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Flow Boiling Critical heat Flux in Reduced Gravity

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Rationale

- Critical heat flux (CHF) is key design parameter for heat-flux-controlled devices
- Ability to predict CHF is of paramount importance to both safety and reliability of two-phase systems
- Vast majority of reduced-gravity boiling studies focused on pool rather than flow boiling
- There are conflicting recommendations concerning viability of pool boiling in microgravity
- Flow boiling is proven method for enhancing CHF relative to pool boiling
- Bulk motion increases CHF by flushing bubbles away from heated wall before they coalesce into insulating vapor blanket, and by constantly replenishing wall with bulk liquid
- Low pumping power favors reducing flow velocity
- Minimum velocity is therefore sought which can adequately increase CHF and suppress detrimental effects of reduced gravity

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Significance

NASA/TM-2004-212940: Workshop on Critical Issues in Microgravity Fluids, Transport, and Reaction Processes in Advanced Human Support Technology

Focus Area: Thermal Systems and Phase Change Processes

- **Future missions for exploration of solar system will require enabling technologies for efficient and reliable energy generation (nuclear, chemical, solar sources), storage (rechargeable batteries, regenerative fuel cells, flywheels, latent heat phase change), and transfer (cabin temperature control, space suit temperature regulation)**
- **Need for improved energy-to-mass ratios suggests replacing present single-phase operations with two-phase systems. Future design of important thermal subsystems in boilers, condensers, evaporators, heat exchangers, cryogenic fluid storage units, fuel cells, radiators and heat pipes involve complex multiphase fluid flow and transport issues**
- **Full understanding of multiphase transport phenomena associated with operation of thermal and phase change subsystems in microgravity needed for both design and safe and efficient operation in space**

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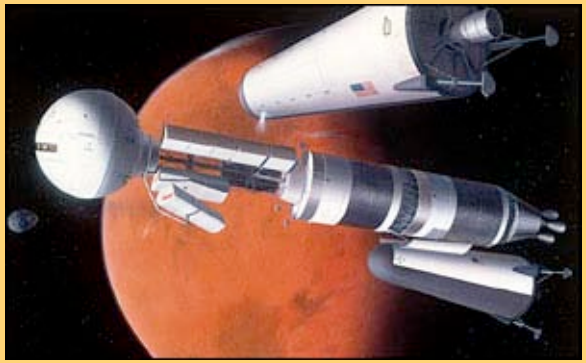
Significance

Pertinent AHST System: Power Generation Cycles, high power-to-weight ratio Rankine cycle for long-duration missions



High Priority Recommendations:

- **Attainment of phenomenological understanding and accumulation of empirical data for two-phase flow in micro- and macro-geometries, boiling heat transfer, and phase-distribution and phase-transition phenomena in microgravity**
- **Development of empirical correlations, theoretical models and scaling laws for two-phase flow in complicated geometries, boiling and condensation heat transfer, and phase-distribution and phase-transition phenomena in microgravity**
- **Development of stability criteria for two-phase heat transfer loops in microgravity**
- **Development of advanced, efficient, and reliable vapor compression heat pump technology**

Challenge

Reduced gravity flow boiling heat transfer and critical heat flux data and models virtually nonexistent!!!

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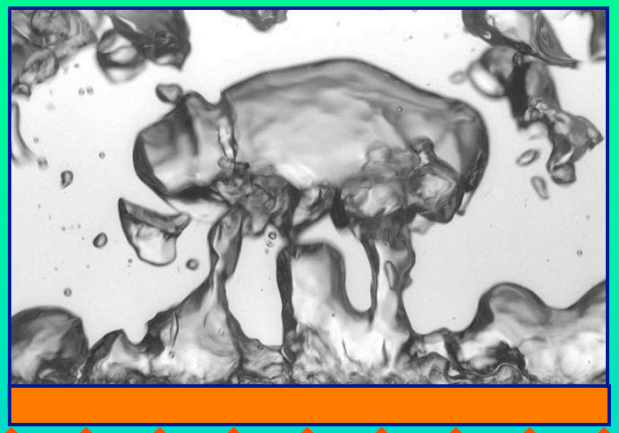
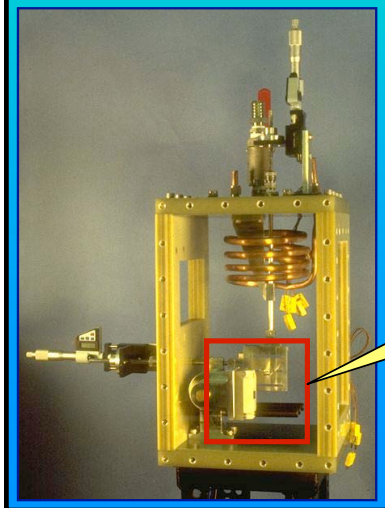
Effects of Orientation on Pool Boiling CHF at One g_e

CHF from a horizontal surface

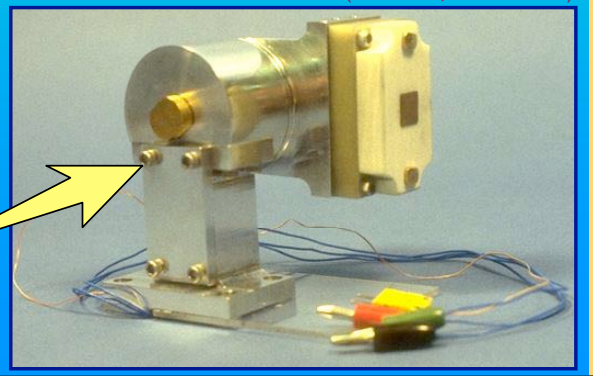
1 g_e



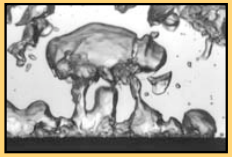
Heat Flux



Phase Change Photo Library
(Mudawar, 1984 - 2004)



Saturated PF-5052



CHF = 26 W/cm^2

0°

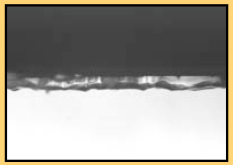
1 g_e

90°

CHF = 20 W/cm^2

180°

CHF = 5 W/cm^2



Howard & Mudawar (1999)

June 23, 2004

Conference on Strategic Research to Enable NASA's Space Exploration Missions

Prof. I. Mudawar

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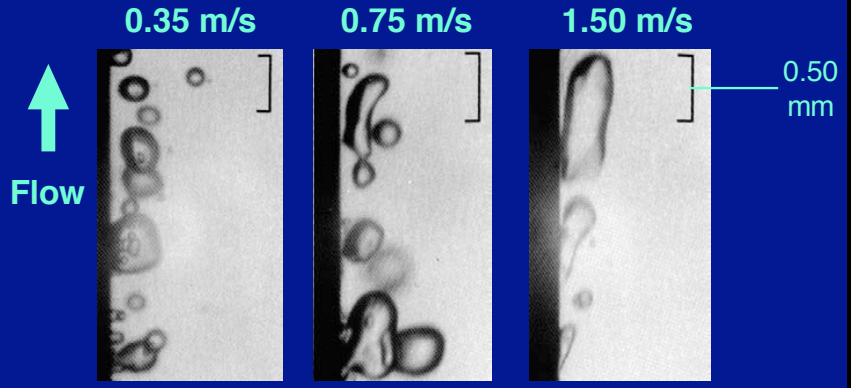
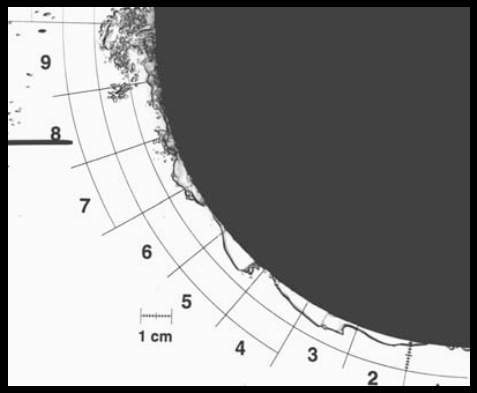
Bubble Coalescence Effects

