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EVeC
TherM

Research Presentation

Boiling Configurations

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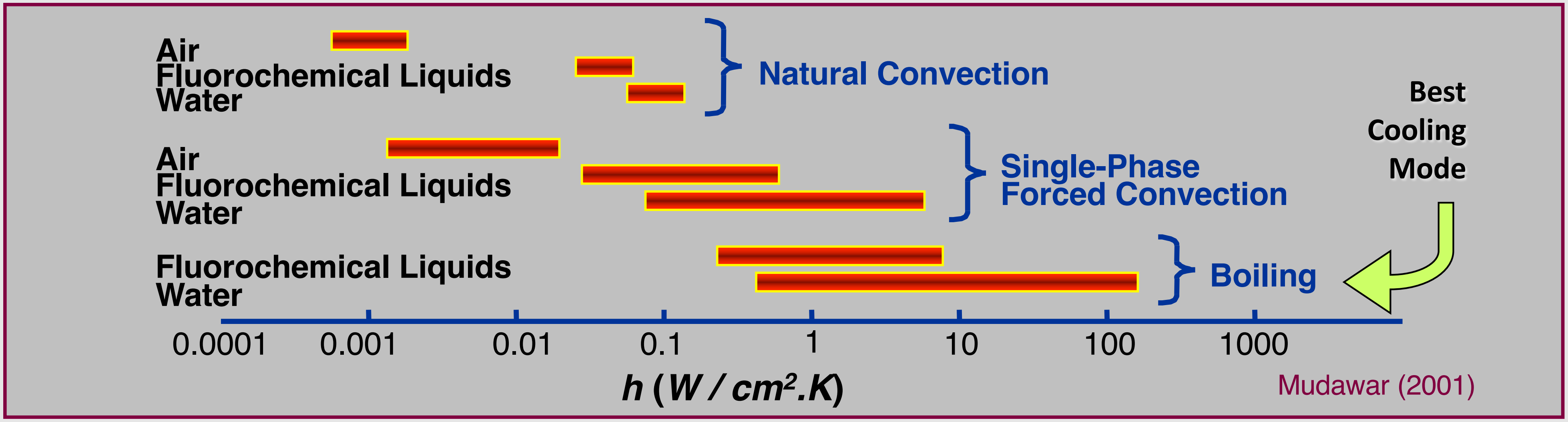
Boiling Applications

High-Flux **(25 - 10^3 W/cm^2)**
- Power plant boilers
- Food production
- Geothermal systems
- Metal production
- Computer chips
- Fuel cells
- Spacecraft electronics

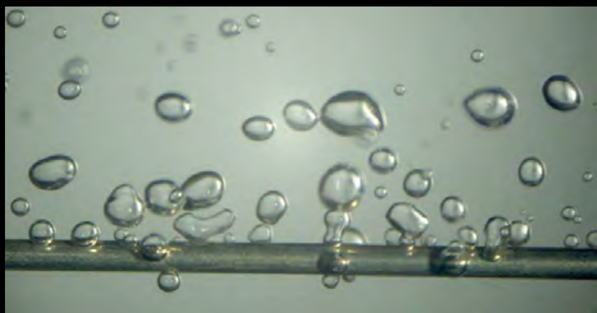
Ultra-High-Flux **(10^3 - 10^5 W/cm^2)**
- Pressurized water reactors
- Particle accelerators
- Laser & microwave weapons
- Radar systems
- Rocket nozzles
- Turbine blades
- Afterburners



- **Constant pursuit of more compact and lightweight packaging, and better performance (lower junction temperature) has lead to alarming increases in power density**
- **Because thermal management is mostly an afterthought, pushing limits of existing cooling solutions (e.g., using air-cooled heat sinks) often results in costly upper bounds to many technologies**
- **What is presently needed is a new class of thermal management solutions capable of dissipating very high power densities**
- **With this capability, these solutions will allow vast advances in performance without the need for costly changes in system packaging**
- **Systems utilizing liquid-to-vapor phase-change are the most effective thermal management solutions for high-power-density applications**

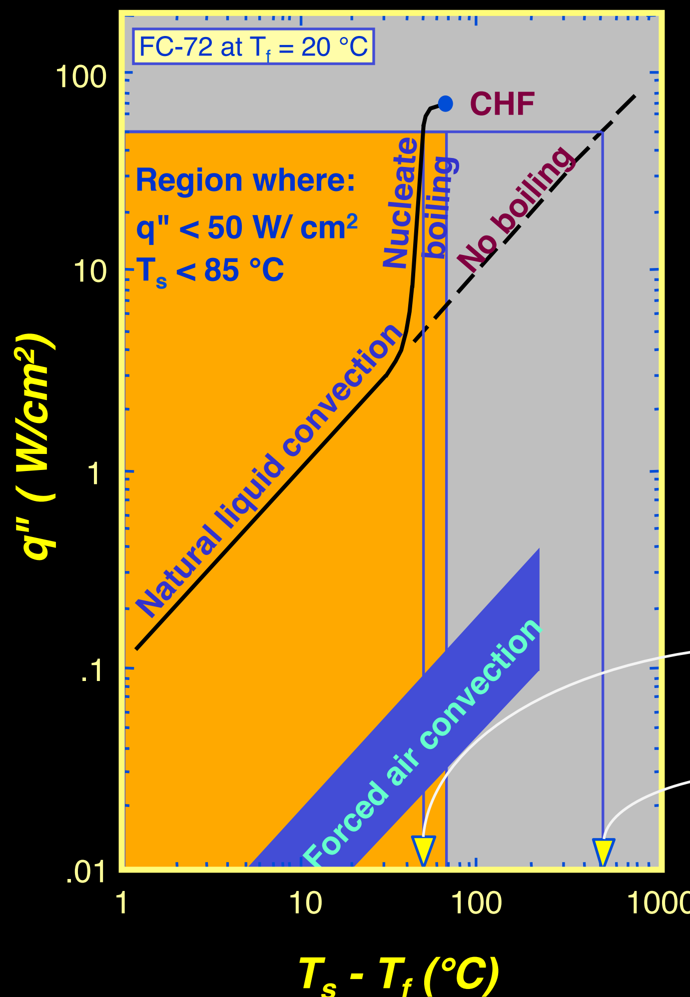
Boiling on a Wire

Nucleate Boiling



Critical Heat Flux

Film Boiling



Key Merits of Boiling:

(1) Modest changes in device temperature corresponding to broad changes in device heat flux (in nucleate boiling region)

(2) Much lower device temperatures than with single-phase cooling. For this device:

