National Aeronautics and Space Administration

NASA Flight Opportunities

Cryogenic Fluid Management for Future In-Space Transfer Systems

Issam Mudawar, Ph.D., Purdue University

Community of Practice Webinar Series – June 5, 2024

Session will start at 10 a.m. PT – Please mute your microphone and turn off your camera

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- Please mute your microphone and turn off your camera
- Today's session will be recorded
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- Please engage!
  - Use the chat throughout the session to ask questions

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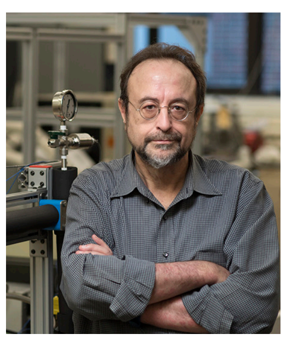
Today's Speaker



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Purdue University

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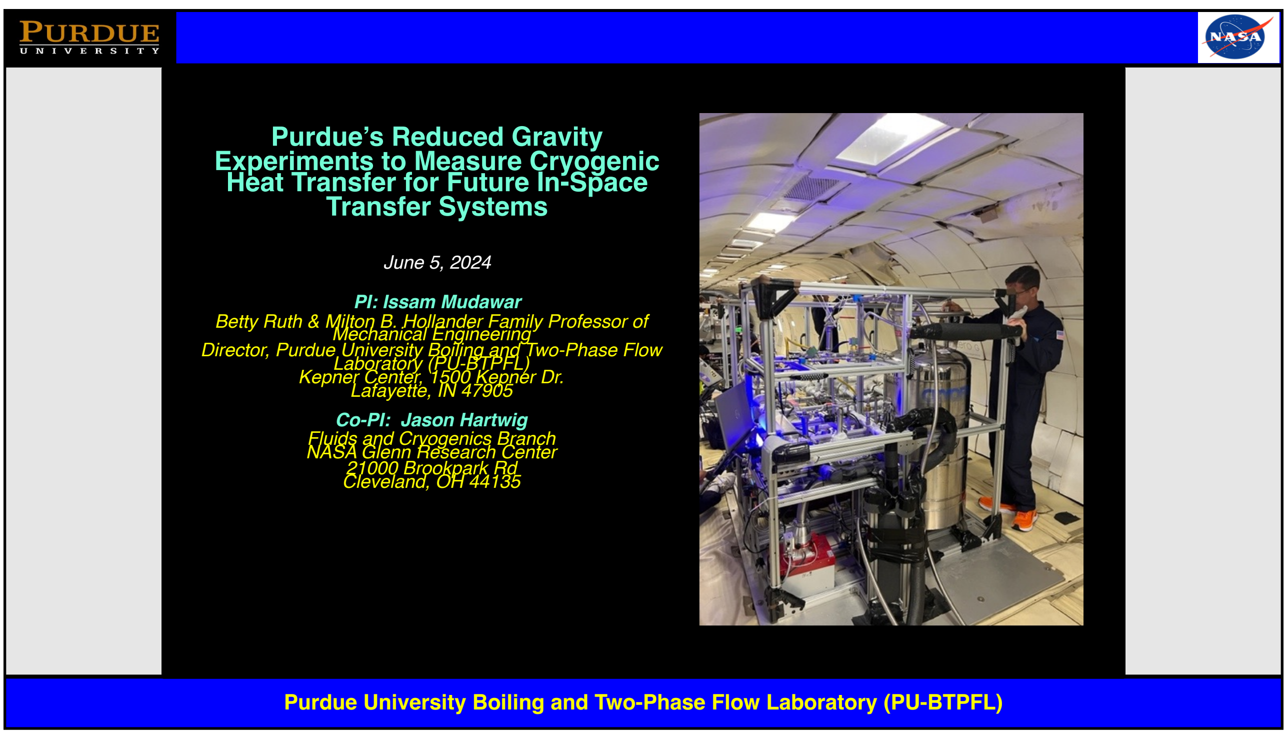
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NASA
Purdue's Reduced Gravity Experiments to Measure Cryogenic Heat Transfer for Future In-Space Transfer Systems
June 5, 2024
PI: Issam Mudawar
Betty Ruth & Milton B. Hollander Family Professor of Mechanical Engineering
Director, Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)
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Fluids and Cryogenics Branch
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
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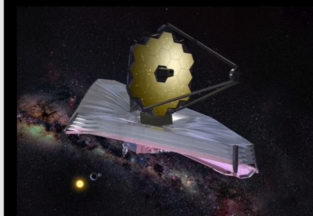
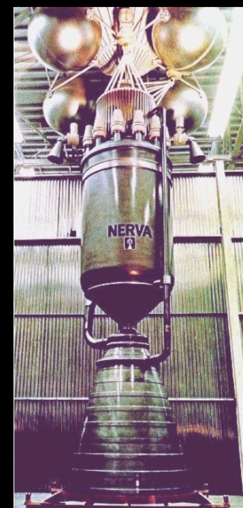
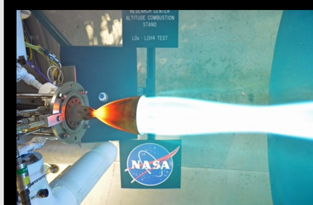
Space Applications of Cryogens



James Webb Space Telescope (LHe)

Orbital Refueling





Propulsion and Cryogenics Advanced Development (PCAD) Project (LOX/LCH_4)

Lunar ascent/descent stages

Nuclear Thermal Propulsion Systems (LH_2)

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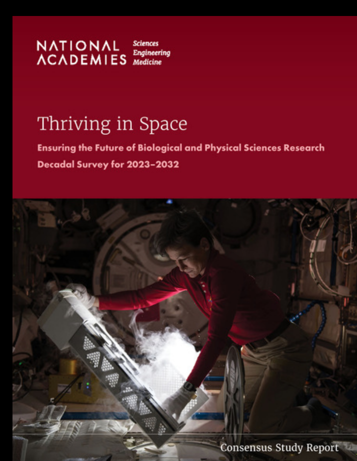
National Academies Decadal Survey for 2023-2032

"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) Current state of knowledge
  (ii) Key science themes and questions
  (iii) Science to enable space exploration
  (iv) Science enabled by 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: Recommendations 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)

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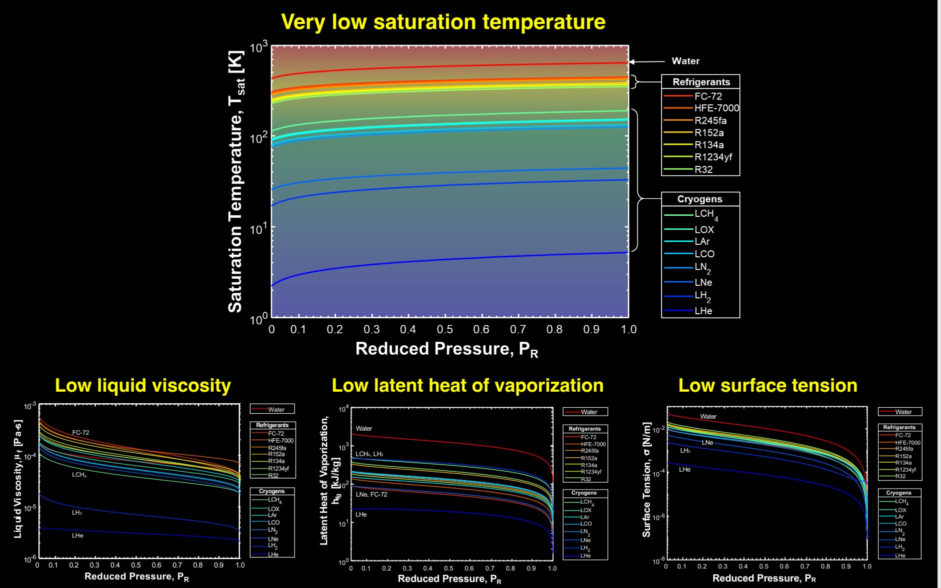
Unique Characteristics of Cryogens



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Technological Gaps in Cryogenic Literature

Cryogenic Database

Cryo	Transient (Quenching)	Steady-state Heating
1g data	Abundant	Scarce
μg data	Few	None
Correlation	Few	None
Uncertainty	High	Low

What is missing?