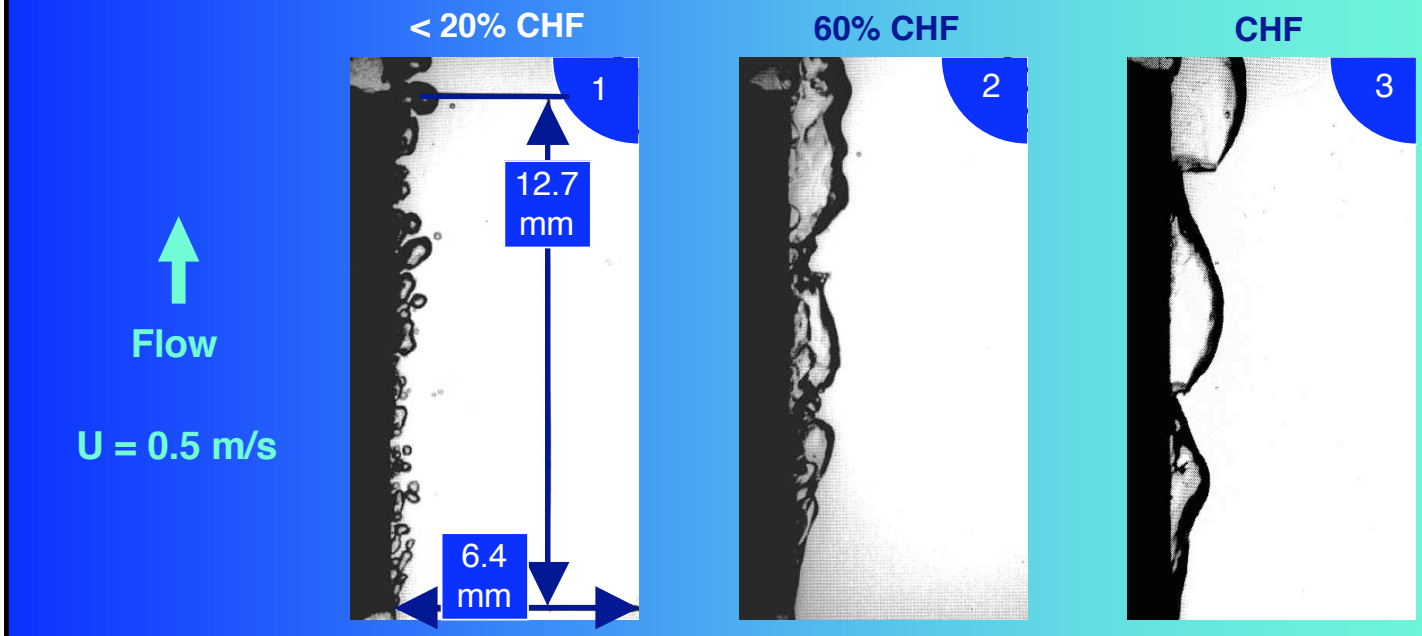
Incipient Flow Boiling



Pool Boiling

(50% CHF)





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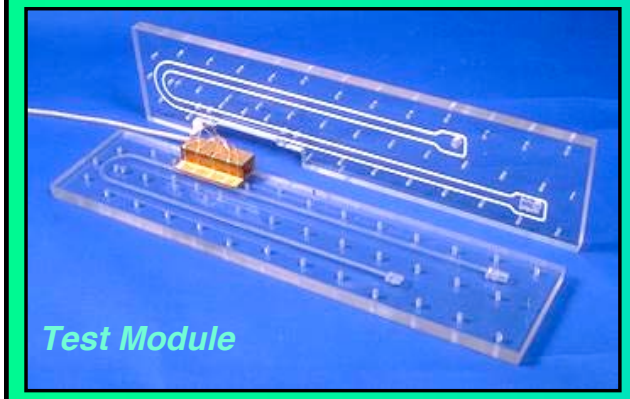
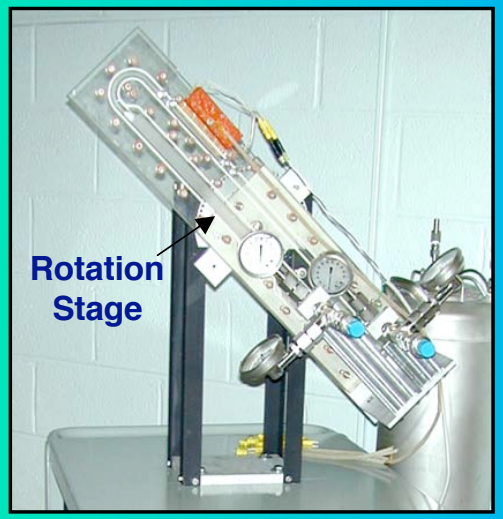
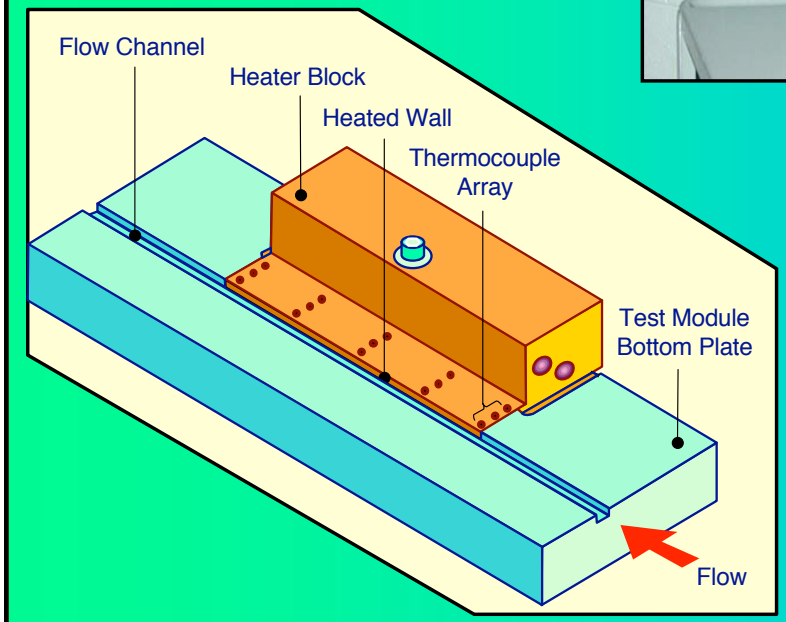
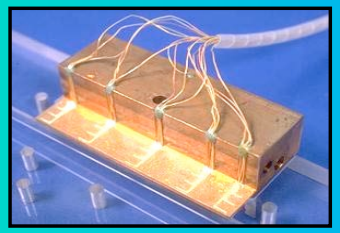
One-g_e Flow Boiling CHF Apparatus









Heater

Boiling Apparatus

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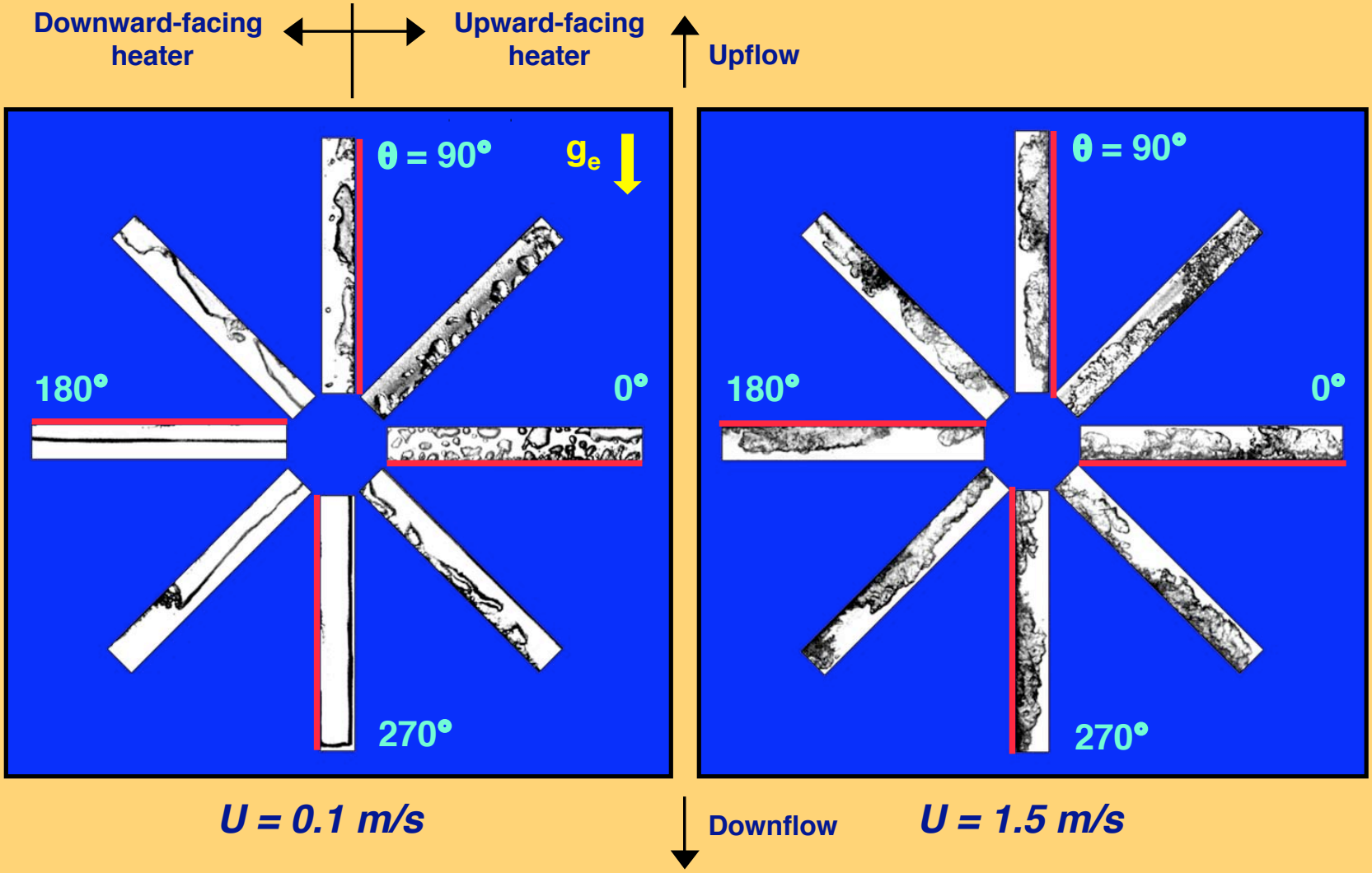
Vapor Behavior for Saturated Flow



