

Flow Boiling & Condensation Experiment (FBCE): Summary of Findings for Flow Boiling based on Completed ISS Experiments

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Title: *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*

... “an agenda for research in the next decade that would use the unique characteristics of the space environment to address complex problems in the life and physical sciences, so as to deliver both new knowledge and practical benefits for humankind as it embarks on a new era of space exploration.”

Applied Physical Sciences Panel:

1. Reduced-gravity multiphase flows, cryogenics, and heat transfer database development and modeling
2. Interfacial flows and phenomena in exploration systems

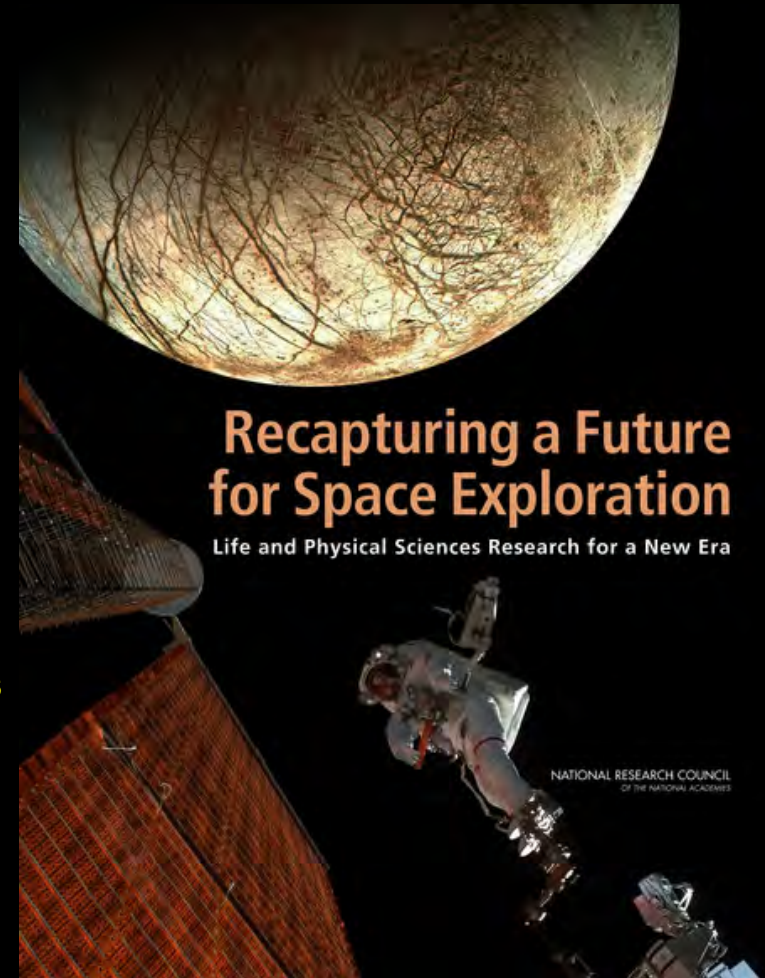
Translation to Space Exploration Systems Panel:

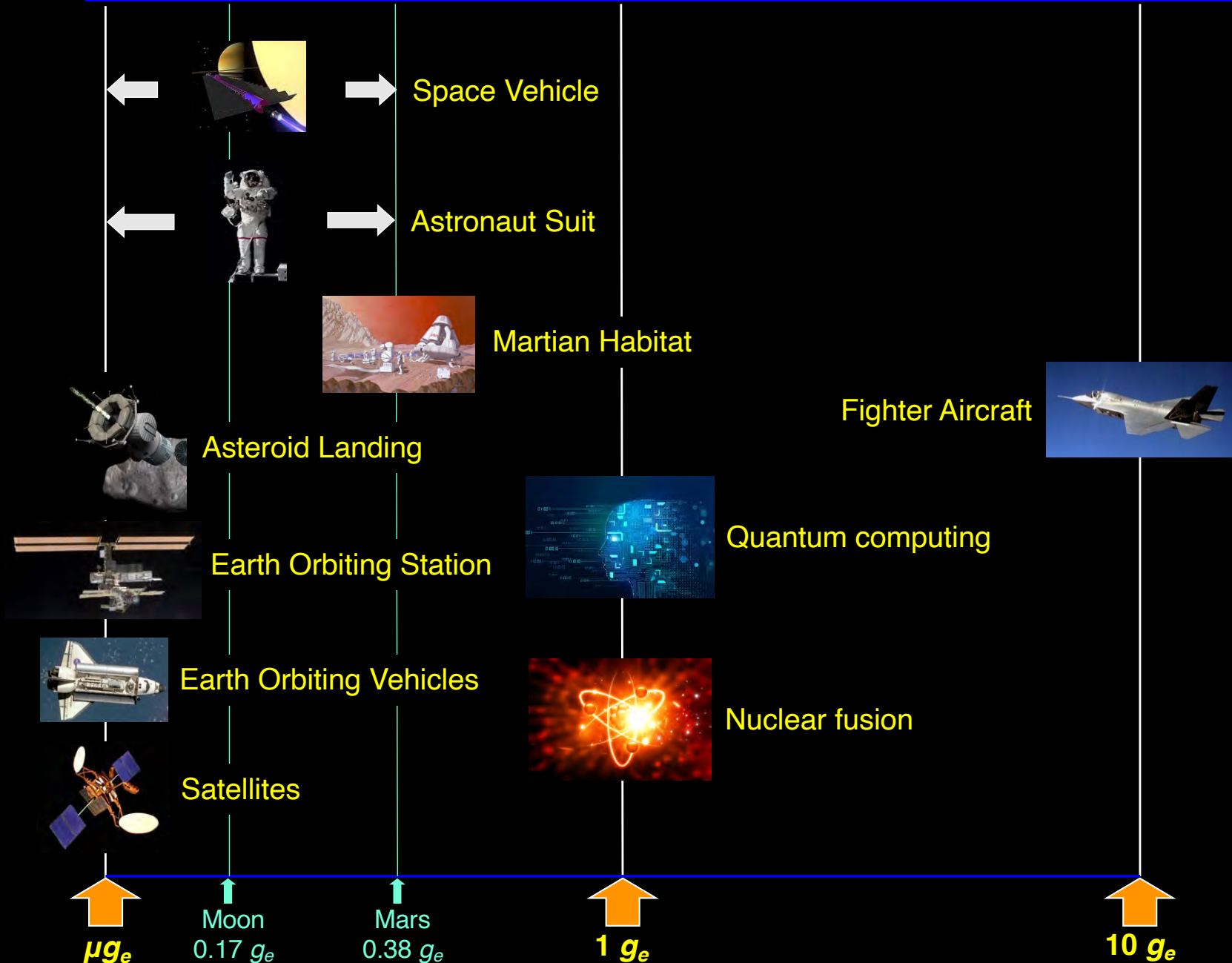
1. Two-phase flow and thermal management
2. Cryogenic fluid management

Recommendations:

“A few studies of flow boiling under reduced gravity have been performed ... Detailed data from systematic experimental studies are needed to validate numerical simulation models.”

“...important scientific questions still remain concerning the effect of gravity on boiling and condensation phenomena..... Experiments to support model development will need access to reduced gravity.”





PI: Issam Mudawar (Purdue University)
Co-PI: Mohammad Hasan (NASA Glenn)

06/2011: FBCE Formulated by Mudawar

11/2011: Science Concept Review (SCR)

04/2012: Zero-gravity Parabolic Flight Condensation Experiments

12/2012: Interim Design Review

09/2013: Zero-gravity Parabolic Flight Boiling Experiments

02/2014: Requirements Definition Review (RDR)

03/2015: Preliminary Design Review (PDR)

10/2015: Phase 0/I Safety Review

03/2017: Internal Design Review (IDR)

01/2018: Critical Design Review (CDR)

06/2018: Phase II Safety Review

11/2020: Ground Integration Unit (GIU)

01/2021: Mission Sequence Testing (MST)

03/2021: Phase III Safety Review; Executive Systems Acceptance Safety Review (SAR); Flight Hardware Availability Review (FHA)

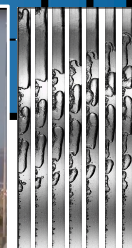
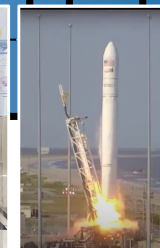
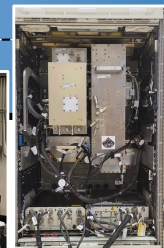
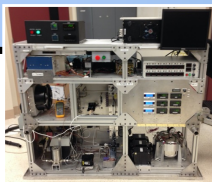
08/2021: Launch of FBCE with FBM to the ISS

12/2021: Assembly and Installation on the ISS

02/2022: Start of Thermal Tests on the ISS

07/2022: Completion of FBM Thermal Tests on the ISS

08/2023: Launch of CM-HT to the ISS



Purdue Team: Issam Mudawar supported by 15 Ph.D. students

2011: FBCE design concept

2013: Detailed designs submitted to Glenn for:

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

2013-2015: Parabolic flight experiments using CM-HT and CM-FV

2014-2017: Analysis of terrestrial and parabolic flight data

- Empirical correlations for flow boiling CHF and flow condensation
- Theoretical models for flow boiling and flow condensation in reduced gravity

2017-2023: CFD models of flow boiling and flow condensation data from terrestrial and parabolic flight experiments

2021-2023: Analysis of terrestrial pre-ISS Mission Sequence Testing (MST) flow boiling data

2021: Lunch of FBCE with FBM to the ISS

2022: Complete acquisition of FBM data on the ISS

2021-2023: Analysis of ISS flow boiling data

2022-2023: CFD models of ISS flow boiling data

2023: Launch of CM-HT

Findings from FBCE project, both flow boiling and flow condensation, and both terrestrial and microgravity, have been published by Purdue in over **70** journal articles, majority in ***International Journal of Heat & Mass Transfer***

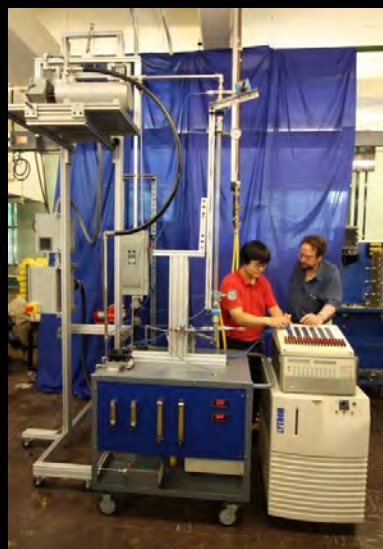
Long Term

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.