T_s = 70 °C at 50 W/cm² with boiling

T_s = 525 °C at 50 W/cm² without boiling

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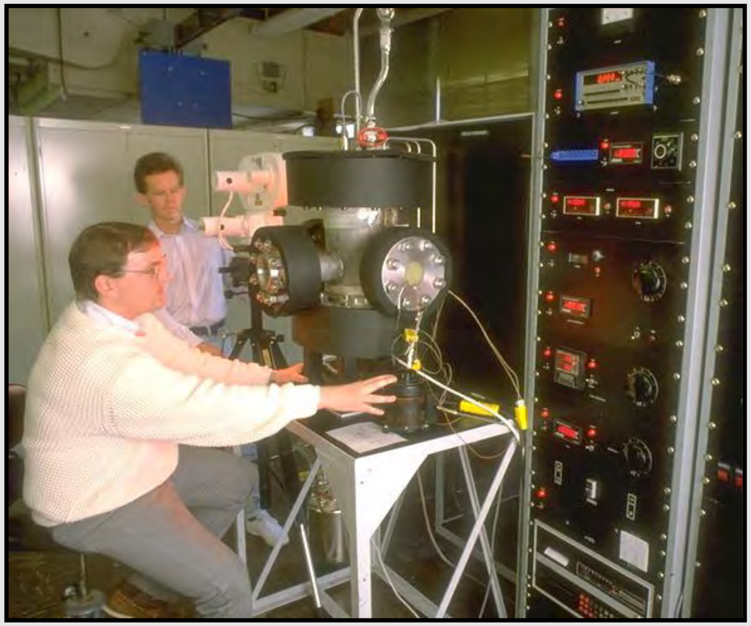
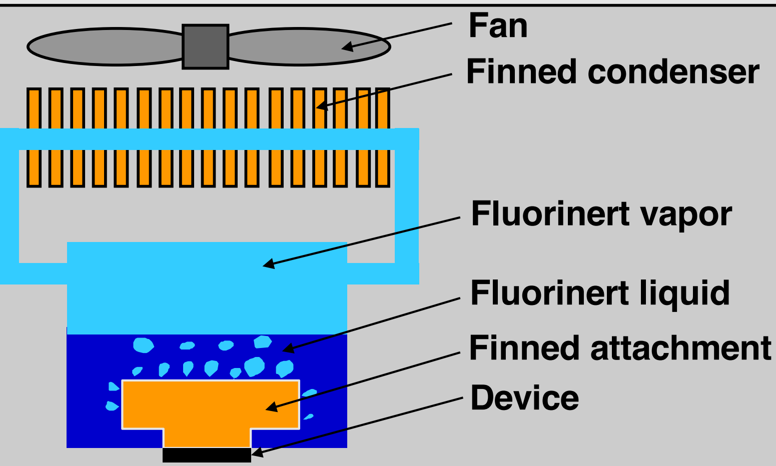
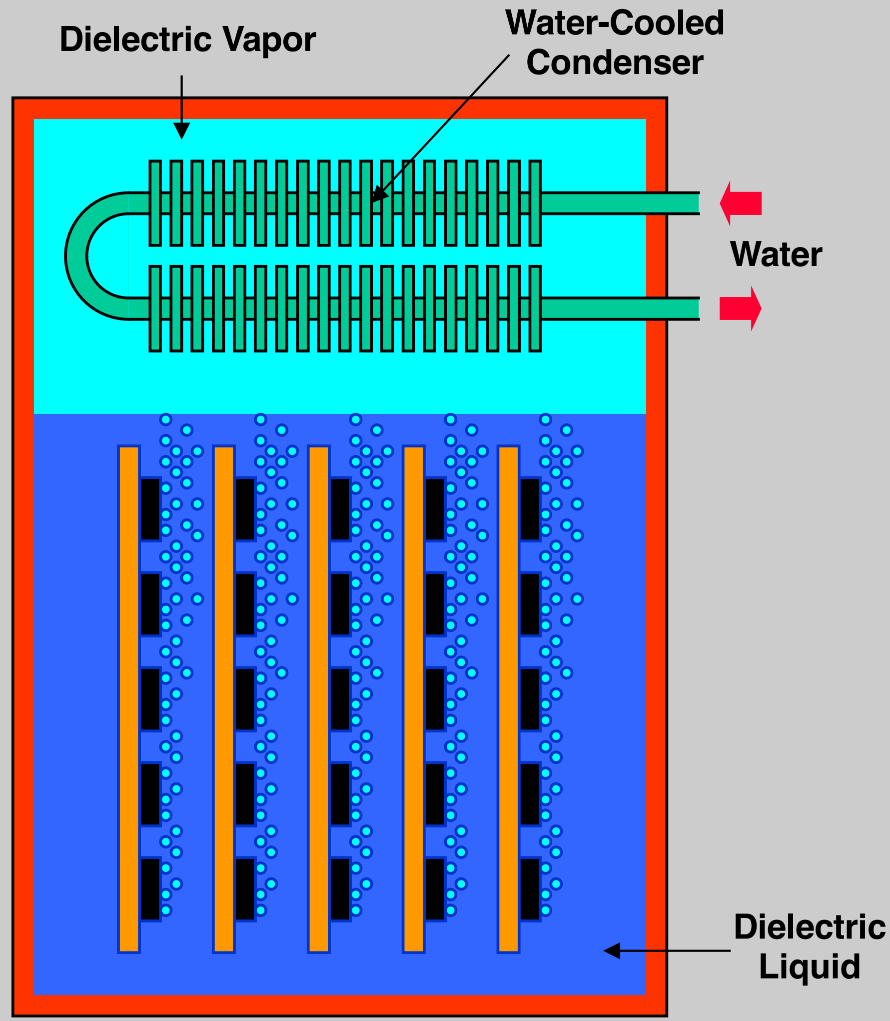
Boiling Configurations: Pool Boiling Thermosyphons



