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Investigations of Physical Processes in Microgravity Relevant to Space Electrochemical Power Systems

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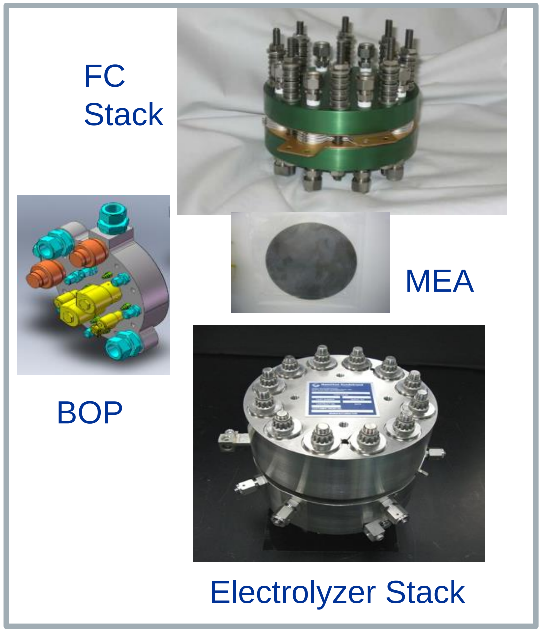
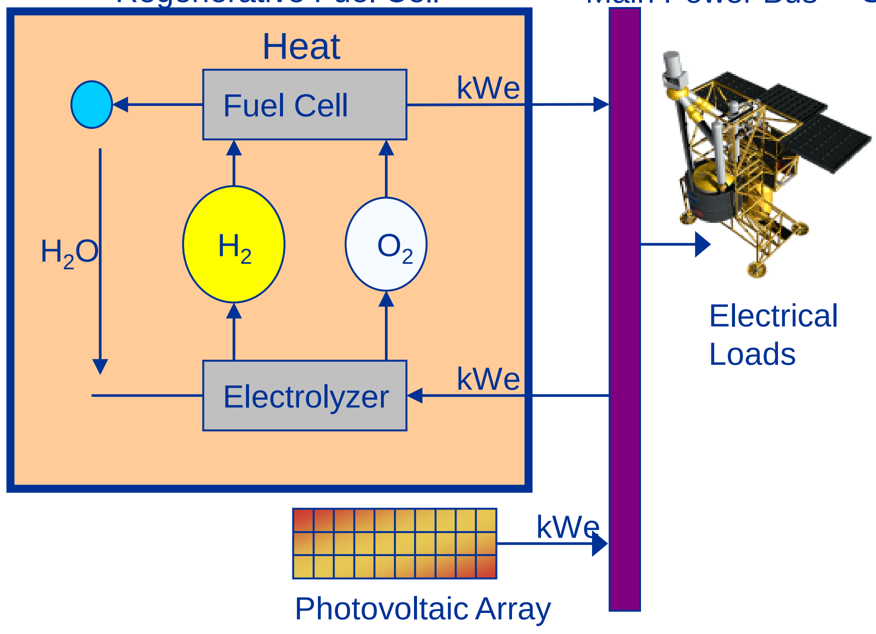
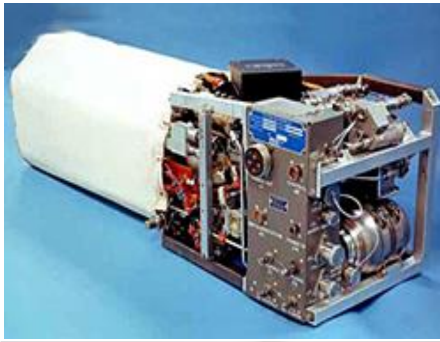
Regenerative Fuel Cells

Components developed to create system

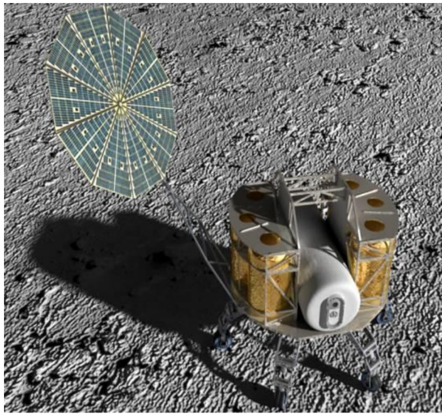




Shuttle Flow-Through Fuel Cell



Non-Flow-Through Fuel Cell

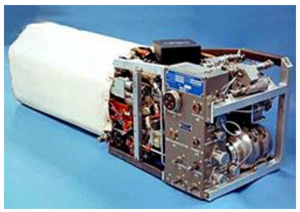


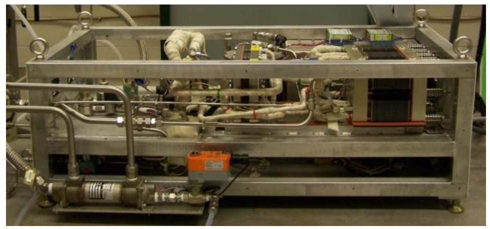
Regenerative Fuel Cell with Array

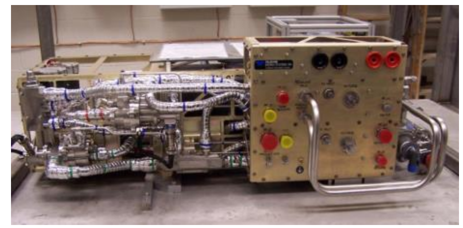
- Develop Components and Integrated Systems
  - kW-size Fuel Cell stacks with advanced water removal
  - Balanced-pressure passive liquid-feed, vapor-feed or hybrid Electrolyzer
  - Advanced MEAs for both Fuel Cells and Electrolyzers
  - Compact, efficient balance-of-plant components
  - Advanced manufacturing processes for high-pressure operation and reduced mass, volume and cost
  - Discrete Fuel Cell and Electrolyzer systems to optimize efficiency of each