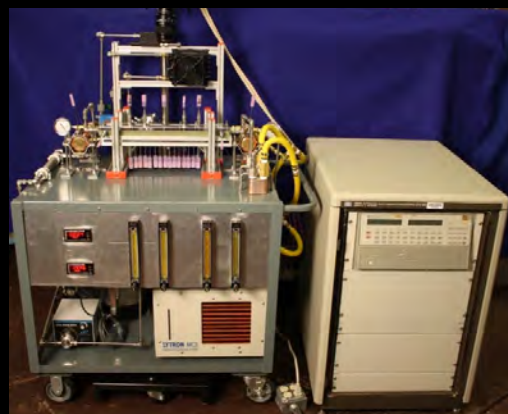
Overriding objectives are to investigate *the two most fundamental mechanisms* for phase change in microgravity: FLOW BOILING and FLOW CONDENSATION. This includes obtaining *long-duration* (1) *heat transfer data* and (2) *video records of interfacial flow structure* for both.

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



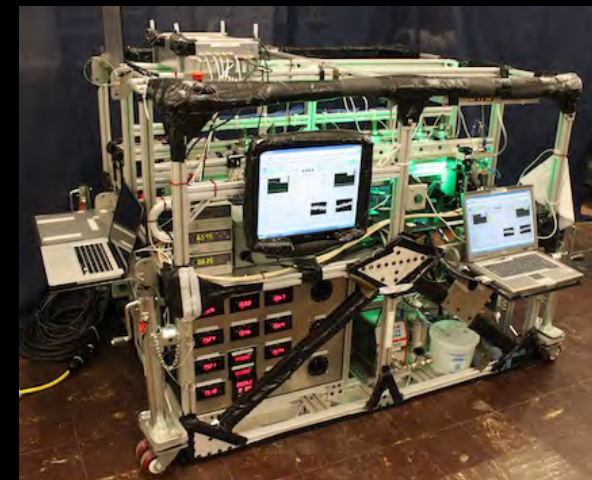
**High-Capacity
Condensation Facility**



**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**

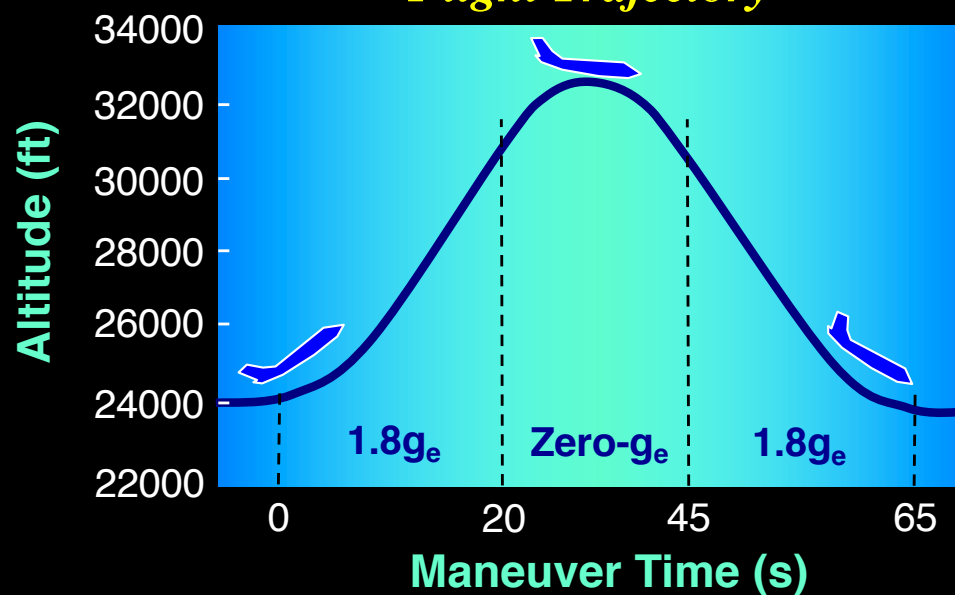
KC-135 Tests (2003 – 2007)

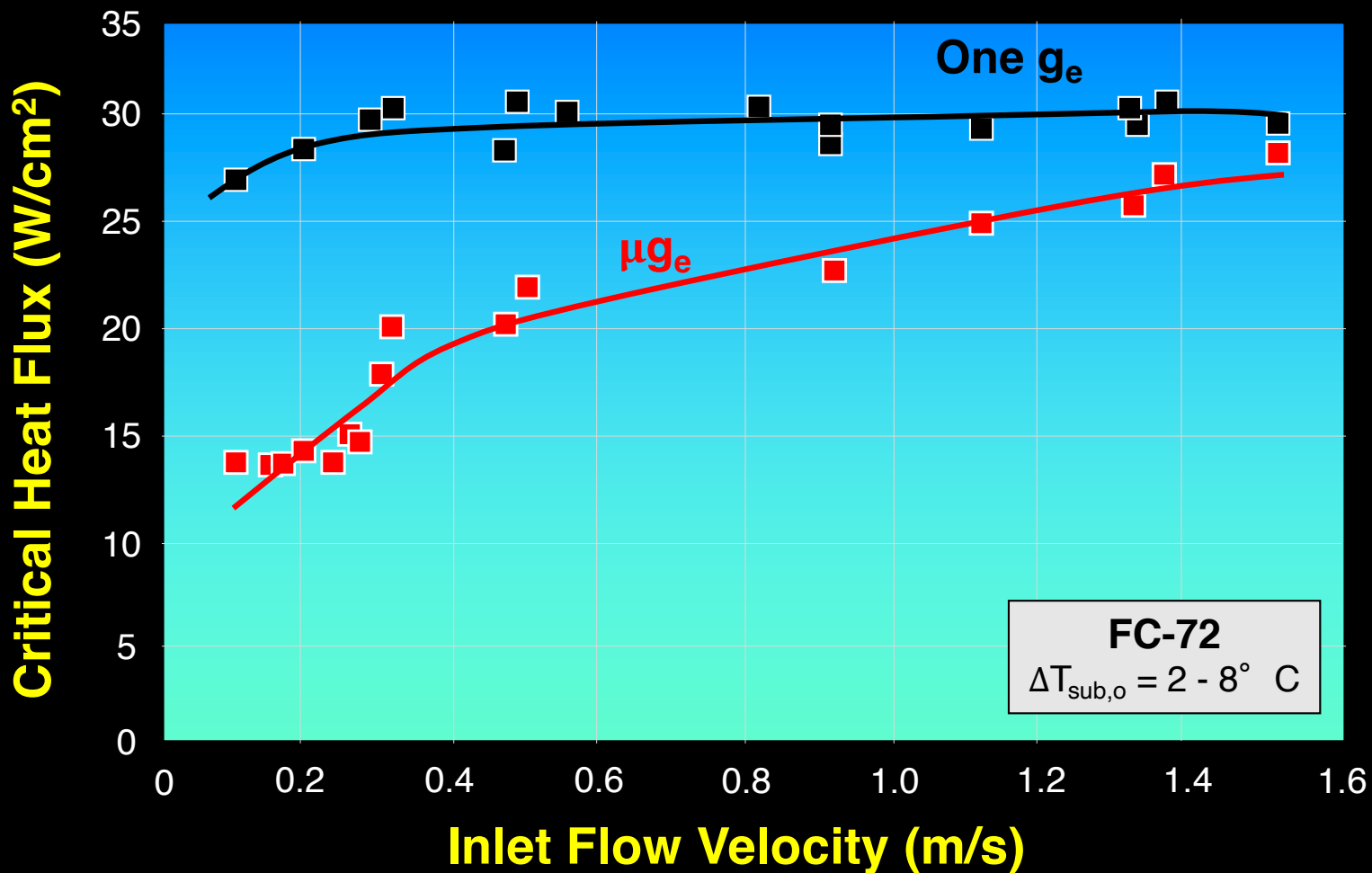


Phase Change Photo Library
(Mudawar, 1984 - 2022)