1. ***No reduced/partial gravity data for steady state cryogenic flow boiling***
2. ***No reliable HTC/CHF correlations for cryogenic two-phase transfer line***

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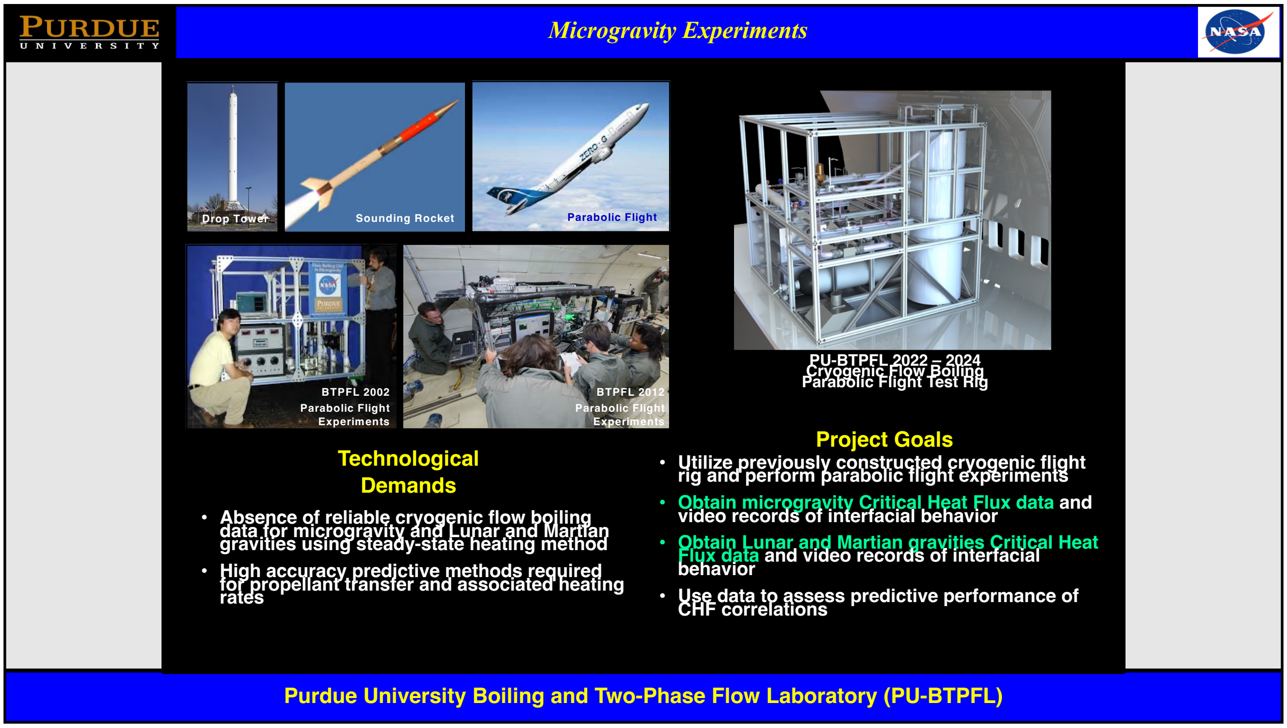
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Microgravity Experiments
NASA
Drop Tower
Sounding Rocket
Parabolic Flight
BTPFL 2002 Parabolic Flight Experiments
BTPFL 2012 Parabolic Flight Experiments
PU-BTPFL 2022 – 2024
Cryogenic Flow Boiling
Parabolic Flight Test Rig
Technological Demands
• Absence of reliable cryogenic flow boiling data for microgravity and Lunar and Martian gravities using steady-state heating method
• High accuracy predictive methods required for propellant transfer and associated heating rates
Project Goals
• Utilize previously constructed cryogenic flight rig and perform parabolic flight experiments
• Obtain microgravity Critical Heat Flux data and video records of interfacial behavior
• Obtain Lunar and Martian gravities Critical Heat Flux data and video records of interfacial behavior
• Use data to assess predictive performance of CHF correlations
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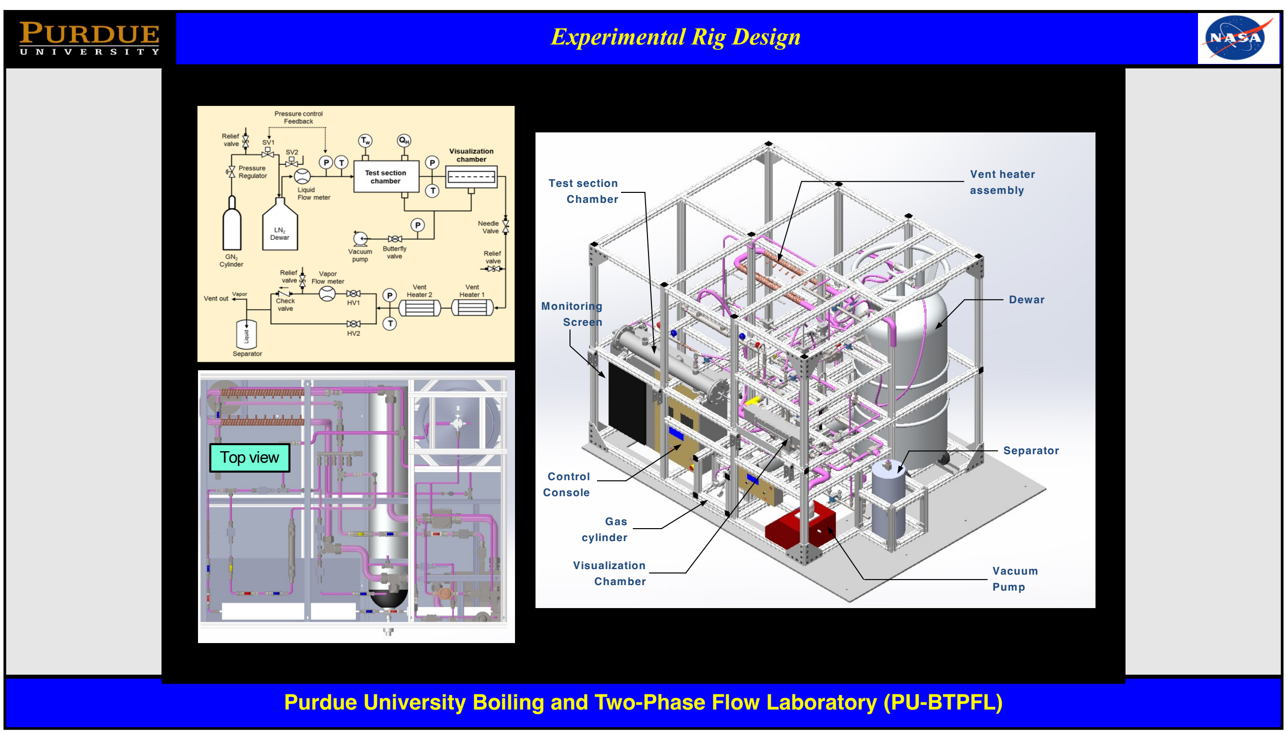
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Experimental Rig Design
NASA
Top view
Test section Chamber
Vent heater assembly
Monitoring Screen
Dewar
Separator
Control Console
Gas cylinder
Visualization Chamber
Vacuum Pump
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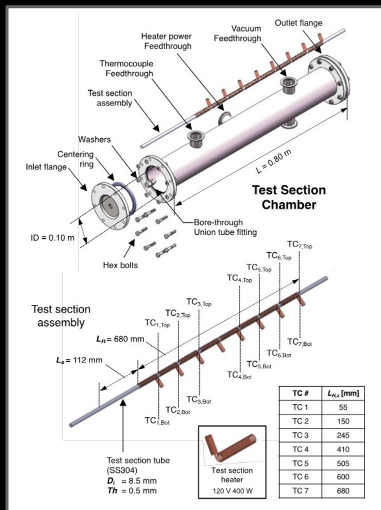
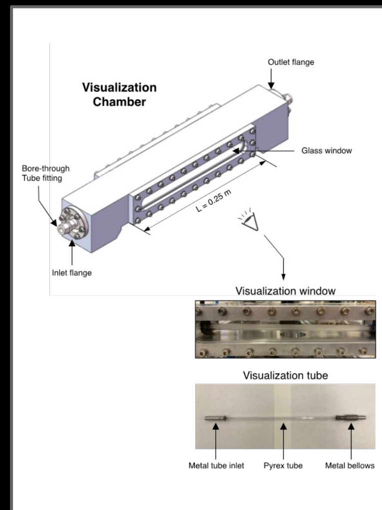
Experimental Rig Design

Test Section



Visualization Section



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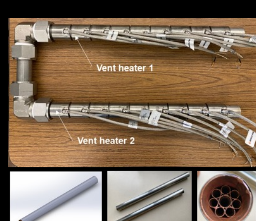
Experimental Rig Construction



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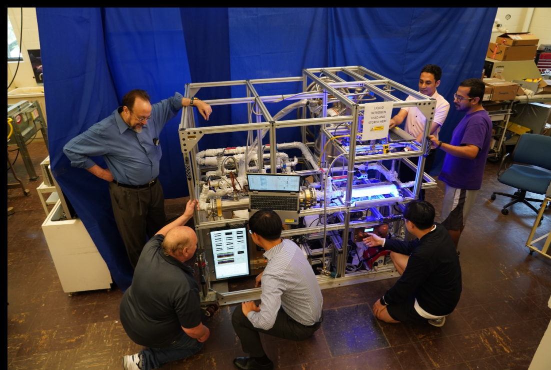
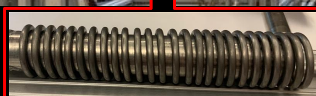
Experimental Rig Design

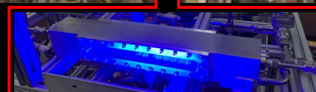


Design Requirements

- Utilize liquid nitrogen as a working fluid
- Utilize high pressure gas for pressurization
- Utilize vacuum chambers to minimize heat gain
- Accommodate LN_2 flow boiling in a tube
- Record high-speed flow visualizations
- Control and record heater power
- Control and maintain system pressure
- Enable recording thermal parameters (T_f, T_w, P)
- Optimize for parabolic flight experiments
  - ✓ *Structure integrity*
  - ✓ *Restricted volume & weight*
  - ✓ *Aircraft power / vent interfaces*



Electrical heater



Flow visualization section

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March 2024 Flight Campaign

Rig Arrival in Fort Lauderdale, FL

Rig system check after landing

Rig Installed on G-Force One

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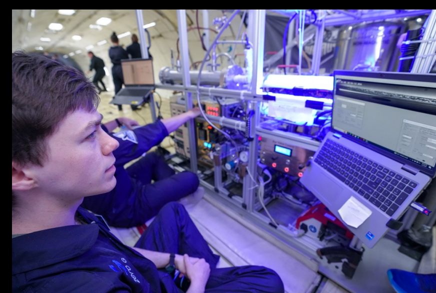
March 2024 Flight Campaign



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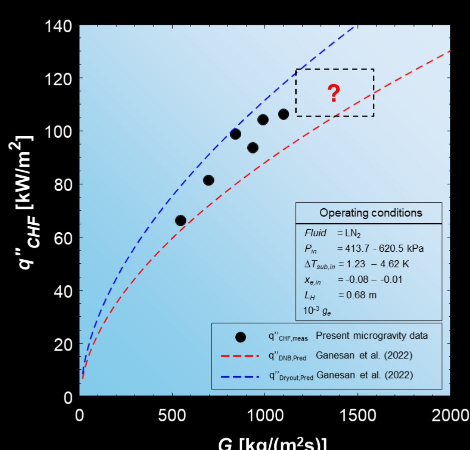
Results from Previous Flight Campaigns

Microgravity CHF



Measured μg CHF trends

- CHF mechanism: annular liquid dryout
- CHF increases with G
- CHF tends to level-off as G *increases*

What is missing?