NASA Fuel Cell Technology Progression

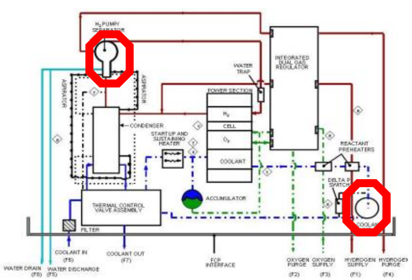
Johnson Space Center	Glenn Research Center	Glenn Research Center	Glenn Research Center
Shuttle “Active BOP” Alkaline	**“Active BOP” PEM**	**“Passive BOP” PEM**	**“Passive BOP” PEM**



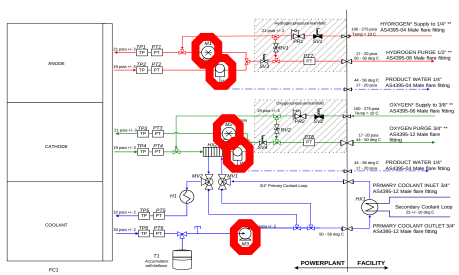




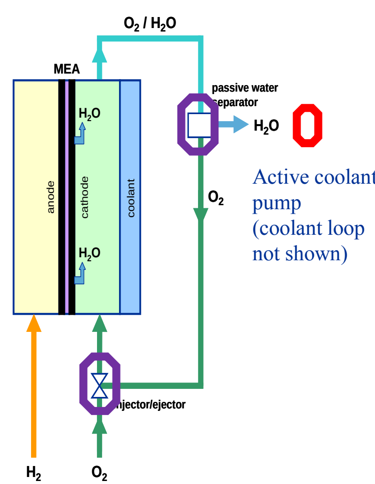
Flow-Through



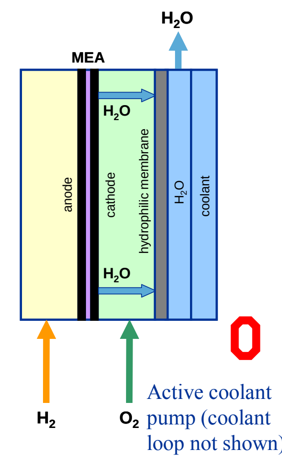
Flow-Through



Flow-Through



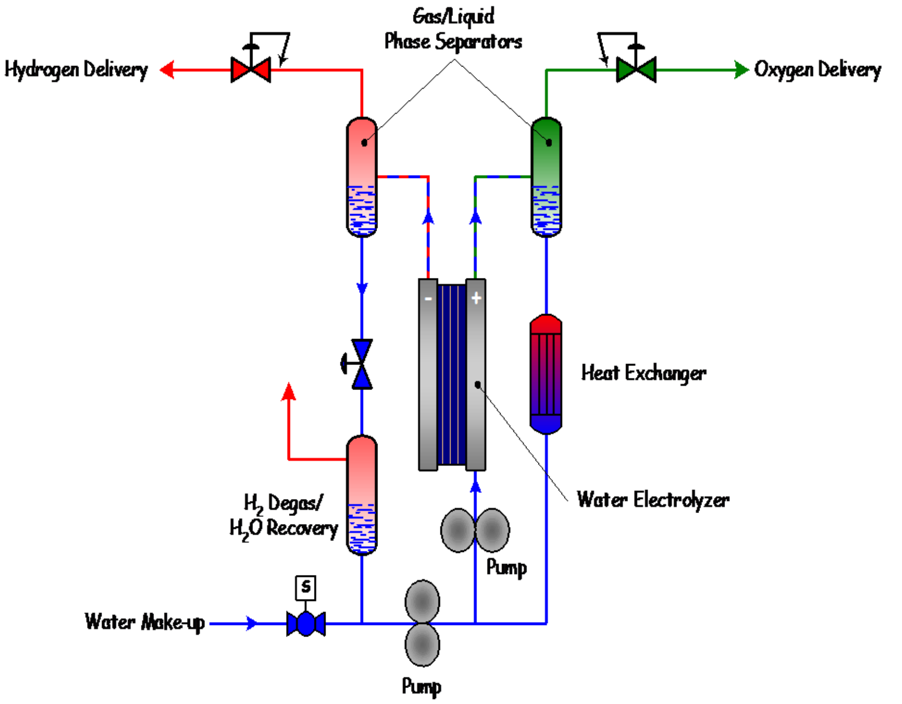
Non-Flow-Through

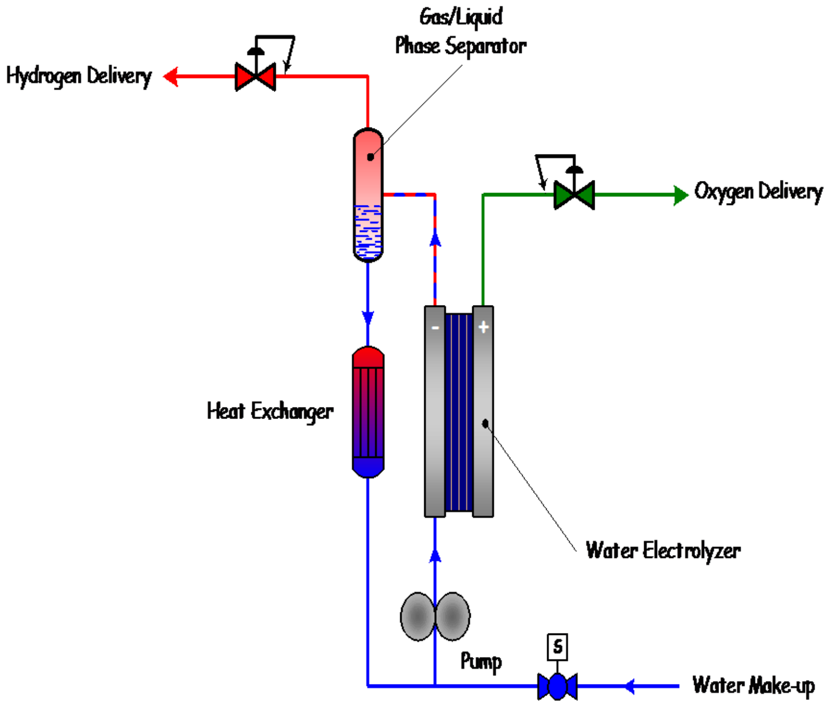


= **Active Mechanical Component (pump, active water separator)**

= **Passive Mechanical Component (injector/ejector, passive water separator)**

PEM Electrolysis Systems





Liquid water Anode Feed

- water fed on anode side, dragged to cathode side
- greatest electrical efficiency
- requires 2 phase separators, 2 pumps
- used by the Navy

Highest rate and efficiency; most complex

Liquid water Cathode Feed

- water fed on cathode side, diffuses to anode
- reduced electrical efficiency
- requires 1 phase separator, 1 pump
- used in OGA (ISS)

Lower rate, simpler system

Physical Science ISS Flight Experiments

- Space Fuel Cell and Electrolysis systems management require separation of gas/liquid multiphase streams in microgravity

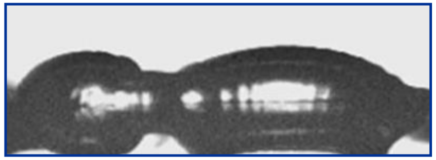
- In this section, we present a quick overview of results from 2 ISS Physical Science flight experiments
  - Involves multiphase flows (i.e. gas/liquid flows)
  - Has analogies to electrochemical work in microgravity