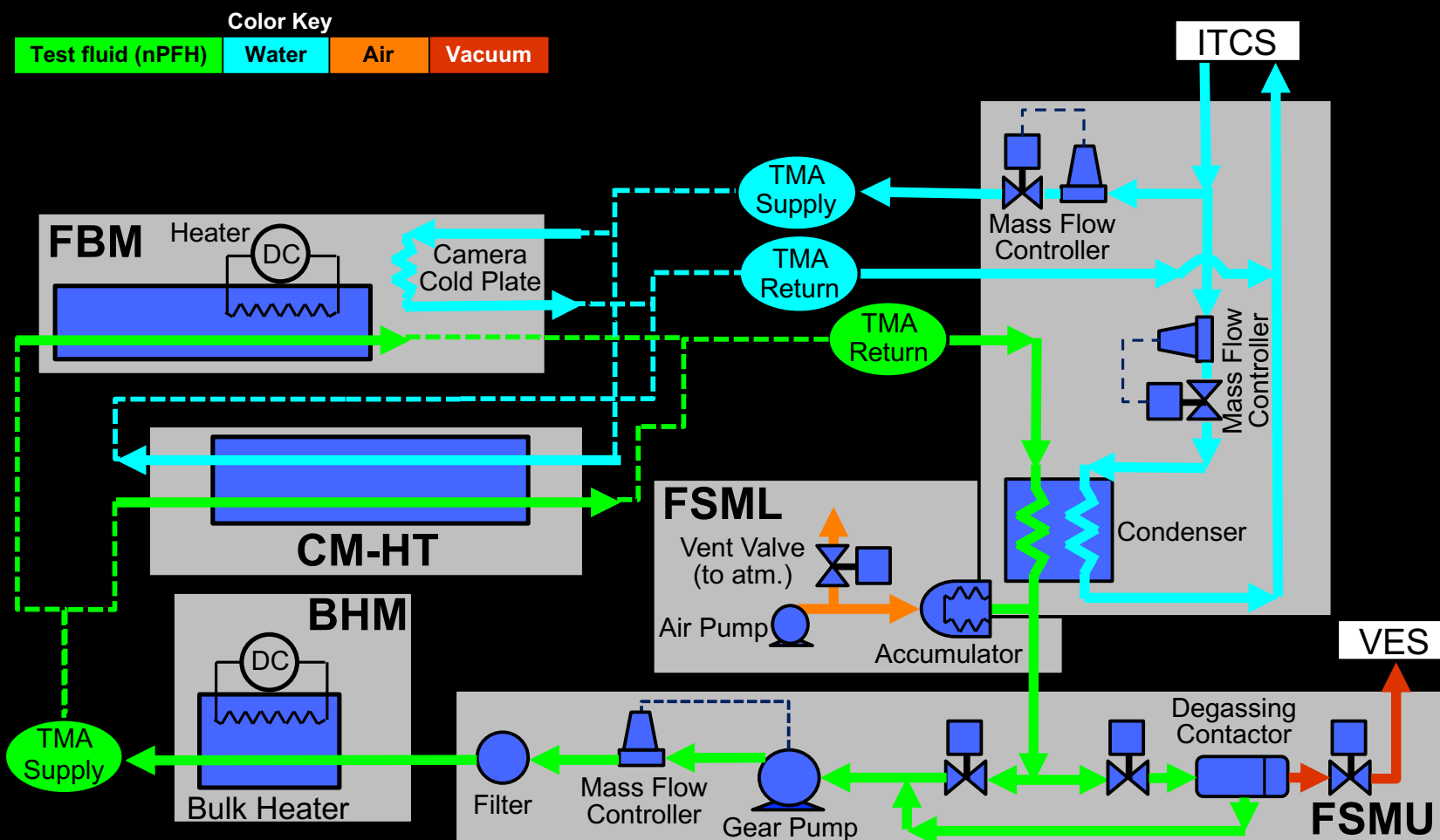


Flight Trajectory



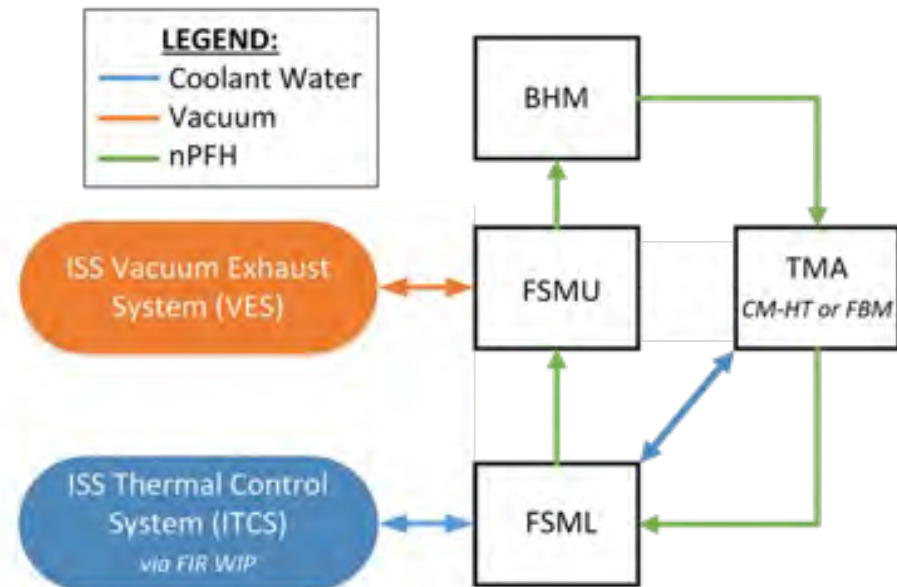
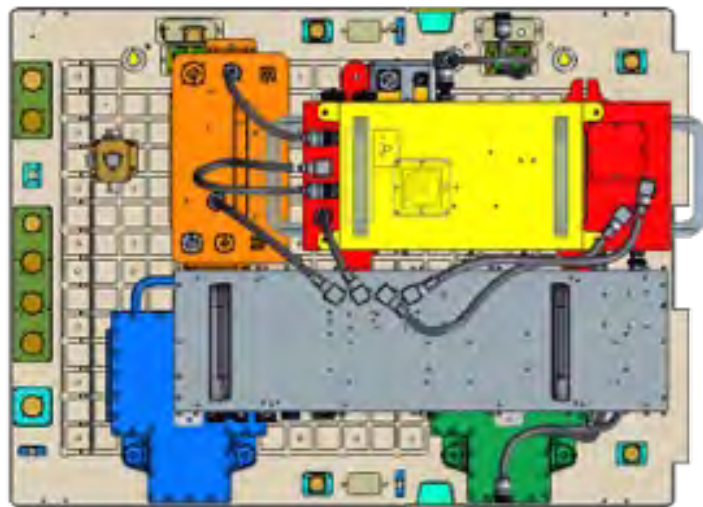


- Critical heat flux (CHF) is the most important design parameter for flow boiling systems, exceeding which can lead to surface overheating or burnout
- Compared to one- g_e CHF data, parabolic flight data show appreciable degradation at low velocities but convergence at high velocities



Note: FBM and CM-HT are operated one at a time rather than simultaneously

ITCS: ISS Thermal Control System
VES: ISS Vacuum Exhaust System



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

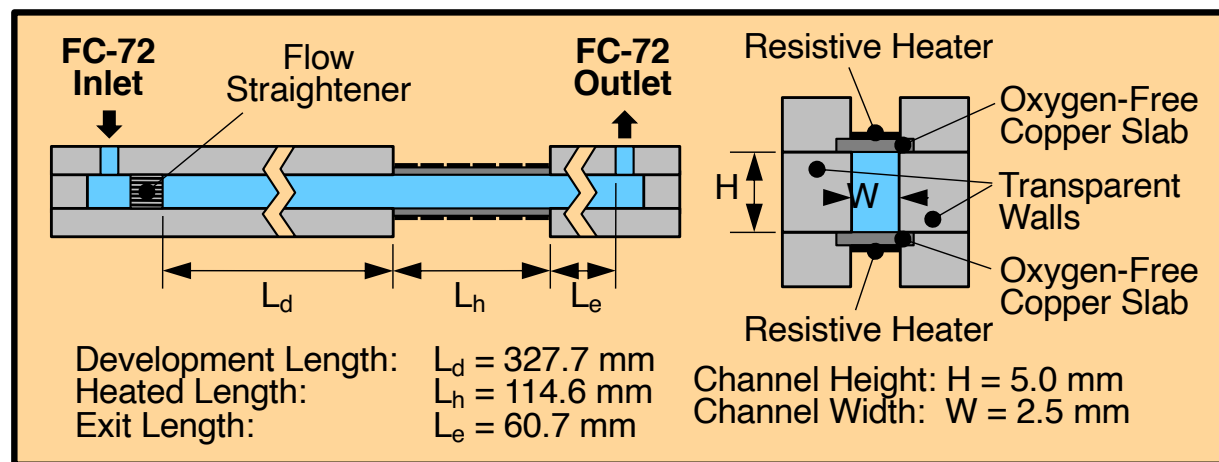
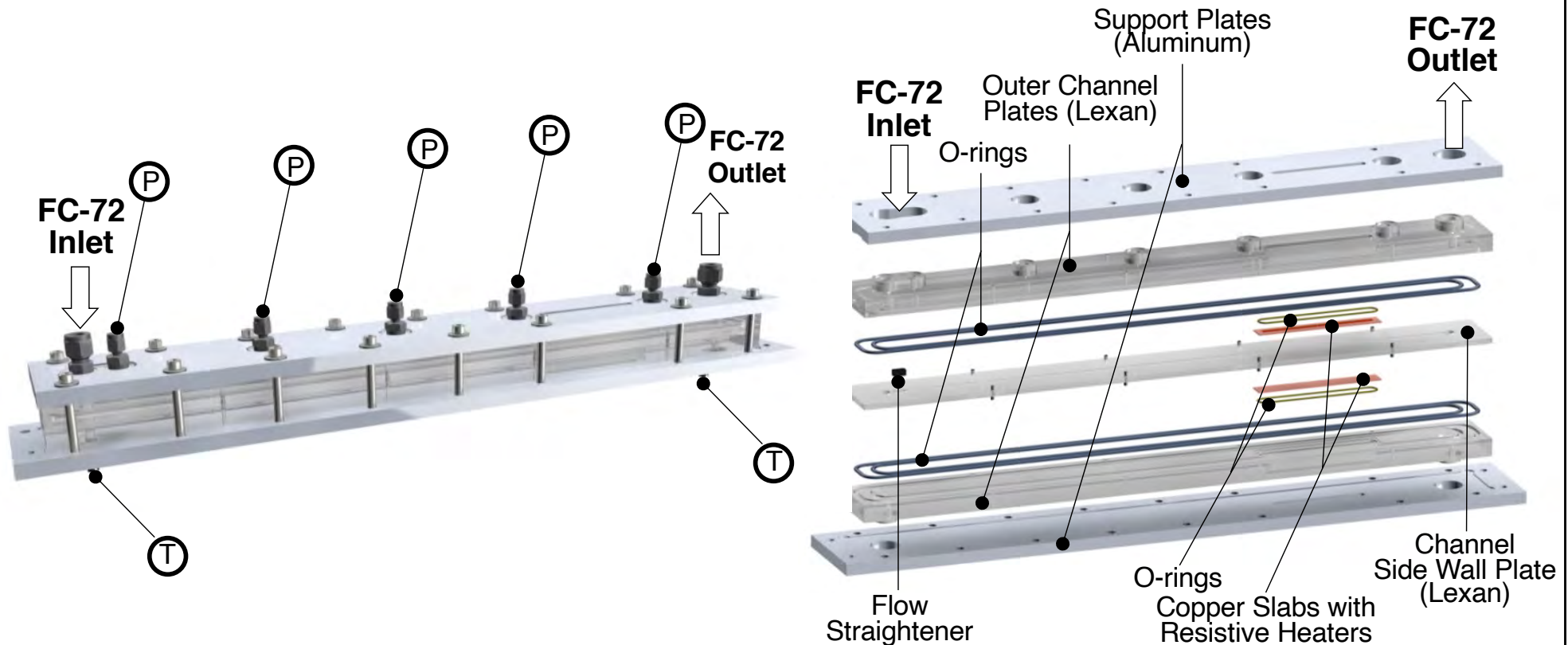
TMA — Test Module Assembly (1 of 2 installed):

