# Gravity Effects in Two-Phase Microgap Flow

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# Motivation

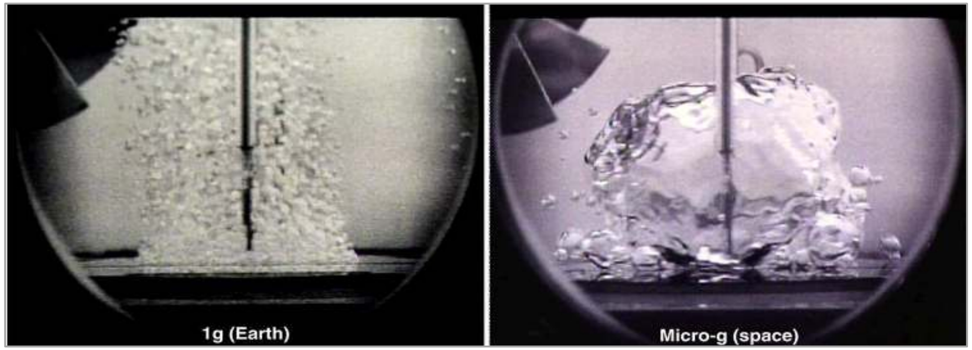
- Increasing power density of electronic devices necessitates better cooling
- Two-phase coolers: high flux heat removal, high efficiency, small temperature drop ($T^4$)
- Pumped loops offer longer transport distances and precise flow rate control

| NASA Thermal Technology Roadmap | |
|---|---|
| **Area** | **Needs** |
| High Flux Heat Acquisition with Constant Temperature | • High flux heat removal (1 MW/m$^2$)<br>• Tight temperature control (± 1 °C) |
| Micro-and Nano-scale Heat Transfer Surfaces | • Very high heat flux removal (10 MW/m$^2$)<br>• Small temperature gradients (< 20 °C) |
| Two-Phase Pumped Loop Systems | • Two-phase heat transport systems for large heat loads (e.g., power plants) |

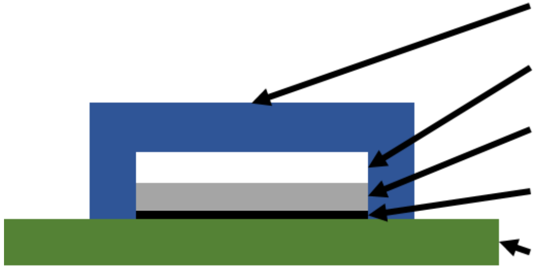
Swanson, Theodore and Motil, Brian. "NASA Technology Roadmaps TA 14: Thermal Management Systems." (2015). https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_14_thermal_management_final.pdf.

# Motivation

- Versatile coolers must work reliably in all orientations, microgravity, and high-g
- Microgap coolers balance performance and simplicity
- Absence of criteria for orientation- and gravity-independent performance



Dhir, Vijay and Warier, Gopinath. "Nucleate Pool Boiling eXperiment (NPBX)." (2018). https://www.nasa.gov/mission_pages/station/research/experiments/229.html.