  - Demonstrates maturity level needed to develop electrochemical flight experiments of similar complexity

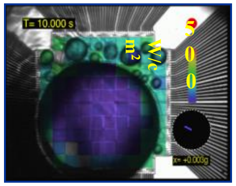
- Microgravity Fluid Physics discipline
  - Boiling and condensation experiment
    - MABE - Microheater Array Boiling Experiment
  - Capillary flows experiment
    - CCF – Capillary Channel Flow

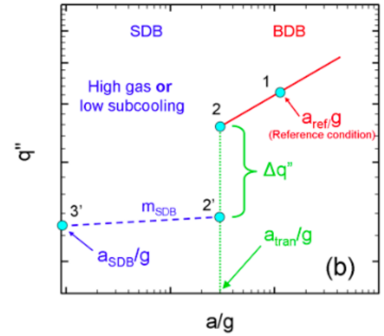
ISS Boiling Flight Experiments

Boiling e**X**periment **F**acility **(BXF) –** 2011

- BXF included two separate pool boiling investigations:
  - **M**icroheater **A**rray **B**oiling **E**xperiment **(MABE)**
  - **N**ucleate **P**ool **B**oiling **E**xperiment **(NPBX)**
- Improved understanding of local boiling heat transfer mechanisms & critical heat flux in microgravity for nucleate and transition pool boiling.
- Detailed measurements of bubble growth, detachment and subsequent motion of single and merged (larger) bubbles
- Developed a criteria for Boiling Transition
  - Buoyancy Dominated Regime (BDB)
    - Heat transfer by bubble growth and departure
    - Heat flux increases with gravity
  - Surface Tension Dominated Regime (SDB)
    - Dominated by the presence of a non-departing primary bubble
    - Effect of residual gravity is very small
  - Transition Criteria based on Capillary Length
- Enhanced the development of two-phase thermal management systems, which provide isothermal control with reduced radiator area and mass.
- Pool boiling studies are the first critical step to understanding flow boiling in 0-g.
- A combined condensation and <u>flow</u> boiling experiment is scheduled for 2018.