FBM — Flow Boiling Module

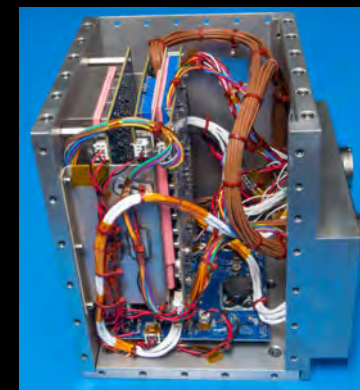
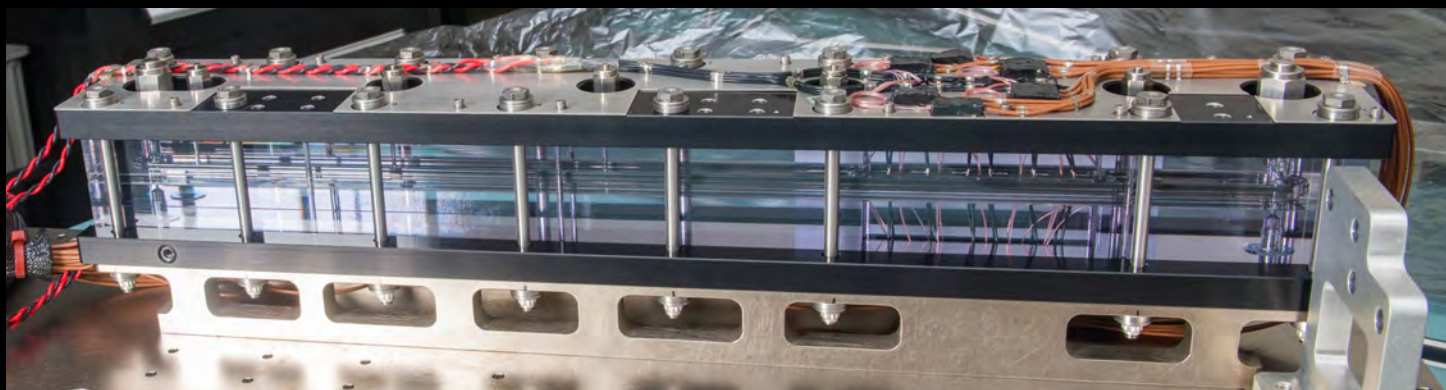
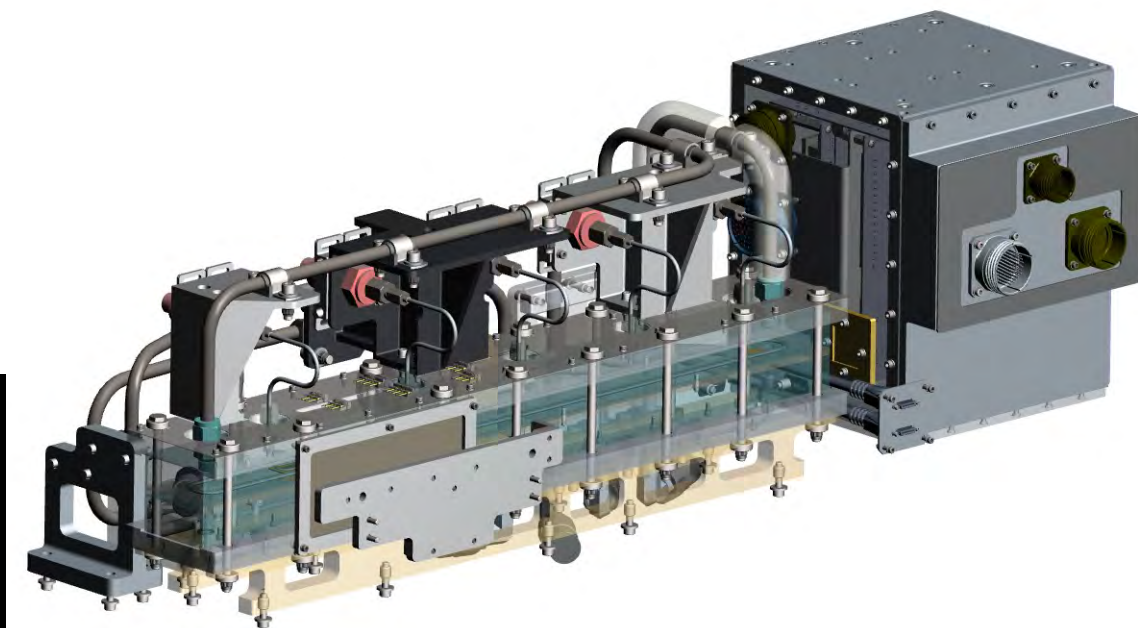
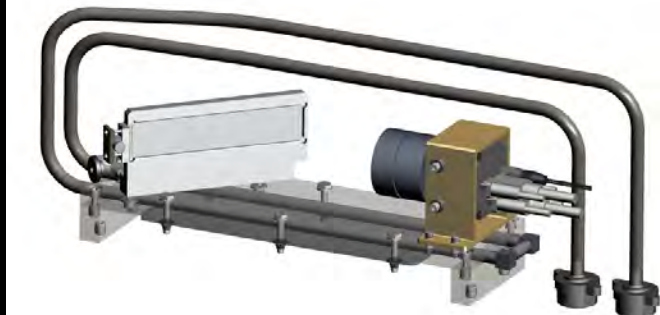
CM-HT — Condensation Module - Heat Transfer

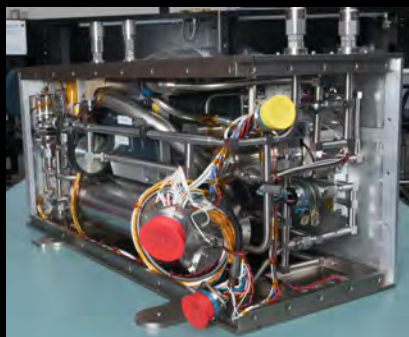
ISS Fluid Integrated Rack (FIR) Provided Hardware:

- 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)

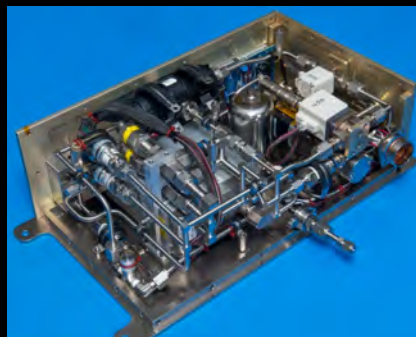


High-Speed Video Camera and Mirror





**Fluid System Module -
Lower**



**Fluid System Module -
Upper**



Bulk Heater Module



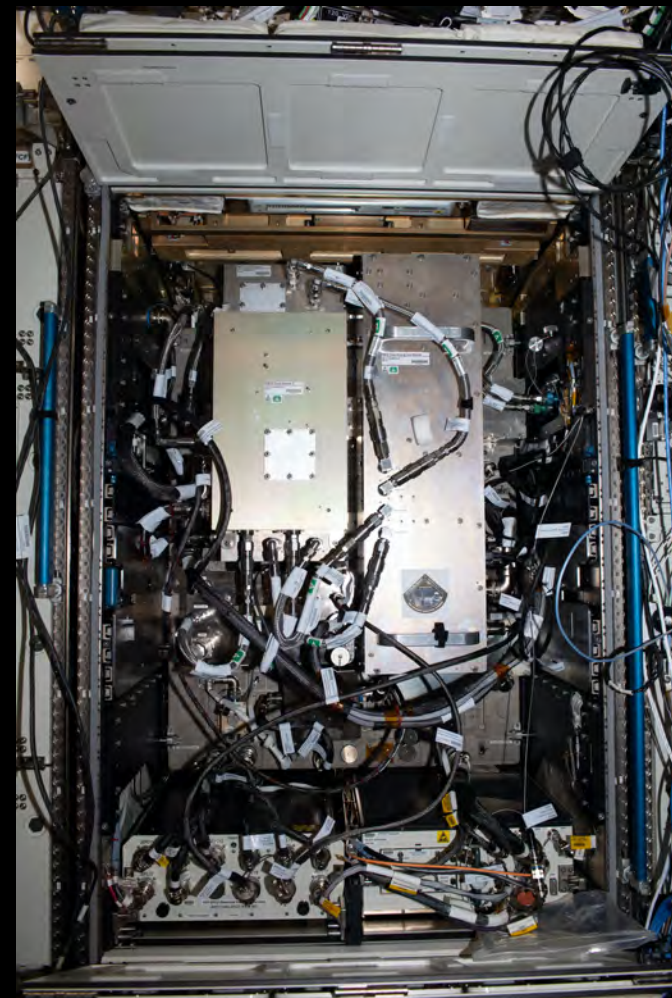
**Remote Data Acquisition
Module 1**



**Remote Data Acquisition
Module 2**



Flow Boiling Module (FBM)



**Fluid Integrated Rack
(FIR) Housing All
components of FBCE**



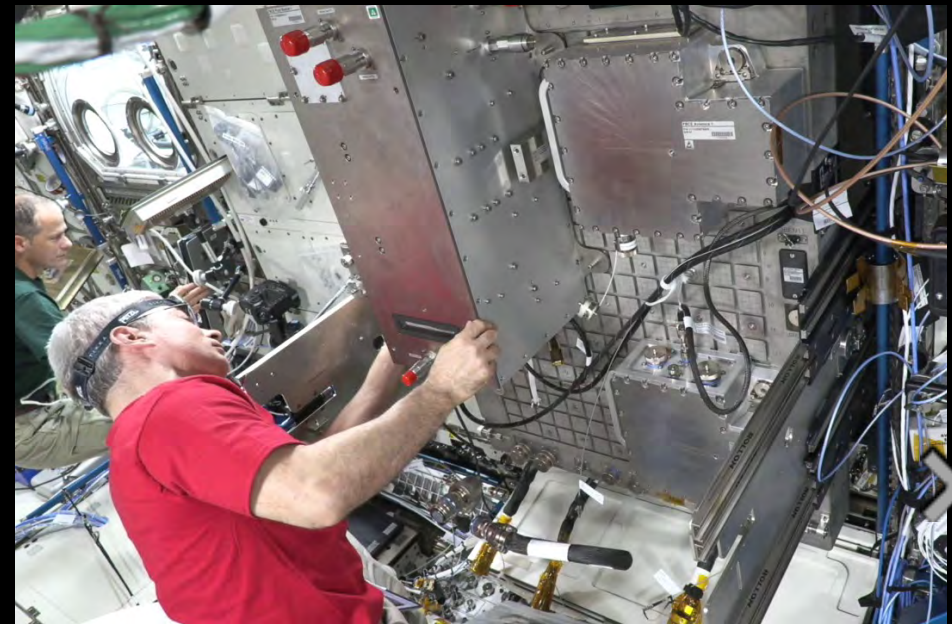
FBCE loading of into Northrop Grumman NG-16 Cygnus Spacecraft



Launch onboard Antares Rocket



August 2022 dock with the ISS



Astronaut Mark Vande Hei assembling FBCE modules into the Fluid Integrated Rack (FIR)

ISS Data Start date: February 23, 2022

ISS Data End Date: July 19, 2022

Database Amassed:

- **Fluid:** n-perfluoroheaxane, C_6F_{14}
- **Boiling curve regimes:** single-phase liquid, nucleate boiling, critical heat flux (CHF)
- **Heat transfer configuration:** single-sided heating, double-side heating
- **Inlet pressure:** 113.30 to 200.44 kPa
- **Inlet quality:** -0.619 to 0.868 (inlet temperature of 23.02 to 80.82 °C)
- **Flow rate:** 2.24 to 40.00 g/s (mass velocity of 179.36 to 3200.13 kg/m²s)
- **Heat flux:** 0 to 100% CHF (1.78 to 56.50 W/cm²)
- **No. of successful tests:** 234
- **No. of data points:** 3800
- **No. of video records:** 3800