Flow enclosure

Microgap channel

Heat-generating device

Solder and underfill

Printed circuit board

**Ground-based Testing**

Characterize parameters that govern thermofluid behavior

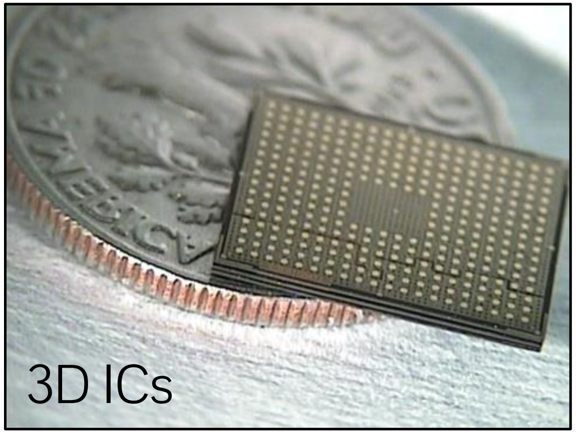
**Suborbital Flights**

Establish effects of microgravity and high-g environments

**Integration with Flight Projects**

Complete the technology maturation process

NASA, 2019



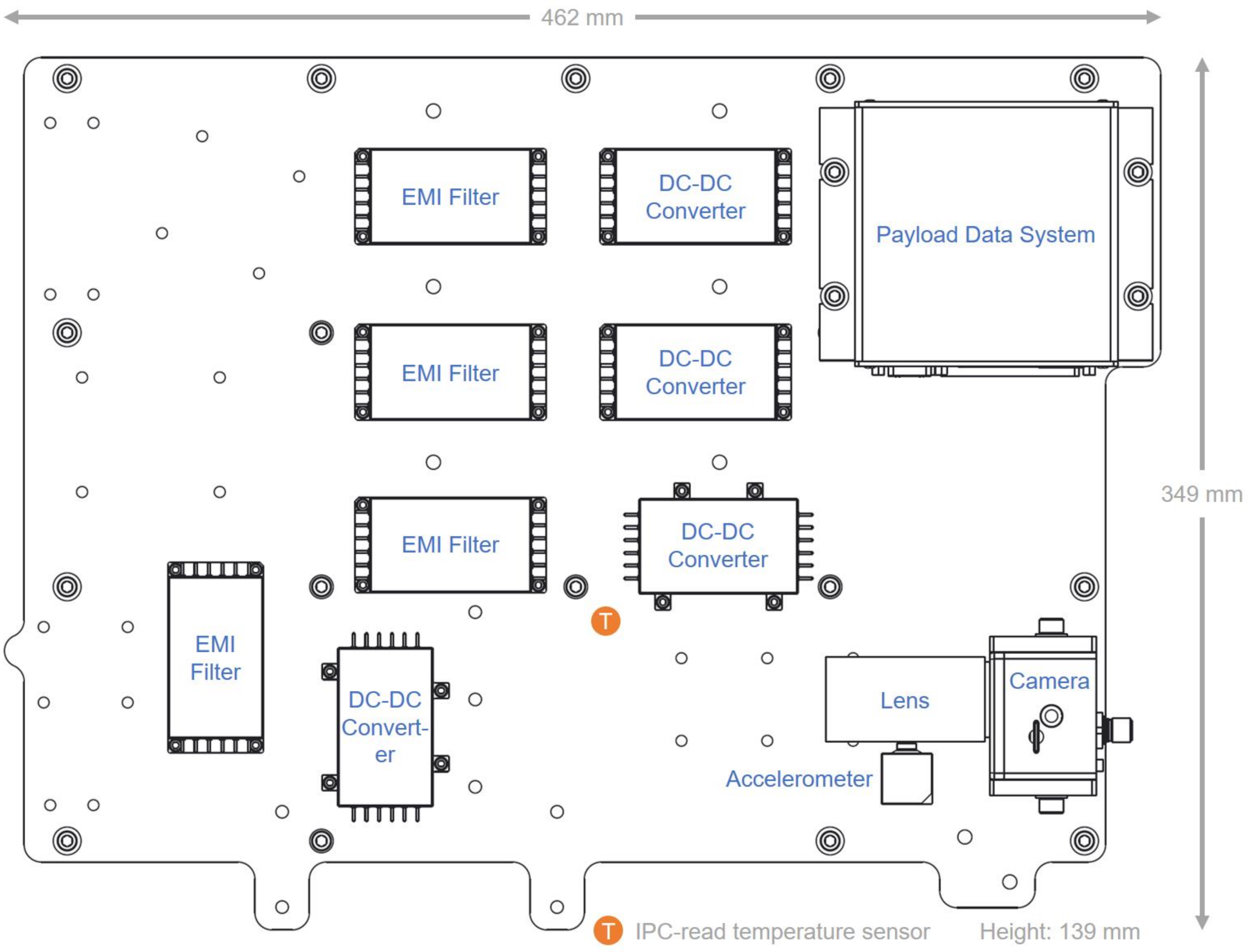
i3 Electronics, 2019

NASA/JPL-Caltech, 2017

# Blue Origin New Shepard

- Suborbital, reusable space vehicle
  - Vertical takeoff, vertical landing
  - 100+ km apogee
  - 150 seconds < 0.01 g
  - Plans for space tourism
- Single Payload Locker
  - 523 x 414 x 241 mm$^3$
  - 11.3 kg
  - 26 Vdc, 200 W
  - Integrated Payload Controller