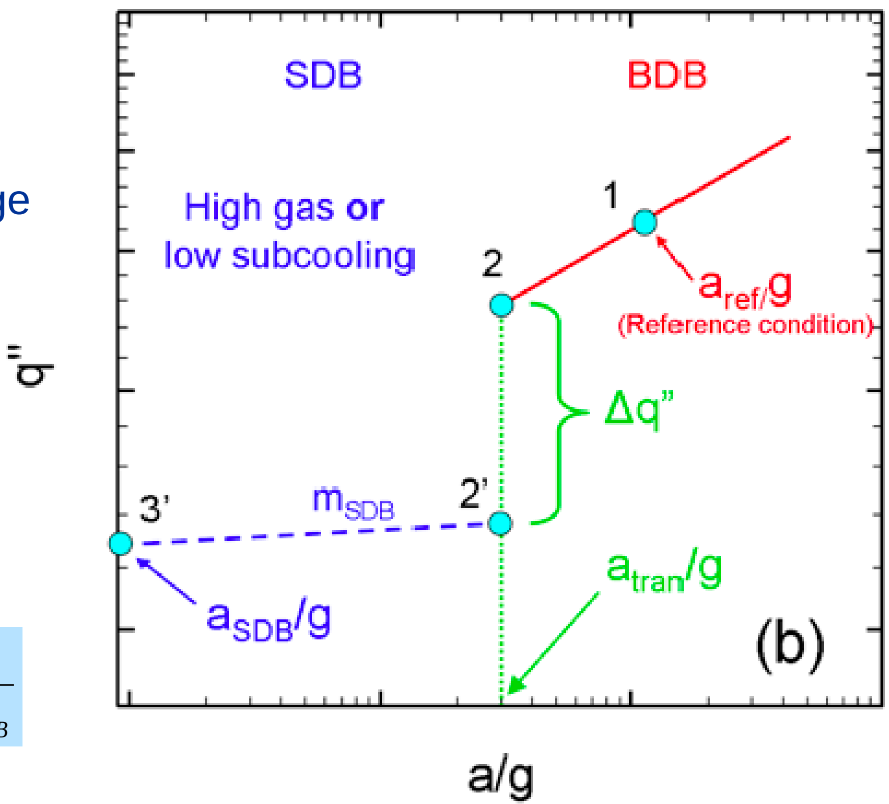
(Top) Paulo Nespoli installing BXF in MSG. (Middle left) Coalescence of vapor bubbles on NPBX wafer. (Middle right) Subcooled nucleate boiling in μg. The MABE microheater array is colorized with actual heat flux data. (Bottom) Transition of boiling Heat Flux as a function of acceleration

Key Result from MABE Flight Investigation: Heat Transfer Model for Varying g-levels

- Two regimes identified
  - Buoyancy Dominated Regime (BDB)
  - Surface tension Dominated Regime (SDB)
- Regime boundary characterized as a large "jump" and is defined by $L_h/L_c = 2.1$.
  - where L_h = width of square heater
  - and L_c = capillary length.
- Magnitude of jump requires further work.
- Slopes for SDB and BDB regimes:

$$m_{BDB} = \frac{0.65T^*}{(1+1.6T^*)}, \quad m_{SDB} = 0$$

$$T^* = \frac{T_W - T_{ONB}}{T_{CHF} - T_{ONB}}$$



Heat flux vs. gravitational acceleration for a given Temperature

Raj, Kim, & McQuillen, *Trans ASME*, 2012.

Boiling Curves Under Varying Gravity Conditions

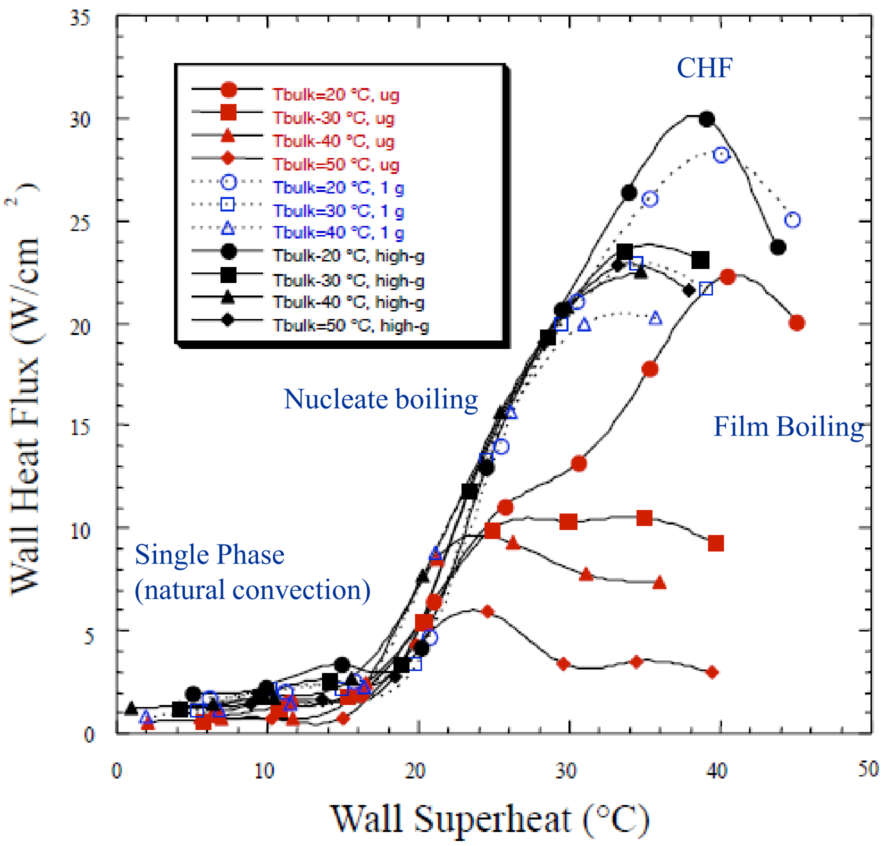
Key results from ground-based testing:

- Boiling in microgravity is possible.
- Bubble departure diameters in μg are greater than 1 g, but smaller than predictions
- CHF are also lower in μg than 1g but higher than correlations.

$$q = h(T_W - T_f)$$

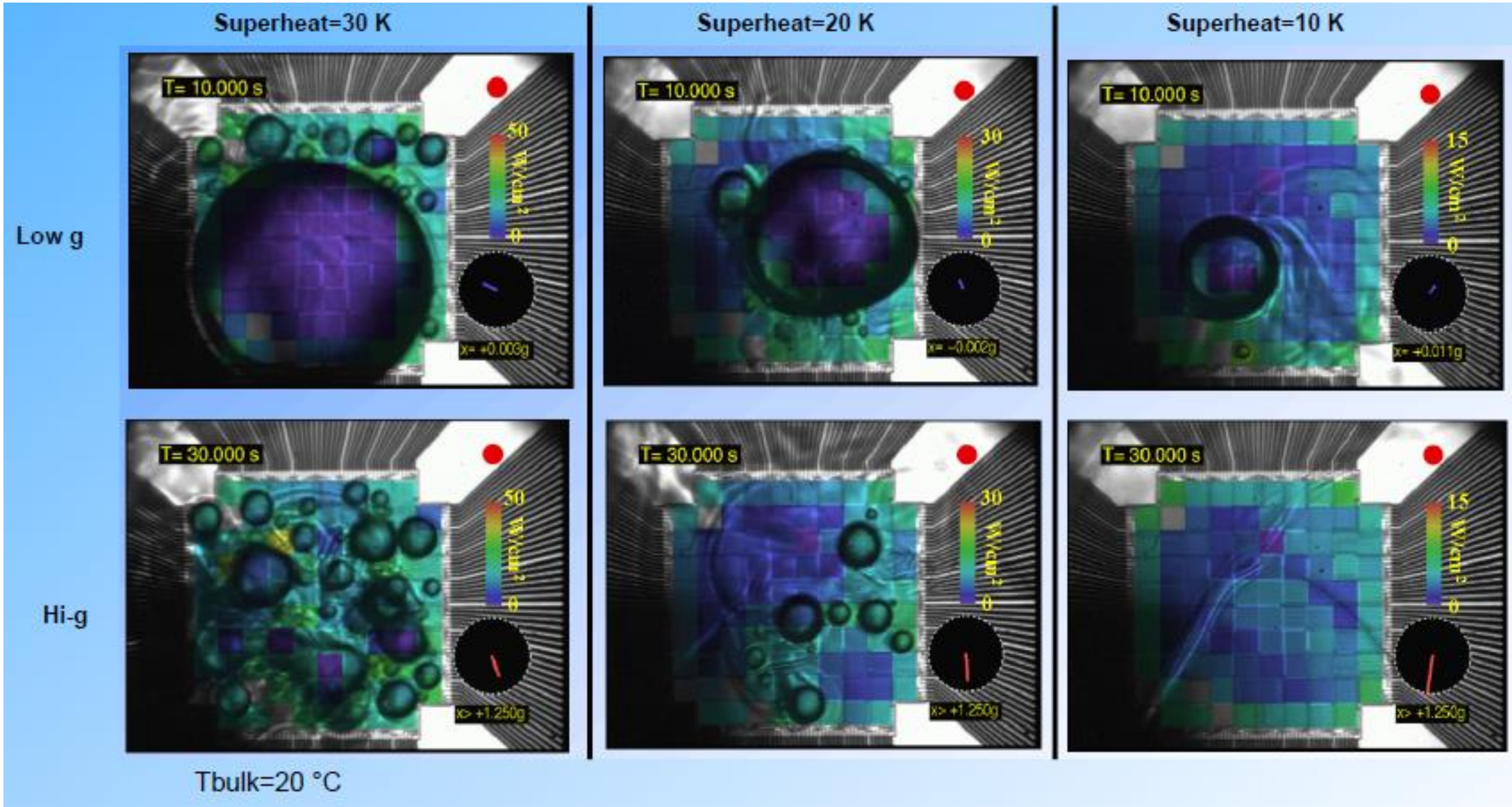
- Surface tension and contact angle affect boiling behavior.
- Bond number (Bo – relative strength of body forces to surface tension) alone cannot be used for correlations (regime indicator).