1. **Microgravity CHF at high G conditions**
2. **Cryogenic CHF under Lunar gravity**
3. **Cryogenic CHF under Martian gravity**

→ ***Aims for the 3rd flight campaign***

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March 2024 Flight Experiments

Flight Test Matrix

TEST MATRIX		Flight day 1 (15 – 15)				Flight day 2 (10 – 10 – 10)			Flight day 3				Flight day 4			
(March Flight)		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	Case11	Case12	Case13	Case14	Case15
# of parabola	[-]	8	4	7	3	6	7	5	4	5	3	4	5	4	3	3
P	[psi]	80	77	80	84	70	70	70	100	100	106	106	80	80	80	90
gravity	[-]	Martian	Martian	Lunar	Lunar	Martian	Lunar	μg	μg	μg	μg	μg	μg	μg	μg	μg
LFR	[gpm]	0.7	1.0	0.7	1.0	0.8	0.8	0.8	1.6	1.4	0.6	0.8	1.7	1.5	1.0	0.8
G	[kg/m²s]	600	792	587	879	660	653	660	1338	1110	485	650	1411	1209	806	650
ΔT_{sc}	[K]	3	2.6	3.5	4.3	2.7	3.2	2	3.7	4.2	4.1	4.1	3.6	3.6	3.6	4.0
CHF	[-]	O	O	Δ	Δ	O	O	X	O	O	O	X	O	X	X	X

- Very successful, nearly flawless campaign
- Outstanding team, including both doctoral candidates and undergraduate student teams
- Achieved good data acquisition despite unexpected situations
- Ten full boiling curves acquired for ten different mass velocities
- Six LN_2 Martian/Lunar CHF data points acquired
- Four LN_2 Microgravity CHF data points acquired
- Total of 714 (51x14) steady-state microgravity/Lunar/Martian HTC data points acquired
- Acquired flow visualization for Microgravity and both Lunar and Martian gravities

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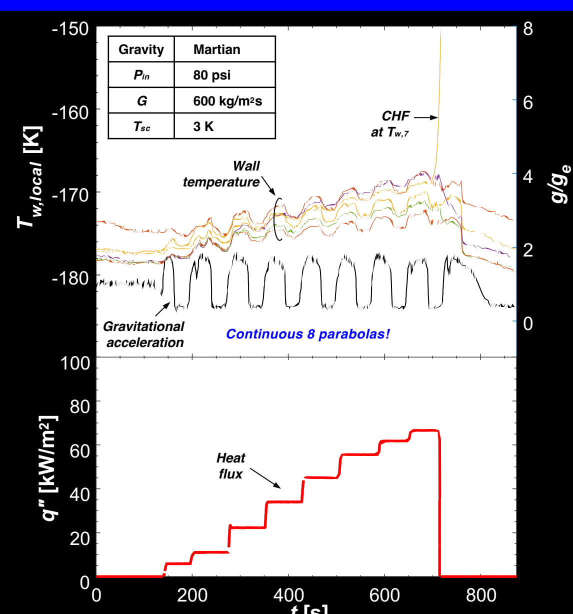
Transient Dynamics Results



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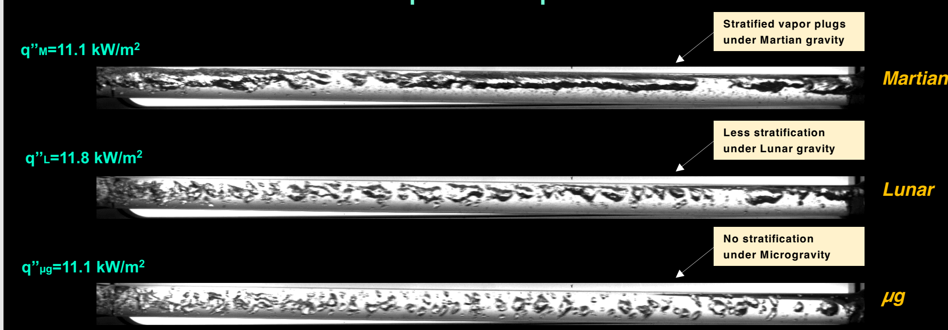
Flow Visualization Results: Parabolic Flight

Gravitational effect on two-phase flow pattern



P_{in}	70 psi
G	650 kg/m^{2}s
T_{sc}	3 K

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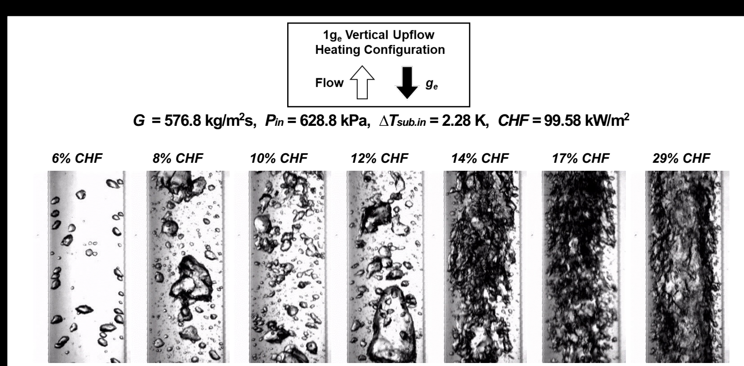
Flow Visualization Results: Ground Experiments

Two-phase flow patterns for 1g_e vertical upflow



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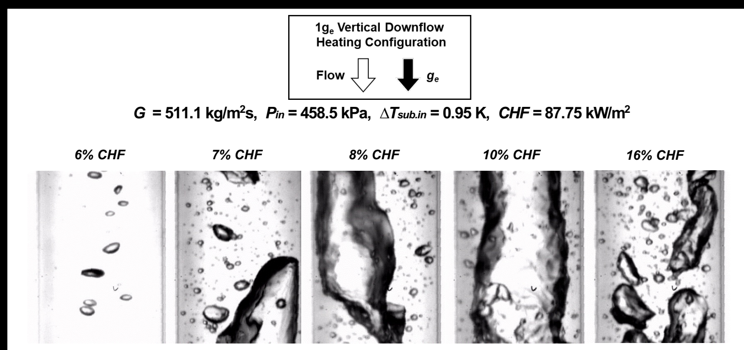
Flow Visualization Results: Ground Experiments

NASA

Two-phase flow patterns for $1g_e$ vertical downflow



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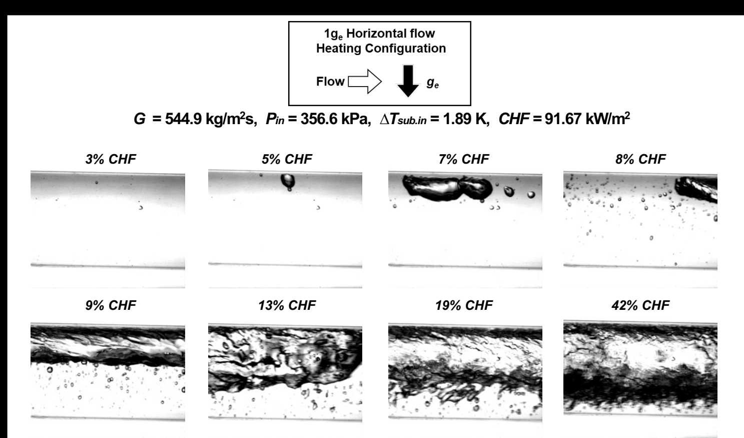
Flow Visualization Results: Ground Experiments

NASA

Two-phase flow patterns for $1g_e$ horizontal flow



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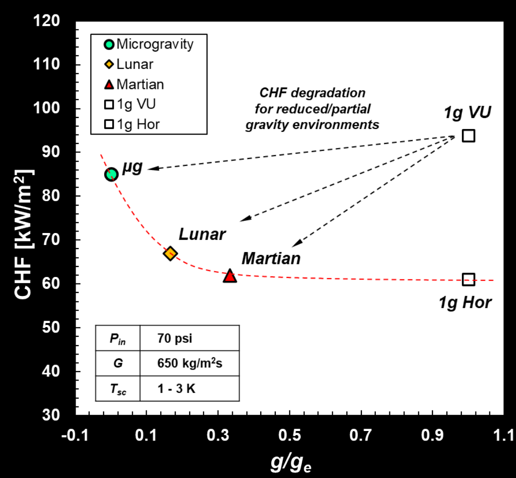
Gravitational Effect on Cryogenic CHF



