
q” = 143 kW/m$^2$
$\Delta T_{sub}$ = 30.81°C

G = 836.64 kg/m$^2$s
q” = 191 kW/m$^2$
$\Delta T_{sub}$ = 31.39°C

G = 2432.51 kg/m$^2$s
q” = 194 kW/m$^2$
$\Delta T_{sub}$ = 33.94°C

Measured wall temperature

Video-captured interfacial structure

CFD results must be validated against BOTH

# The Team

## Purdue University (16):

**Principal Investigator:** Issam Mudawar

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Kim, Sung-Min (Ph.D.)
Lee, Hyoung-Soon (Ph.D.)
Konishi, Christopher (Ph.D.)
Mascarenhas, Nikhin (Ph.D.)

Park, Ilchung (Ph.D.)
Kharangate, Chirag (Ph.D.)
Lee, Seunghyun (Ph.D.)
O'Neill, Lucas (Ph.D.)
Devahdhanush, V.S. (Ph.D. candidate)

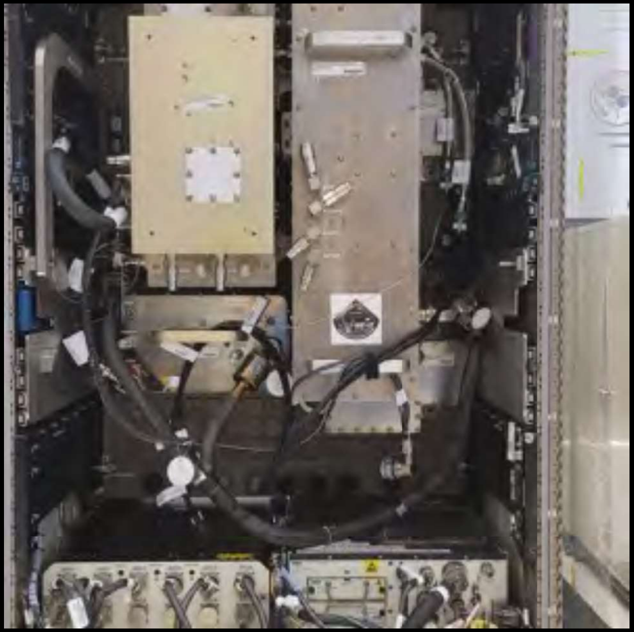
Lee, Jeongmin (Ph.D. candidate)
Ganesan, Vishwanath (Ph.D. candidate)
Damle, Nishad (Ph.D. candidate)
Kim, Sunjae Kim (Ph.D. candidate)
Patel, Raj (M.S. candidate)

## NASA Glenn (37):

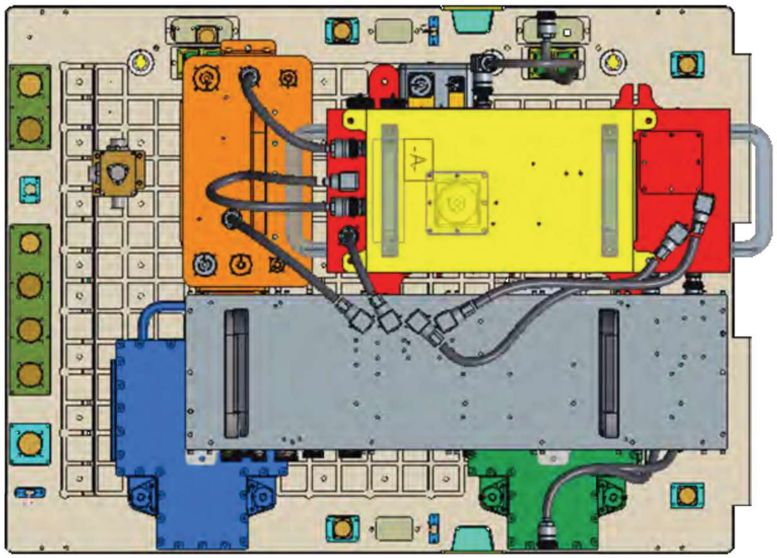
| | |
|---|---|
| **Project Management** | |
| Project Manager | Nancy Hall |
| Configuration Management | Kathy Kachmar |
| Configuration Management | Barb Wamsley |
| FCF | Andrea Marchica |
| Scheduler | Erin Wood |
| | |
| **Science Team** | |
| Co-Principal Investigator | Mojib Hasan |
| Project Scientist | Henry Nahra |
| Research Scientist | Balasubramaniam Ramaswamy |
| | |
| **Engineering Team** | |
| Chief Engineer | Monica Guzik |
| Chief Safety Officer | Martin Bradish |
| AST, S&MA | Brandon White |
| Lead Systems Engineer | Tim Schuler |
| V&V Lead | Mark Sorrells |
| AI&T Engineer | Mark Lefebvre |
| Diagnostics | Chris Lant |
| Diagnostics Discipline Lead & TMA Product Lead | Jeff Mackey |
| Electrical | Glenn Lindamood |

