Joint CSA/ESA/JAXA/NASA ISS Increment 66 Science Symposium

Flow Boiling & Condensation Experiment (FBCE)

Issam Mudawar

Purdue University Boiling & Two-Phase Flow Laboratory (PU-BTPFL)
Mechanical Engineering Building, 585 Purdue Mall
West Lafayette, IN 47907

Mohammad Hasan, Henry Nahra, R. Balasubramaniam, Nancy Hall & Monica Guzik

NASA Glenn Research Center
21000 Brookpark Rd
Cleveland, OH 44135

Jeffrey Mackey

HX5, LLC
3000 Aerospace Parkway, Brook Park,
Cleveland, OH 44142

- Science Team and Management & Engineering Teams
- Science Background and Hypothesis
- Investigation Goals and Objectives
- Measurement Approach
- Importance and Reason for ISS
- Expected Results and how they will Advance the Field
- Earth Benefits/Spin-off Applications

Science Team

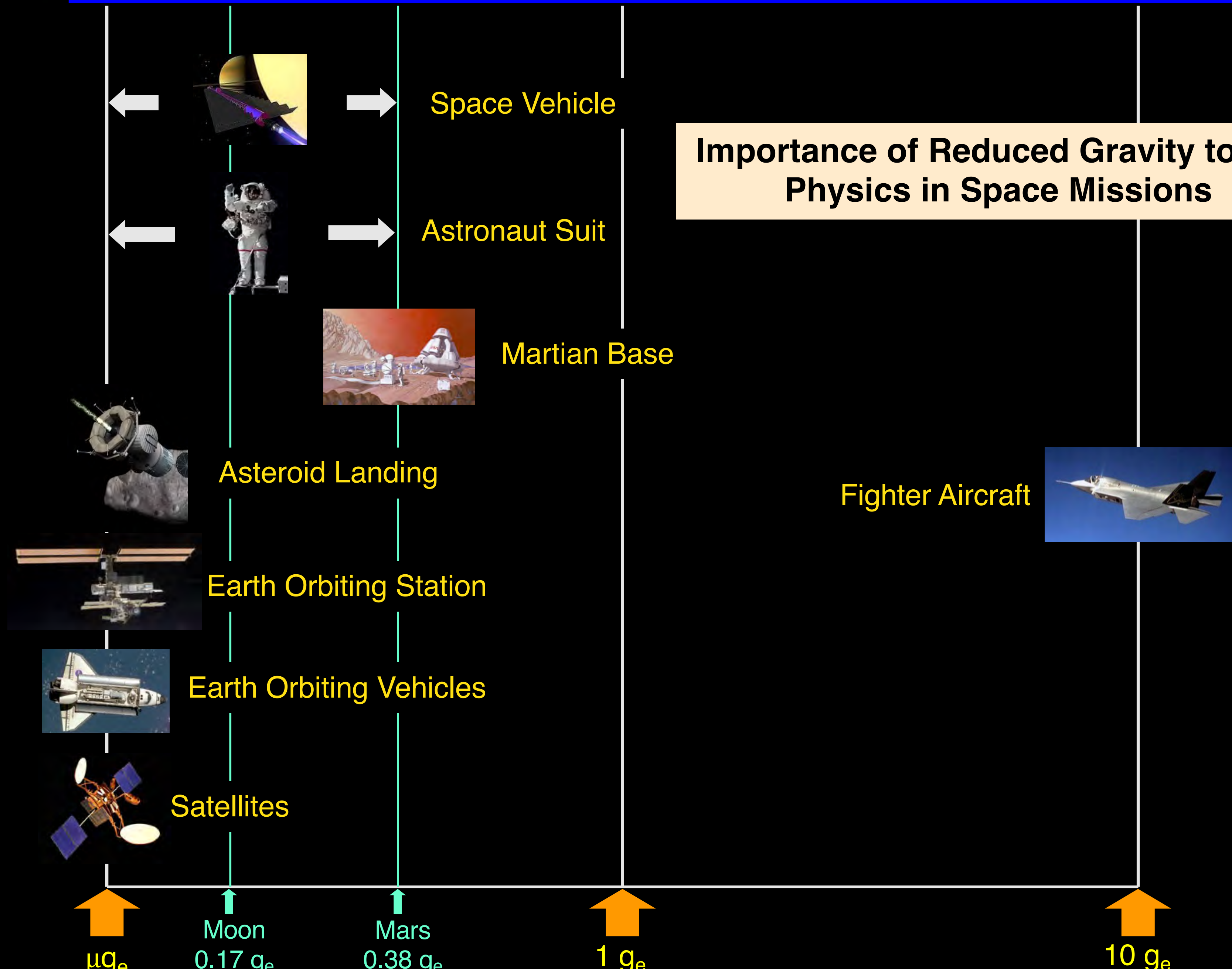
- FBCE PI: Prof. Issam Mudawar
- Co-I: Dr. Mohammad Mojibul Hasan
- Project Scientist: Dr. Henry K. Nahra
- Science Support: Dr. Ramaswamy Subramaniam
- Diagnostics & Optics: Dr. Jeffrey Mackey