Gravitational effect on CHF for Low G

- Order of CHF:
  1g VU > μg > Lunar > Martian > 1g Hor
- Compared to 1g VU, CHF for reduced gravity always smaller
- 1g VU benefited most from effective vapor removal assisted by buoyancy force
- Compared to 1g Hor, CHF for reduce gravity always larger
- 1g Hor most susceptible to stratification due to normal buoyancy force vector

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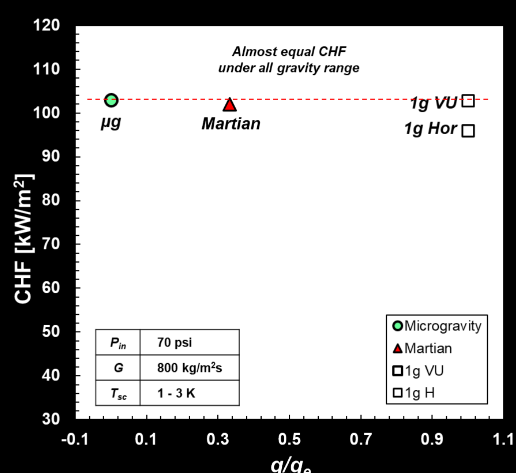
Gravitational Effect on Cryogenic CHF



At high G

CHF independent of gravity!

Gravitational effect on CHF for high G

- CHF measured to be almost the same among any gravitational environments
- With strong flow inertia, effect of gravity is overridden, fading out CHF differences
- Even among 1g VU and 1g Hor, CHF difference is minimal

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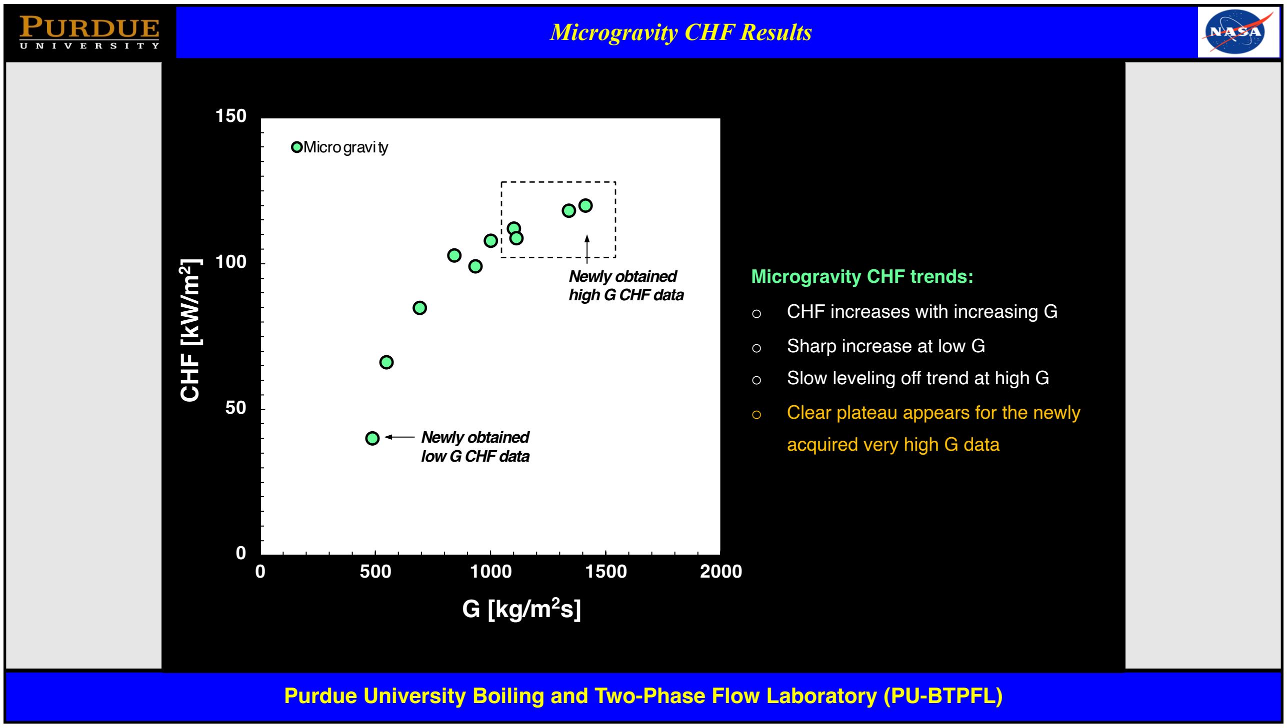
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Microgravity CHF Results
NASA
150
100
50
0
CHF [kW/m^2]
0
500
1000
1500
2000
G [kg/m^{2}s]
Microgravity
Newly obtained high G CHF data
Newly obtained low G CHF data
Microgravity CHF trends:
CHF increases with increasing G
Sharp increase at low G
Slow leveling off trend at high G
Clear plateau appears for the newly acquired very high G data
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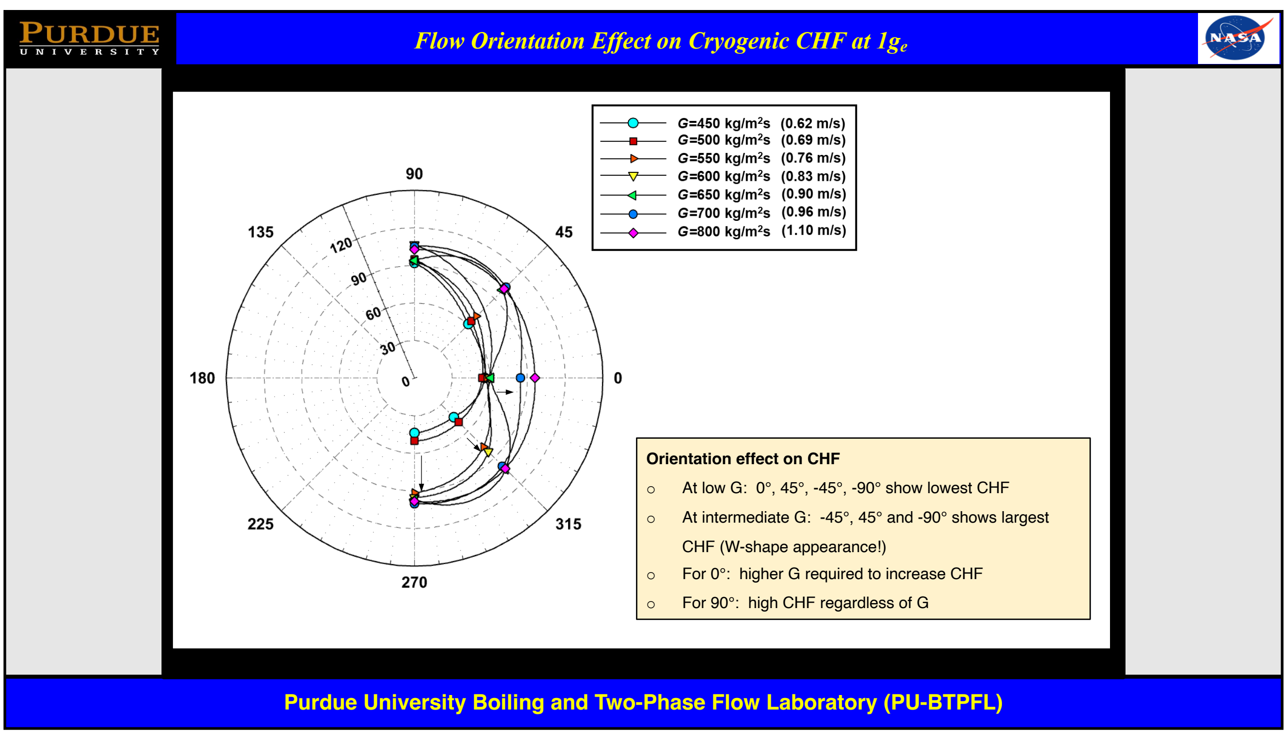
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Flow Orientation Effect on Cryogenic CHF at 1g_e
NASA
G=450 kg/m^{2}s (0.62 m/s)
G=500 kg/m^{2}s (0.69 m/s)
G=550 kg/m^{2}s (0.76 m/s)
G=600 kg/m^{2}s (0.83 m/s)
G=650 kg/m^{2}s (0.90 m/s)
G=700 kg/m^{2}s (0.96 m/s)
G=800 kg/m^{2}s (1.10 m/s)
90
135
45
180
0
225
315
270
120
90
60
30
0
Orientation effect on CHF
At low G: 0°, 45°, -45°, -90° show lowest CHF
At intermediate G: -45°, 45° and -90° shows largest CHF (W-shape appearance!)
For 0°: higher G required to increase CHF
For 90°: high CHF regardless of G
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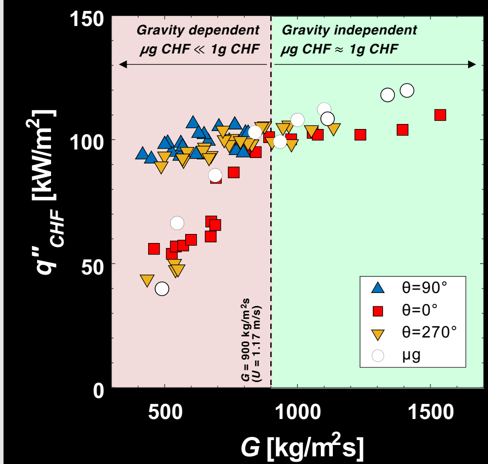
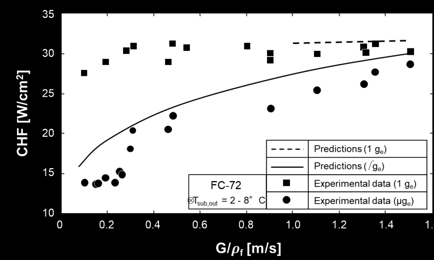
Body Force Effect on CHF