IBM

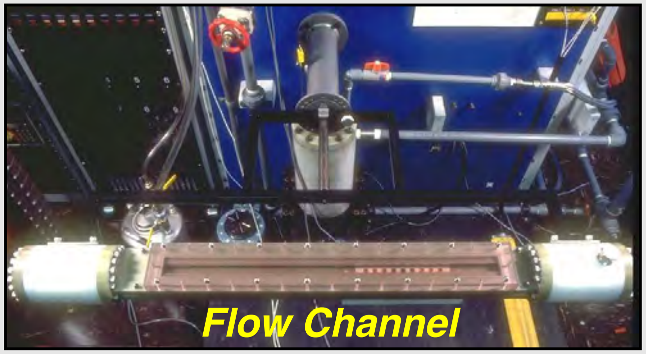


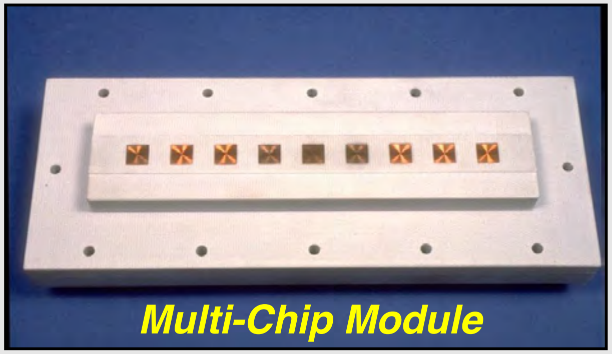
Air-cooled: Microprocessor Cooling



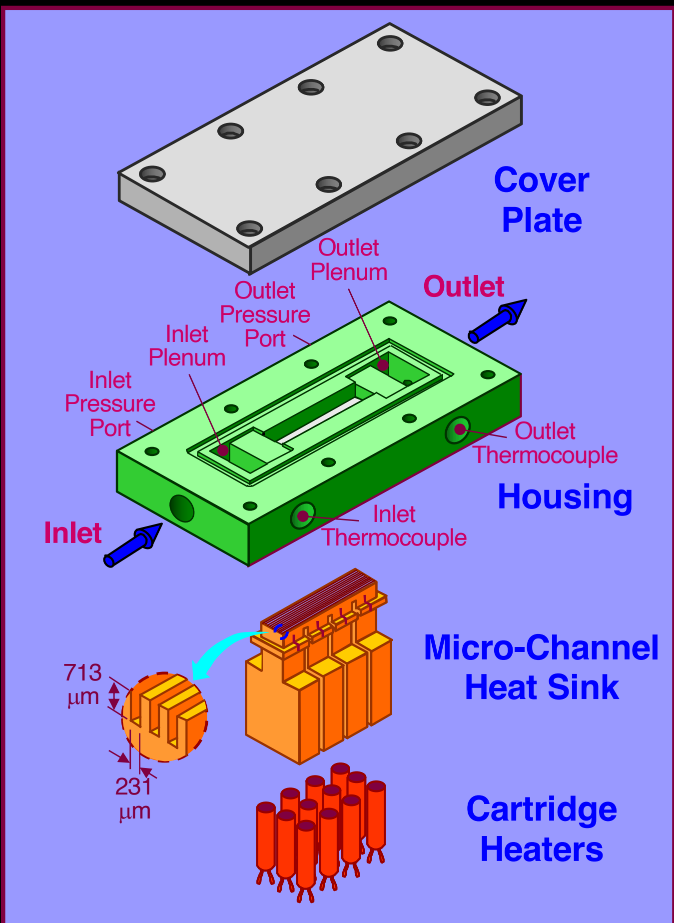
Liquid-cooled: Multi-Chip Modules

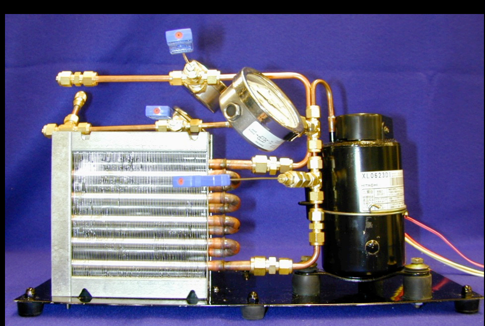
Boiling Configurations: Channel Flow

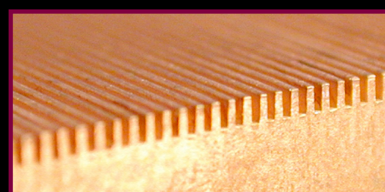


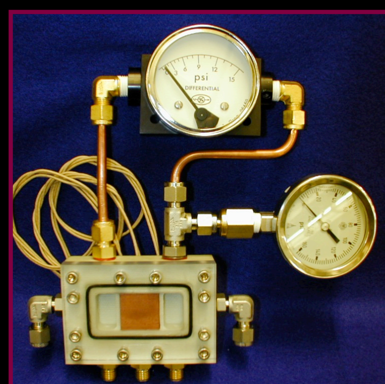


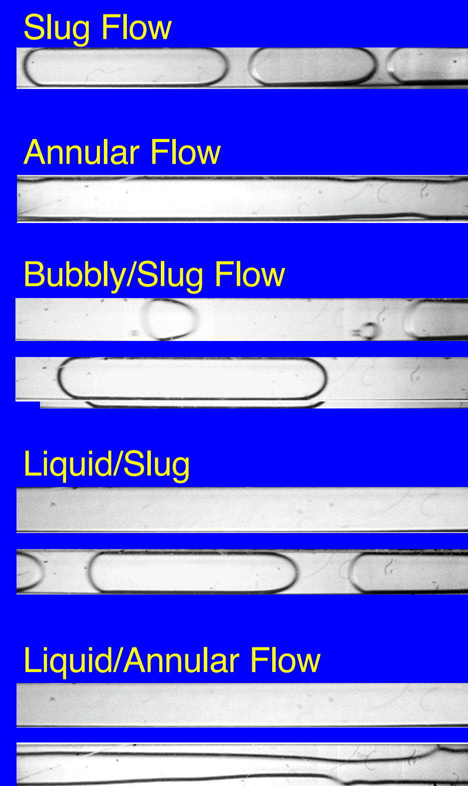
Boiling Configurations: Mini/Micro-channel Flow