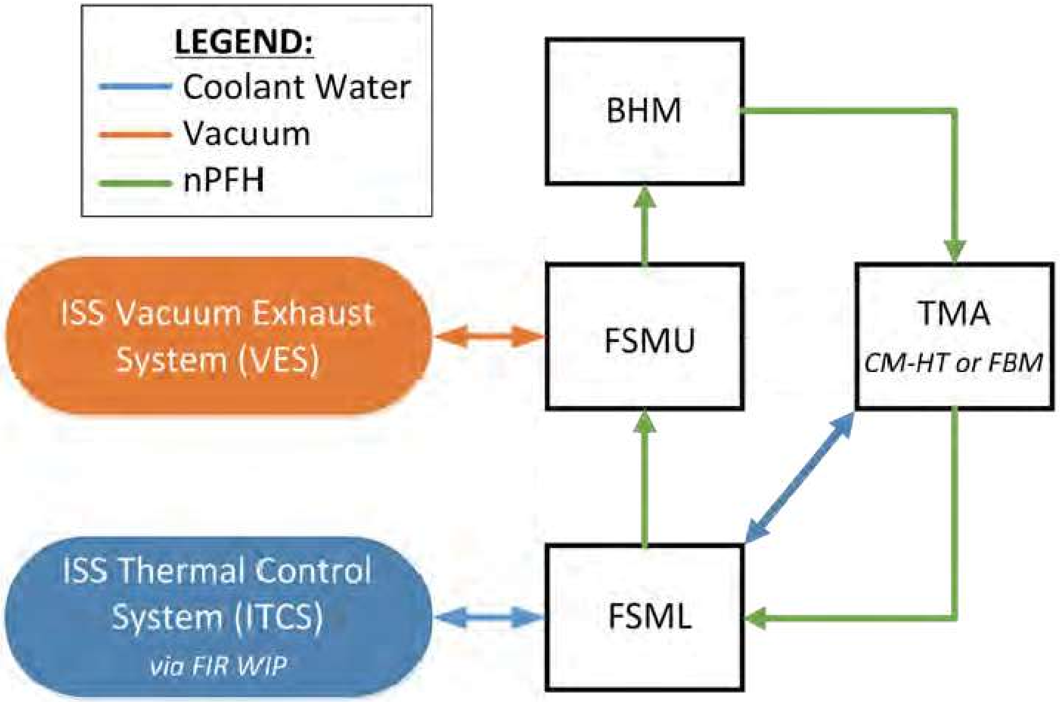
| | |
|---|---|
| Electrical | Nick Purpera |
| Electrical | Issam Boukabou |
| Electrical Lead | Hector Dominguez |
| Fluid Systems Discipline Lead | Jesse Defiebre |
| Payload Lead | Monica Guzik |
| Fluids Integrated Rack Support | Chris Rogers |
| Mission Ops | Chanisara Netsuwan |
| Fluids Integrated Rack Support | Brandon Wagner |
| Mechanical Designer Discipline | Dave Nawrocki |
| RDAQM Product Lead | Bob Dolesh |
| Software (Flight Software) | Phil Gonia |
| Software Product Lead/SW Discipline Lead | Rochelle May |
| Thermal Discipline Lead | Erik Stalcup |
| | |
| **Safety and Mission Assurance** | |
| System Safety Lead | Deboshri Sadhukan |
| Software Safety Mgr./Software QA | Rick Plastow |
| Materials and Processes | Logan Micham |
| Quality Assurance Engineer | Brian Loucks |
| Risk Management | Bennett Straker |
| | |
| **Bldg 110 Lab Technicans** | |
| Mechanical Engineering | Dan Gedeon |
| Electronics Technician | Bob Paulin |
| Electronics Technician | Tiffany Vanderwyst |