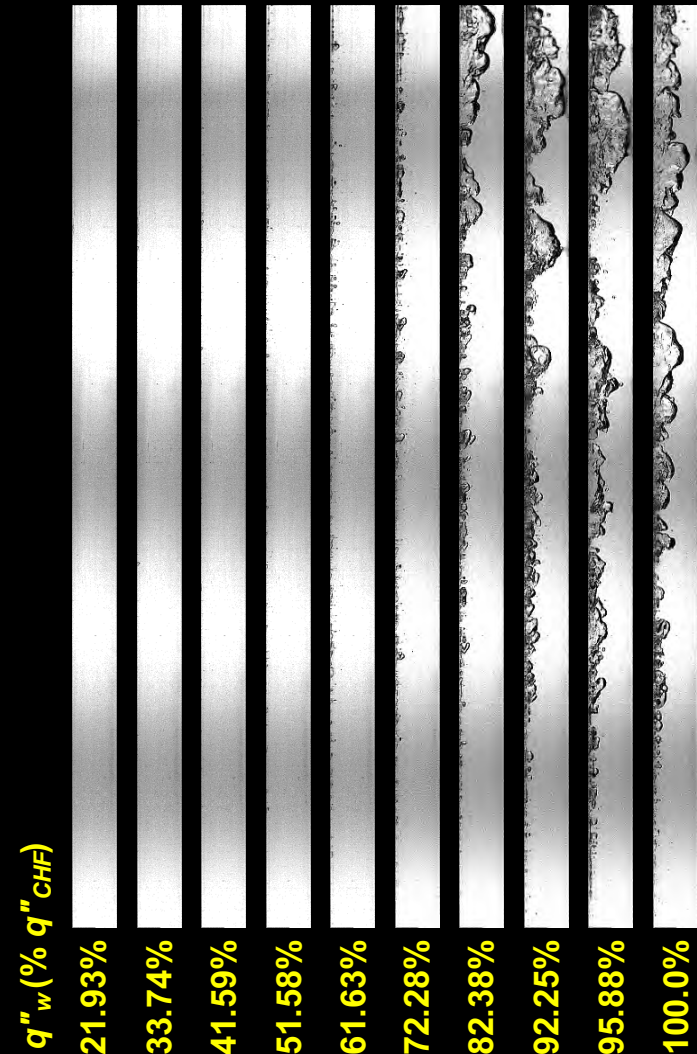
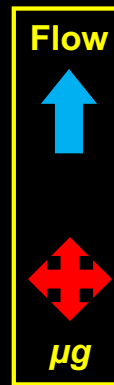
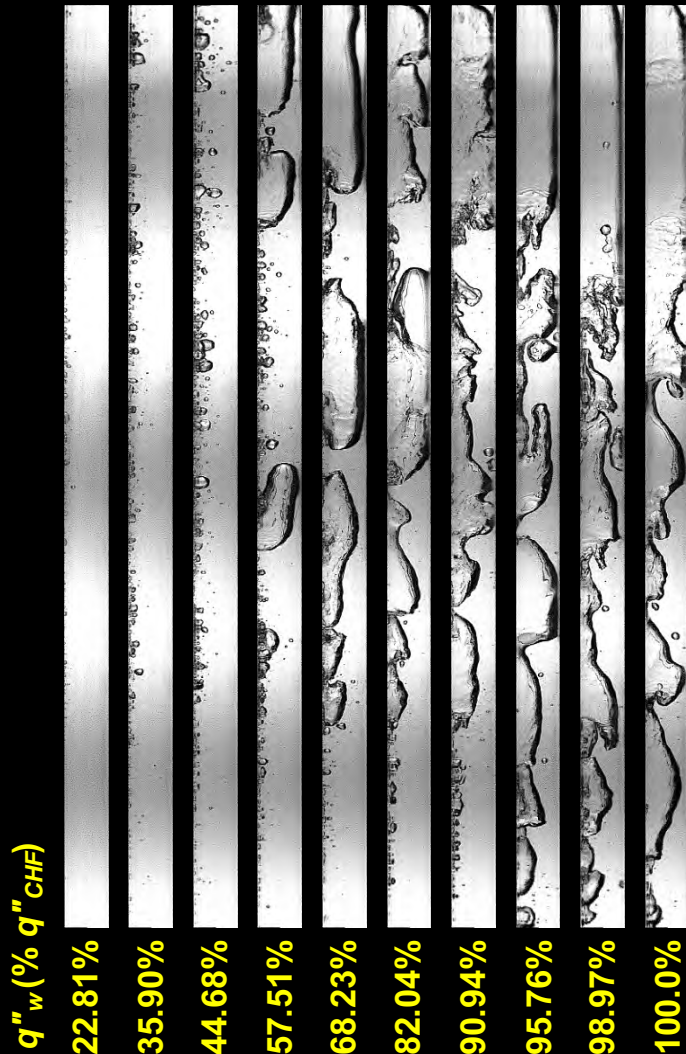
Goals: Develop experimentally validated:

1. Correlations, Machine Learning
2. Theoretical models
3. CFD models

Single-sided Heating

$G = 201.45 \text{ kg/m}^2\text{s}$, $p_{in} = 148.94 \text{ kPa}$
 $T_{in} = 39.94^\circ\text{C}$, $\Delta T_{sub,in} = 29.06^\circ\text{C}$, $x_{e,in} = -0.392$
 $q''_{CHF} = 24.98 \text{ W/cm}^2$

$G = 1599.92 \text{ kg/m}^2\text{s}$, $p_{in} = 150.45 \text{ kPa}$
 $T_{in} = 39.60^\circ\text{C}$, $\Delta T_{sub,in} = 29.72^\circ\text{C}$, $x_{e,in} = -0.402$
 $q''_{CHF} = 42.56 \text{ W/cm}^2$



Use separated flow model to determine axial variations of:

U_{g1}, U_{g2}	Near-wall vapor layer velocities
U_f	Liquid layer velocity
δ_1, δ_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: $g_{n,1} = g_{n,2} = \mu g_e \cong 0$ $\Rightarrow \lambda_c = \frac{2\pi\sigma(\rho_f'' + \rho_g'')}{\rho_f'' \rho_g'' (U_g - U_f)^2}$

Mean pressure difference across wetting front

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

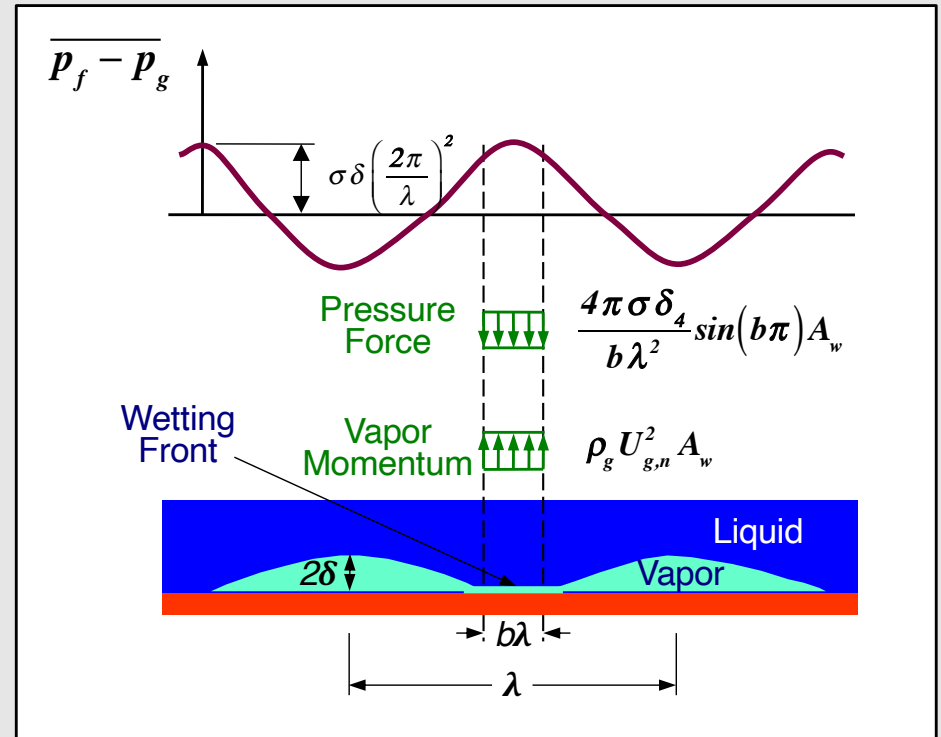
where $b = 0.20$ is ratio of wetting front length to wavelength