Blue Origin, 2019


462 mm
349 mm
EMI Filter
DC-DC Converter
Payload Data System
EMI Filter
DC-DC Converter
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DC-DC Converter
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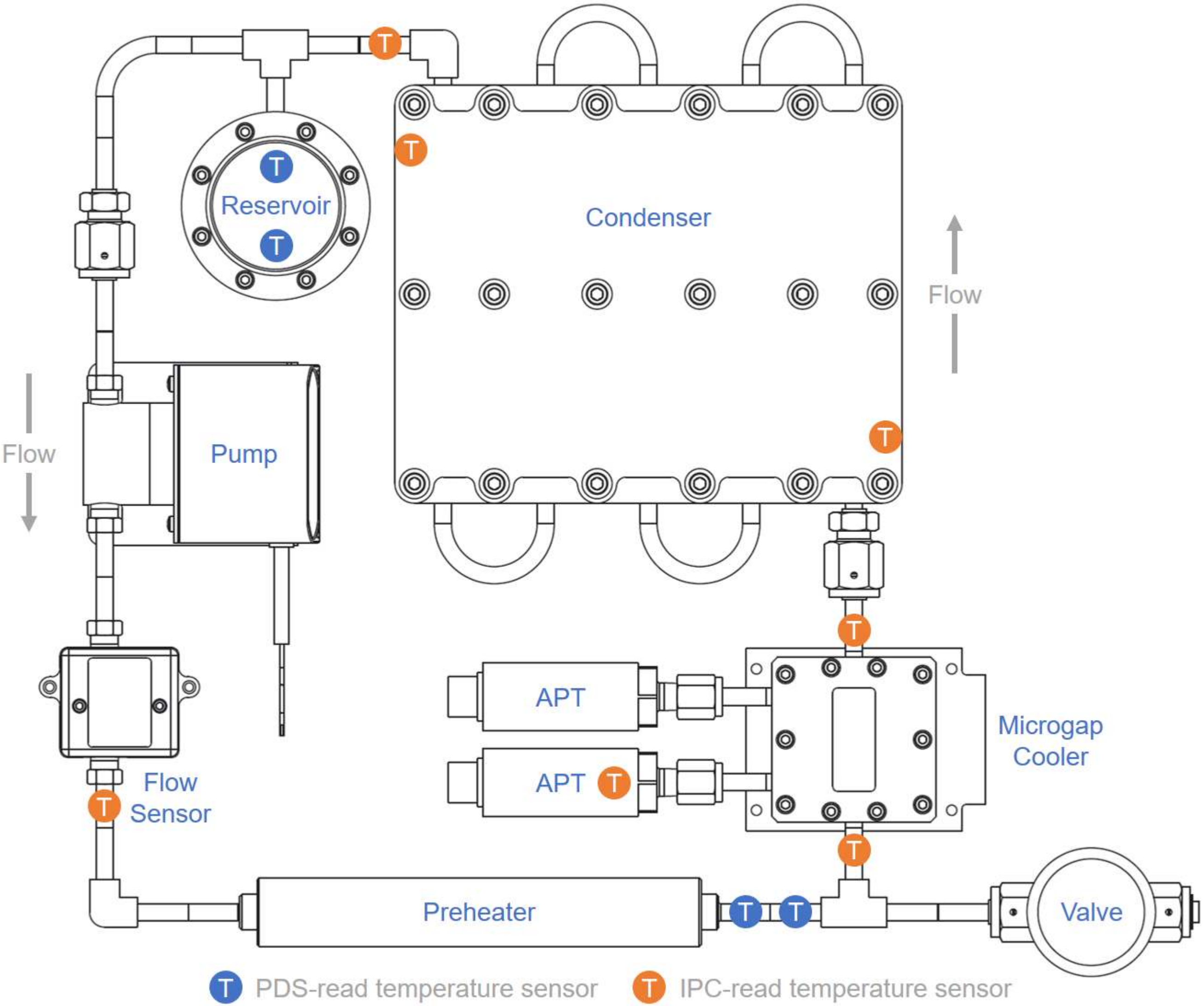
Camera
Accelerometer