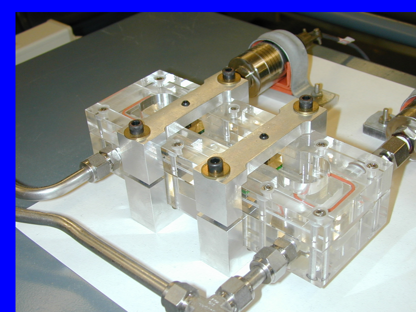


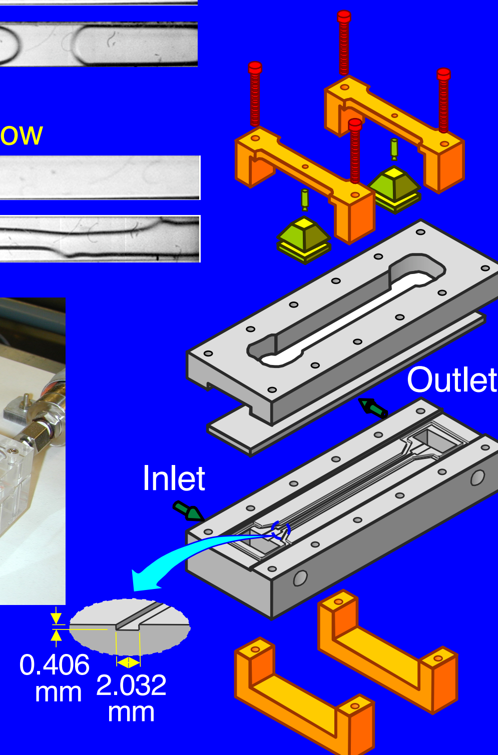




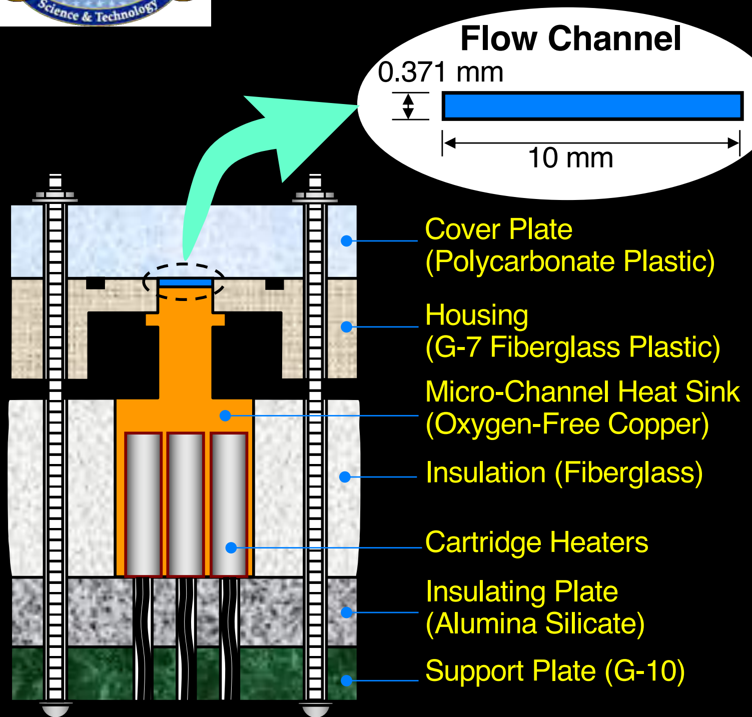


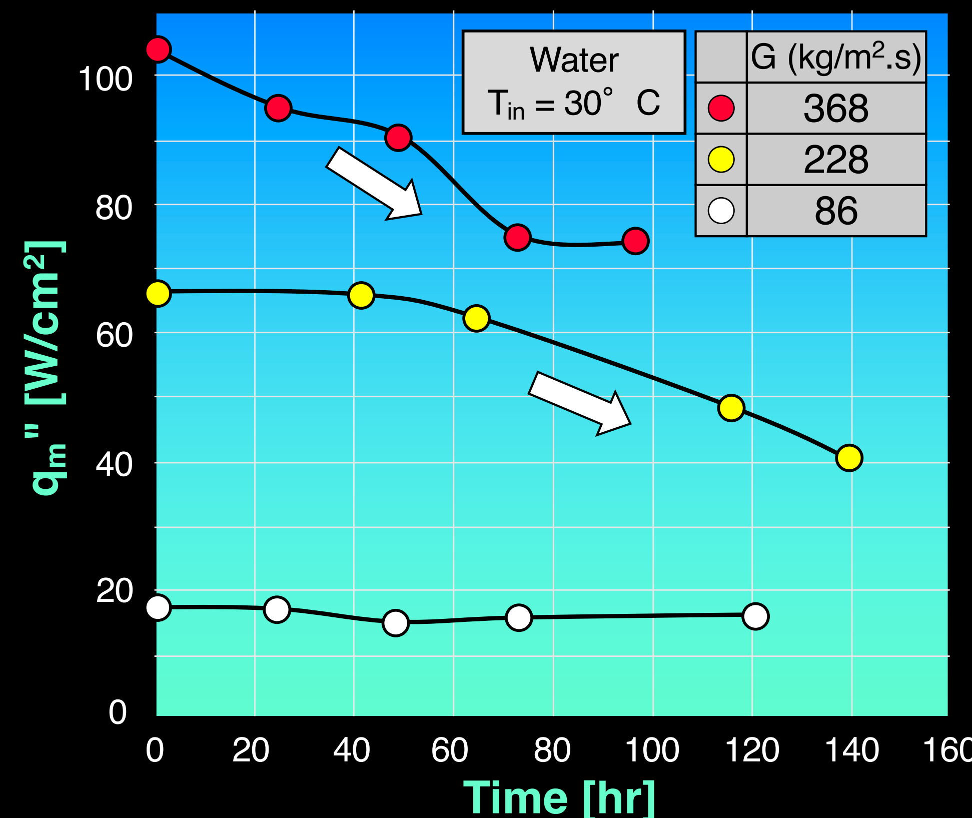


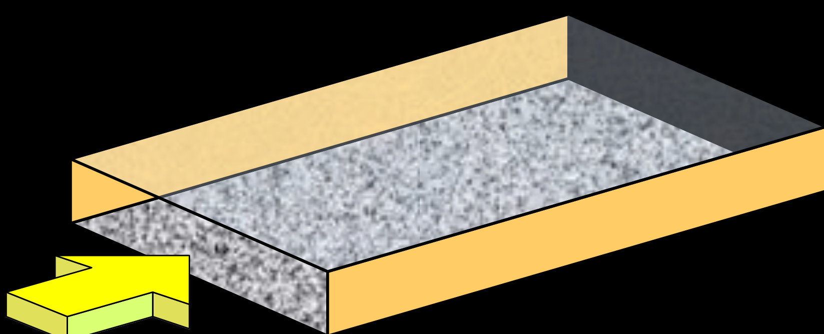


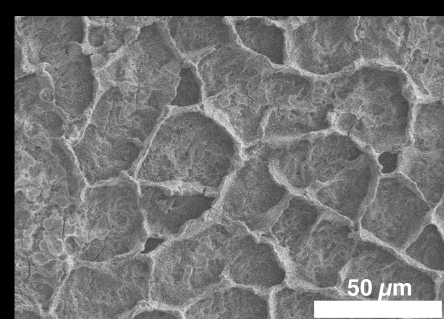


Boiling Configurations: Mini/Micro-channel Flow/Carbon Nanotubes

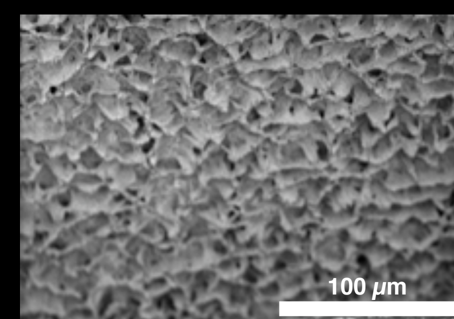








Isolated cellular formations

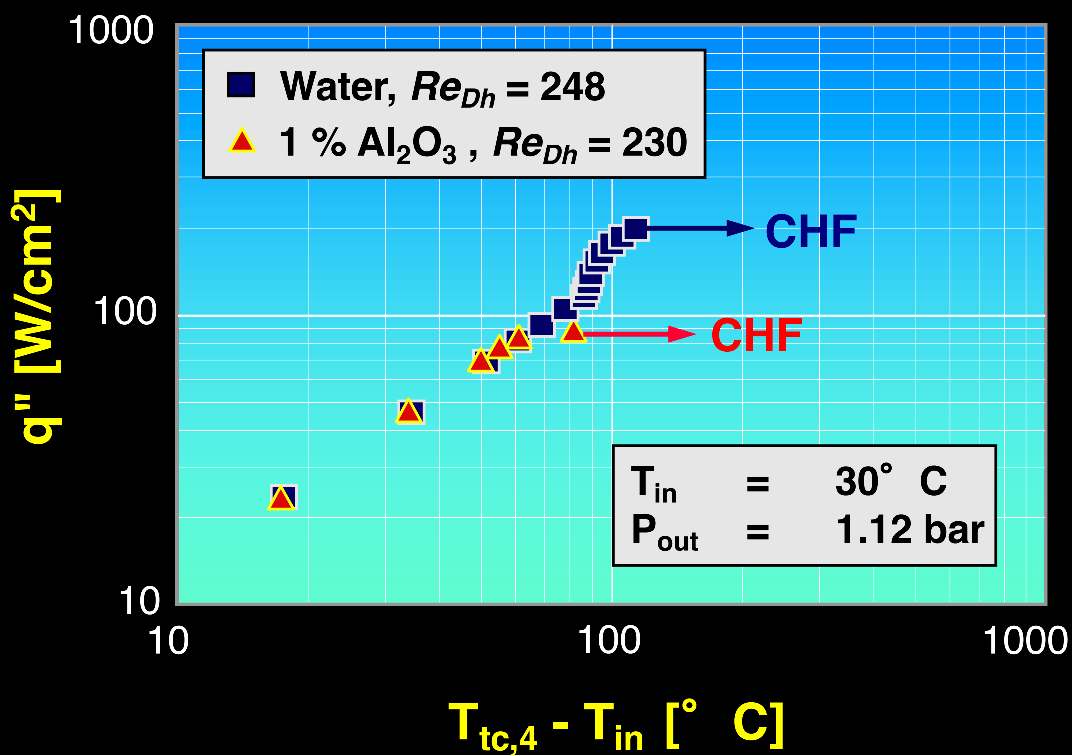


Dominant 'fish-scale' pattern

G = 368 kg/m^2.s, T_{in} = 30° C, after 5 tests

Khanikar, Mudawar & Fisher (2009)