Interfacial lift-off criterion

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

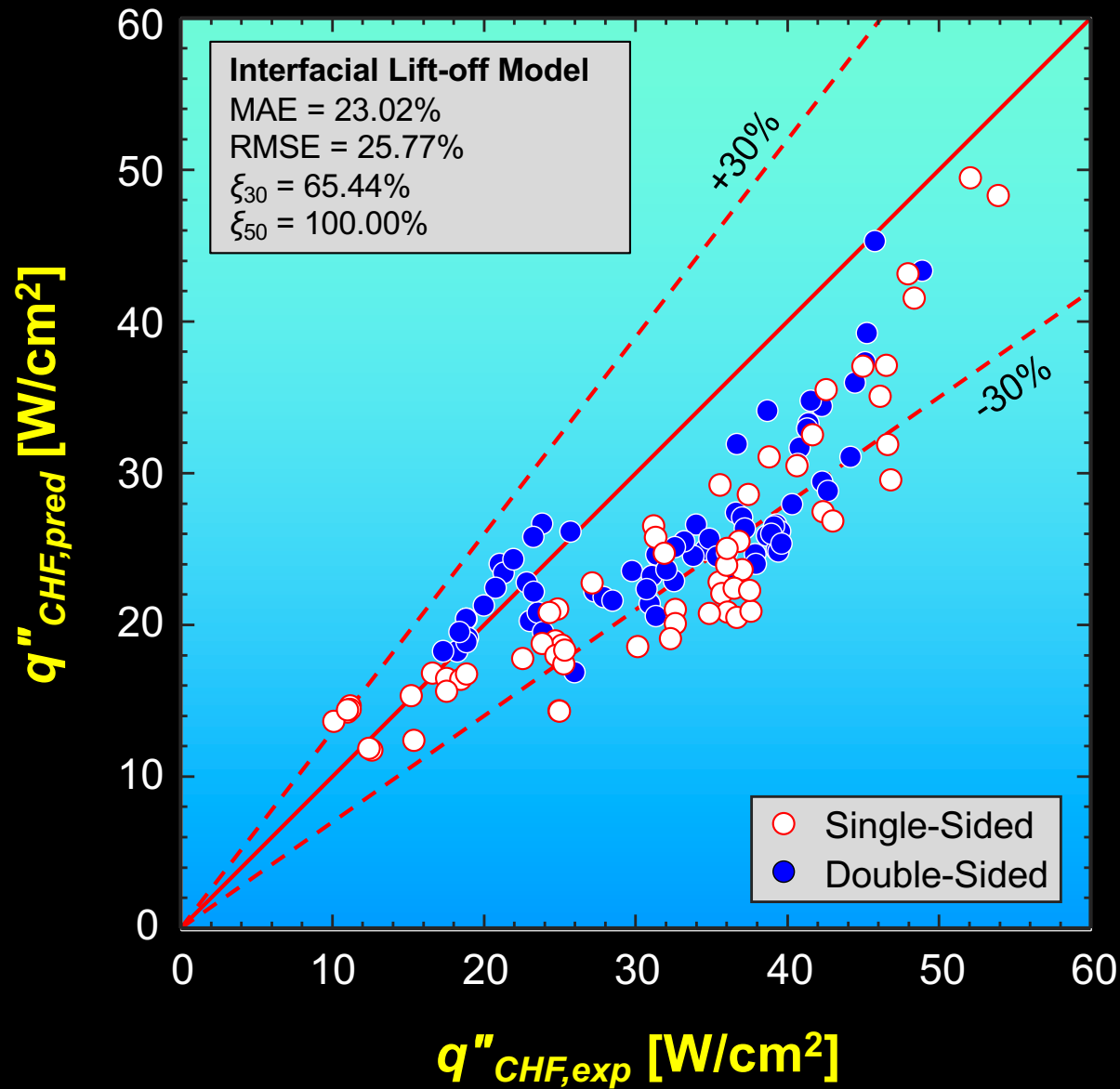
Surface energy balance

$$q_m'' = b q_w''$$



Critical heat flux

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

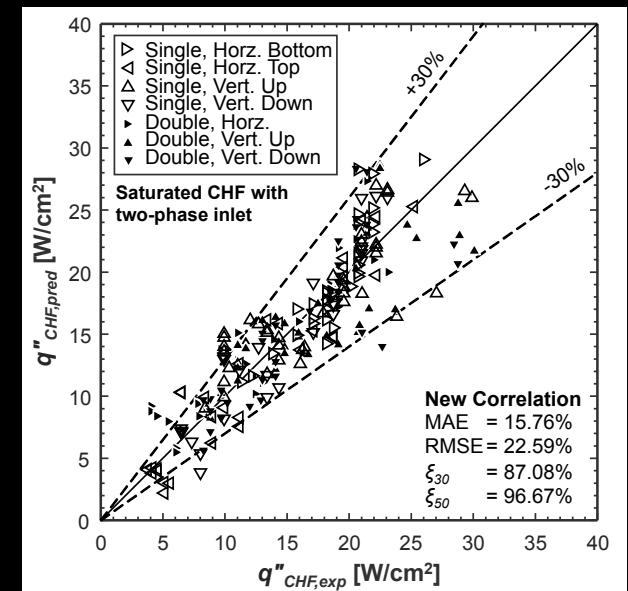
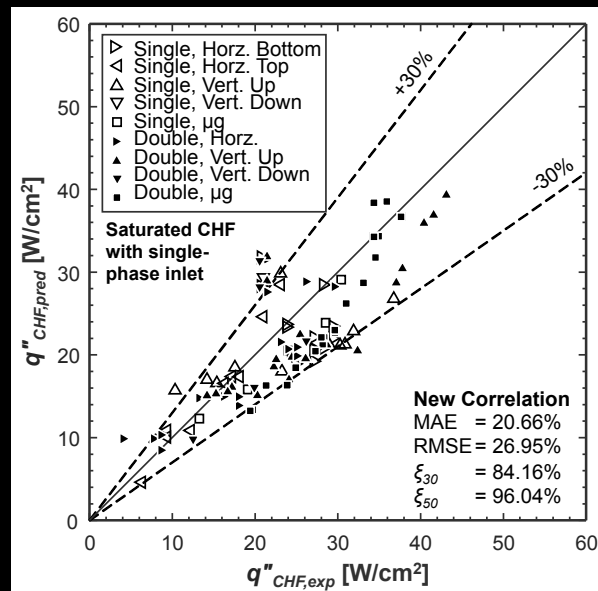
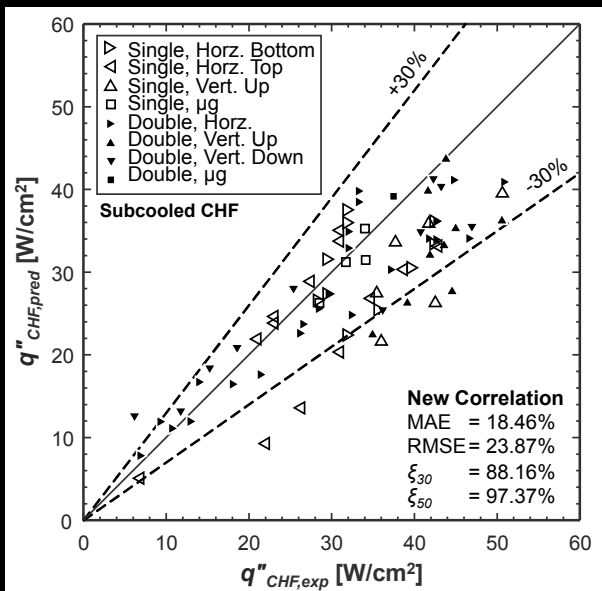


New CHF Correlation Developed using Large Consolidated FBCE Flow Boiling Database

$$Bo_{CHF} = 0.353 We_{D_e}^{-0.314} \left(\frac{L_h}{D_e} \right)^{-0.226} \left(\frac{\rho_f}{\rho_g} \right)^{-0.481} \left(1 - \left(\frac{\rho_f}{\rho_g} \right)^{-0.094} x_{e,in} \right) \left(1 + 0.034 \frac{1}{Fr_{\theta,D_e}} \right) \left(1 + 0.008 \frac{Bd_{\theta,D_e}}{We_{D_e}^{0.543}} \right)$$

$$Bo_{CHF} = \frac{q''_{CHF}}{Gh_{fg}} \quad We_{D_e} = \frac{G^2 D_e}{\rho_f \sigma} \quad Fr_{\theta,D_e} = \frac{G^2}{(\rho_f^2 g \sin \theta D_e)} \quad Bd_{\theta,D_e} = \frac{g \cos \theta (\rho_f - \rho_g) D_e^2}{\sigma} \quad D_e = \frac{4A_c}{P_h}$$

θ : orientation angle of channel



- Applicable to all 3 types of CHF: Subcooled CHF, Saturated CHF with 1-phase inlet, Saturated CHF with 2-phase inlet
- Considers the effects of gravity on CHF, and is applicable to all flow orientations in both Earth gravity and microgravity
- Predicts the entire consolidated FBCE database with a mean absolute error of 17.44%

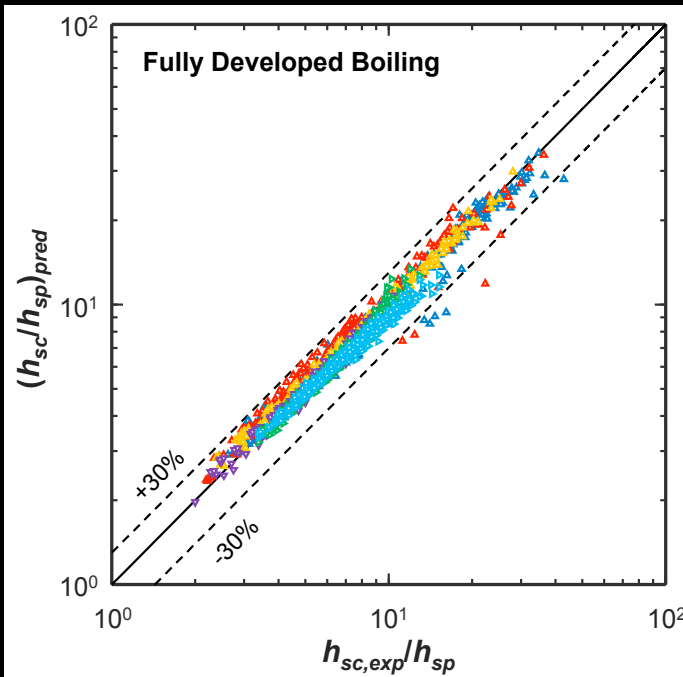
New Correlation Developed for Subcooled Flow Boiling Heat Transfer

$$\frac{h_{sc}}{h_{sp}} = \frac{Nu_{sc}}{Nu_{sp}} = 312.8 Bo^{0.769} (0.1 + Ja^{**})^{-0.632} \quad Nu_{sp} = 0.023 Re_{fo}^{0.8} Pr_f^{0.4}$$

$$Bo = \frac{q_w''}{G h_{fg}} \quad Ja^{**} = \frac{c_{p,f} \Delta T_{sub}}{h_{fg}} \quad Nu_{sp} = \frac{h_{sp} D_h}{k_f} \quad Re_{fo} = \frac{G D_h}{\mu_f} \quad D_h = \frac{4 A_c}{P_F}$$

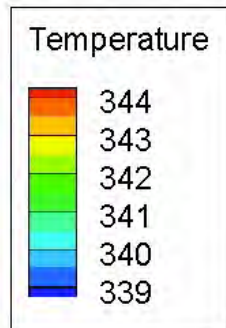
- Fully-explicit functions
- Free of artificial singularities
- Thermophysical properties accounted for within **Bo** and **Ja^{**}**

- △ Vertical up, single (MST)
- △ Vertical up, double (MST)
- △ Vertical up, double (2016)
- ▽ Vertical down, double (2016)
- △ Horizontal, double, top (2016)
- △ Horizontal, double, bottom (2016)



	Datapoints	MAE	±30% Inliers
Fully Developed Boiling (FDB)	1275	6.91%	99.37%
Partially Developed Boiling (PDB)	812	9.59%	92.86%
Nucleate Boiling Degradation (NBD)	922	41.71%	52.71%
Overall Consolidated Database	3009	20.06%	80.86%

- **Simple to use, yet highly effective!**
- Uniform predictions throughout the parameter ranges
- Correlation independent of both heating configuration and flow orientation in Earth's gravitational field
- New correlation clearly outperforms all prior seminal correlations for the entire consolidated database, evidenced by an overall mean absolute error of 20.06%
- It yields excellent heat transfer predictions for both the PDB and FDB regimes
- Although predictions for the NBD regime are higher than expected, these values can be treated as upper limits to heat transfer here

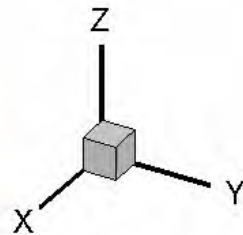


Gravity



FC-72
Flow

$G = 445.75 \text{ kg/m}^2\text{s}$
 $q'' = 143 \text{ kW/m}^2$
 $\Delta T_{\text{sub}} = 30.81^\circ\text{C}$
 Vertical upflow
 One-G

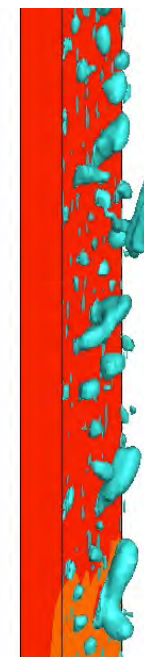
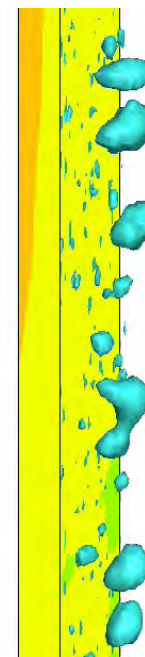
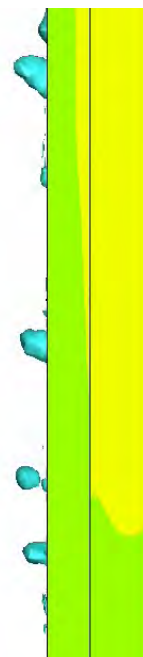
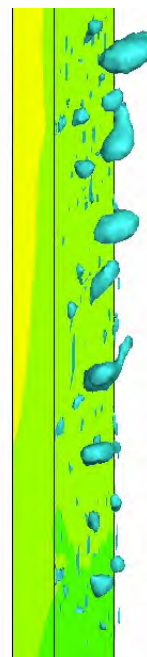
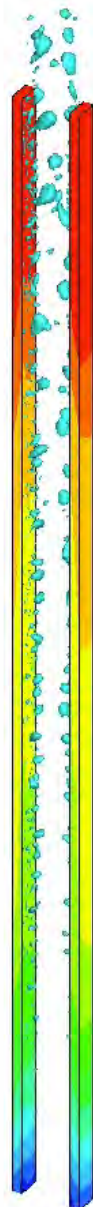