T IPC-read temperature sensor
Height: 139 mm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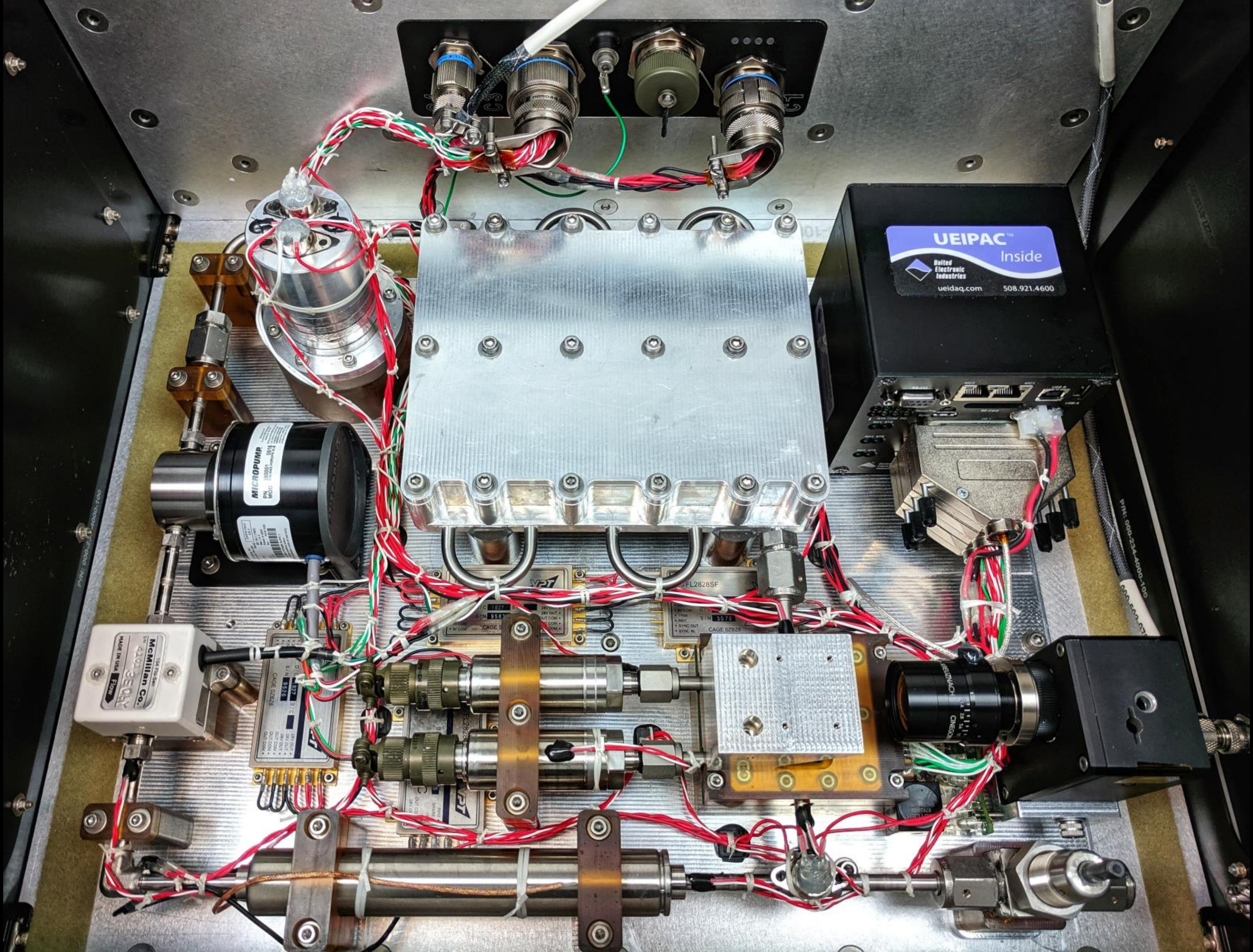
T IPC-read temperature sensor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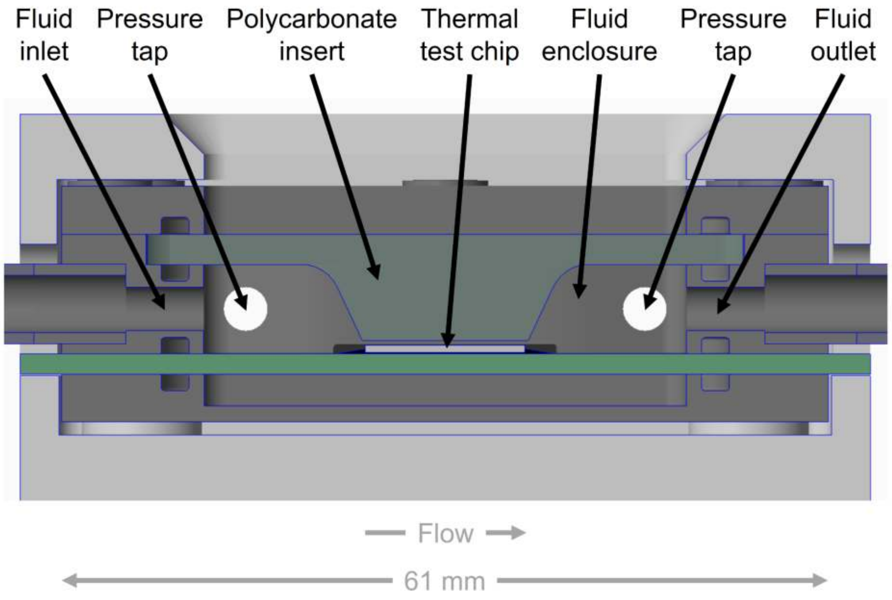
# Microgap Cooler