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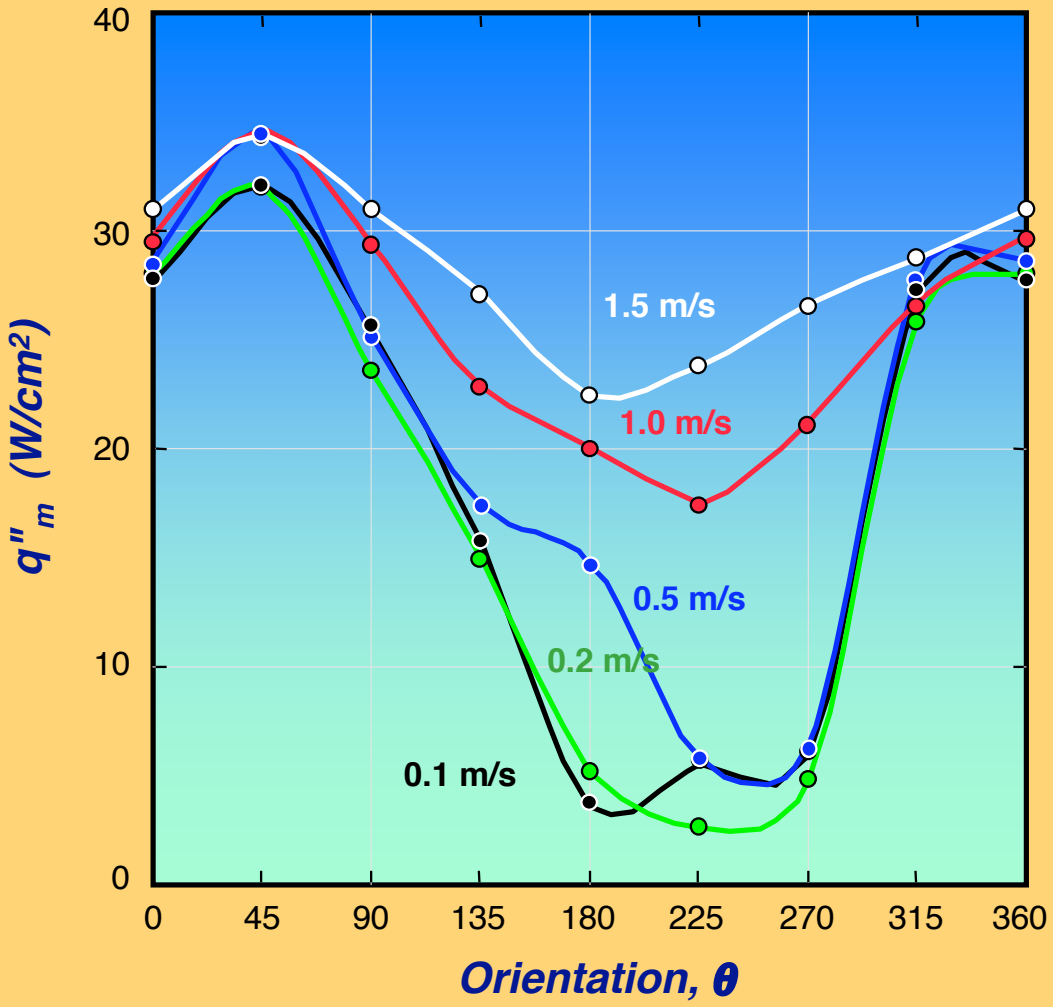
Variation of CHF with Orientation and Flow Velocity at 1 g_e



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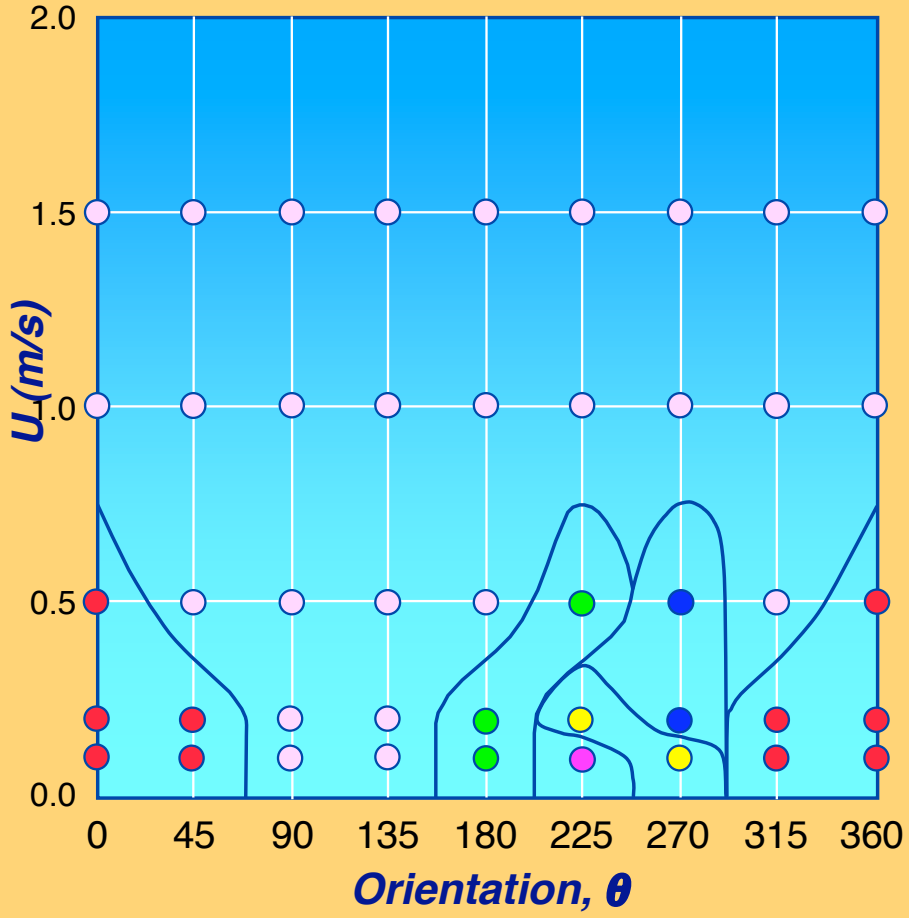
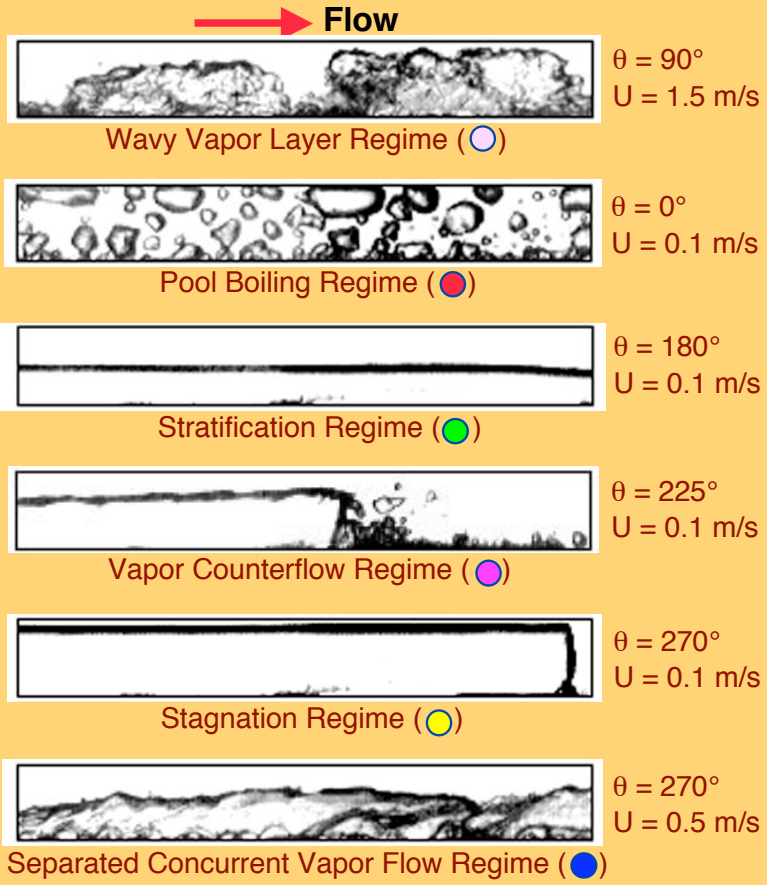
CHF Regime Map