# FBCE: The Final Configuration!



# FBCE System Overview





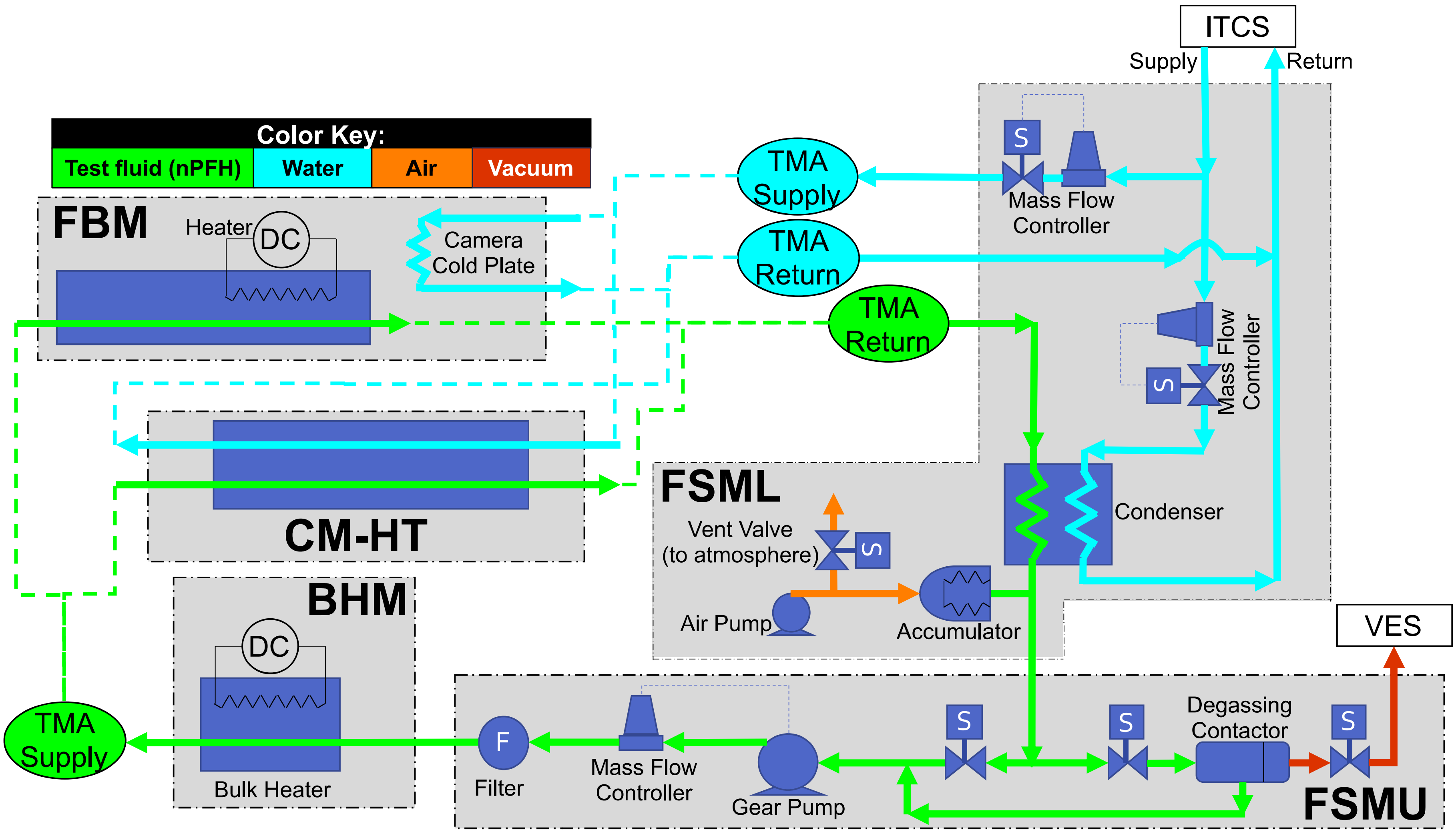
## FBCE Modules:

- **BHM** – Bulk Heater Module
- **FSMU** – Fluids System Module - Upper
- **FSML** – Fluids System Module - Lower
- **RDAQM 1** – Remote Data Acquisition Module 1
- **RDAQM 2** – Remote Data Acquisition Module 2
- **TMA** – Test Module Assembly (1 of 2 installed):
  - **FBM** – Flow Boiling Module
  - **CM-HT** – Condensation Module - Heat Transfer

## FIR Provided Hardware:

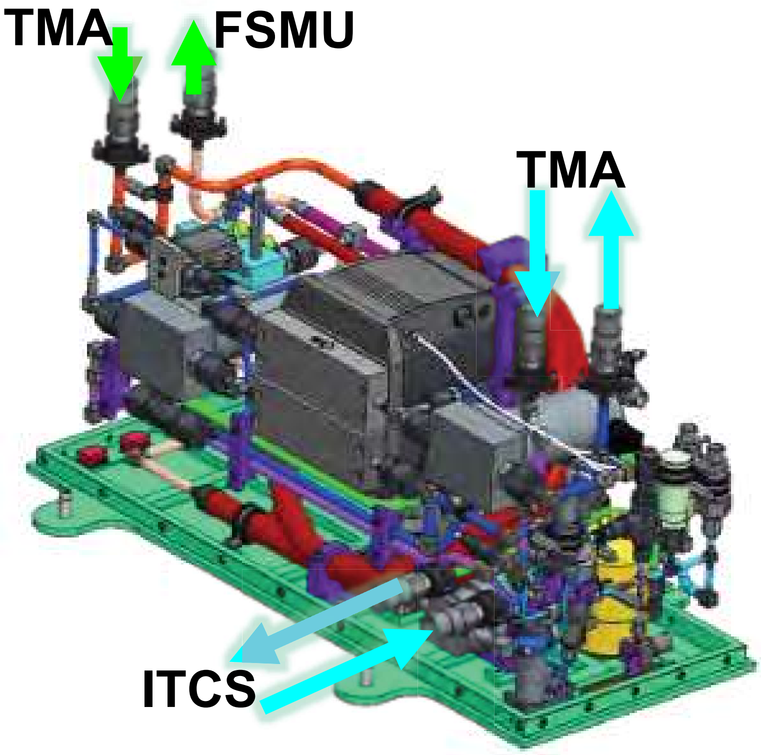
- SAMS – Space Acceleration Measurement System
- CCU – Confocal Control Unit (on back of rack)
- IPSU-CL – Imaging Processing Storage Unit – Camera Link (on back of rack)