- 12.7 mm by 12.7 mm by 0.6 mm thermal test chip (TTC)
- 0.17 mm tall by 13.0 mm wide by 12.7 mm long channel
- Flow boiling of HFE7100
  - Heat flux: 142 kW/m$^2$
  - Mass flux: 509 kg/m$^2$-s
  - Saturation temperature: 50 °C
  - Inlet subcooling: 5 °C
  - Differential pressure: 5.9 kPa



Blue Origin, 2019

Blue Origin, 2019

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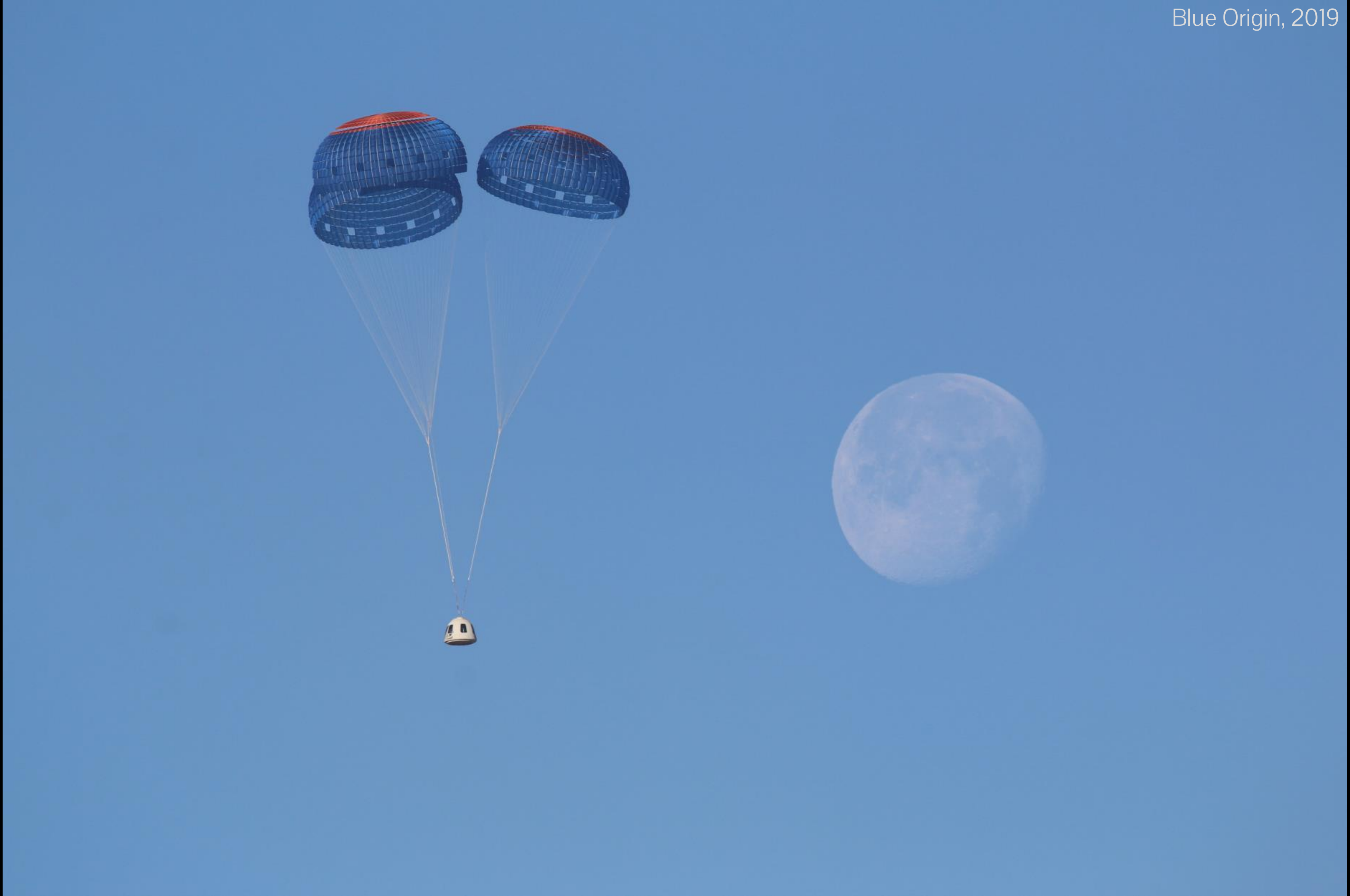
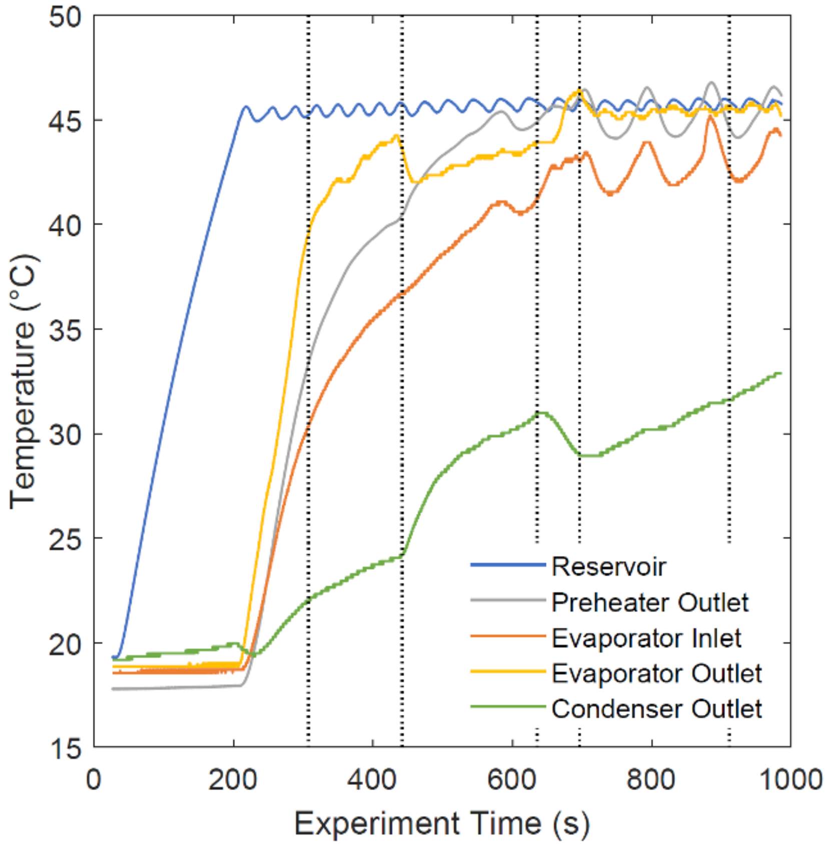