Boiling Configurations: Mini/Micro-channel Flow/Nano Particles



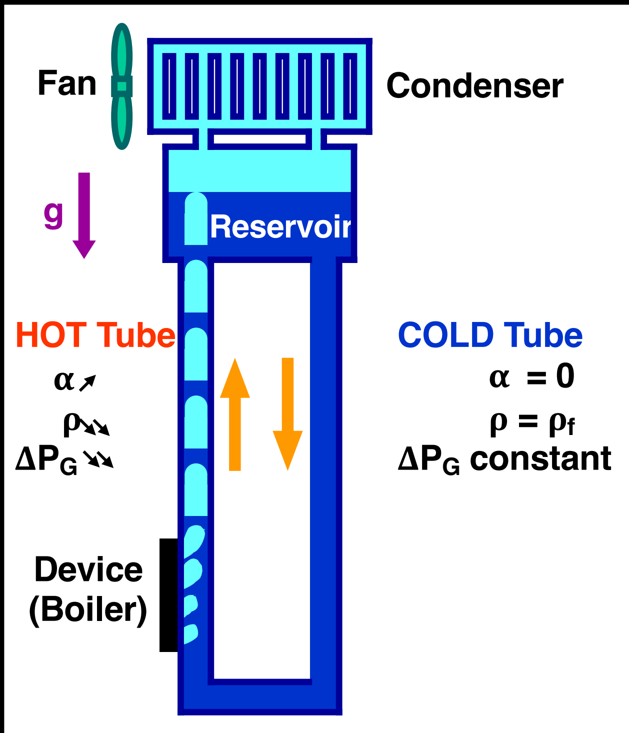
- Stable flow boiling never achieved due to CHF occurrence shortly following onset of boiling
- Severe nano particle deposition inside micro-channels
- Particle clustering began forming at channel outlet, then propagated rapidly upstream
- Temperature of heat sink rose continuously after particle clogging

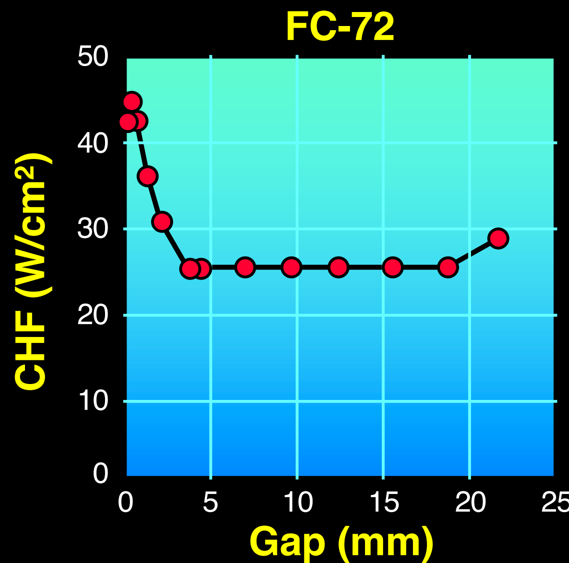
215 µm x 821 µm

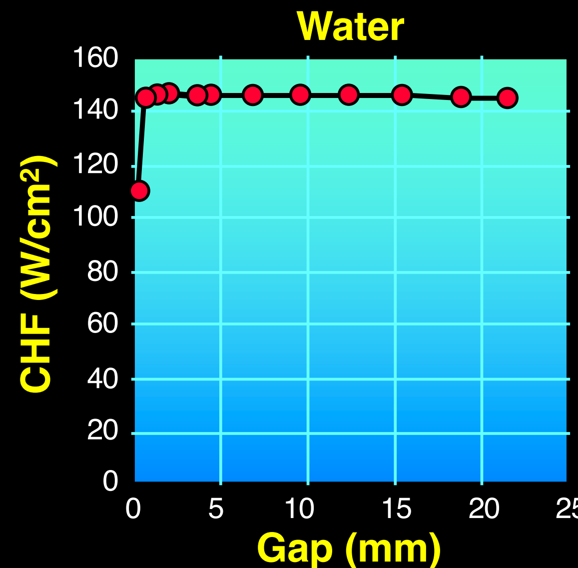
Enhancement efforts should focus on surface itself, not fluid!

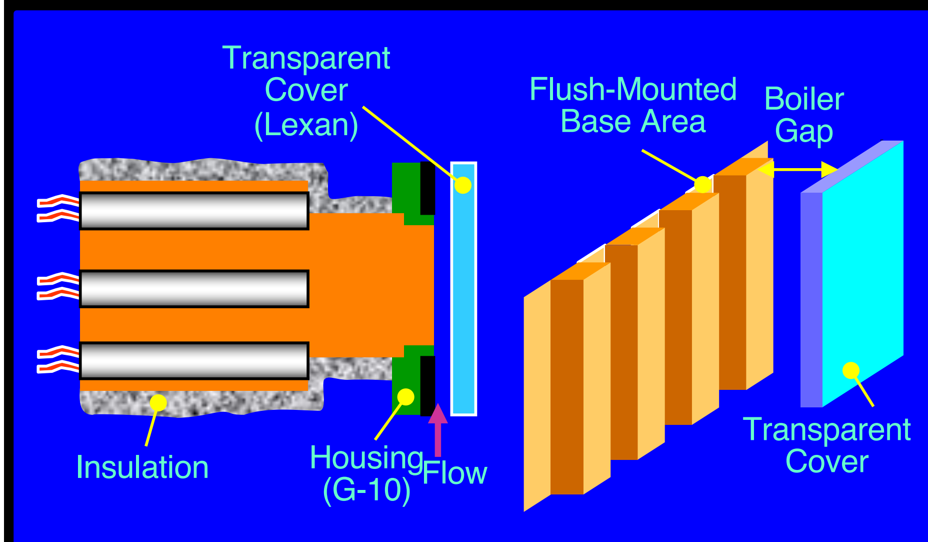
Lee & Mudawar (2006)

Boiling Configurations: Mini/Micro-channel Flow using Smart, Pump-Free Loop









FC-72
0.51 mm gap
50% CHF

Water
0.13 mm gap
50% CHF

Mukherjee & Mudawar (2003)