$$Bo = \frac{(\rho_L - \rho_V) a L^2}{\sigma}$$



Compendium of ground-based test results by Kim, Univ. of Maryland

Example Boiling Results in Low and High-g Conditions



Capillary Channel Flow Experiments on the ISS

ESA PI: Prof. Michael Dreyer, ZARM
Co-I: Prof. Mark Weislogel, Portland State University
PM: Robert Hawersaat, NASA GRC
PS: Robert Green, NASA GRC

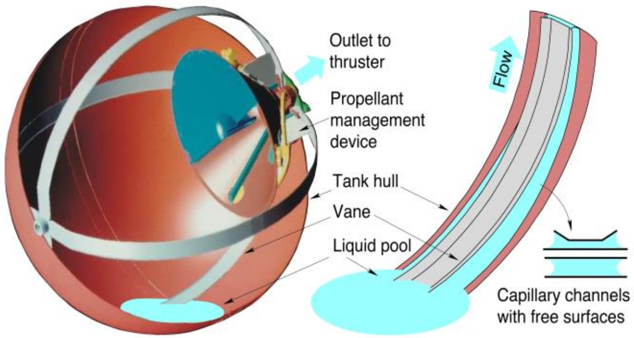
Objectives

- To enable design of spacecraft tanks that can supply gas-free propellant to spacecraft thrusters, directly through capillary vanes, significantly reducing cost and weight, while improving reliability.
- Experiment #1 (EU#1)
  - Determine critical flow-rates (choking) in the capillary-inertial regime as a function of channel length for true channel and half channel.
  - Probe the nature of critical behavior by introducing wave oscillation of variable amplitude and frequency for both channel configurations and variable lengths.
- Experiment #2 (EU#2)
  - Determine critical flow rates (choking) in the capillary-inertial, visco-capillary, and overlap regimes for wedge channels as a function of channel length.
  - Probe the nature of bubble transport, migration, and phase separation as a function of flow rate, channel length, bubble diameter and frequency.

Topics

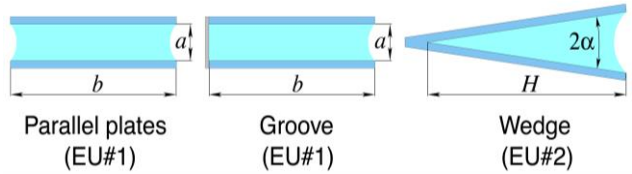
- Experimental studies of open capillary channel flow stability.
- Two experiment units with three different channel geometries.
- Steady, oscillating, unsteady, and two-phase flow conditions.
- Total of 50 days of effective experimental time aboard the ISS.
- Main ground station located at ZARM in Bremen, Germany.
- Interactive access to the ISS for controlling and data download.

Motivation: capillary channel flow in surface tension tanks



Capillary channels with free liquid surfaces are widely used for propellant management in surface tension tanks. Vanes provide channels of various shapes to transport the liquid to the outlet. The free surfaces have to withstand the pressure difference and prevent gas ingestion; the stability is of significant importance for the spacecraft propulsion system.

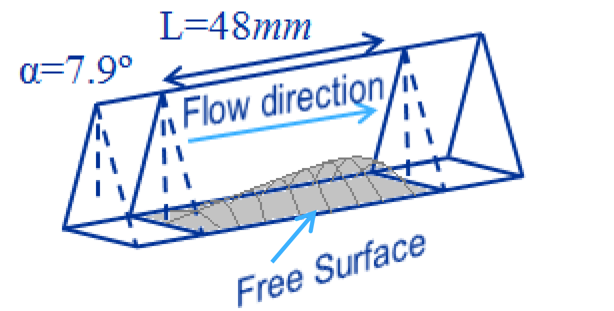
Experimentally investigated geometries of capillary channels



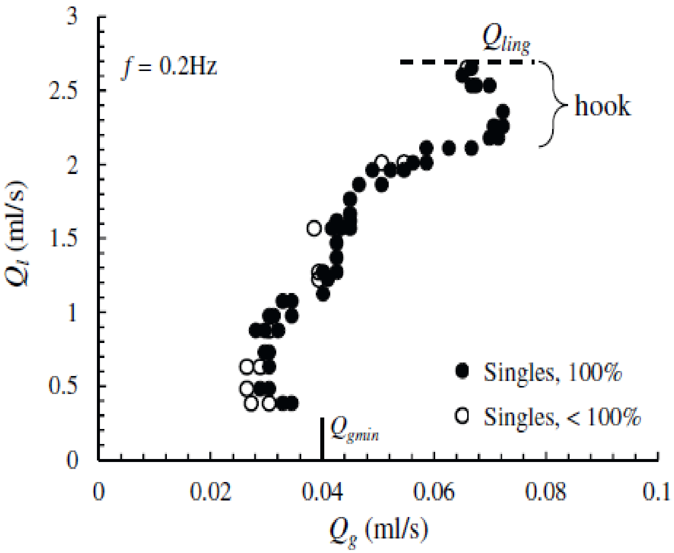
Two experiment units (EU#1, EU#2) provide three different channel geometries, each with one or two free liquid surfaces. The plates are manufactured of glass for camera observation and surface image analysis; *a=5 mm, b=25 mm, H =30 mm,* α*=7.9°, variable length l =0...48 mm.*