Blue Origin, 2019

Blue Origin, 2019

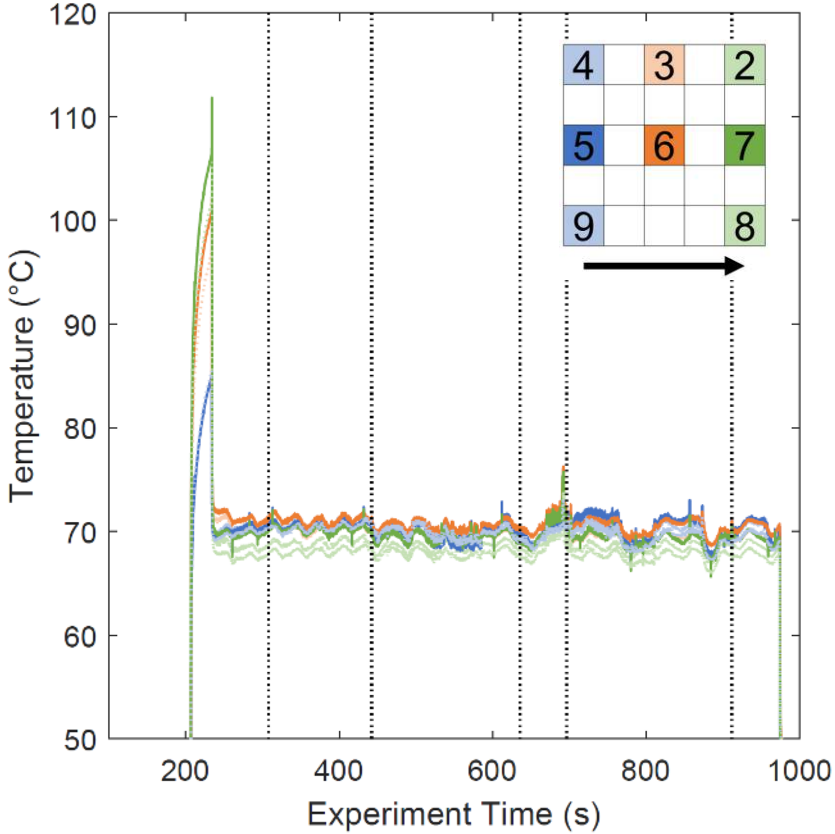
# Results – Fluid Temperatures

- Initial rapid increase in reservoir temperature
- After reservoir reaches set point, pump, preheater, and TTC enabled in succession
- Preheater reaches set point during microgravity coast
- Shutdown sequence initiated after landing