# Fluid System Overview

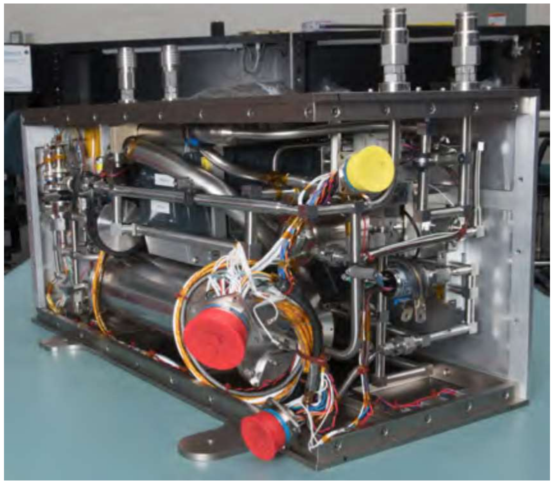


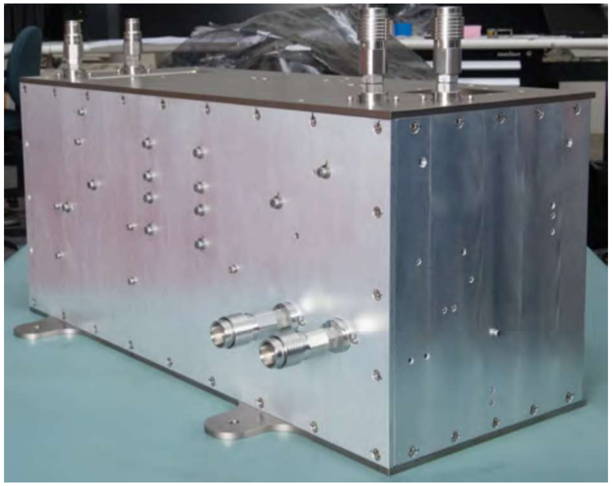
# *Fluid System Module - Lower*

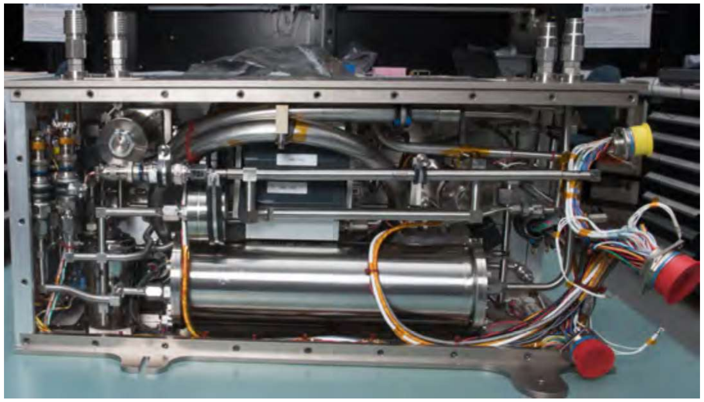
- Provides primary cooling for the test fluid exiting the test section, and the test section itself
- System pressure set by pressurizing or venting the air-side of a bellows accumulator