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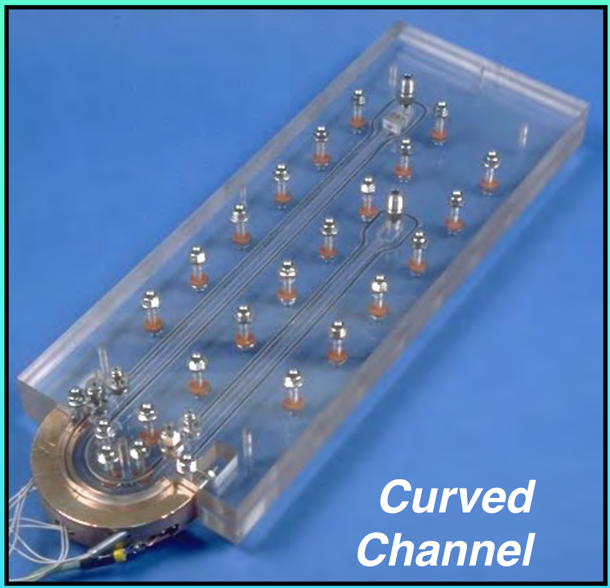
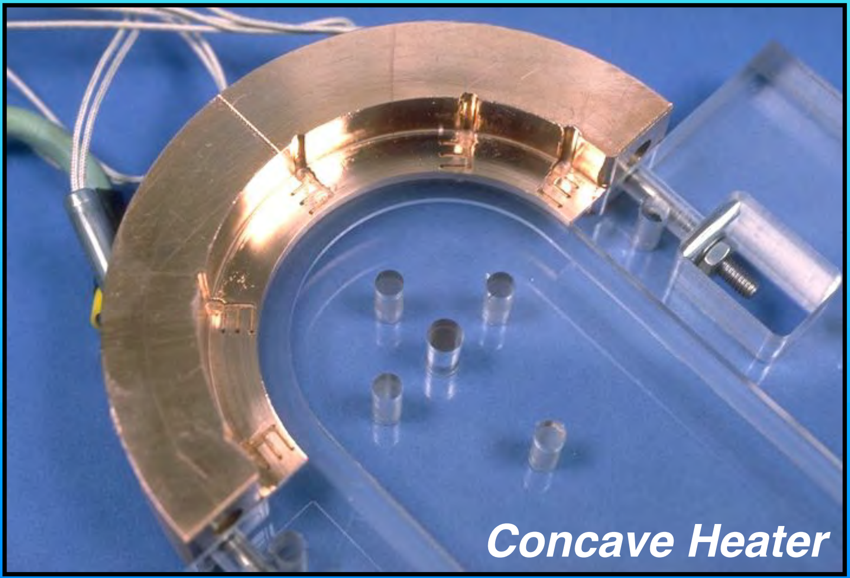
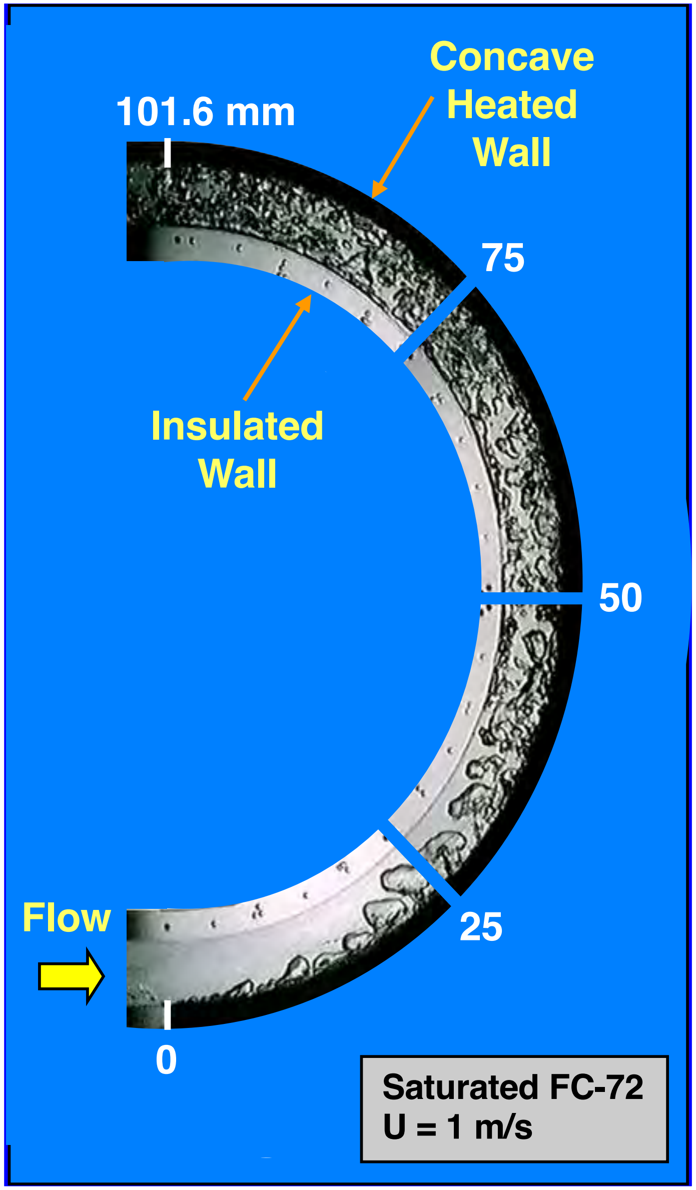
Boiling Configurations: Curved Channel Flow

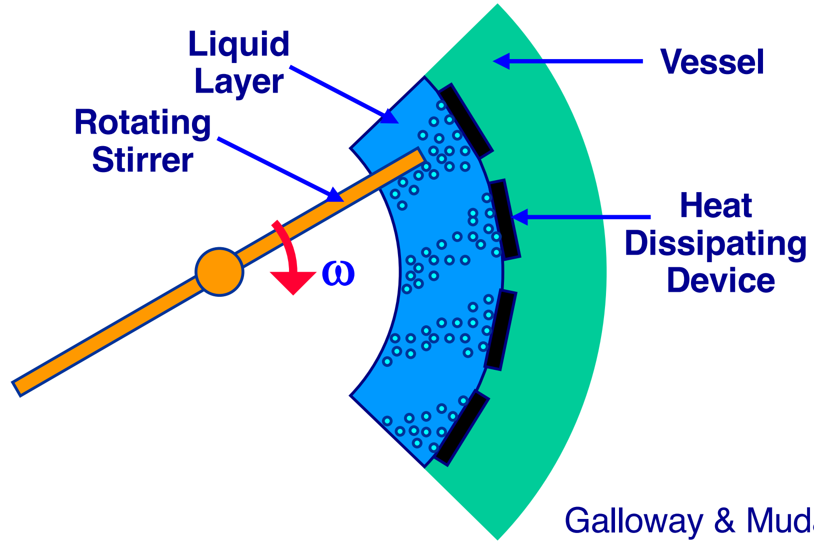




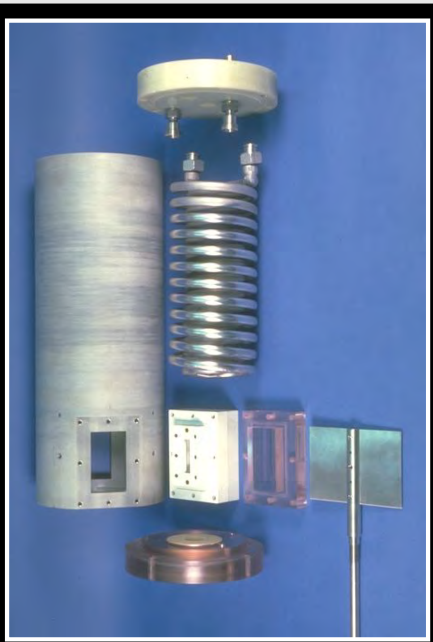


Galloway & Mudawar (1995)