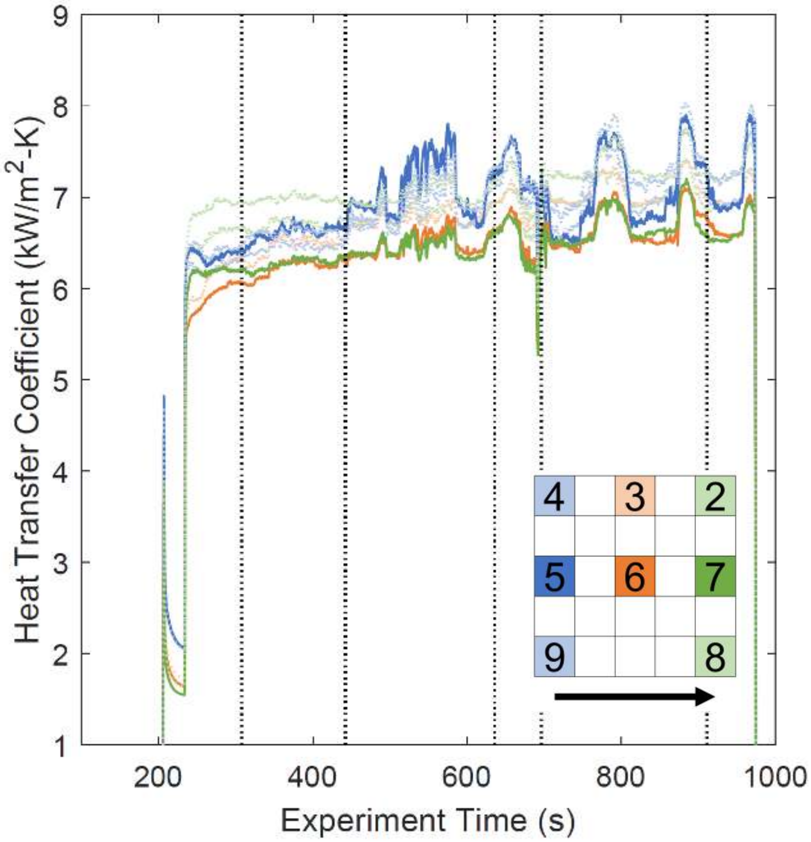
# Results – TTC Temperatures

- Rapid increase after TTC heater enabled
  - Single-phase liquid cooling
  - 21 °C gradient across TTC
- Dramatic drop after onset of boiling, prior to liftoff
  - 4 °C gradient across TTC
- Minor fluctuations throughout coast, descent, and landing linked to preheater control



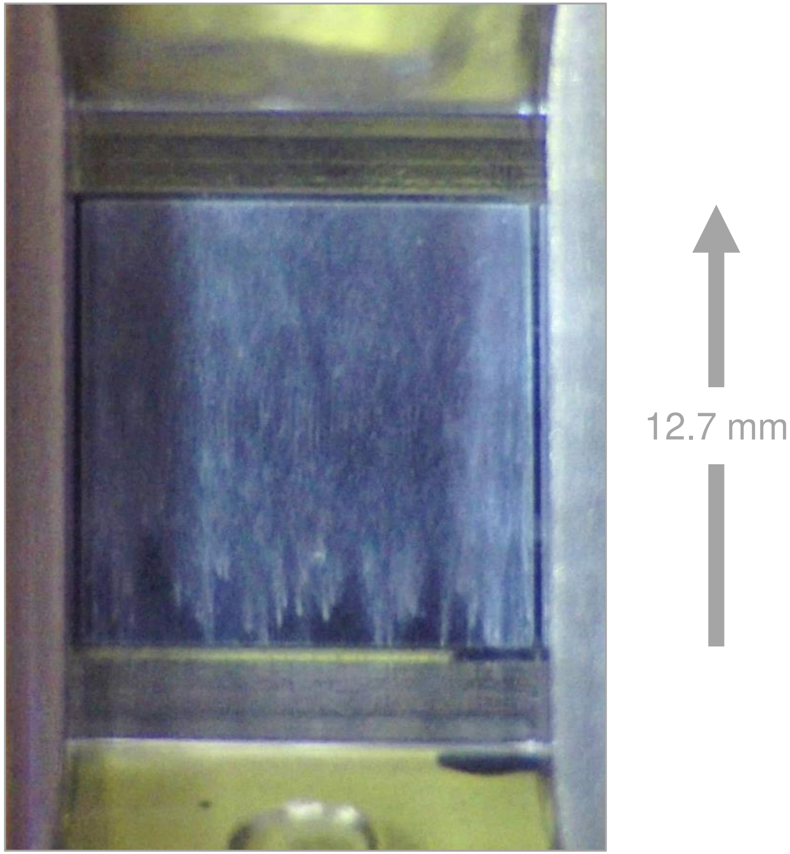
# Results – Heat Transfer Coefficients

- Single-phase variation due to developing flow
- Two-phase variation due to entrance and wall effects
  - Vapor enters inlet manifold during microgravity coast
  - Heat transfer coefficients spike when inlet temperature and/or quality increases
- No clear trends with gravity