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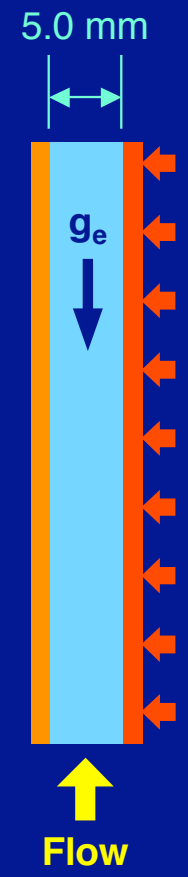
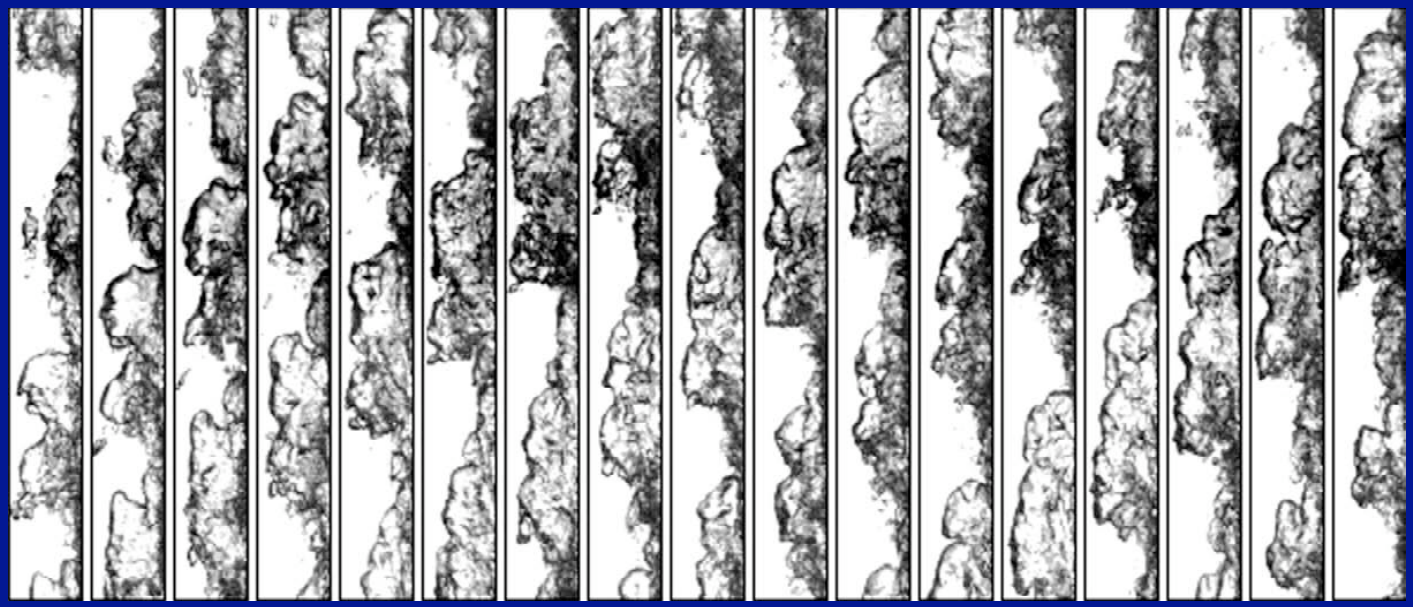
Wavy Vapor Layer Regime



U = 1.5 m/s



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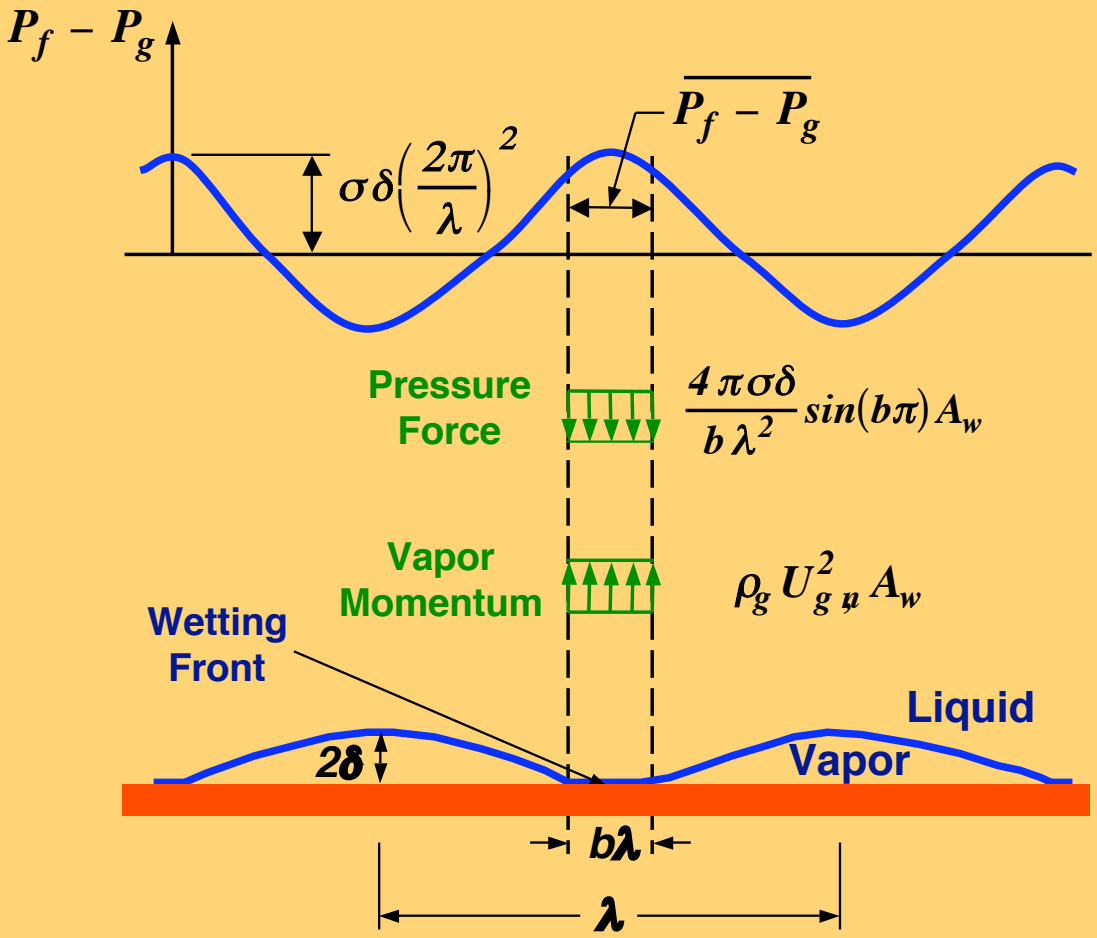
Vapor Momentum vs Interfacial Pressure



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Interfacial Lift-off Model

- **Critical Wavelength:**

$$\frac{2\pi}{\lambda_c} = \frac{\rho_f'' \rho_g'' \left(U_g - U_f\right)^2}{2\sigma\left(\rho_f'' + \rho_g''\right)} + \sqrt{\left[\frac{\rho_f'' \rho_g'' \left(U_g - U_f\right)^2}{2\sigma\left(\rho_f'' + \rho_g''\right)}\right]^2 + \frac{\left(\rho_f - \rho_g\right) g \cos\theta}{\sigma}}$$

- **Interfacial Pressure Difference:**

$$\overline{P_f - P_g} = \frac{4\pi\sigma\cos\theta}{b\lambda^2}\sin(b\pi x)$$

- **Interfacial Lift-Off Heat Flux:**

$$q_w'' = \rho_g \left(c_{p,f}\Delta T_{sub,i} + h_{fg}\right)\left(\frac{\overline{P_f - P_g}}{\rho_g}\right)^{1/2}$$