CHF trend

- Body force effect on CHF
  - → *Microgravity CHF << 1g vertical upflow CHF*
  - → *Gravity independent for G > 900 kg/m²s*

Significance for space missions

1. Avoid extreme low mass velocity operation
2. If necessary, consider low CHF limit for two-phase system design
3. Gravity independence system can be achieved above G of 900 kg/m²s

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Challenges During Flight Campaign

- **Test rig far more complex than all our prior parabolic flight rigs**
- **Unexpected flight day delays and cancellations**
- **Unusual delays acquiring parts from vendors**
- **Parabolic flight database limited by expendable mass of LN_2 from Dewar. Possible long-term solution is to employ a separate rig containing multiple Dewars!**

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Undergraduate Student Involvement

10 Seniors completed design projects as part of Mechanical Engineering Capstone Senior Design course ME463, including:

- Assisting with CAD design of heat transfer and flow visualization modules
- CAD Design of test rig
- Detailed structural design of test rig
- CAD design of rotation platform for terrestrial experiments at different flow orientations
- Construction of rotation platform
- Assistance with pre-flight tests

5 Juniors and Sophomores completed undergraduate research projects, including:

- Assisting with CAD design of heat transfer and flow visualization modules
- Construction of heat transfer and flow visualization modules
- Modifying CAD design for improved integration of heat transfer and flow visualization modules

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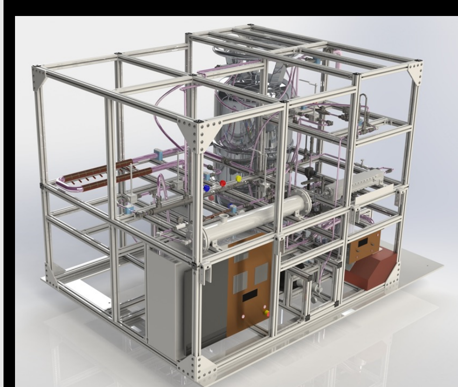
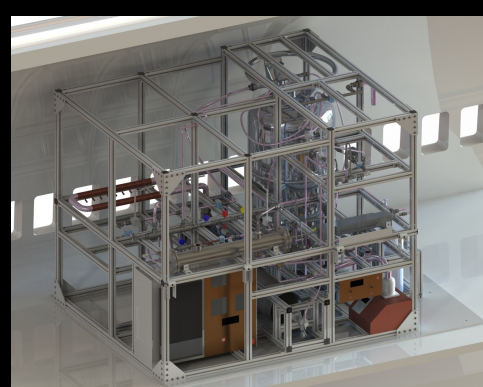
Undergraduate Student Involvement

CAD of Test Rig

Ground View



In Flight View



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Undergraduate Student Involvement

CAD of Test Rig with Rotating Platform

Rotating platform is being used to conduct terrestrial experiments at different flow orientations

Assembled Rotating Platform

Assembled Test Rig with Rotating Platform

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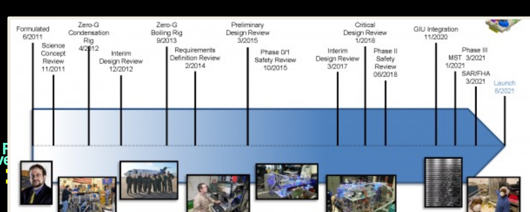
Other NASA Grants

"Flow Boiling and Condensation Experiment (FBCE)," 2012-2024, Mudawar, PI

- FBCE is NASA's largest and most complex flow boiling and flow condensation facility constructed to date for microgravity tests on the ISS
- Initiated in 2011
- Applications include Rankine Power Cycle, thermal control system (TCS) for space vehicles, vapor compression system for Lunar and Martian habitats
- Aims to develop empirical, theoretical, and CFD models for microgravity flow boiling and flow condensation
- Transported to the ISS in 2021
- First phase (boiling portion) of experiments successfully completed in July 2022



NASA F … y Heat Tra … Receive …

- … d gravity on spr …

NASA STTR Phase II (Purdue Research Park): "Heat Transfer Correlations for Complete Cryogenic Pool Boiling Curve," 2022-2024, Michael Meyer, PI

- Phase I completed in 2022
- Phase II involves obtaining data in $1g_e$ and developing new correlations for all regimes and transition points of the boiling curve
- Will take advantage of the spray cooling flight rig to obtain reduced gravity pool boiling data during possible STTR II-E study

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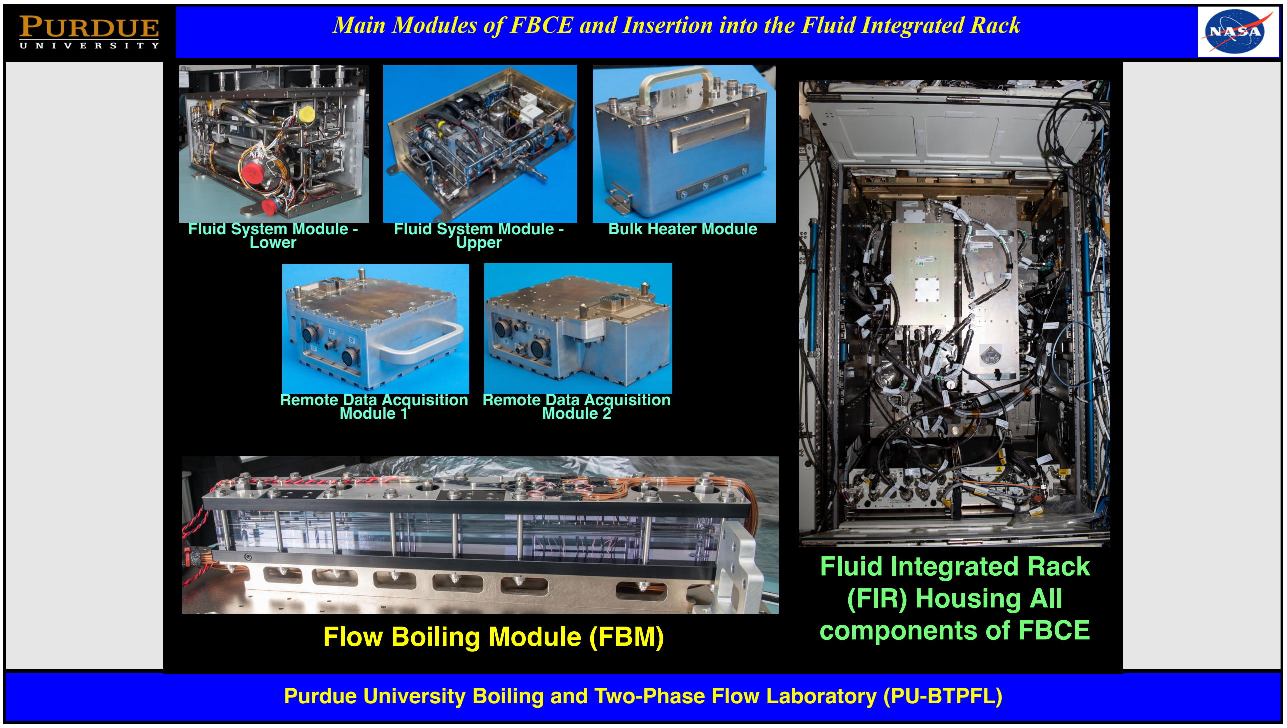
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Main Modules of FBCE and Insertion into the Fluid Integrated Rack
NASA
Fluid System Module - Lower
Fluid System Module - Upper
Bulk Heater Module
Remote Data Acquisition Module 1
Remote Data Acquisition Module 2
Flow Boiling Module (FBM)
Fluid Integrated Rack (FIR) Housing All components of FBCE
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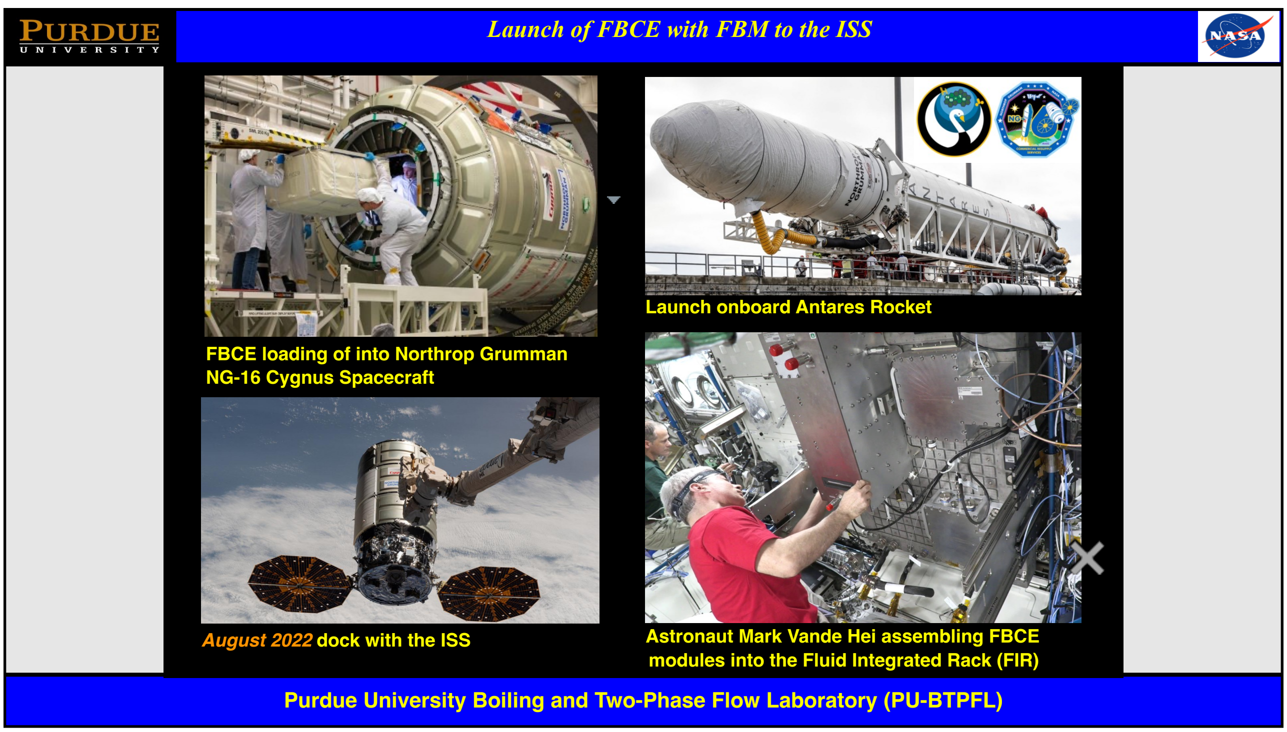
PURDUE UNIVERSITY
Launch of FBCE with FBM to the ISS
NASA
FBCE loading of into Northrop Grumman NG-16 Cygnus Spacecraft
Launch onboard Antares Rocket
August 2022 dock with the ISS
Astronaut Mark Vande Hei assembling FBCE modules into the Fluid Integrated Rack (FIR)
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)