Models used:

- Volume of Fluid (VOF)
- Coupled Level Set VOF (CLSVOF)

Employ User-defined functions for:

- Shear-lift Force
- Bubble Collision Dispersion Force



Upstream

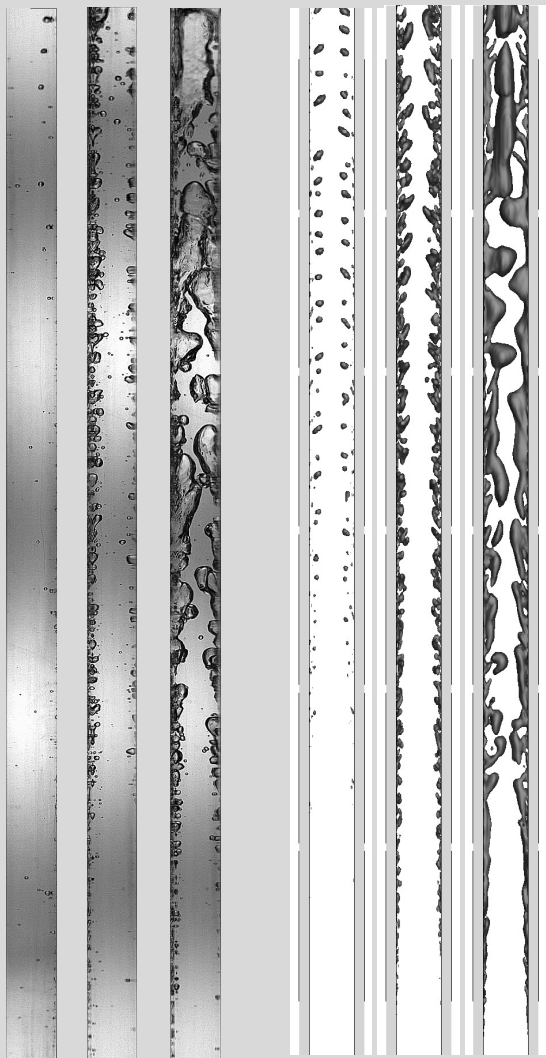
Middle

Downstream

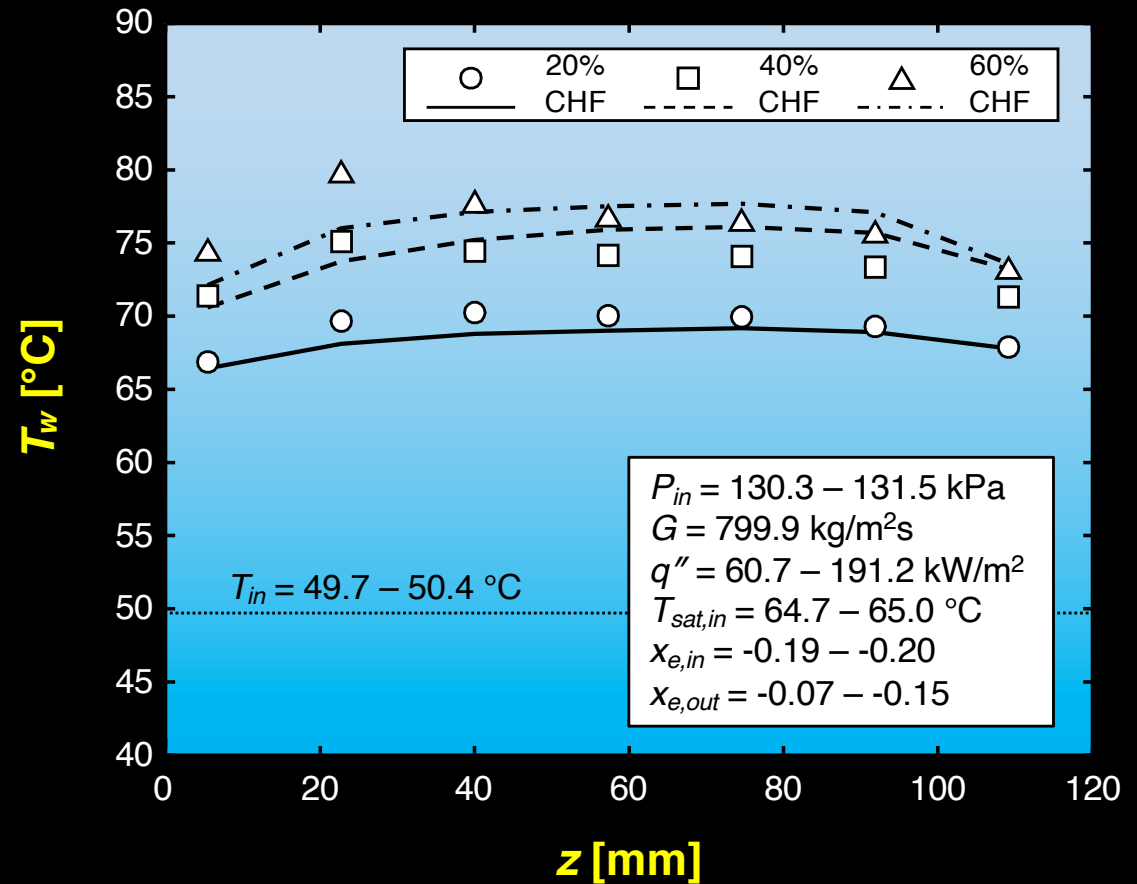
Adapted in **ANSYS FLUENT**

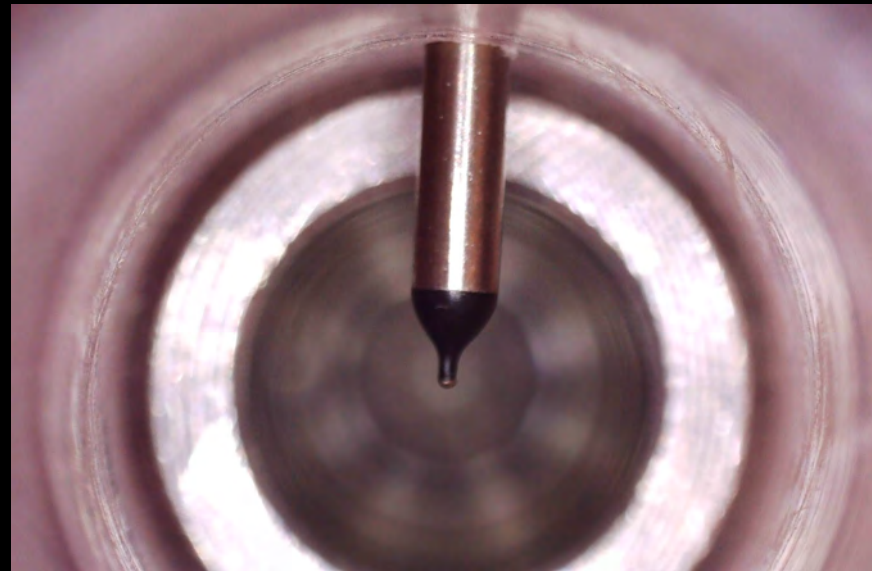
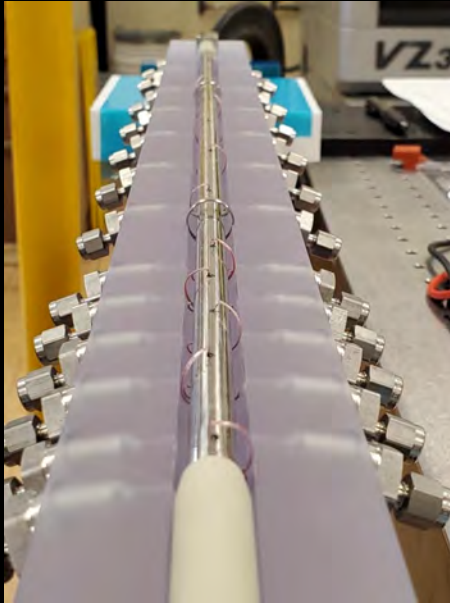
Video frame rate is 5 fps
 Individual images in sequence separated by 1 ms

20% 42% 62% of q''_{CHF}



$P_{in} = 130.02 - 131.26 \text{ kPa}$
 $G_{in,avg} = 799.9 \text{ kg/m}^2\text{s}$
 $q''_{total} = 6.07 \text{ W/cm}^2 - 12.90 \text{ W/cm}^2$
 $x_{e,in} = -0.198 - -0.199$







CM-HT loading of into Northrop Grumman NG-19 Cygnus Spacecraft



Launch onboard Antares Rocket



August 2023 dock with the ISS



“Thriving in Space, Ensuring the Future of Biological and Physical Sciences Research”

... serves as agenda for research in the following decade, using the space environment to address pressing life and physical sciences in pursuit of new fundamental knowledge and practical solutions important to space exploration.

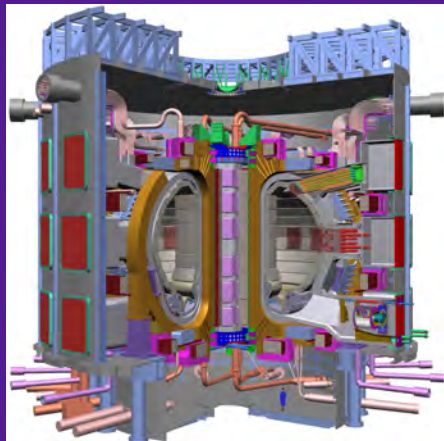
- Based on over 250 topical input papers from science and engineering communities
- Assembled by the 50+ report co-authors
- Included presentations from both government and industry
- Addressed:
 - (i) the current state of knowledge
 - (ii) key science themes and questions
 - (iii) science to enable space exploration
 - (iv) science enabled by the space environment
 - (v) research campaigns
 - (vi) Infrastructure, access, and community

Mudawar:

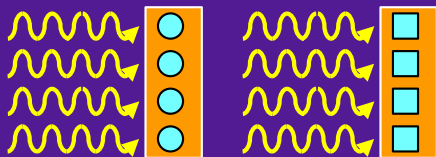
- p. 28: Fluid Physics Background
- p. 80: Success of Flow Boiling and Condensation Experiment (FBCE) on the ISS as response to recommendations from 2011 Decadal Report
- p. 81: Recommendation for Fluid Physics and Thermal Management of cryogenic Fluids
- p. 154: Effects of space environment on transport and materials synthesis, including critical heat flux (CHF)



Fusion Reactor Blankets

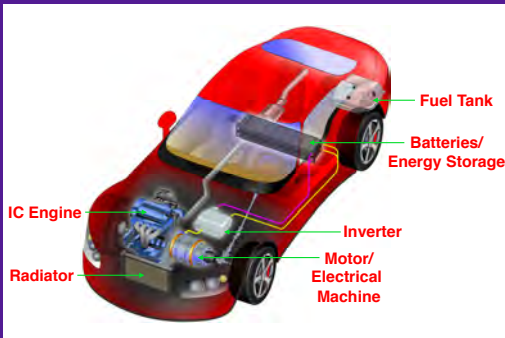


International Thermonuclear Experimental Reactor (ITER)