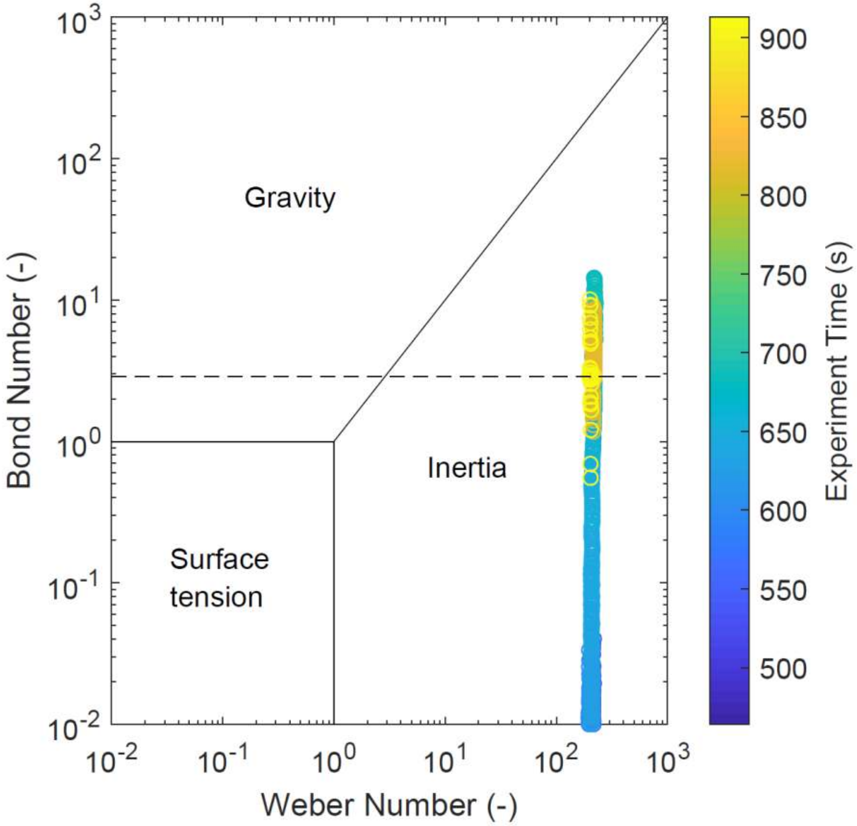
# Results – TTC Temperature Excursion

- Brief temperature excursion near end of high-g descent
- Likely caused by vapor collapsing at preheater outlet
    - Inlet pressure dropped, but outlet pressure was unchanged
    - Reduced flow through microgap
- Preheater vapor generation explained by Richardson number



# Results – Force Regime Map

- During flight, range of Bond numbers result from dynamic gravity environment
  - On ground, achieved through re-orienting the evaporator
- Flight and ground data agree with force regime map proposed by Reynolds et al.
- May need to account for three-dimensional accelerations



Reynolds, William, Saad, Michel, and Satterlee, Hugh. "Capillary Hydrostatics and Hydrodynamics at Low g." Technical Report No. LG-3. Stanford University, Stanford, CA. 1964.

# Summary and Conclusions

- Effect of gravitational acceleration on flow boiling of near-saturated HFE7100 in a 0.17 mm tall by 13.0 mm wide microgap channel was studied
  - Flow boiling provided much higher heat transfer coefficients and much smaller temperature gradients than liquid cooling
  - Despite modest mass flux of about 500 kg/m$^2$-s, gravitational acceleration had little effect on thermofluid behavior observed in microgap cooler
  - Dominant force regime maps calculated using formulations developed during ground tests predicted lack of gravity effects during flight

# Ongoing and Future Work

- Non-dimensional analysis of previously published research
- Three-dimensional analysis of suborbital flight accelerations
- Preparation for upcoming suborbital flight
  - Configuration changes: larger microgap height, reduced mass flux, lower preheater temperature set point, and wider field of view
  - Hardware upgrades: accelerometers, payload data system, and lighting

# Acknowledgments

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