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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*
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: $g_{n,1} = g_{n,2} = \mu g_e \cong 0$ ➡ $\lambda_c = \dfrac{2\pi\sigma(\rho''_f + \rho''_g)}{\rho''_f \rho''_g (U_g - U_f)^2}$

Mean pressure difference across wetting front

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

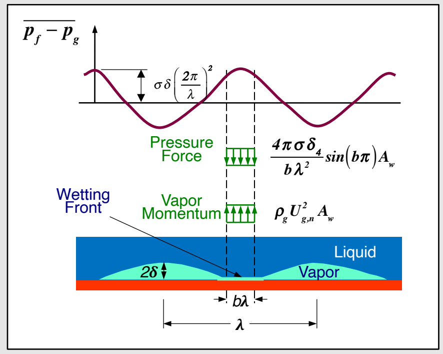
where b = 0.20 is ratio of wetting front length to wavelength

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

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

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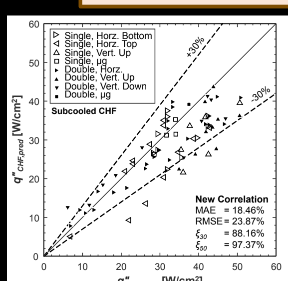
New CHF Correlation

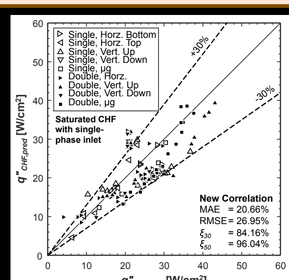
New CHF Correlation Developed using Large Consolidated FBCE Flow Boiling Database

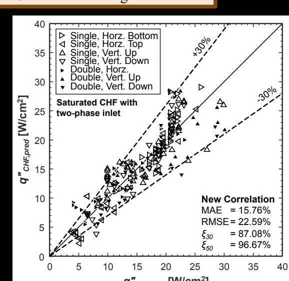
$$Bo_{CHF} = 0.353 We_{D_e}^{-0.314}\left(\frac{L_h}{D_e}\right)^{-0.226}\left(\frac{\rho_f}{\rho_g}\right)^{-0.481}\left(1 - \left(\frac{\rho_f}{\rho_g}\right)^{-0.094} x_{e,in}\right)\left(1 + 0.034\frac{1}{Fr_{\theta,D_e}}\right)\left(1 + 0.008\frac{Bd_{\theta,D_e}}{We_{D_e}^{0.543}}\right)$$

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

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%**

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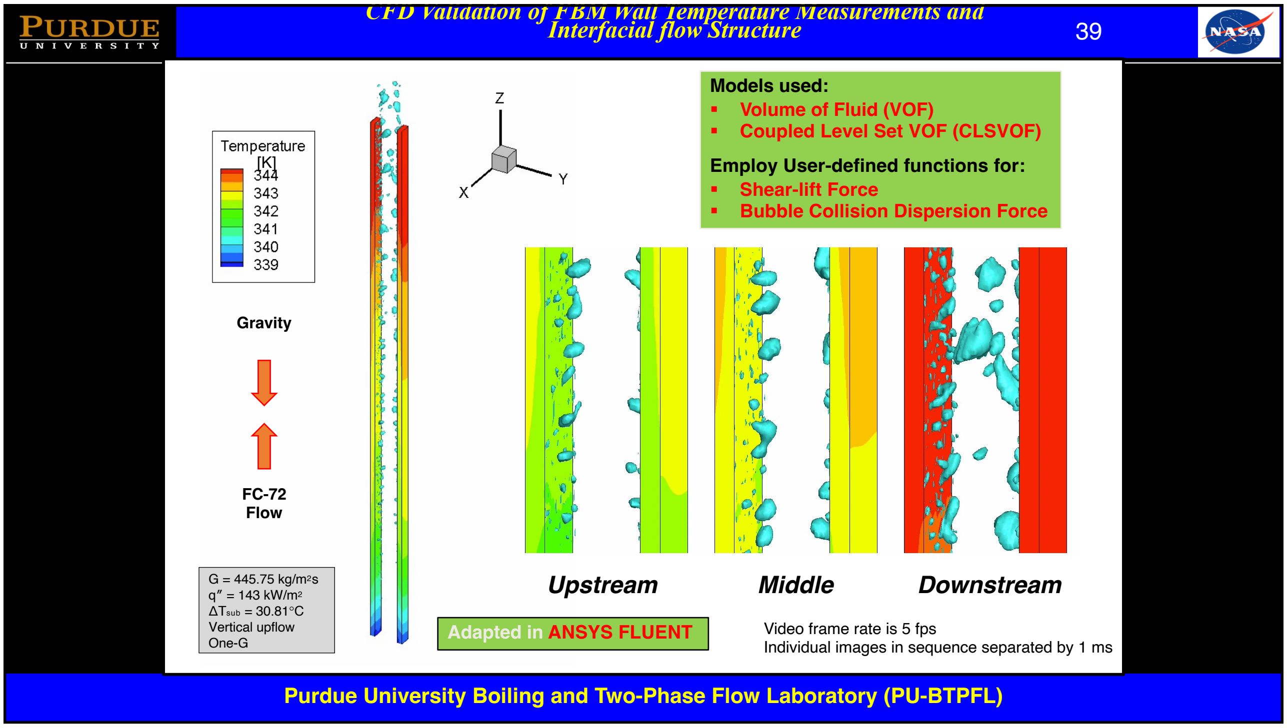
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CFD Validation of FBM Wall Temperature Measurements and Interfacial flow Structure
39
NASA
Temperature [K]
344
343
342
341
340
339
Gravity
FC-72 Flow
G = 445.75 kg/m²s
q″ = 143 kW/m²
ΔTsub = 30.81°C
Vertical upflow
One-G
Z
X
Y
Models used:
Volume of 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
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)