- **Heater Energy Balance:**

$$q_m'' = b\, q_w''$$

- **Critical Heat Flux:**

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

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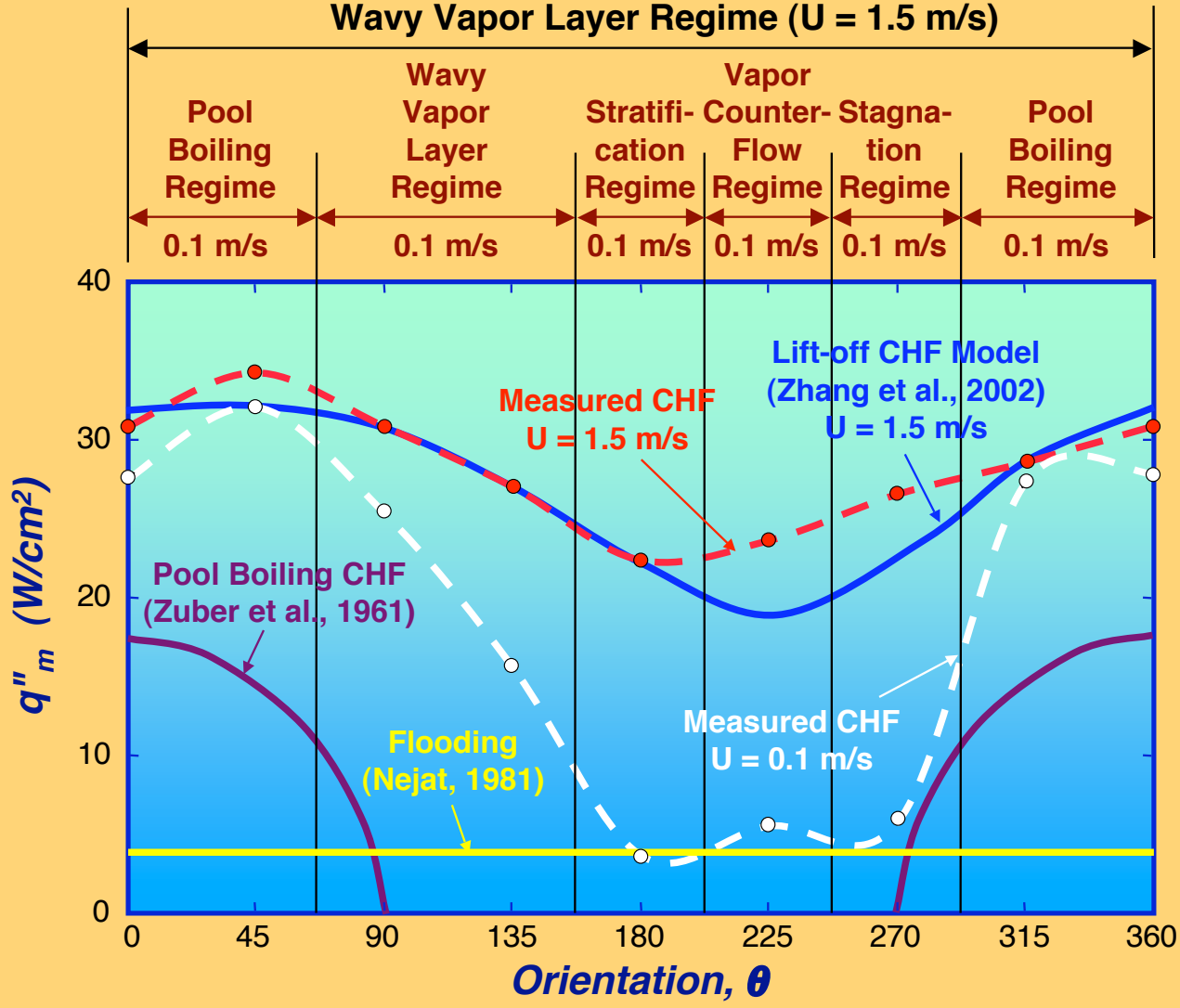
Comparison of Measured and Predicted CHF at 1 g_e



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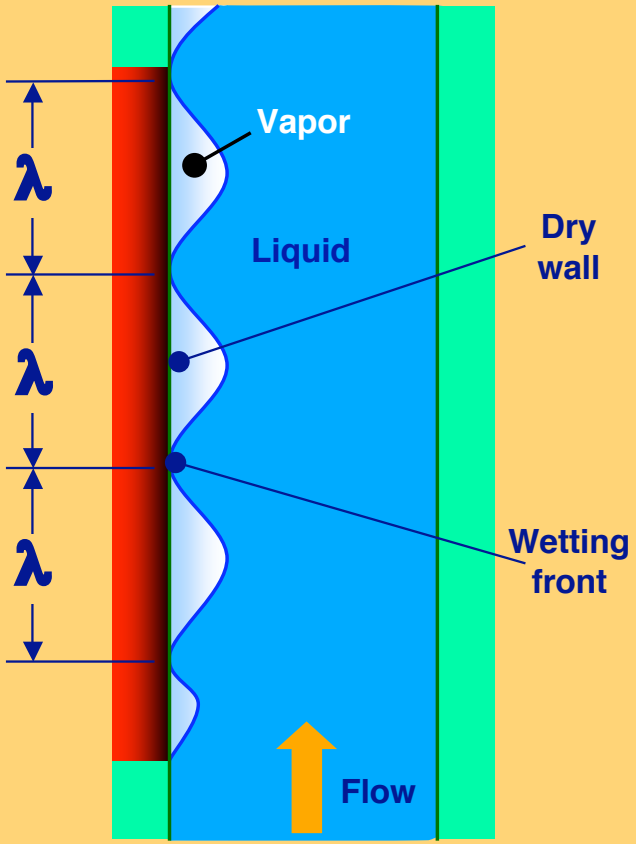
Minimum Velocity Required to Overcome Body Force Effects

Negligible Component of Body Force Perpendicular to Wall

$$\frac{2\pi}{\lambda_c}\frac{\sigma\left(\rho_f+\rho_g\right)}{\rho_f\rho_g\left(\Delta U\right)^2}=\frac{1}{2}\left\{1+\sqrt{1+4\frac{\left(\rho_f-\rho_g\right)\left(\rho_f+\rho_g\right)^2\sigma g}{{\rho_f}^2{\rho_g}^2\left(\Delta U\right)^4}}\right\}$$

$$\frac{Bo}{We^2}=\frac{\left(\rho_f-\rho_g\right)\left(\rho_f+\rho_g\right)^2\sigma g}{\rho_f^2\rho_g^2U^4}\le 0.09$$

$$Bo=\frac{\left(\rho_f-\rho_g\right)gL^2}{\sigma}\qquad We=\frac{\rho_f\rho_gU^2L}{\left(\rho_f+\rho_g\right)\sigma}$$



Negligible Component of Body Force Parallel to Wall

$$U_\infty\sim\frac{\left[\left(\rho_f-\rho_g\right)gD_h\right]^{1/2}}{\rho_f^{1/2}}<<U$$

$$\frac{1}{Fr}=\frac{\left(\rho_f-\rho_g\right)gD_h}{\rho_fU^2}\le 0.13$$

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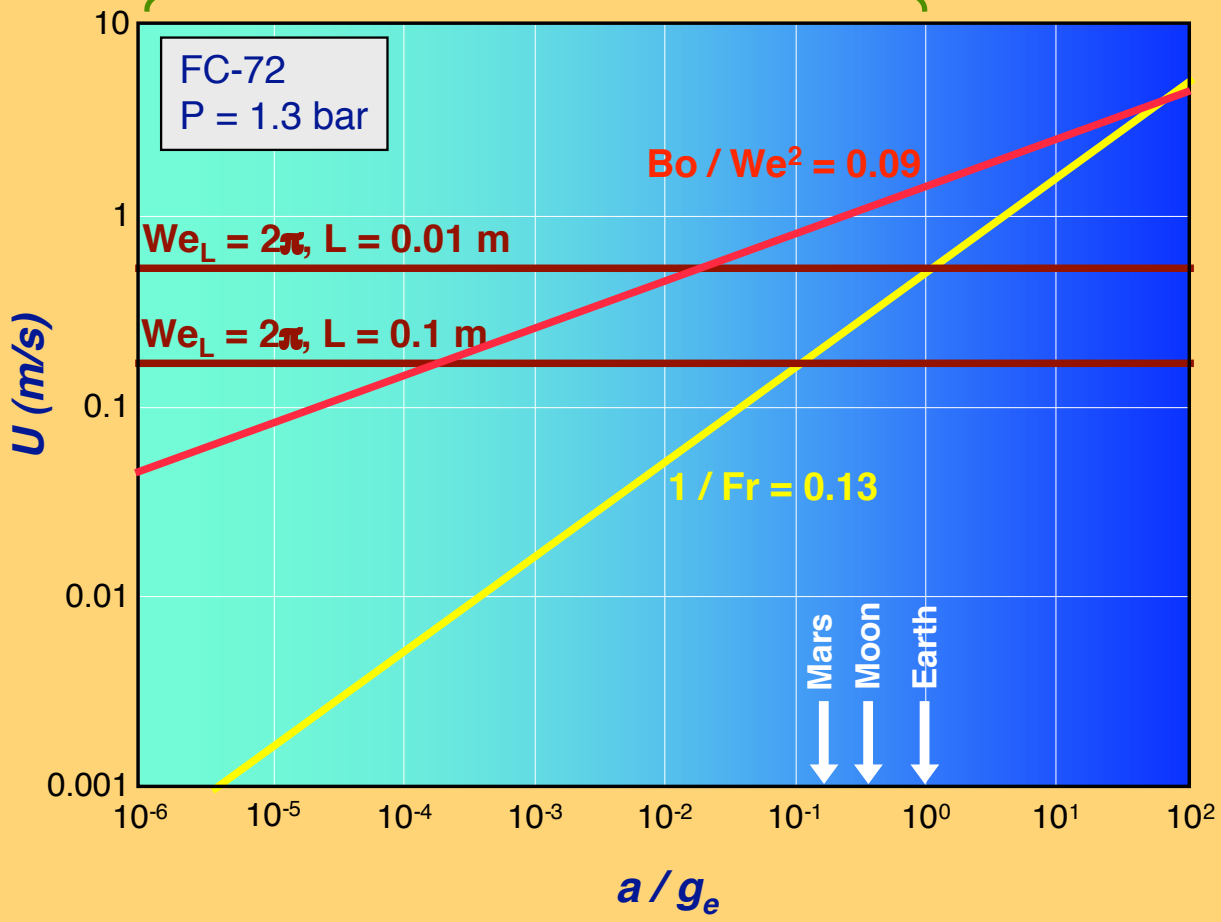
Minimum Velocity Required to Overcome Body Force Effects