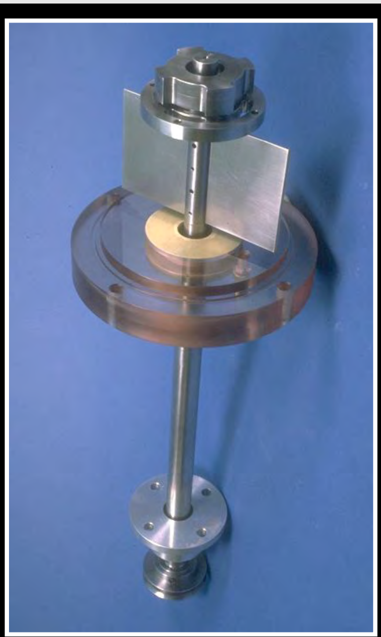
Boiling Configurations: Centrifugal Flow



Galloway & Mudawar (1992)

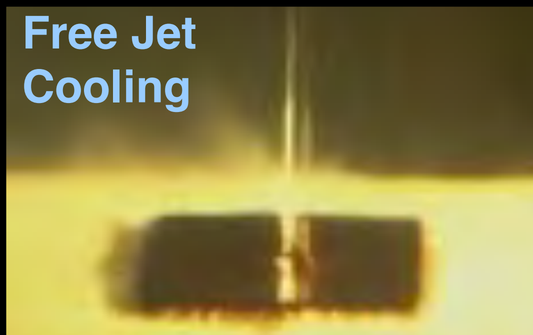


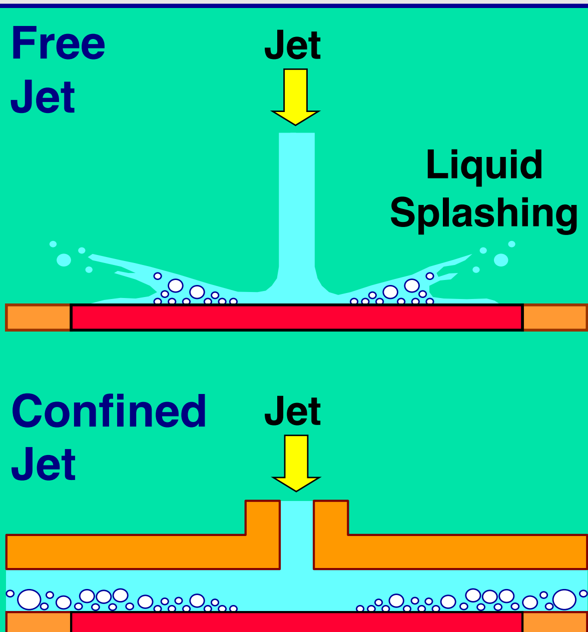
Test Apparatus



Stirrer Assembly

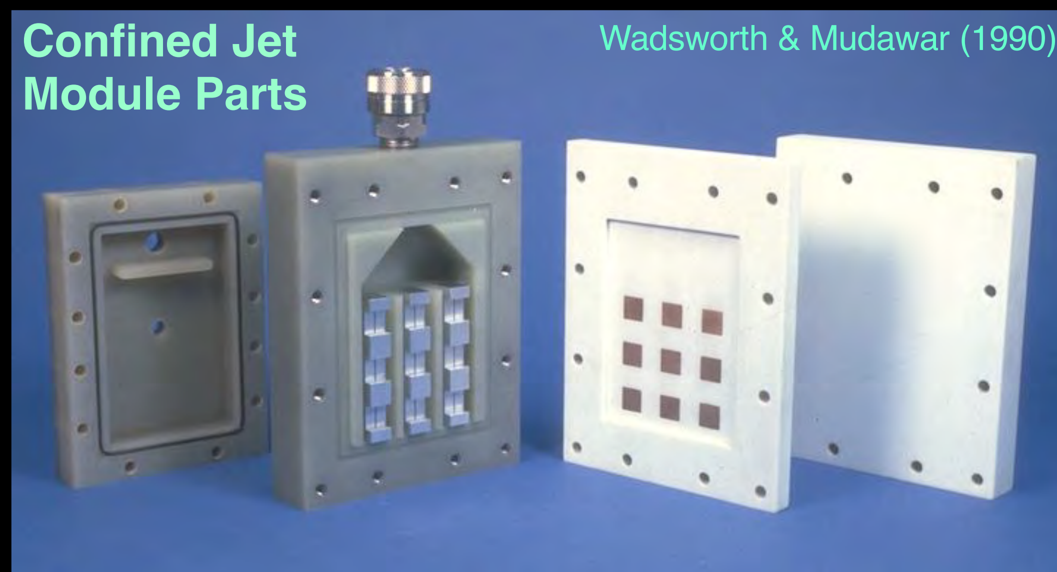
Boiling Configurations: Jet Impingement



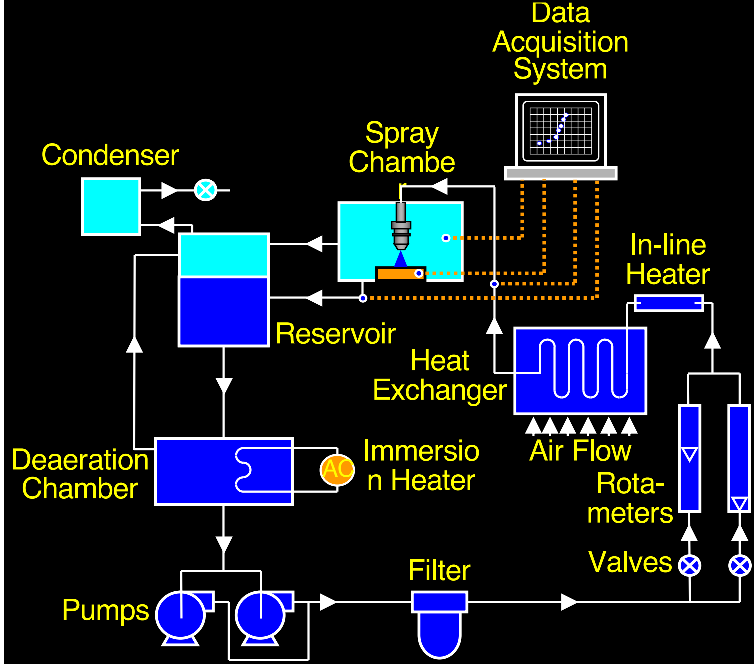


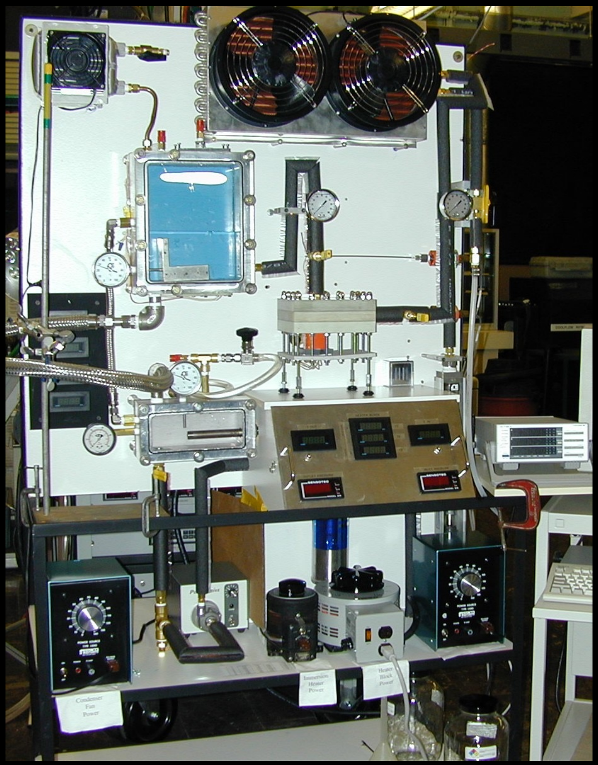
Estes & Mudawar (1995)