Management & Engineering Team

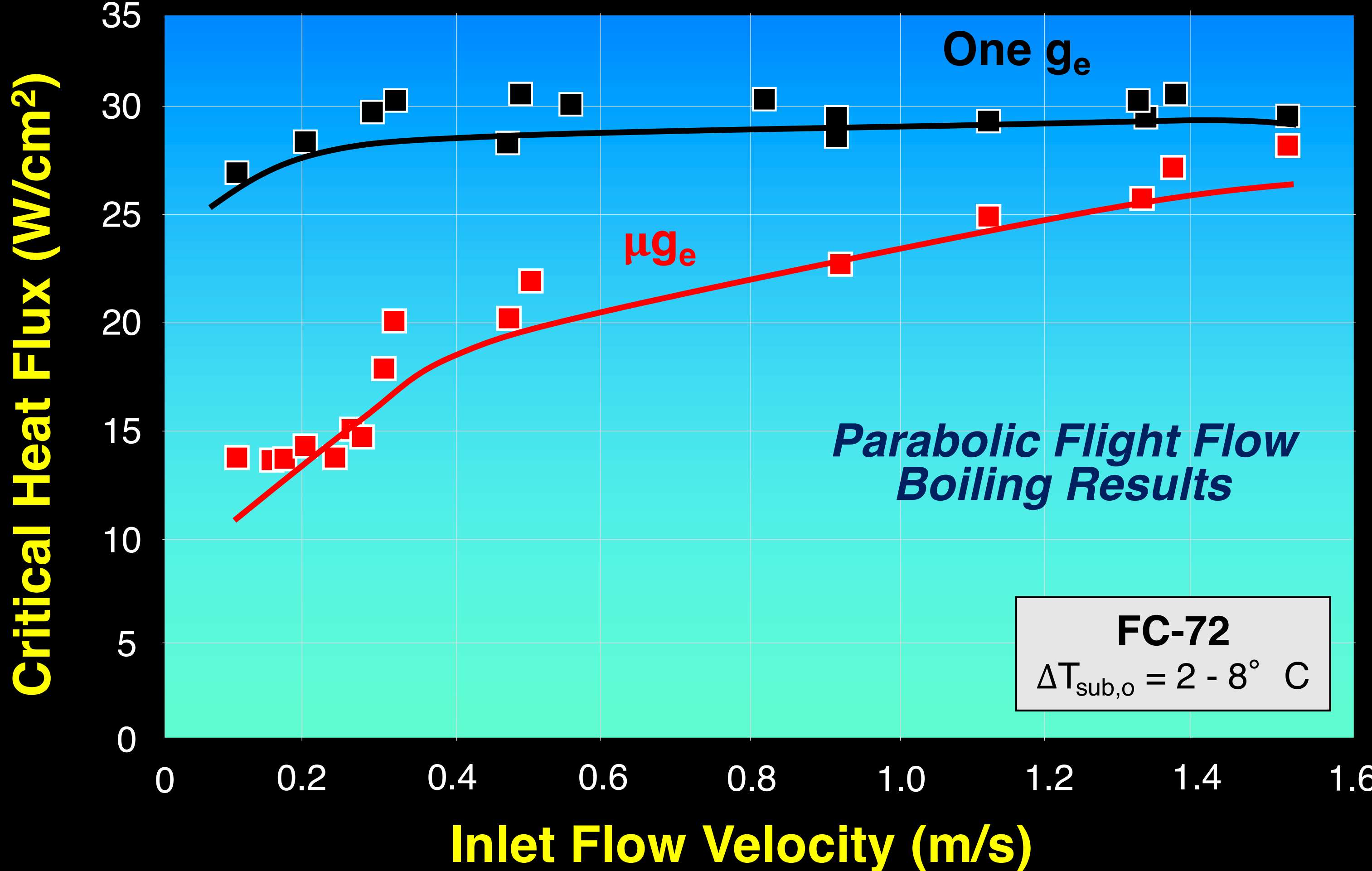
- Project Manager: Nancy Hall
- Chief Engineer: Monica Guzik

Science Background and Hypothesis

Importance of Reduced Gravity to Fluid Physics in Space Missions



Science Background and Hypothesis



- **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**
- **Development of accurate fluid physics predictive tools will require validation against long duration ISS microgravity data**

Long Term Goal

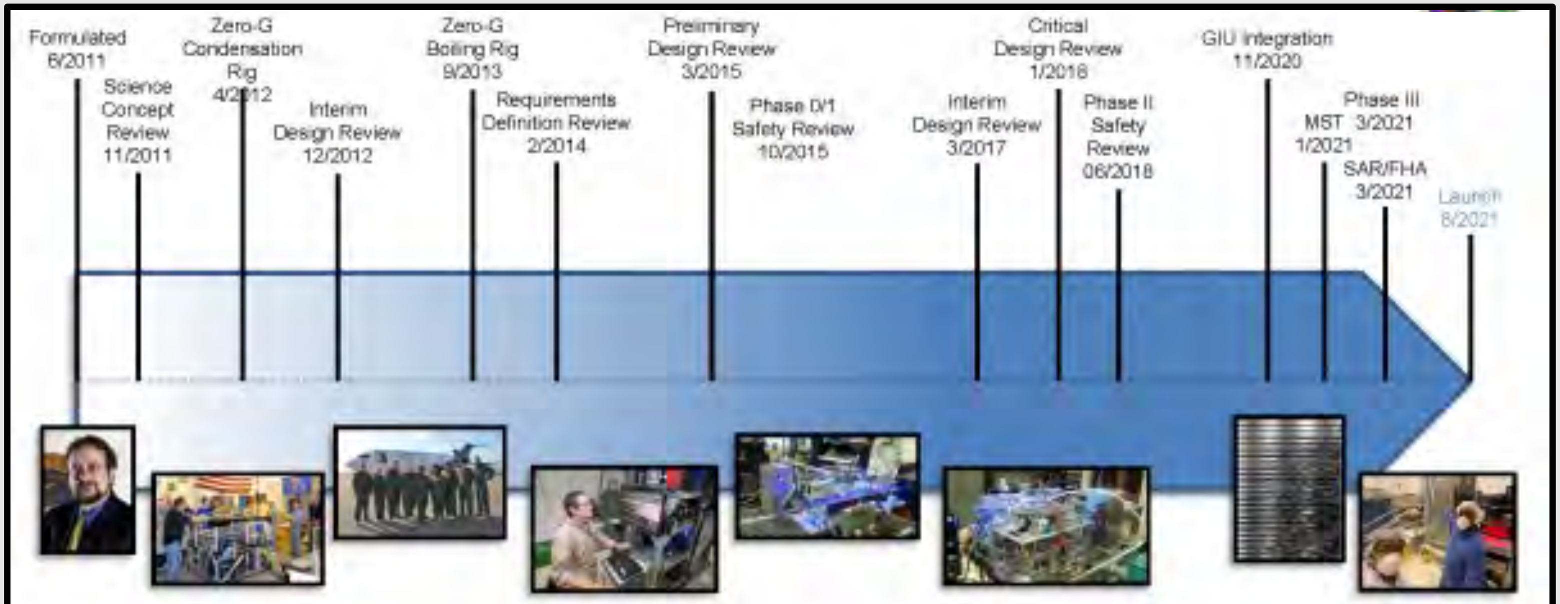
The proposed research aims to develop an integrated two-phase flow boiling/ condensation facility for the International Space Station (ISS) to serve as primary platform for entire fluid physics community to obtain two-phase flow and heat transfer data in microgravity.