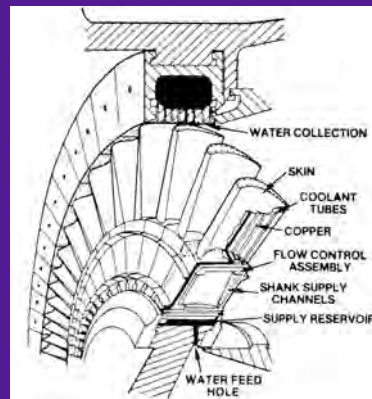
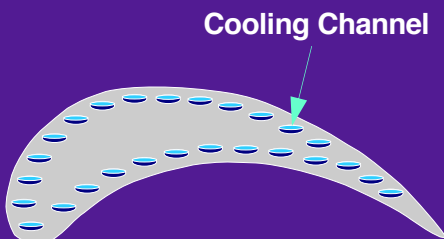


Heat flux in cooling channels can exceed 10^4 W/cm²

Thermal Management of Power Electronics in Hybrid Vehicles



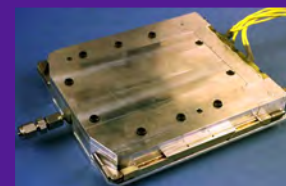
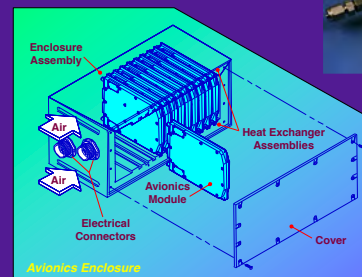
Liquid-Cooled Turbine Blades



Heat Exchanger for High-Pressure Hydride Hydrogen Storage



Military Avionics

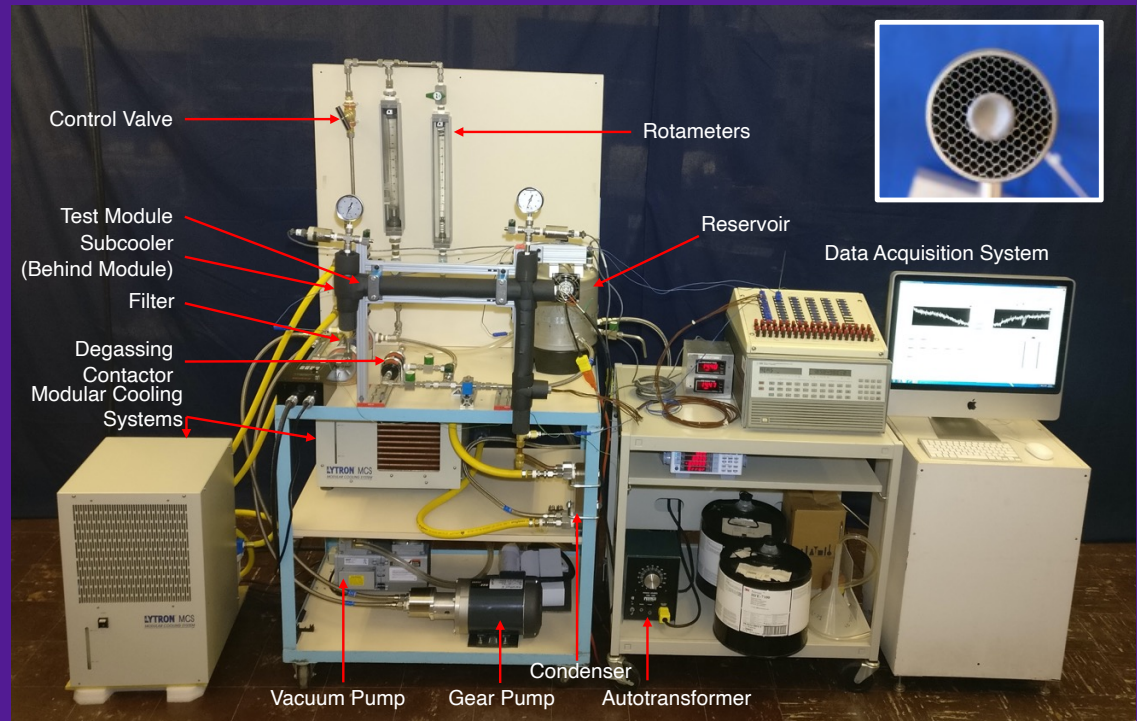
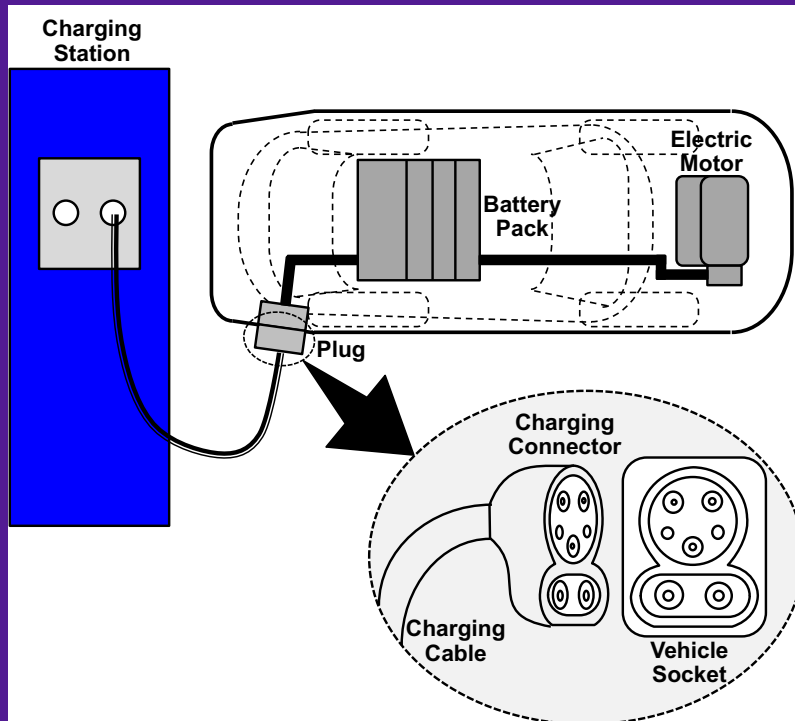


Fuel-Air Heat Exchanger for High-Mach Turbine Engines

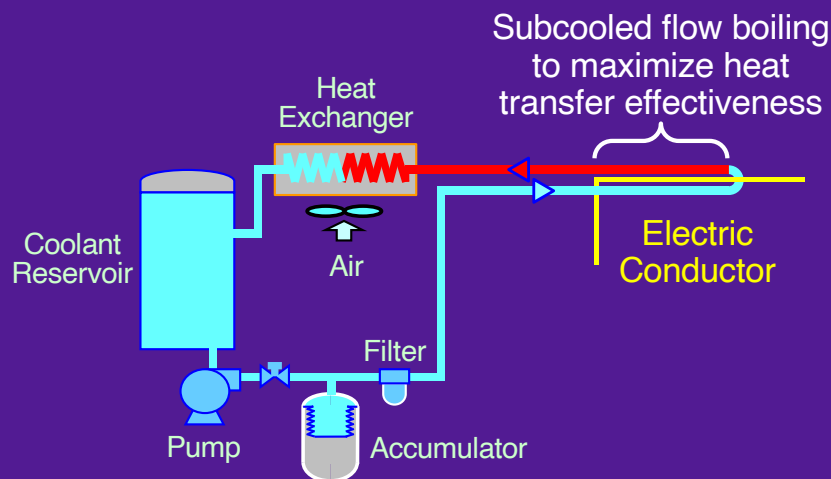


Military Laser, Microwave, and Advanced Radar Systems



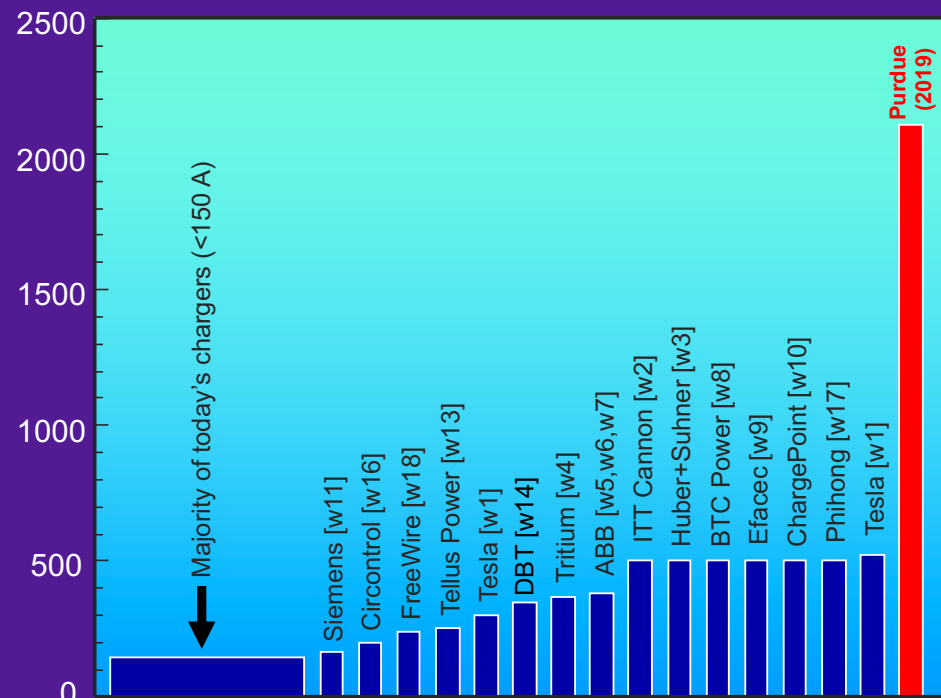


- Present most advanced EV charging technologies require in excess of 20 minutes for a full charge compared to 5 minutes for gas charging
- Slow EV charging has greatly discouraged customer adoption of EVs and negatively impacted the EV market
- Slow EV charging is outcome of relatively low current (500 Amps max) that can be supplied through charging cable, capped by heating in the cable's conductor
- Achieving 5-minute EV charging will require advanced cooling methods to boost current delivery to about 1400 Amps



Subcooled boiling: liquid coolant supplied at a temperature well below boiling point, allowing very high frequency formation and departure of very small vapor bubbles. This enables very efficient removal of heat while minimizing pumping power.

Maximum Current Through Charging Cable [A]



EV Chargers Available Worldwide

- Using thermal management lessons learned from FBCE, Purdue developed a new patented cable cooling technology that enables delivery of upwards of 2400 Amps through the charging cable
- By exceeding the 1400 Amps required for 5-minute EV charging, Purdue's new technology enables even faster charging of EVs than gas charging