U > 1.5 m/s to overcome body force effects below 1 g_e



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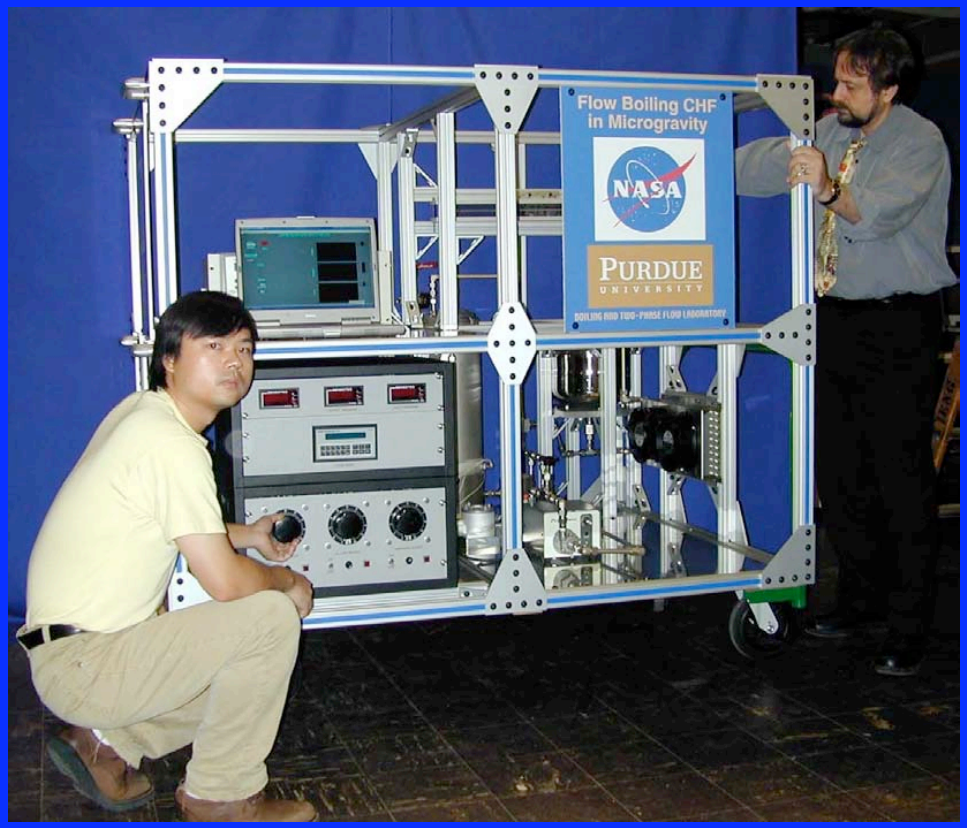
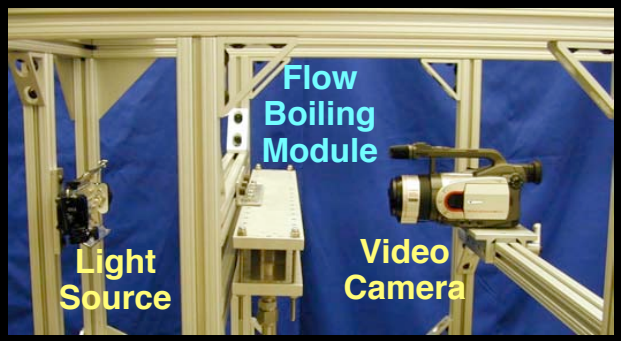
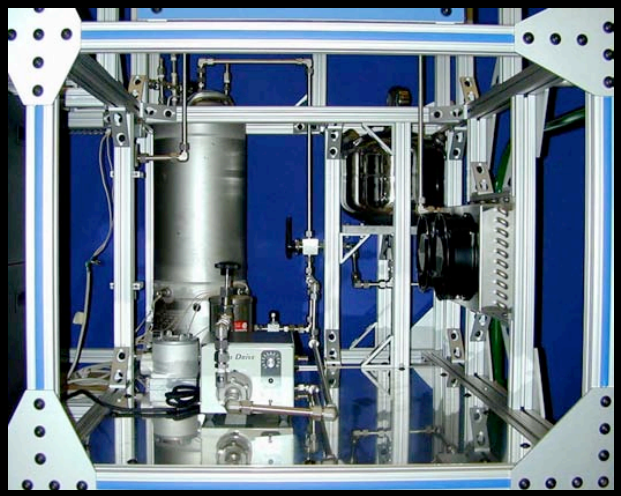
Reduced Gravity Flow Boiling CHF Apparatus



Flight Rack





Two-Phase Loop

Phase Change Photo Library (Mudawar, 1984 - 2004)

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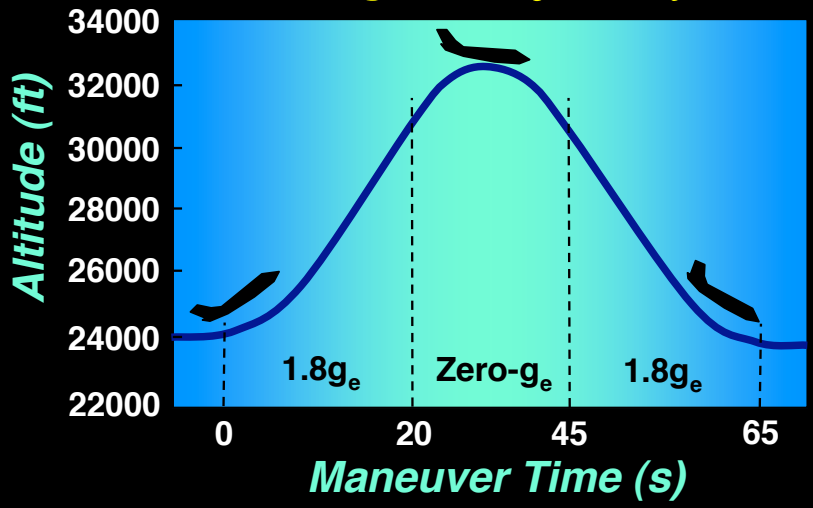
KC-135 Microgravity Experiments

NASA Glenn Research Center, April 2004

Flight Trajectory



Operators:

Dwayne Kiefer (QSS)
Dr. Charles Niederhaus (NASA)
Dr. Juan Agui (NASA)

Phase Change Photo Library
(Mudawar, 1984 - 2004)

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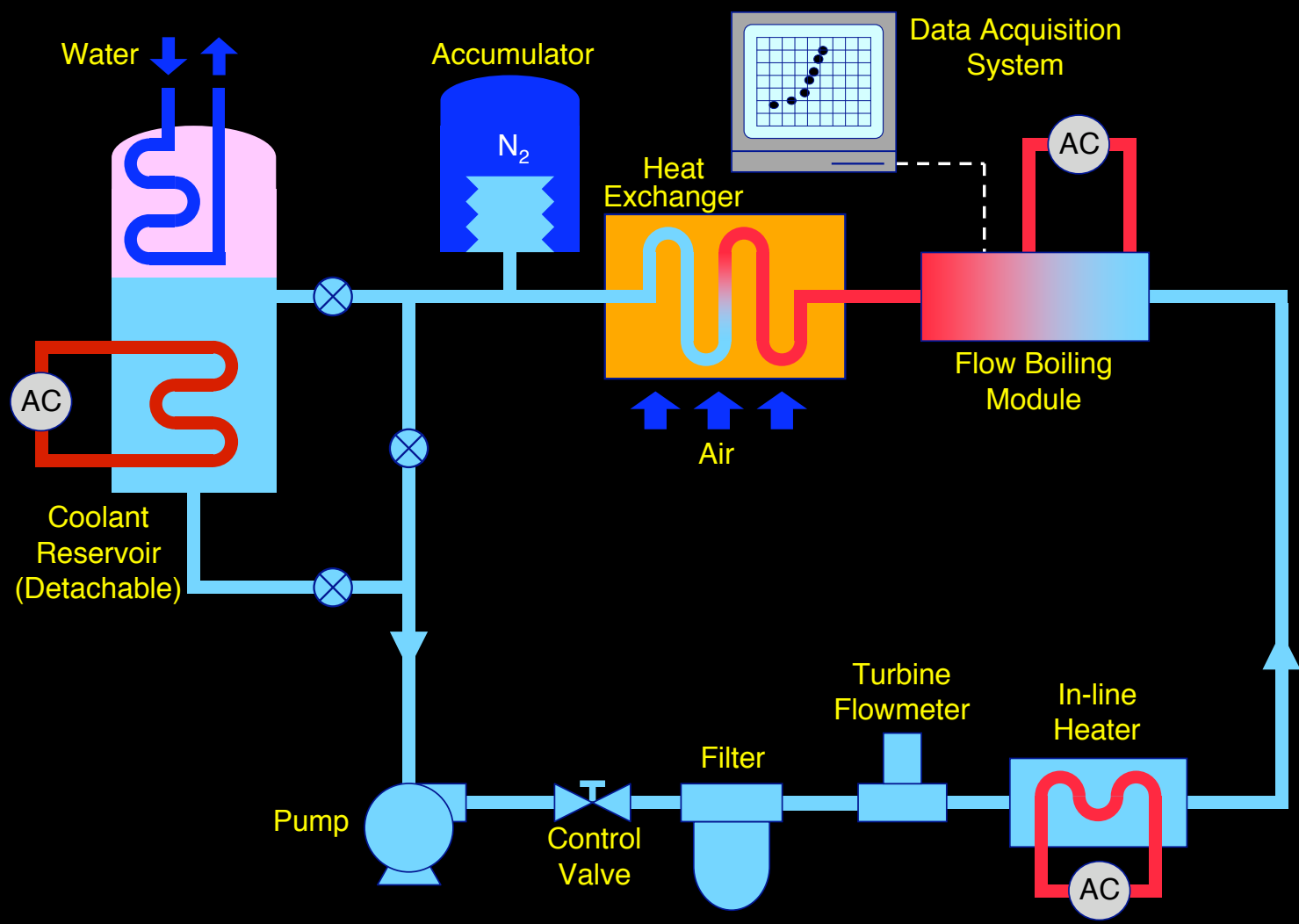
Reduced Gravity Flow Loop