Overriding Objectives

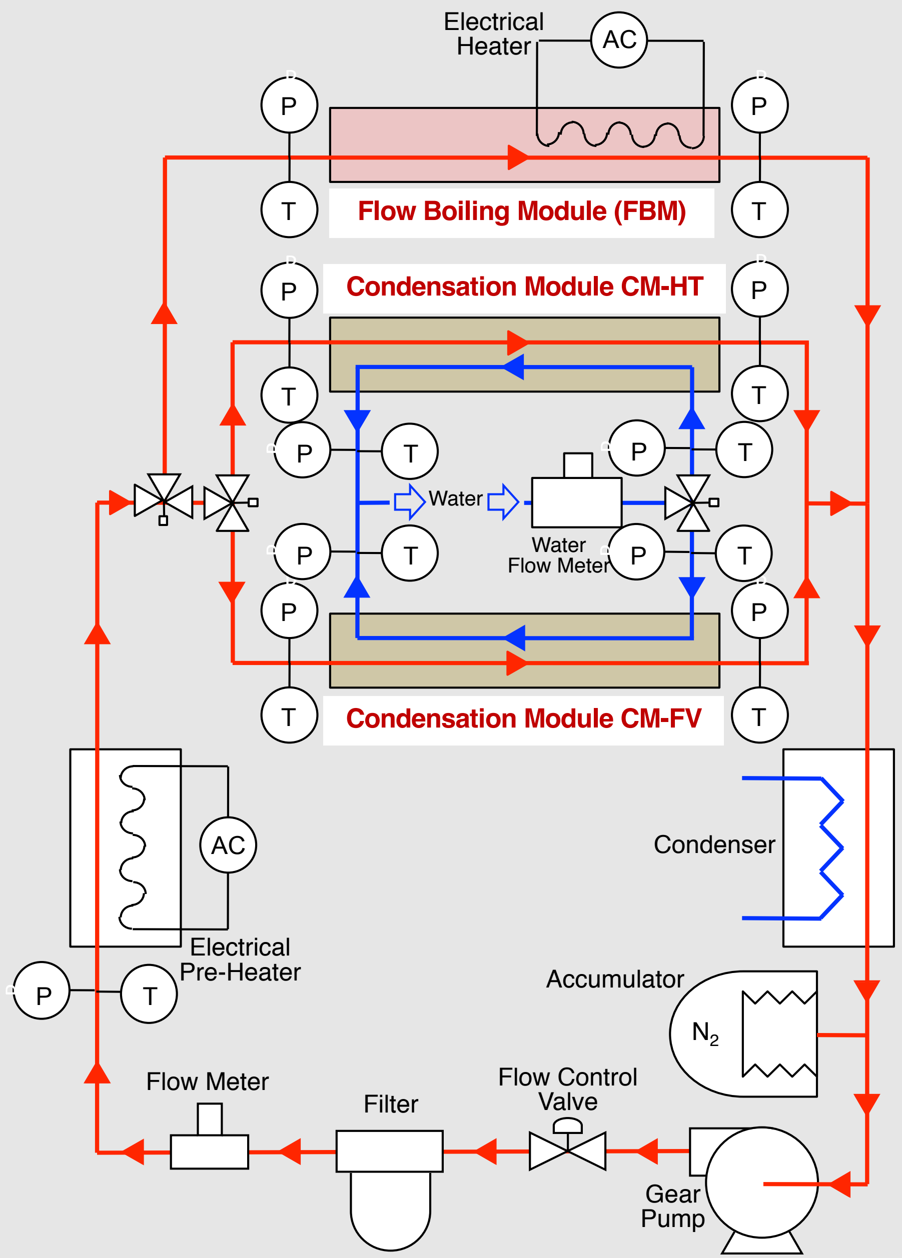
Investigate *the two most fundamental mechanisms* for phase change in microgravity: FLOW BOILING and FLOW CONDENSATION. This includes obtaining *long-duration* (1) *heat transfer data* and (2) *video records of interfacial flow structure* for both.

Measurement Approach

- **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)
- **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:** initiated CFD modeling of flow boiling and flow condensation



System Concept



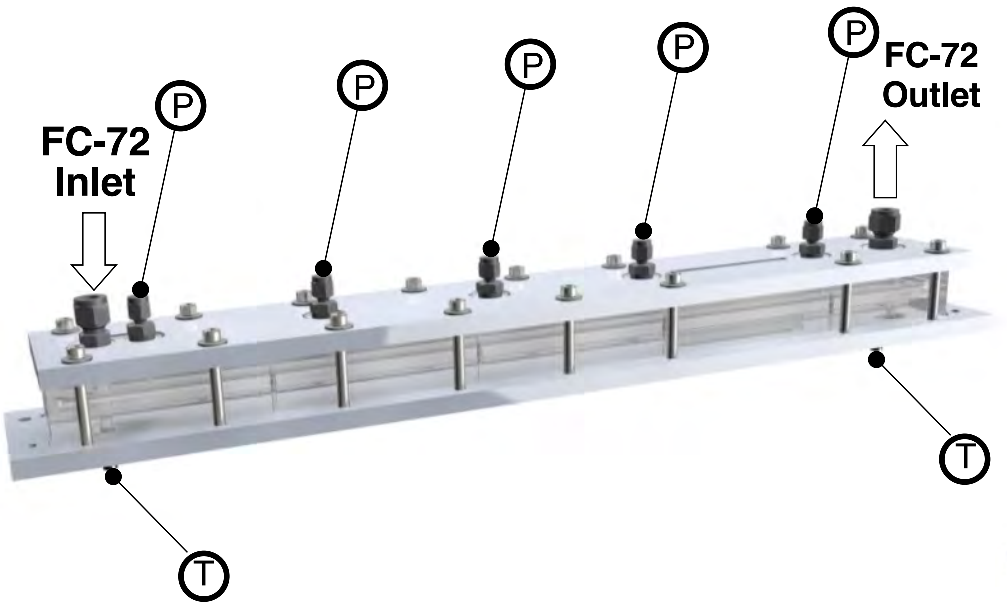
Consists of:

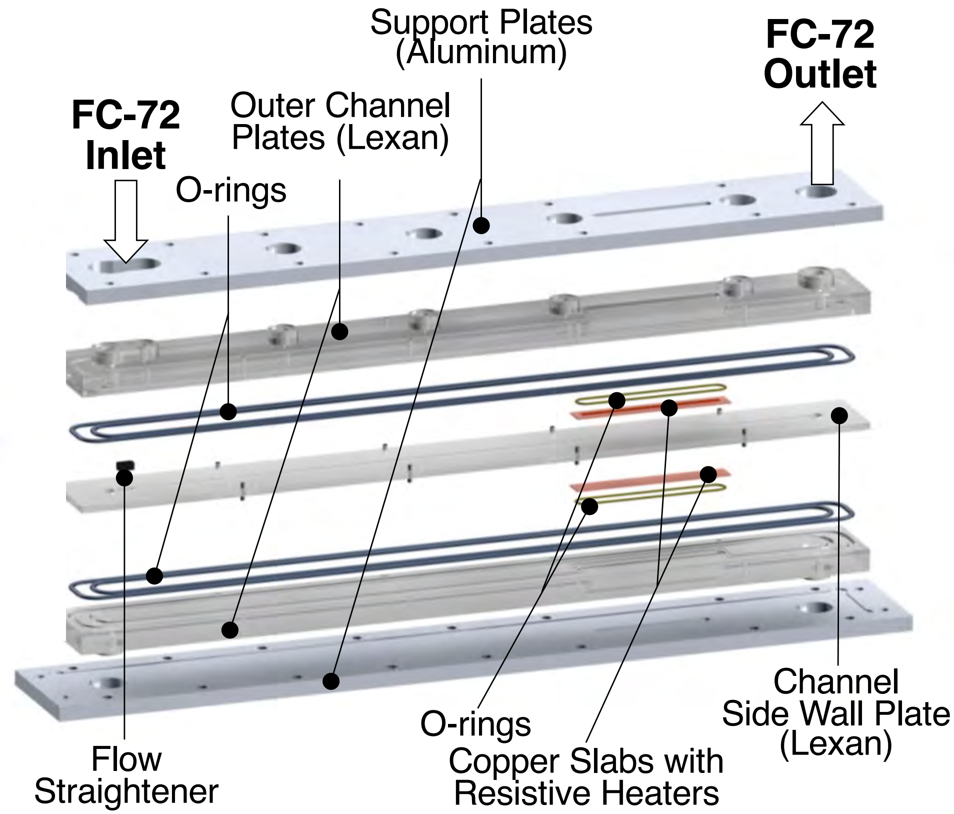
- nPFH (normal perfluorohexane, C_6H_{14}) sub-loop
- Water sub-loop

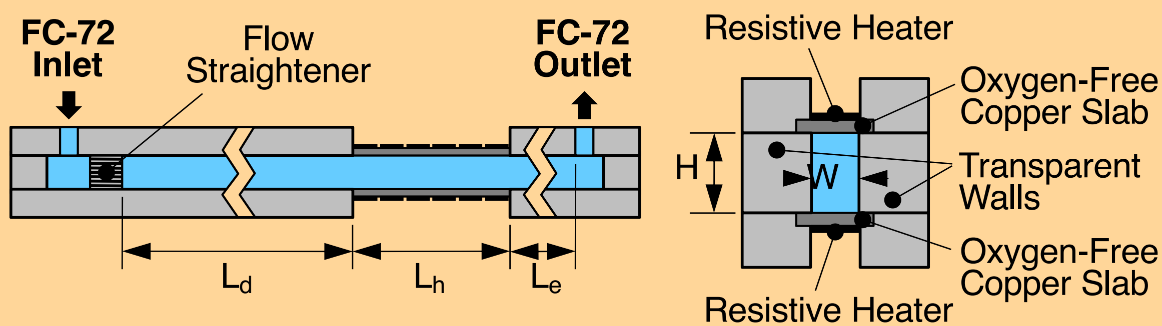
Three interchangeable test modules:

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

FBM Construction





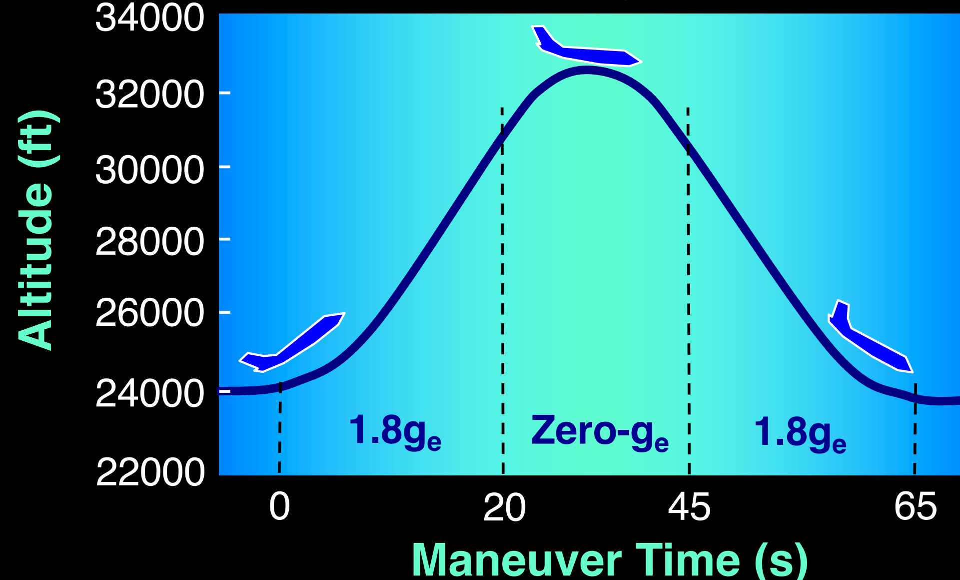


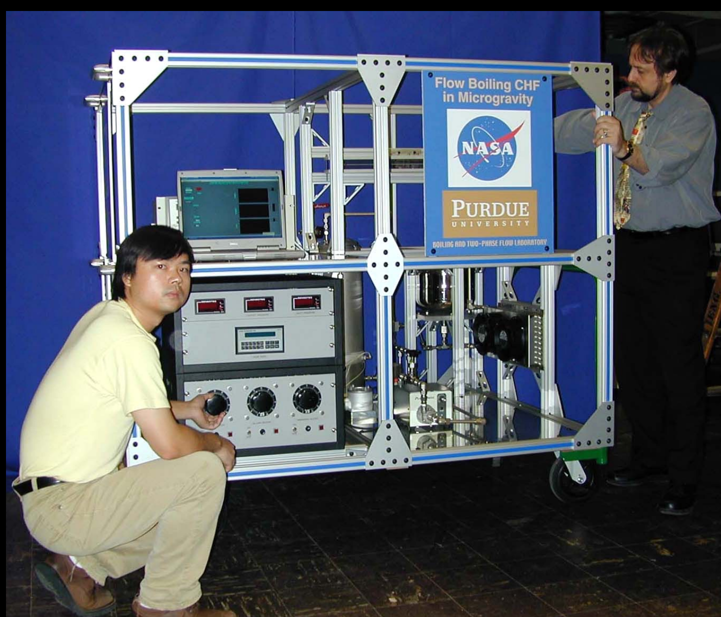
Development Length:	L_d = 327.7 mm
Heated Length:	L_h = 114.6 mm
Exit Length:	L_e = 60.7 mm

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

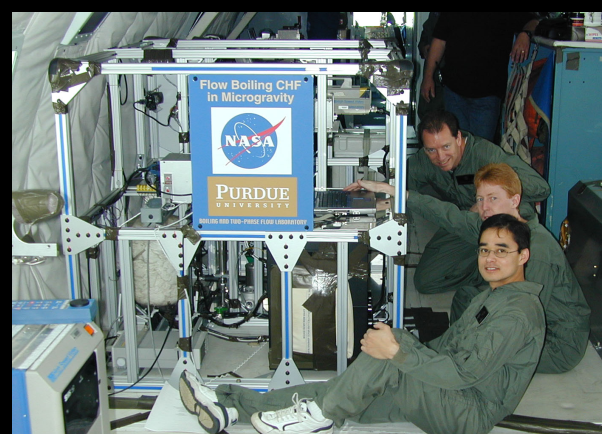
FBM: Pre-ISS Parabolic Flight Experiments

Flight Trajectory

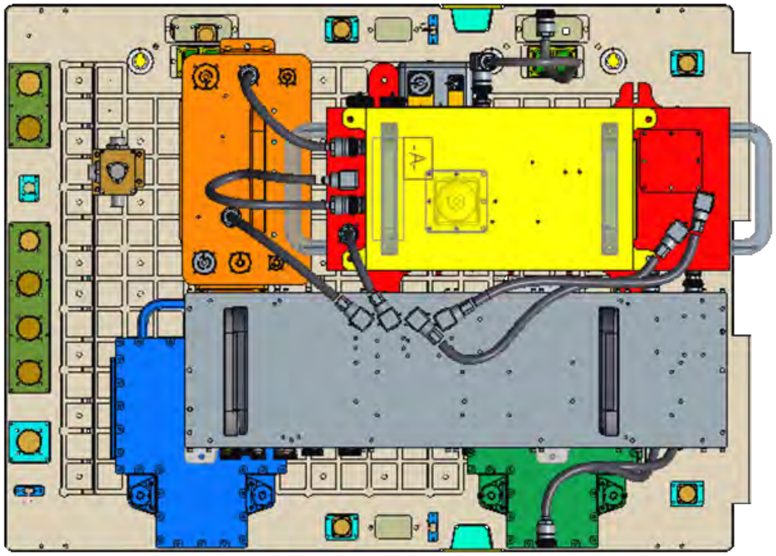


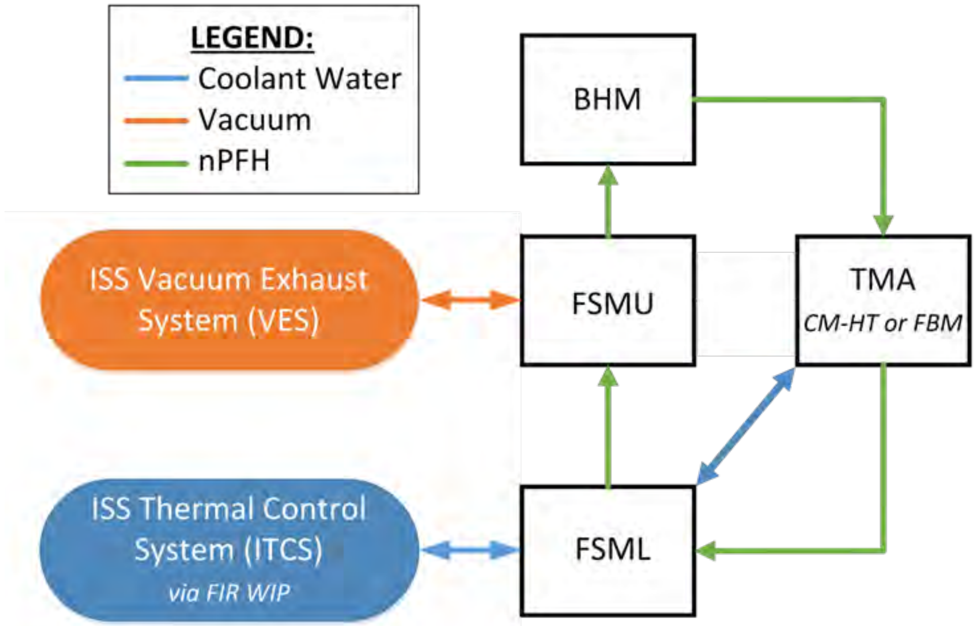


Phase Change Photo Library
(Mudawar, 1984 - 2016)



ISS FBCE 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:

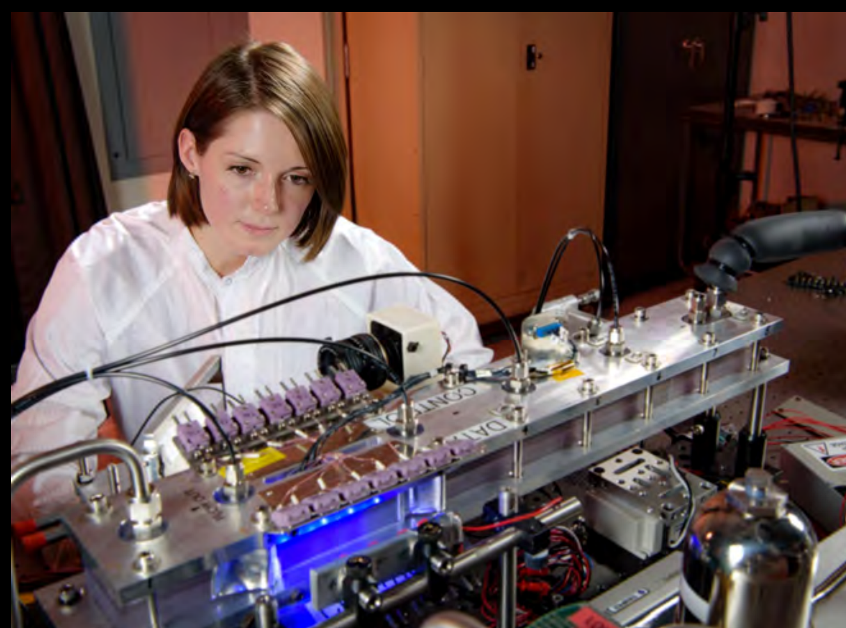
- SAMS – Space Acceleration Measurement System
- CCU – Confocal Control Unit (on back of rack)
- IPSU-CL – Imaging Processing Storage Unit – Camera Link (on back of rack)

Fluid System Module - Lower

Fluid System Module - Upper

Bulk Heater Module

ISS FBCE Components



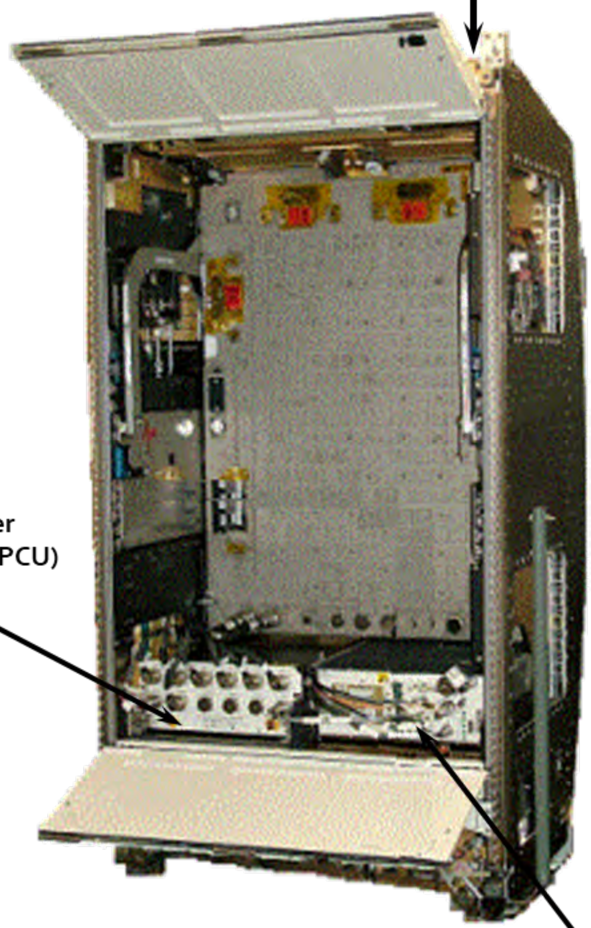
Flow Boiling Module (FBM)

Remote Data Acquisition Module 1

Remote Data Acquisition Module 2

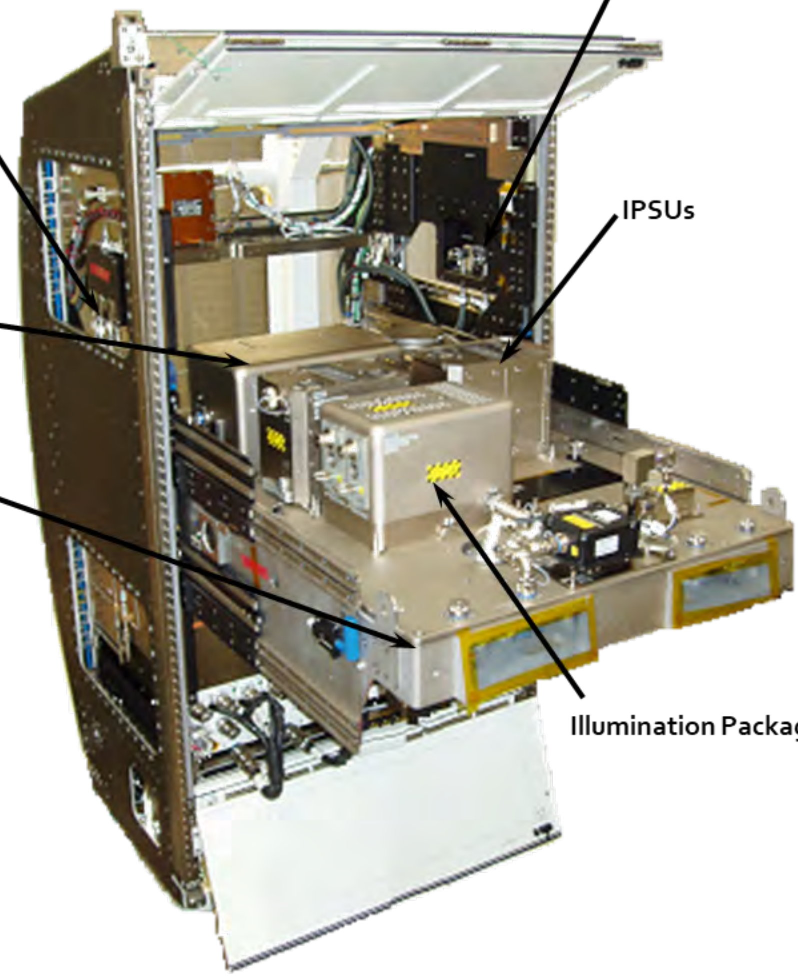
ISS FBCE: Insertion into the Fluids Integrated Rack (FIR)