| Color Key: | | |
|---|---|---|
| Test fluid (nPFH) | Water | Air |

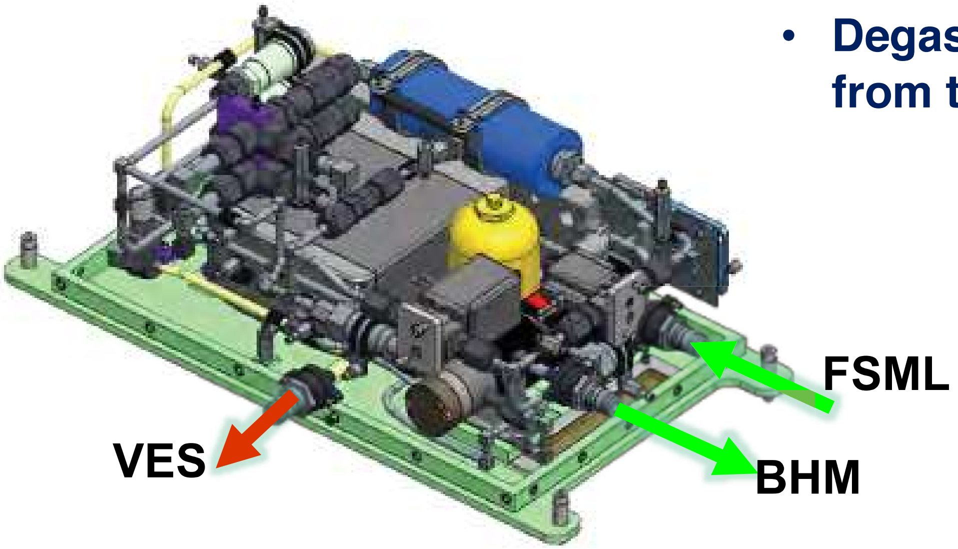




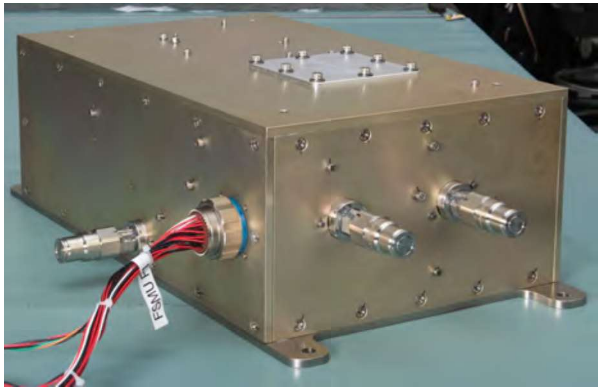


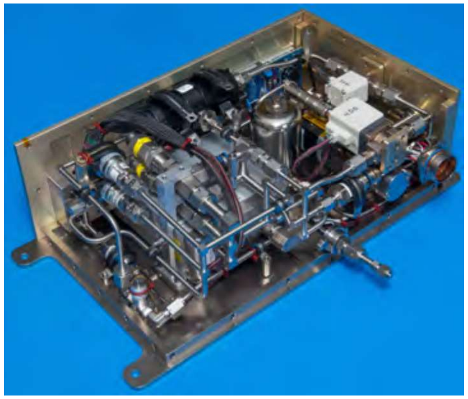
# *Fluid System Module - Upper*

- Mass flow controller drives a gear pump to provide flow throughout the closed loop system
- Multiple controls in place to prevent over-pressurization
- Degassing contactor removes dissolved gases from test fluid when membrane exposed to vacuum



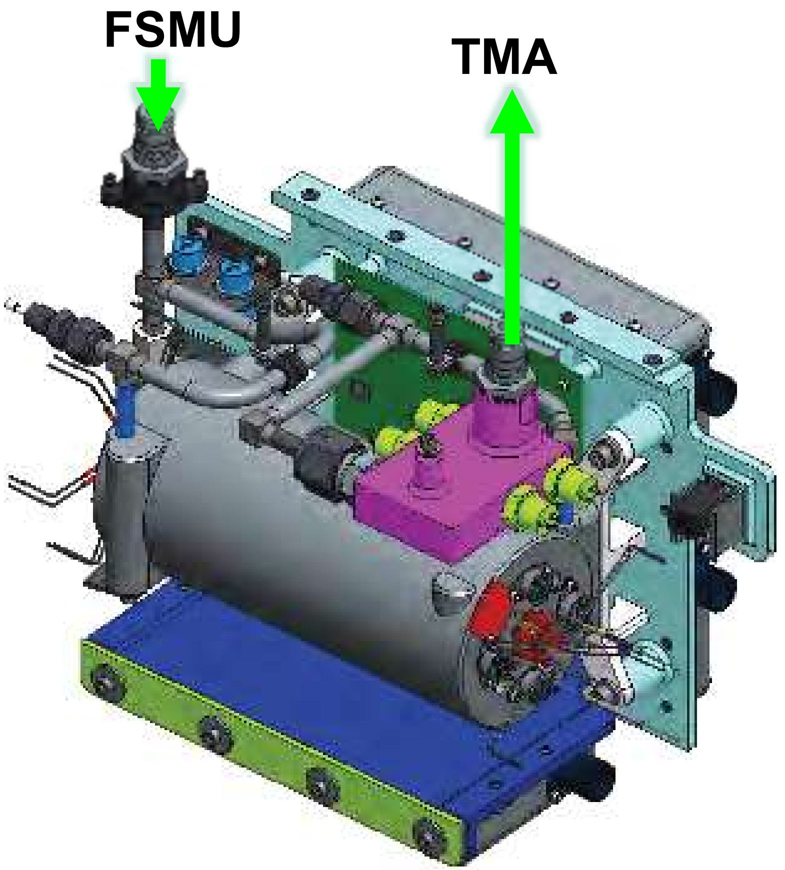
| Color Key: | |
|---|---|
| Test fluid (nPFH) | Vacuum |



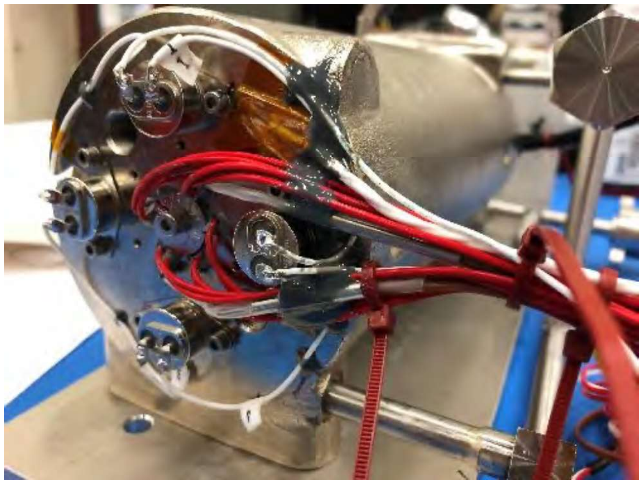


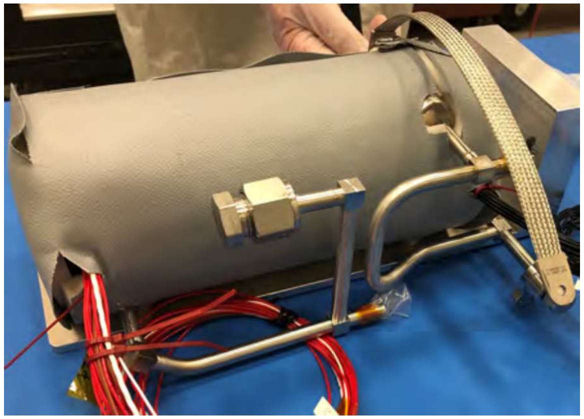
# Bulk Heater Module

- Primary source of heating to condition test fluid to required test section inlet conditions
- Three 120V primary heaters and three 28V booster heaters can be operated at any time, with backup heaters available