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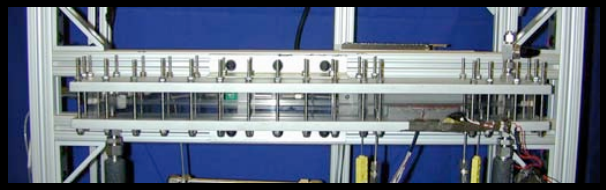
Reduced Gravity Flow Loop

Coolant Reservoir

Accumulator

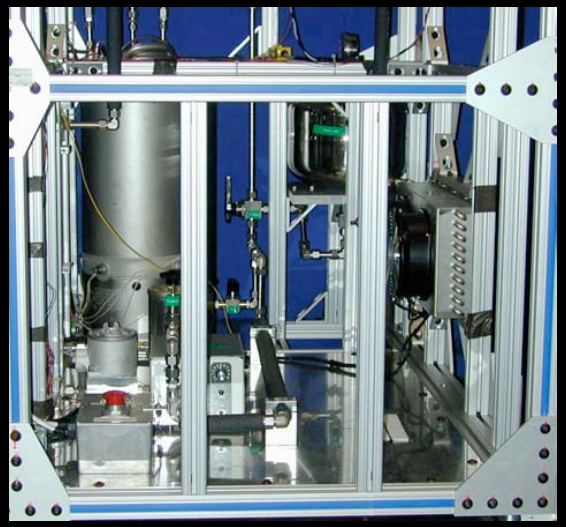
Heat Exchanger



Flow Boiling Module

Pump

Filter



Turbine Flowmeter

In-Line Heater

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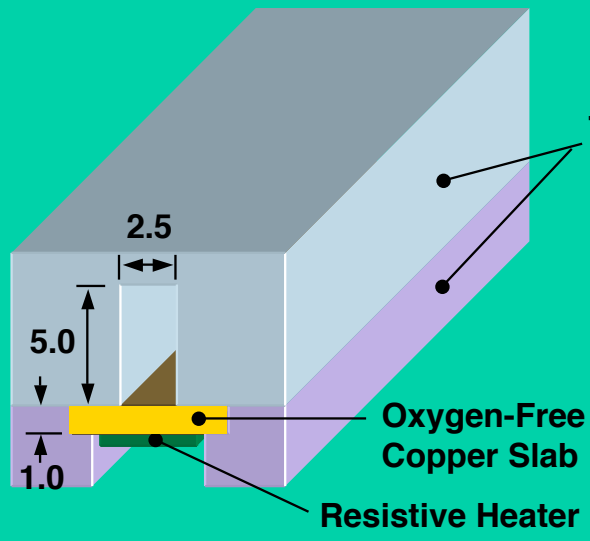
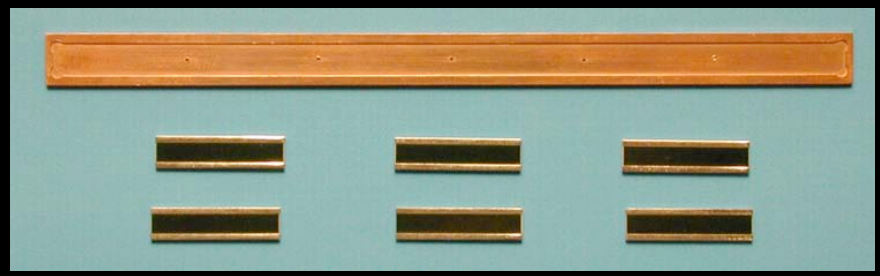
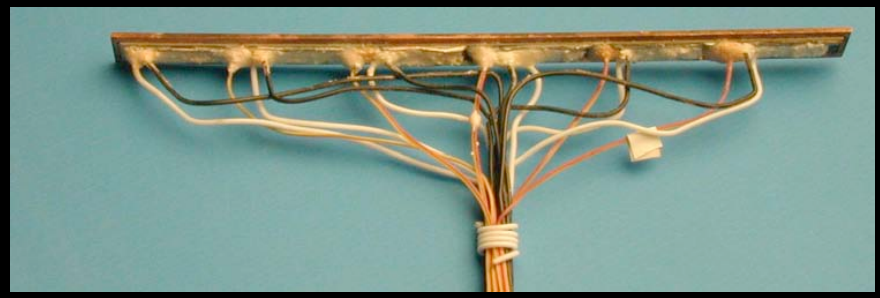
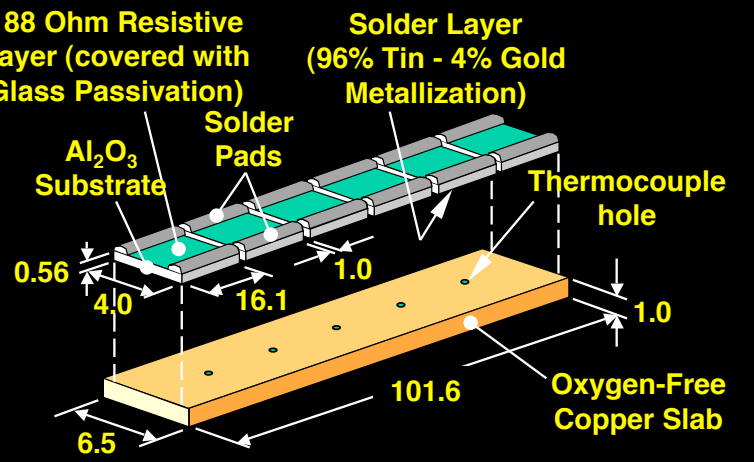
Flow Boiling Module









All dimensions in mm

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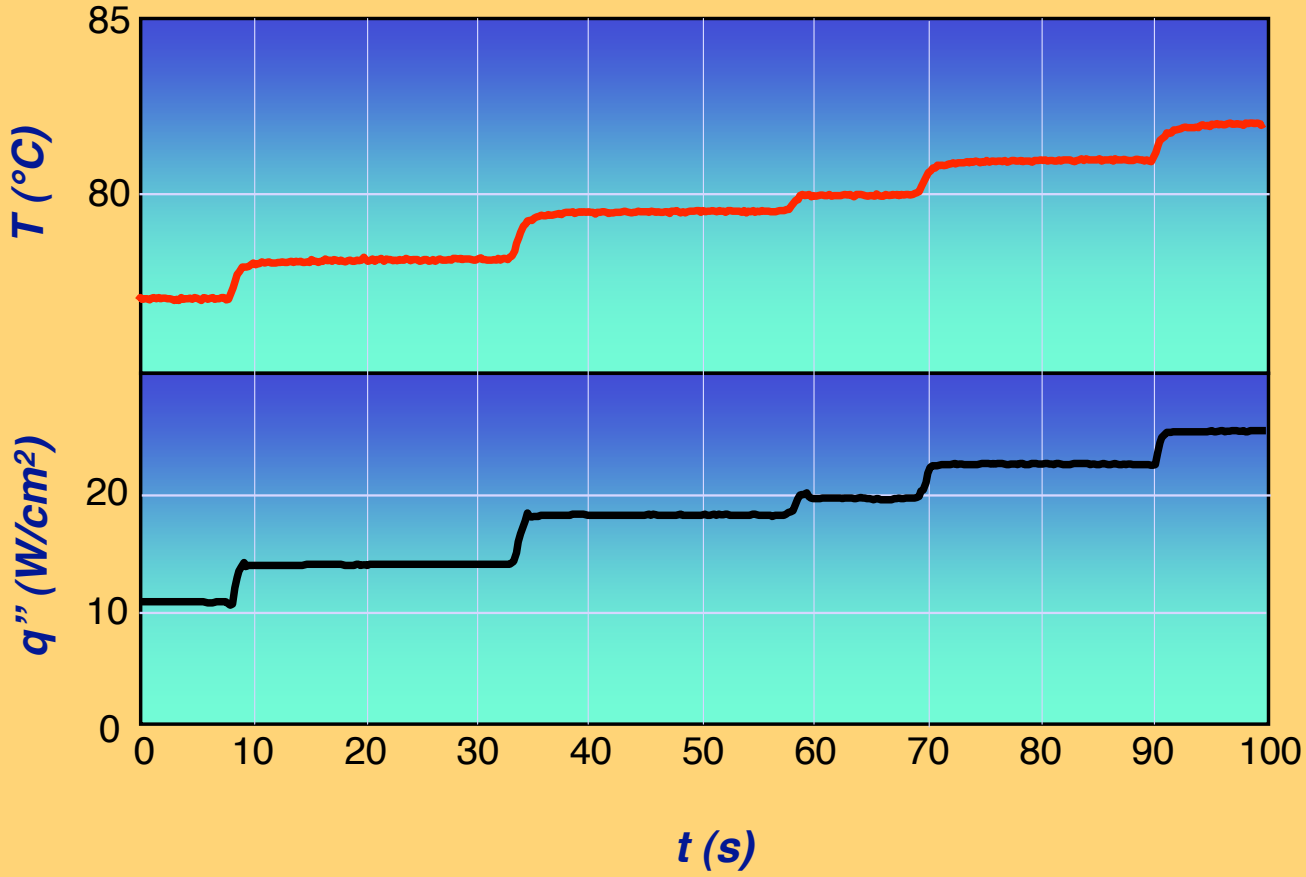
Thermal Response of Heater