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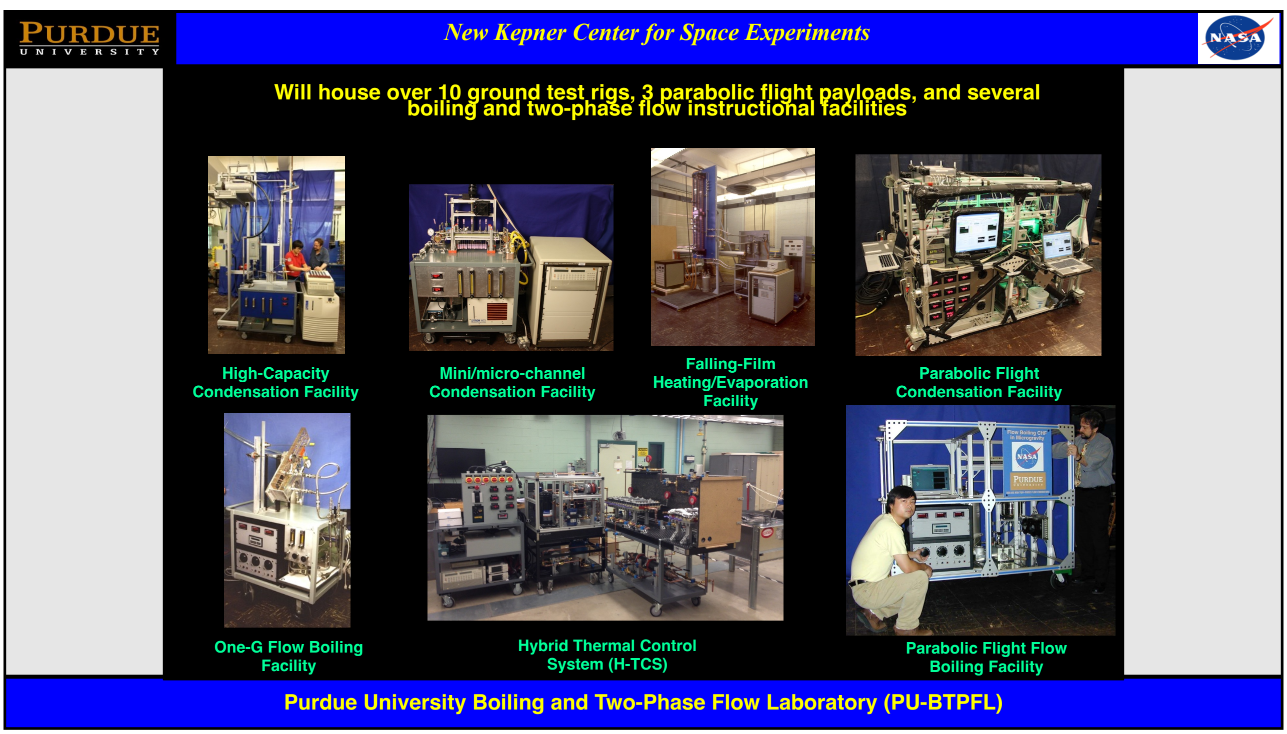
PURDUE UNIVERSITY
New Kepner Center for Space Experiments
NASA
Will house over 10 ground test rigs, 3 parabolic flight payloads, and several boiling and two-phase flow instructional facilities
High-Capacity Condensation Facility
Mini/micro-channel Condensation Facility
Falling-Film Heating/Evaporation Facility
Parabolic Flight Condensation Facility
One-G Flow Boiling Facility
Hybrid Thermal Control System (H-TCS)
Parabolic Flight Flow Boiling Facility
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)

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Journal Publications

Findings from FBCE project, both flow boiling and flow condensation, and both terrestrial and microgravity, have been published by Purdue in over 80 journal articles, majority in *International Journal of Heat & Mass Transfer*

Publications based on tube flight experiments

1. S. Kim, J. Lee, I. Mudawar, J. Hartwig, Computational investigation of vertical upflow boiling of liquid nitrogen and effects of bubble collision dispersion force, *Int J Heat Mass Transf* 203 (2023) 123780.
2. S. Kim, N. Damle, I. Mudawar, J. Hartwig, Cryogenic flow boiling in microgravity: effects of reduced gravity on two-phase fluid physics and heat transfer, *Int J Heat Mass Transf* 218 (2024) 124751.
3. S. Kim, D. Foster, N. Damle, I. Mudawar, J. Hartwig, Experimental investigation of flow orientation effects on cryogenic flow boiling, *Int J Heat Mass Transf* 220 (2024) 124940.
4. S. Kim, S. Darges, J. Hartwig, I. Mudawar, Assessment and development of saturated and subcooled heat transfer coefficient correlations for cryogenic flow boiling in tubes, *Int. J. Heat and Mass Transf* 224 (2024) 125297
5. S. Kim, N. Damle, J. Hartwig, I. Mudawar, Experimental heat transfer results and flow visualization of horizontal near-saturated liquid nitrogen flow boiling in uniformly heated circular tube under earth gravity, *Appl Therm Eng* 246 (2024) 122934.
6. S. Kim, J. Hartwig, I. Mudawar, Computational fluid dynamics simulation of cryogenic vertical upflow boiling under terrestrial gravity, *Appl Therm Eng*, in review.
7. S. Kim, N. Damle, D. Foster, J. Hartwig, I. Mudawar, Gravitational Effects on critical heat flux of cryogenic flow boiling, in preparation.

Mudawar and Hartwig would be happy to share within NASA the cryogenic data acquired during the parabolic flight experiments

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

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Mudawar Team's World Rankings

Clarivate ISI **(formerly Thomson Reuters):**

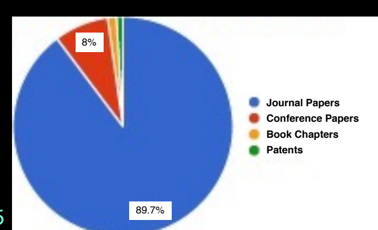
- Highly Cited Researcher since 2015

Google Scholar (5/4/2024):

- 33,900 citations, h-index: 106
- World rankings: Flow Boiling #1, Spray Cooling #1, Microchannels #1, Microgravity Boiling #1, Electronics Cooling #3

ScholarGPS (5/4/2024):

- Highly Ranked Scholar
  Lifetime:
- 32,820 citations, h-index: 107
- World Rankings: Heat sink #1, Boiling #3, Heat Transfer #5, Electronic Packaging #6
  Five Year:
- World Rankings: Boiling: #1, Condensation: #5



Exaly (5/4/2024):

- Most cited author in ***International Journal of Heat and Mass Transfer***

AD Science Index (5/7/2024):

- Most cited author in Purdue's School of Mechanical Engineering

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

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Purdue's just announced Space Engineering Certificate

- **Provides Purdue undergraduate students with an opportunity to acquire documented educational experiences in space engineering**
- **16-credit certificate guides students through their choice of topics within the vast collections of topics that make up space exploration, space power, space commerce, space communications, space life support and habitation, and space policy**
- **Provides opportunities for undergraduate students to actively participate in research projects alongside graduate students**
- **Benefits the Nation by better preparing Purdue undergrads for careers in space engineering**

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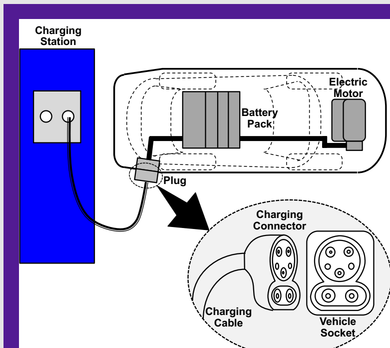
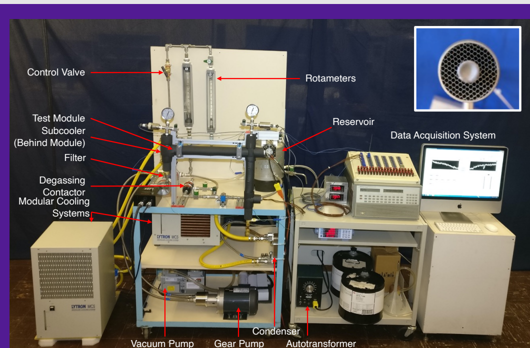
Ultra-Fast Charging of Electric Vehicles (EVs)





- **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**

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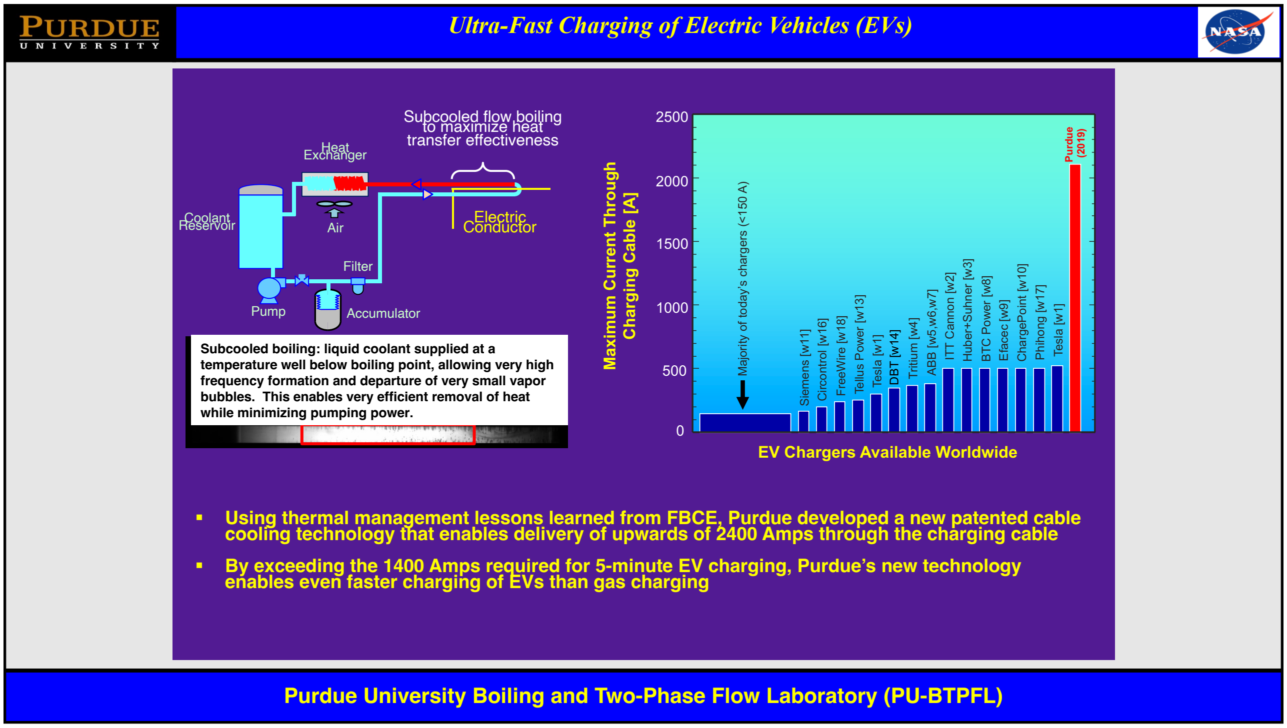
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Ultra-Fast Charging of Electric Vehicles (EVs)
NASA
Subcooled flow boiling to maximize heat transfer effectiveness
Heat Exchanger
Coolant Reservoir
Air
Electric Conductor
Filter
Pump
Accumulator
Subcooled boiling: liquid coolant supplied at a temperature 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]
2500
2000
1500
1000
500
0
Majority of today's chargers (<150 A)
Siemens [w11]
Circontrol [w16]
FreeWire [w18]
Tellus Power [w13]
Tesla [w1]
DBT [w14]
Tritium [w4]
ABB [w5,w6,w7]
ITT Cannon [w2]
Huber+Suhner [w3]
BTC Power [w8]
Efacec [w9]
ChargePoint [w10]
Phihong [w17]
Tesla [w1]
Purdue (2019)
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
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)