CCF Results:
Liquid-Gas Phase Separation Regime Maps

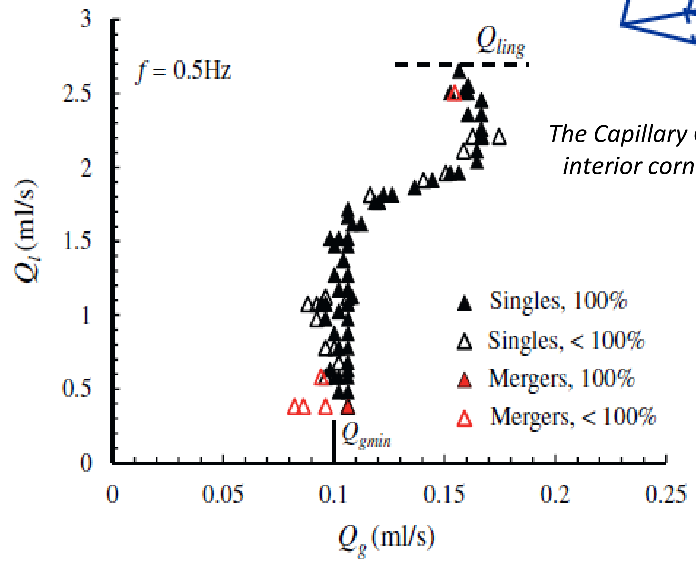
- Data reduction indicates well-defined boundaries between full and partial (or no) gas/liquid phase separation.
- Two example regime maps are shown bubble generation frequencies ($Q_g = fV_{bubble}$).



The Capillary Channel Flow (CCF) test section is an inverted interior corner geometry with a triangular cross-section.