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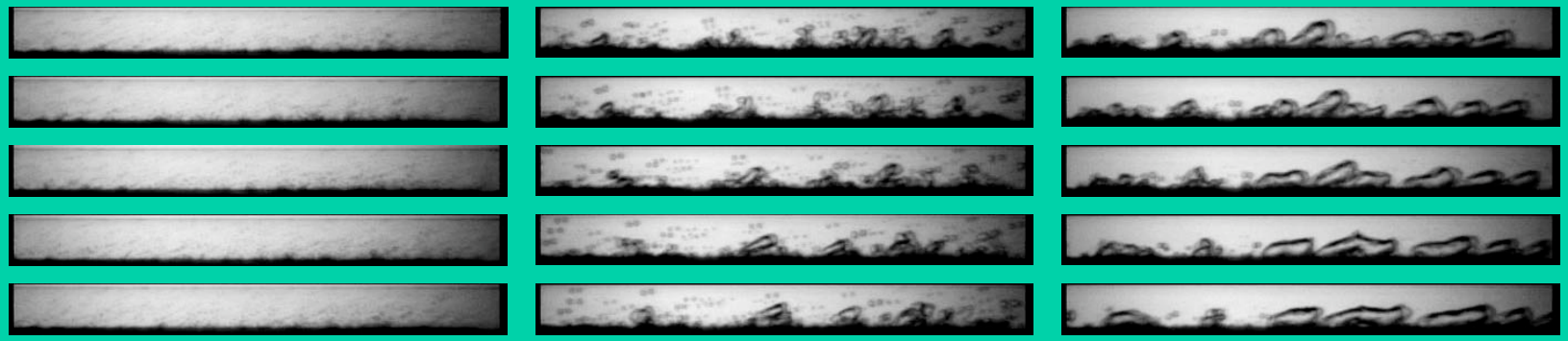
Parabolic Flight Results

FC-72, U = 0.14 m/s



1.8g_e | **0.17g_e (Lunar)** | **Zero-g_e**

Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)

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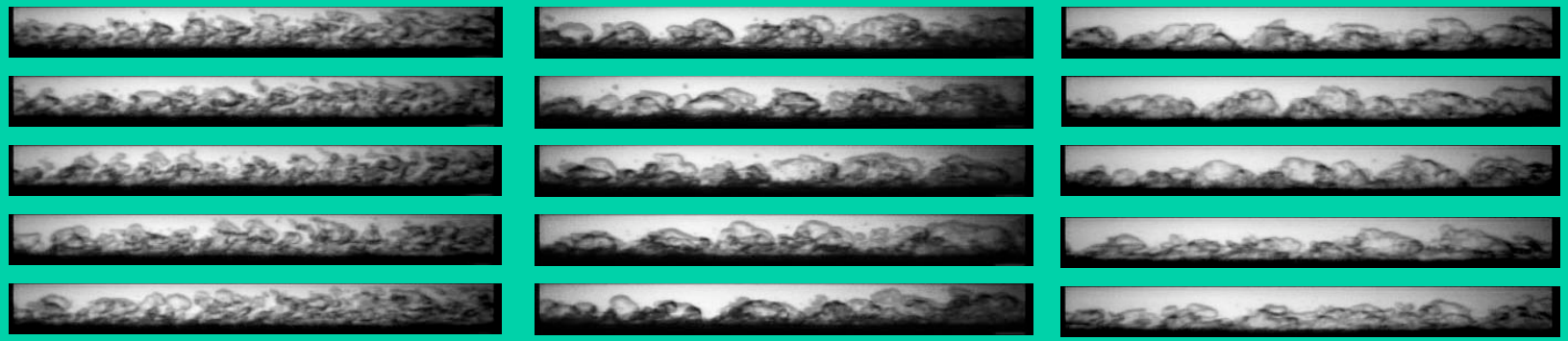
Parabolic Flight Results

FC-72, U = 1.40 m/s



1.8g_e | **0.377g_e (Martian)** | **Zero-g_e**

Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)

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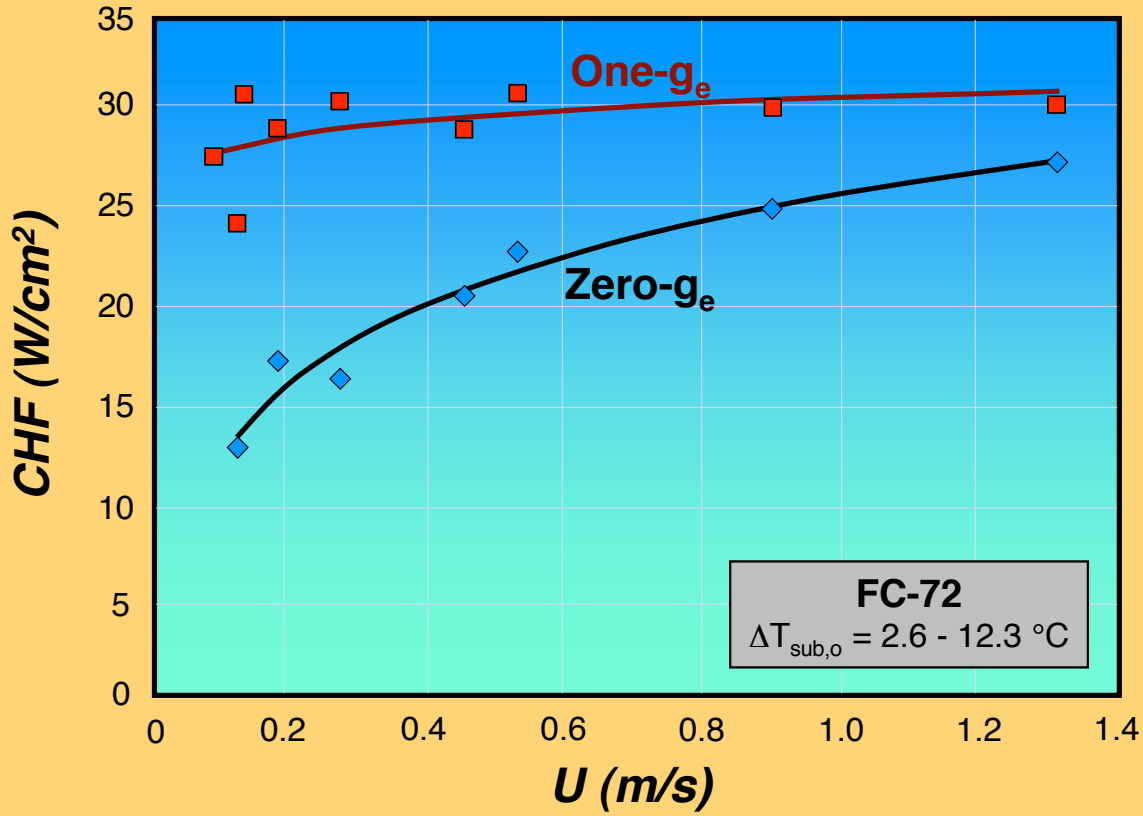
Parabolic Flight Results



Phase Change Photo Library
(Mudawar, 1984 - 2004)

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Conclusions

One-G Flow Orientation Study

- At high velocities, CHF at all orientations dominated by Wavy Vapor Layer Regime. Vapor layer layer propagates along heated wall permitting liquid contact only in troughs of interfacial waves. CHF occurs when liquid contact regions are lifted from wall due to intense vapor effusion
- Interfacial Lift-off Model very effective at capturing overall dependence of CHF on orientation in Wavy Vapor Layer Regime
- Flooding limit better suited to CHF prediction in low velocity downflow orientations
- Dimensionless criteria developed for minimum flow velocity required to overcome body force effects on flow boiling CHF

Conclusions

Reduced Gravity Study

- Body force has significant effect on nucleate flow boiling at low flow velocities
- Very low coolant velocities (especially below 0.5 m/s) greatly reduce CHF in microgravity
- Increasing flow velocity reduces CHF sensitivity to body force and can eliminate detrimental effects of microgravity on CHF
- Experimental CHF data corresponding to microgravity, lunar and Martian environments demonstrate existence of minimum velocity above which effects of body force on CHF are suppressed
- Experimental CHF data support predictions of theoretical dimensionless minimum velocity criteria

Conclusions

Practical Implications

- This study provides systematic method for reducing power consumption in reduced gravity systems by adopting minimum velocity required to provide adequate CHF and preclude detrimental effects of reduced gravity

- This study proves it is possible to use existing 1 g_e flow boiling and CHF correlations and models to design reduced gravity systems provided minimum velocity criteria are met