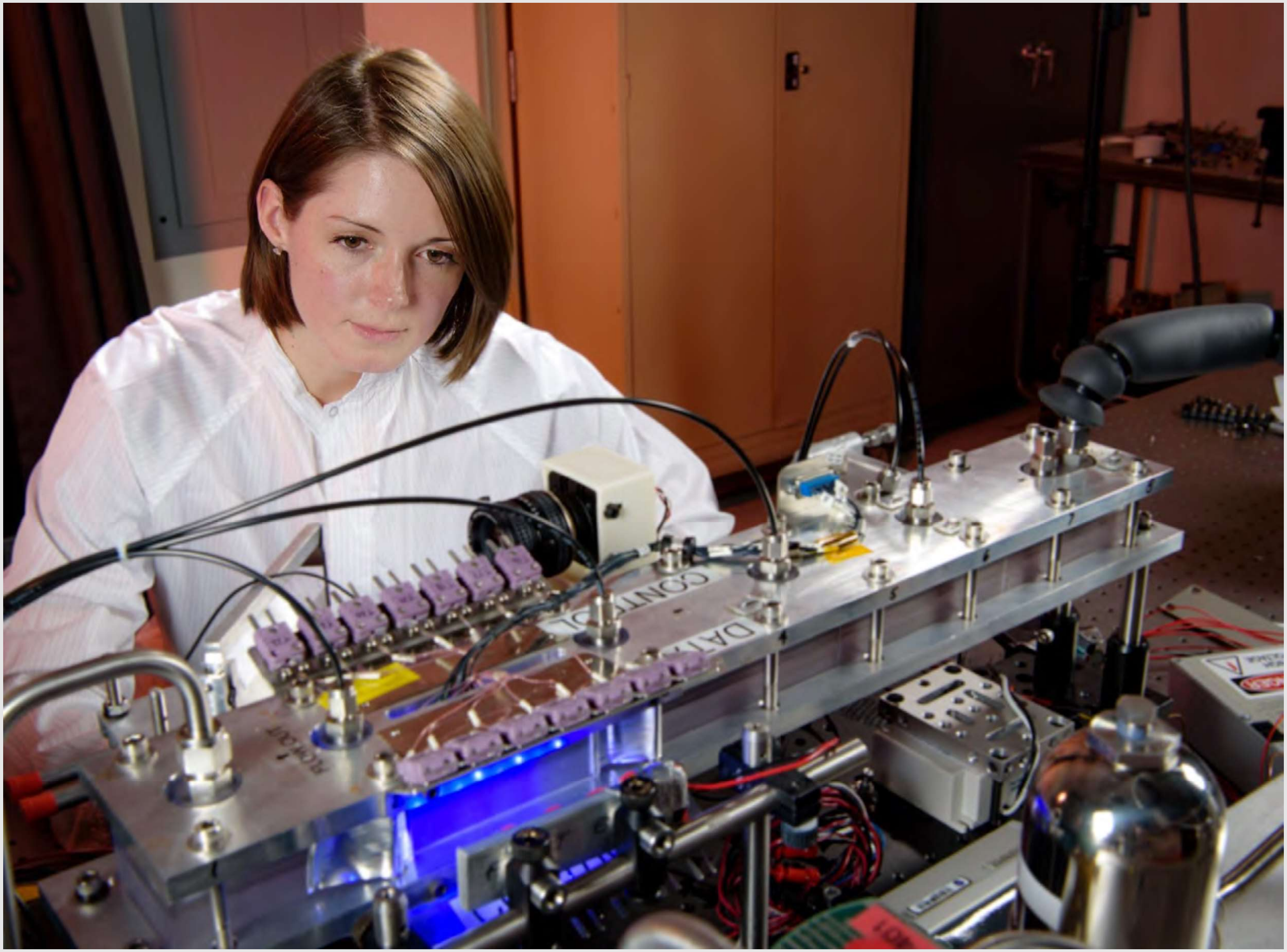


**Color Key:**
🟩 Test fluid (nPFH)



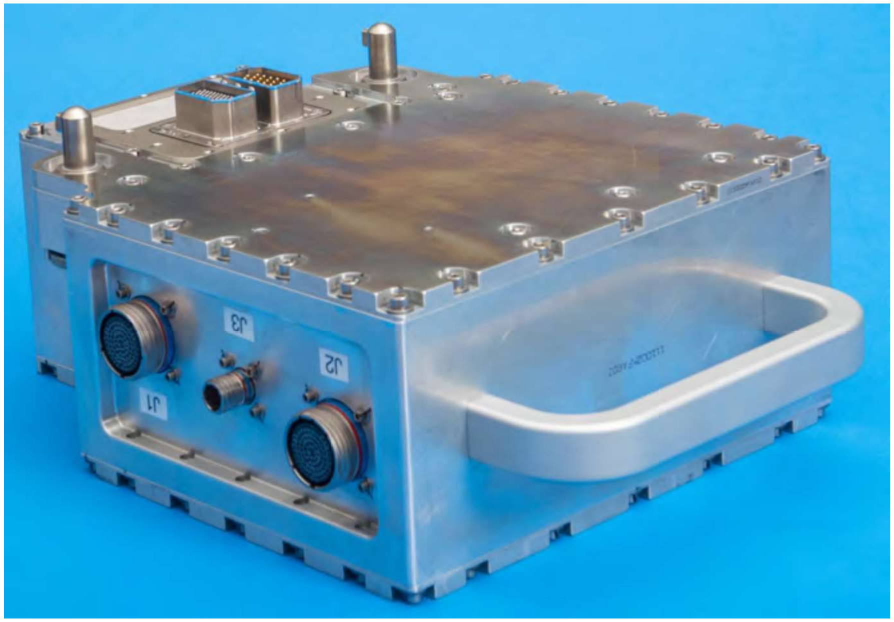


# *Flow Boiling Module (FBM)*



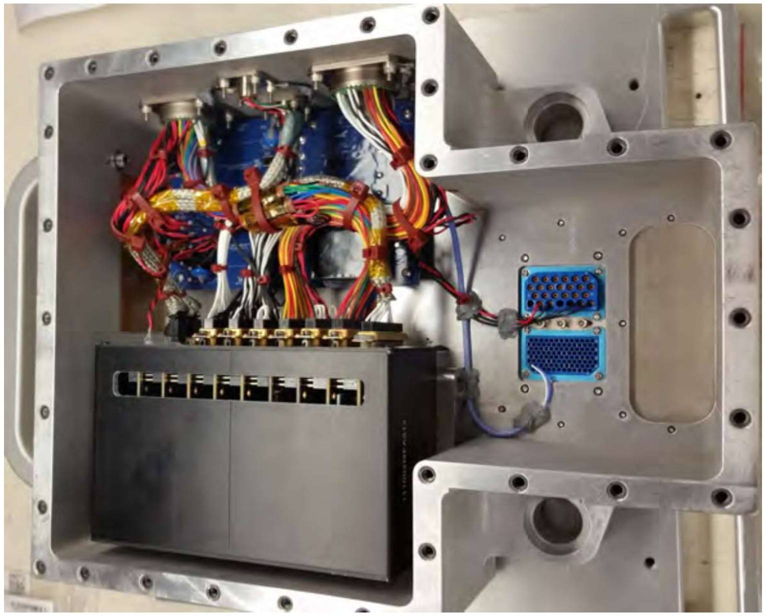
# Remote Data Acquisition Modules

## Remote Data Acquisition Module 1 (RDAQM1)



UEI Data Cubes (Thermocouple Signal Conditioning)