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



Electrical Power Control Unit (EPCU)

PI-specific hardware and FIR diagnostics



Gas Interface Panel (GIP)

Water Interface Panel (WIP)

IPSUs

CCU

Optics Bench

Illumination Package

PURDUE UNIVERSITY

ISS FBCE: Preparations for Launch

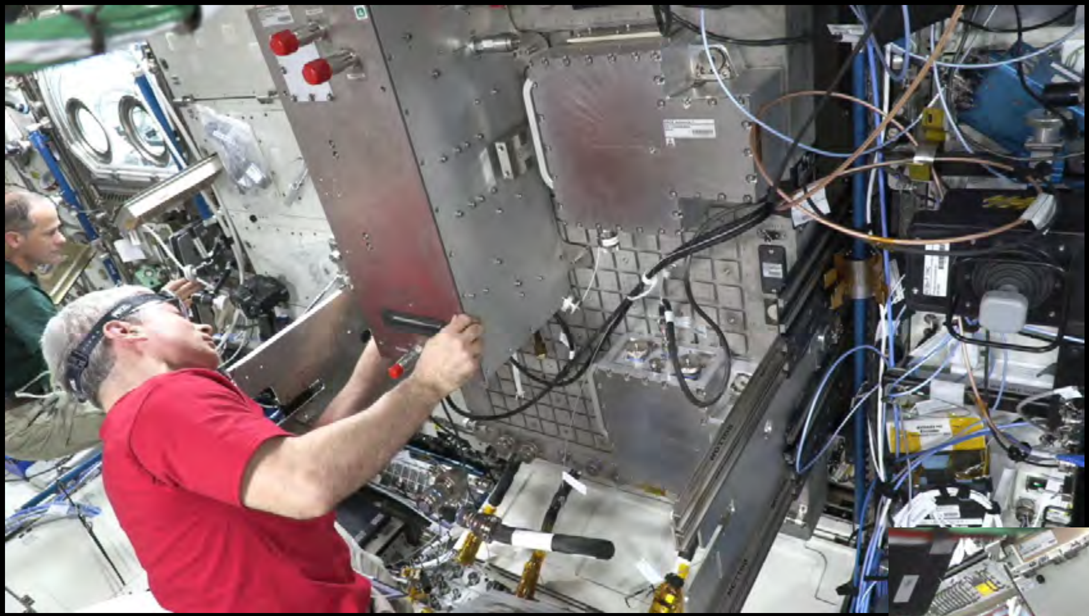
ISS FBCE: August 10, 2021 Launch from NASA's Wallops Flight Facility in Virginia

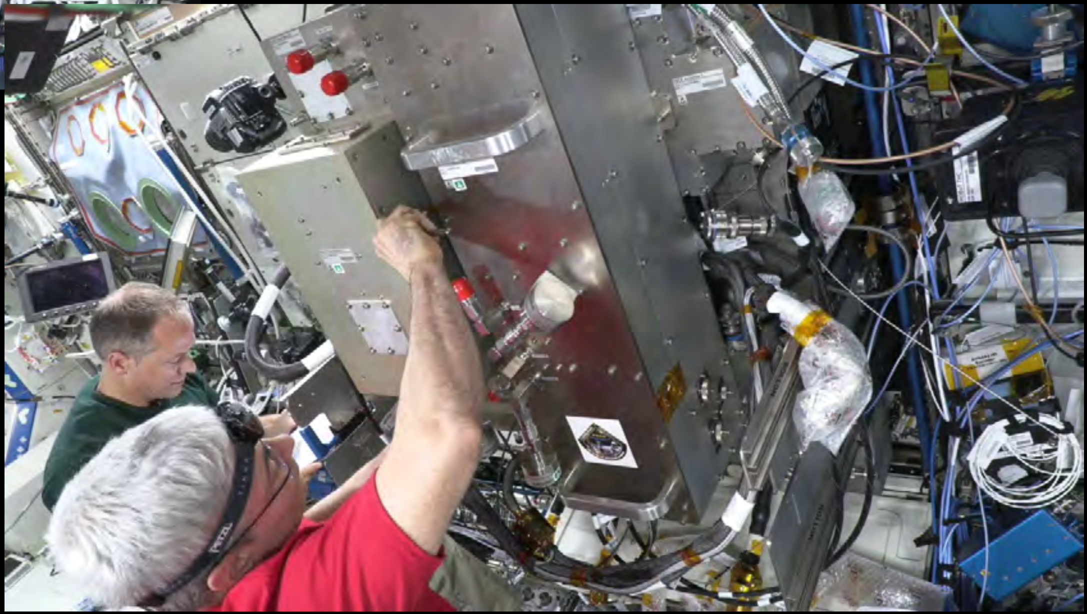
Launch (August 10, 2021, 6:01 pm ET)

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

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

FBCE Installation on the ISS





ISS FBM Tests:

Measurements of pressure, temperature, flow rates, and power will be made

- **Measure pressure along developing length and at beginning and end of heated section in FBM**
- **Measure temperature of heated surfaces**
- **Measure power (heat flux) through heated surfaces**

Post ISS Tests:

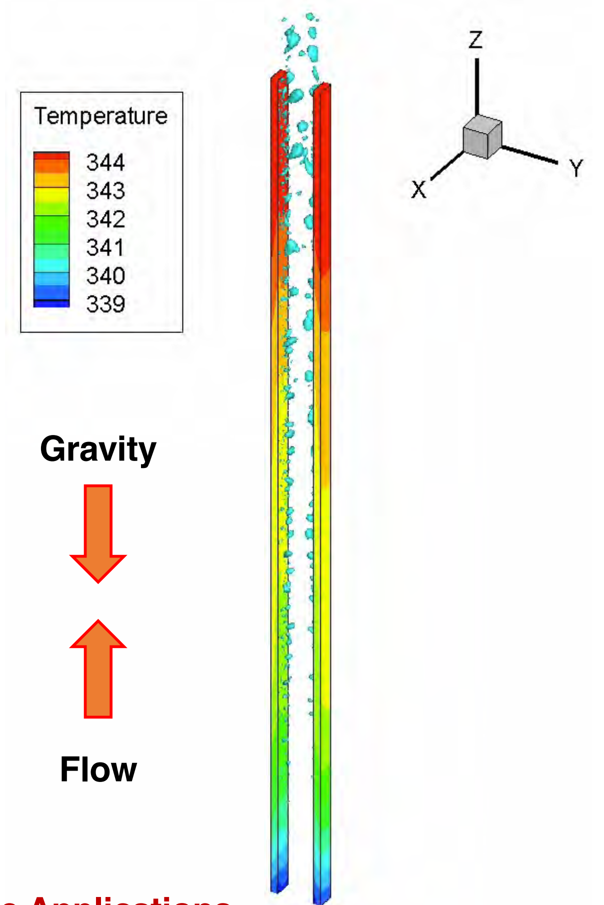
- **Refine empirical correlations, theoretical models, and CFD models using ISS data**

ISS will enable:

1. **Obtaining long duration steady state wall temperature measurements and video records of interfacial structure; both are essential for validation correlations, theoretical models, and CFD models that will be used for design of future space systems.**

2. **Eliminating effects of body force on two-phase flow structure.**

Expected Results and how they will Advance the Field



- **Critical heat flux and gravity independence criterion**
- **Boiling curves in microgravity**
- **Numerical simulation and model validation**

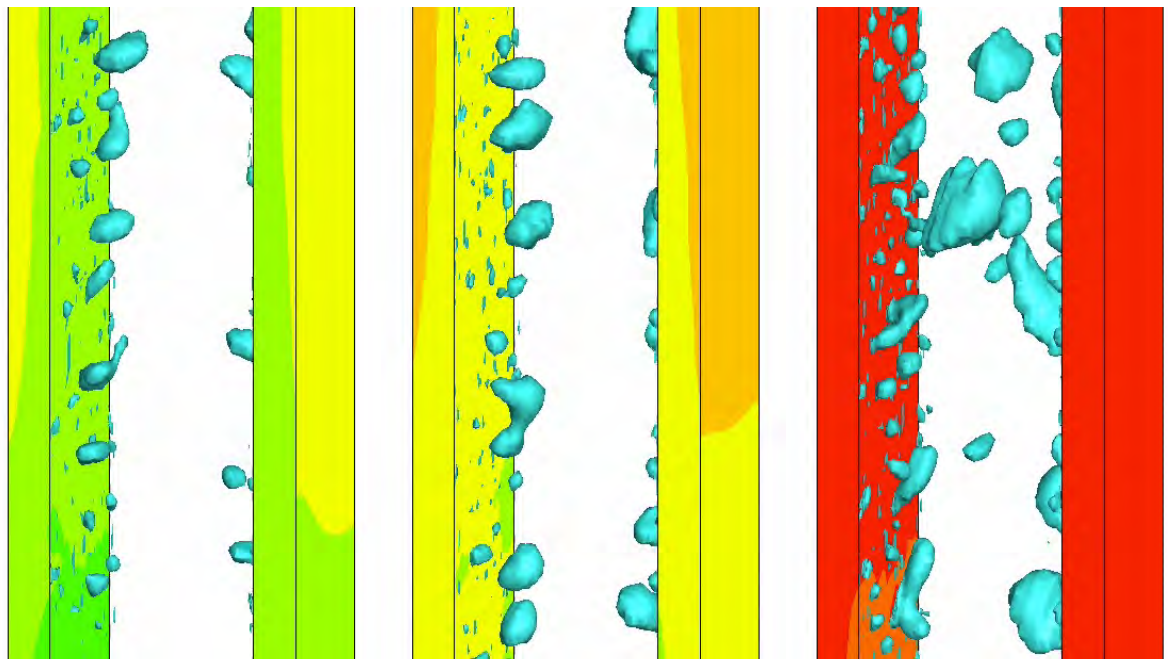
G = 445.75 kg/m²s → $G = 445.75\ kg/m^2s$

$q'' = 143\ kW/m^2$

$\Delta T_{sub} = 30.81°C$

Vertical upflow

One-G



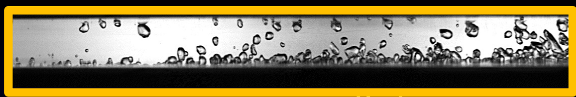
Upstream ***Middle*** ***Downstream***

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

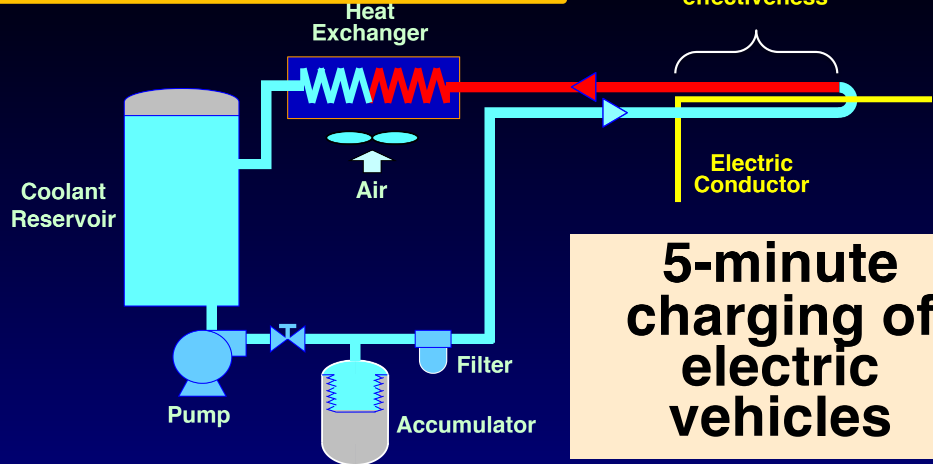
Space Applications

- 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

Earth Benefits/Spin-off Applications



Subcooled flow boiling with flow passage enhancement to maximize heat transfer effectiveness



5-minute charging of electric vehicles