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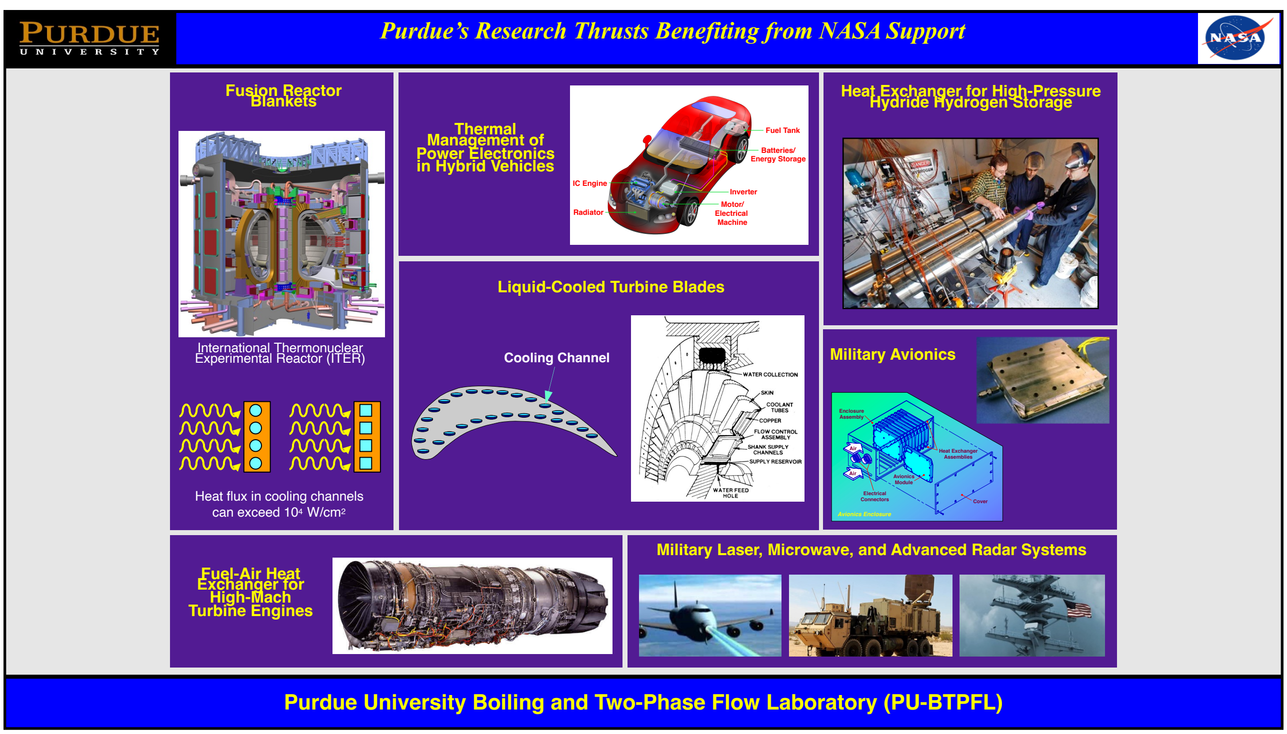
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Purdue's Research Thrusts Benefiting from NASA Support
NASA
Fusion Reactor Blankets
International Thermonuclear Experimental Reactor (ITER)
Heat flux in cooling channels can exceed 10⁴ W/cm²
Thermal Management of Power Electronics in Hybrid Vehicles
Fuel Tank
Batteries/ Energy Storage
IC Engine
Radiator
Inverter
Motor/ Electrical Machine
Heat Exchanger for High-Pressure Hydride Hydrogen Storage
Liquid-Cooled Turbine Blades
Cooling Channel
WATER COLLECTION
SKIN
COOLANT TUBES
COPPER
FLOW CONTROL ASSEMBLY
SHANK SUPPLY CHANNELS
SUPPLY RESERVOIR
WATER FEED HOLE
Military Avionics
Enclosure Assembly
Heat Exchanger Assemblies
Avionics Module
Electrical Connectors
Cover
Avionics Enclosure
Fuel-Air Heat Exchanger for High-Mach Turbine Engines
Military Laser, Microwave, and Advanced Radar Systems
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL)

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Value of Flight Opportunities Program to Cryogenic Research & Applications

NASA

1. **Absent ability to perform cryogenic fluid experiments onboard the ISS, parabolic flight experiments represent an essential means for study of transport behavior of cryogens in pursuit of data acquisition, and development of empirical correlations, theoretical models, and computational models for use in design of NASA's space systems**
2. **Parabolic flight experiments remain the most cost-effective means for investigating transport behavior of cryogens**
3. **Same parabolic flight rigs enables complementary investigation of transport behavior of cryogens in ground experiments for assessment of gravity effects**
4. **With additional hardware modifications, same parabolic flight rig can be used to investigate other transport mechanisms of cryogens, including pool boiling and spray cooling**

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NASA

Thank you!

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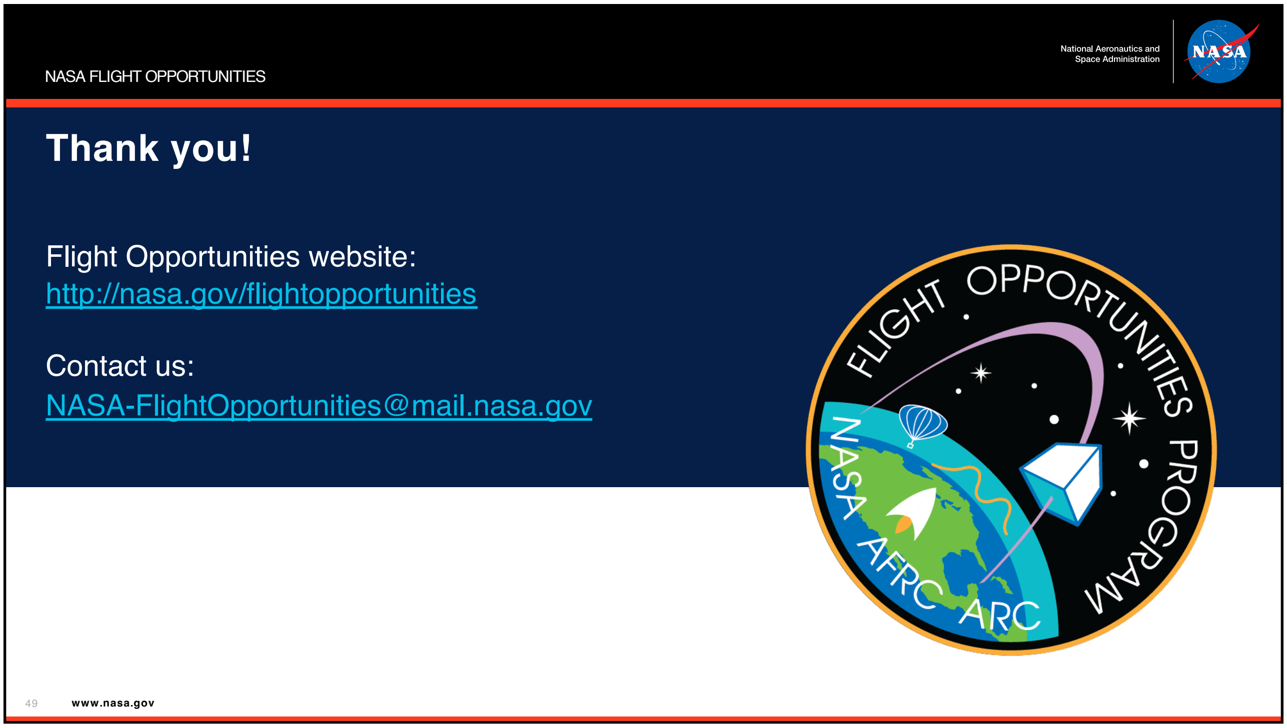
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National Aeronautics and Space Administration
Thank you!
Flight Opportunities website:
http://nasa.gov/flightopportunities
Contact us:
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NASA AFRC ARC
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www.nasa.gov

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