## Remote Data Acquisition Module 2 (RDAQM2)

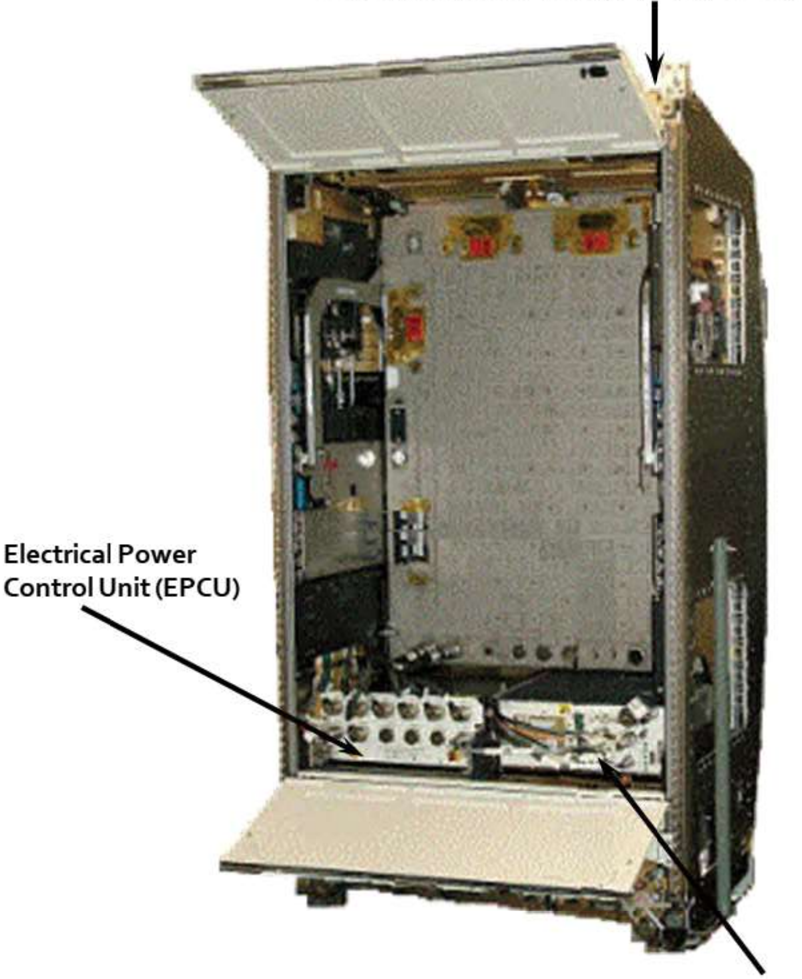


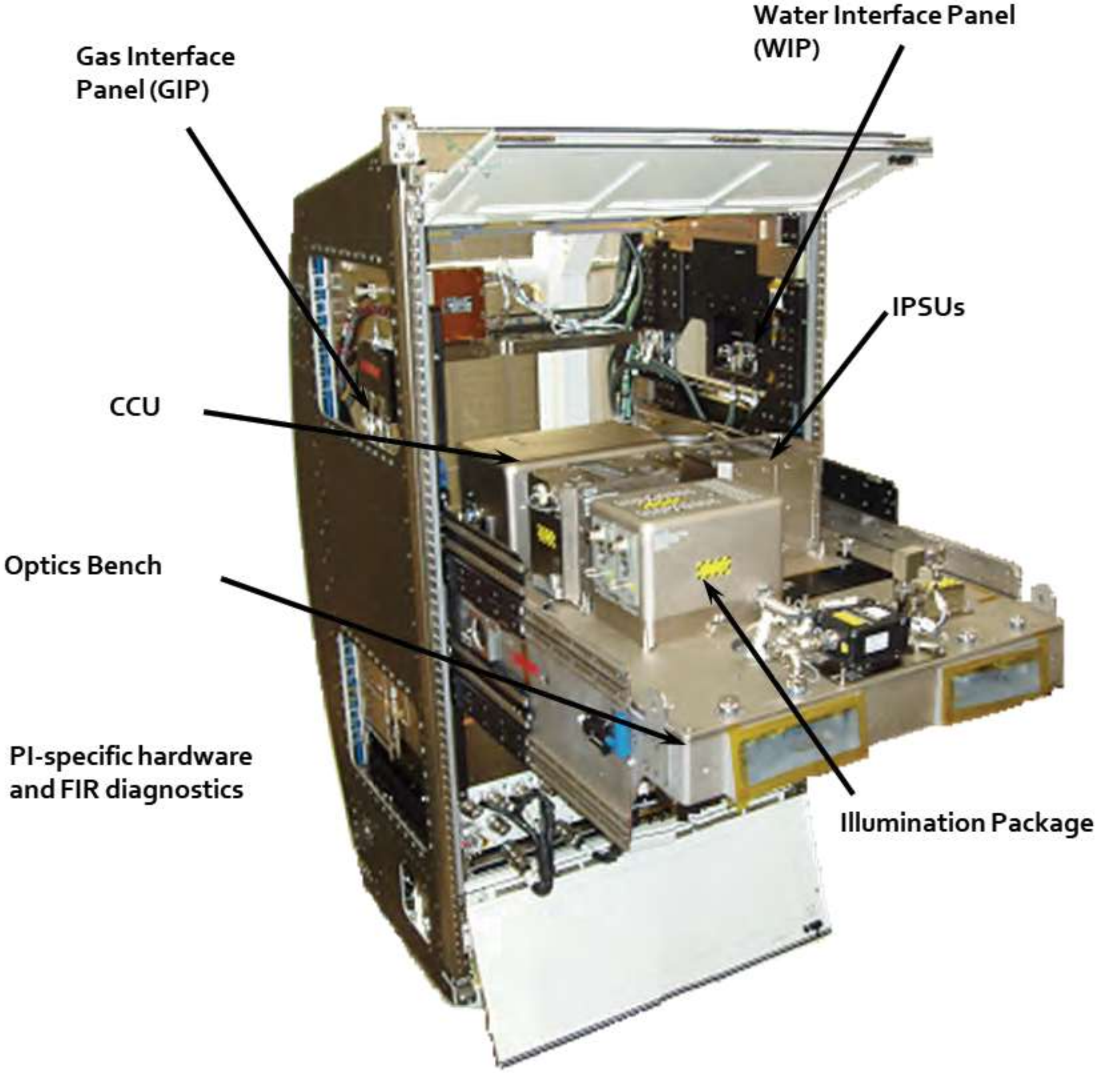
UEI Data Cube and Custom Sensor Supply Printed Circuit Board
(Signal Conditioning and Power Distribution)

# *Fluids Integrated Rack (FIR)*

**Environmental Control (ECS)**

- Air Thermal Control
- Fire Detection & Suppression
- Water Thermal Control
- Gas Interfaces ($GN_2$, VES, VRS)





# Preparations for Launch

## NG-16 Cygnus

SS Ellison Onizuka

**Operator**
Northrop Grumman

**Launch site**
Launch Pad 0A
*Wallops Island, Virginia*

**Launch vehicle**
Antares 230+

**ISS docking location**
Unity nadir

**Cargo mass**
~3,700 kilograms

6.39 meters

3.1 meters

**What's aboard?**
(Not an exhaustive list)

**Pressurized Cargo Module**
- Cardinal Muscle evaluation
- Redwire Regolith Print study
- The Flow Boiling and Condensation Experiment
- Kentucky Re-Entry Probe Experiment
- Four Bed CO2 Scrubber
- Blob investigation
- Slingshot Deployment System
- ISS Power Augmentation Mod Kit
- Upgraded acrylic scratch panes for Cupola windows
- Airlock Stowage Platform

**Service Module**
- 2 UltraFlex solar arrays
- Nanoracks External CubeSat Deployer

# August 10, 2021 Launch from NASA's Wallops Flight Facility in Virginia

Largest Cygnus cargo ever launched to ISS (3,723 kg)

Launch (August 10, 2021, 6:01 pm ET)

Arrival at ISS (August 12, 2021, 6:10 am ET)