a

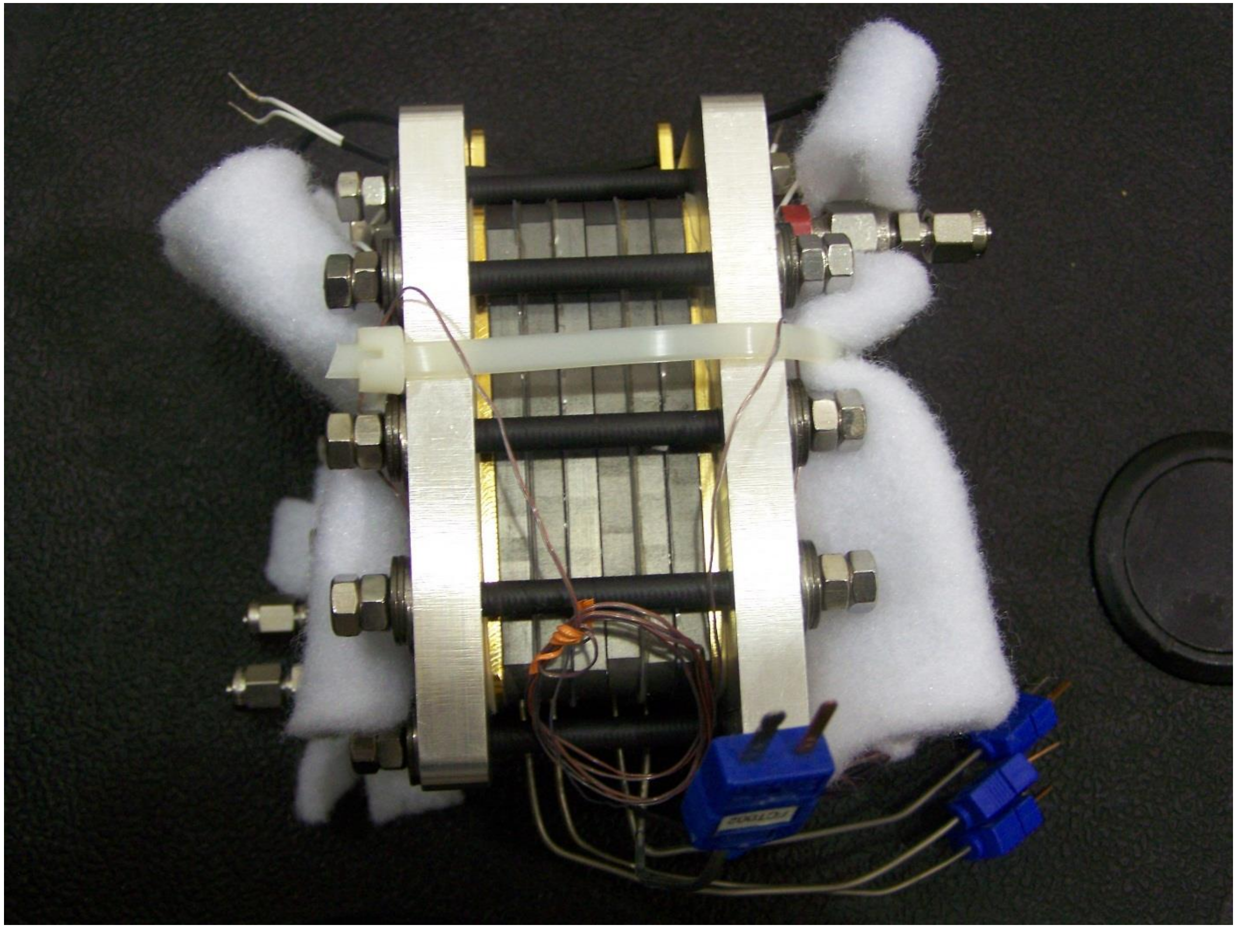


b

Flow conditions for 100% bubble separation in an open wedge channel

From Jenson et. al., Int. J. Multiphase Flow, 2014

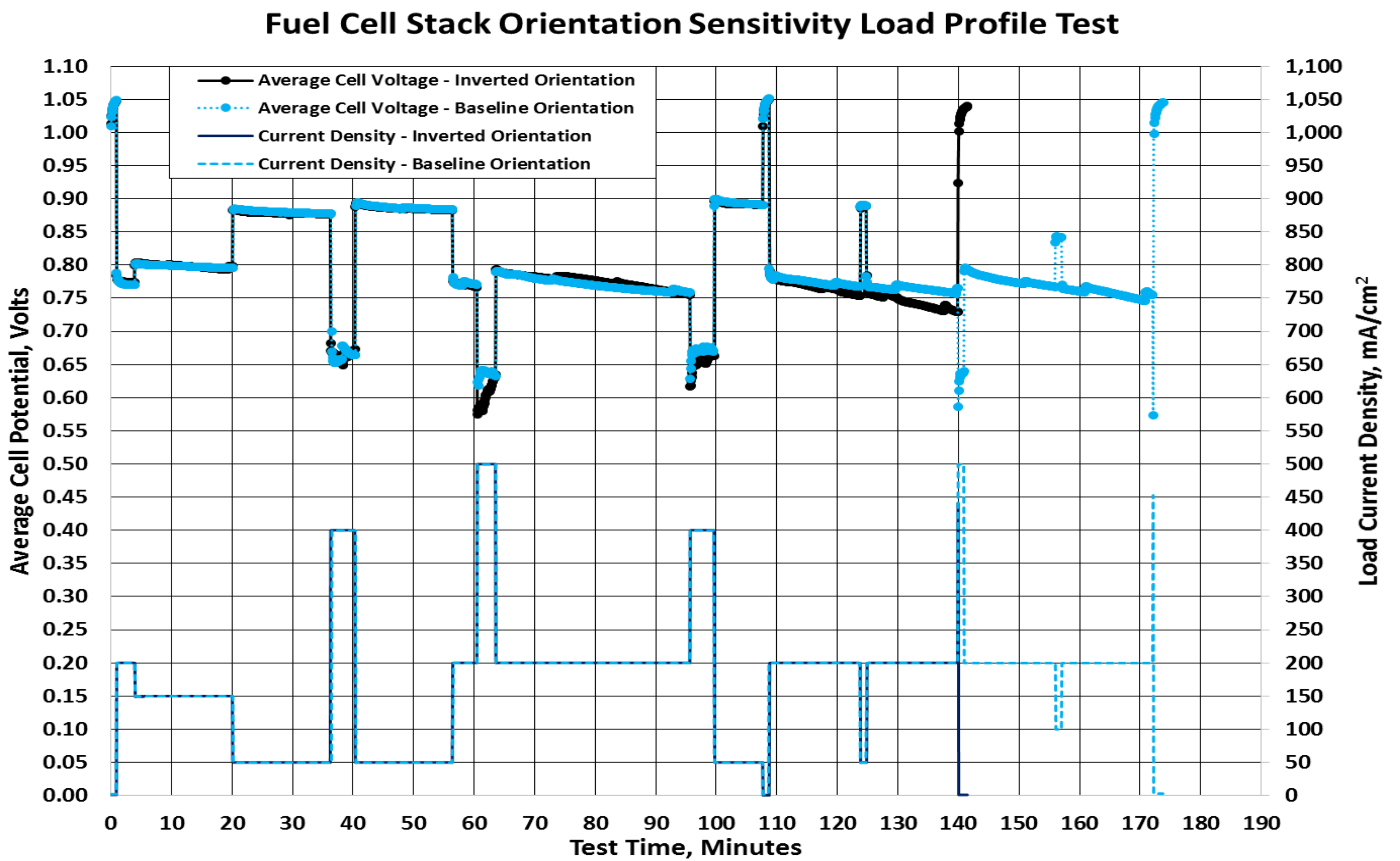
NASA Fuel Cell Stack Ground Orientation Testing



Two orientations of the stack in 1-g gravity with respect to water flow

- “baseline” (preferred for water removal)
- “inverted” (impeding water removal)

NASA Fuel Cell Stack Ground Orientation Testing



Conclusions

- Understanding of gas-liquid separation processes are very important for effective management of advanced regenerative fuel cell systems
- Gas-liquid separation process patterns are different in 1-G and 0-G
- Boiling experiment (q vs. T) in microgravity, has analogy to electrochemical work (I vs. V) with non-departing primary bubble resulting in both higher wall temperature (T_W) and higher voltage (V) for same heat flux (q) and current (I).
- Capillary channel flow with “free surface” can be used for passive gas-liquid multiphase separation in 0-G.
- Fuel cell stack orientation in 1-G experiments affects long term power performance