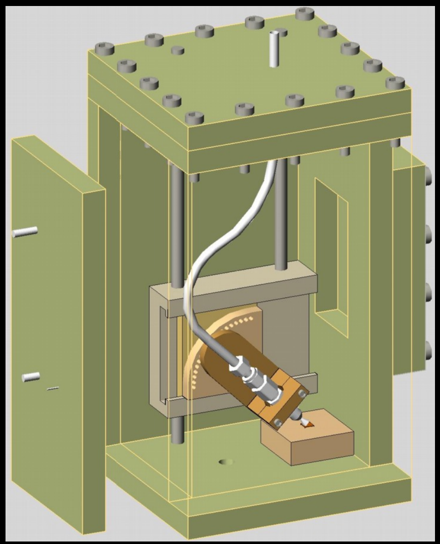
Highest CHF of 411 W/cm^2 achieved with subcooled flow boiling FC-72 & Surface Enhancement

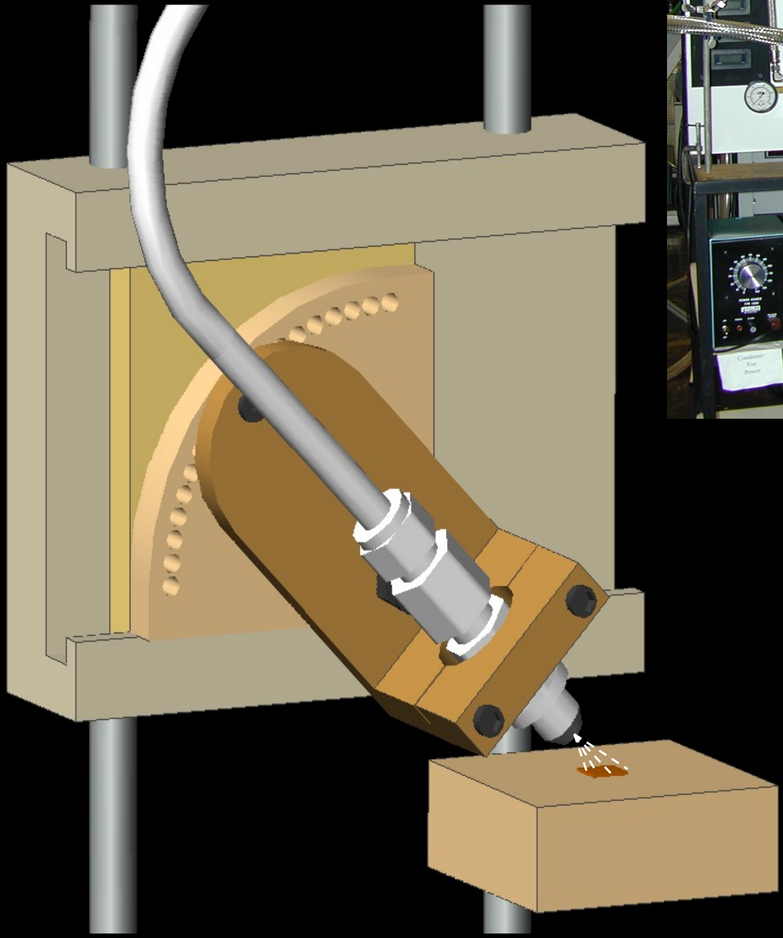


Boiling Configurations: Spray Cooling









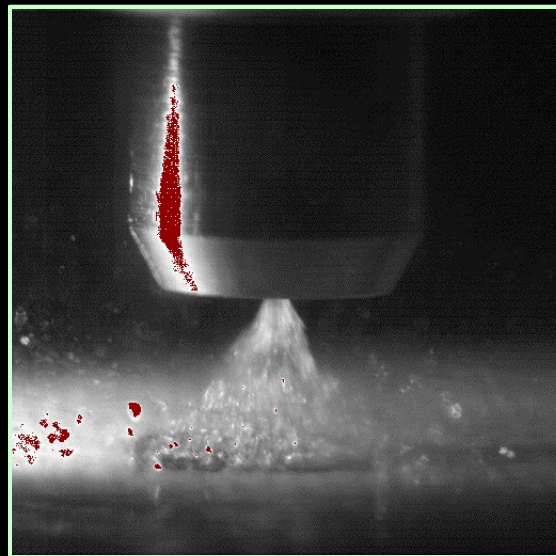
Visaria & Mudawar (2008)

Boiling Configurations: Spray Cooling

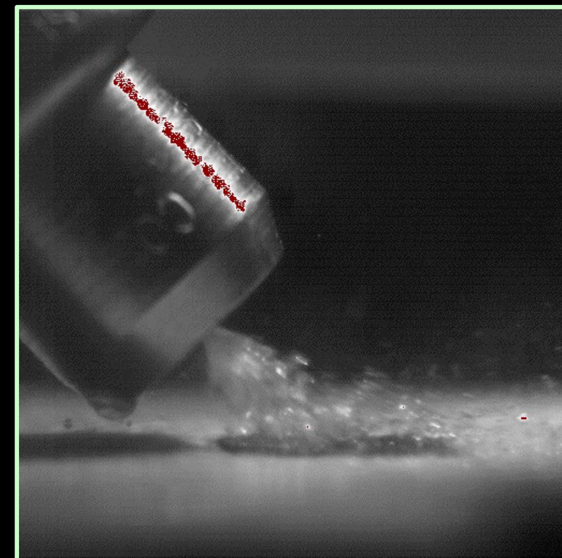
Nozzle 1 ($\alpha = 55.8^\circ$)
PF 5052 ($T_{sat} = 50^\circ$ C)
$T_{in} = 24^\circ$ C
$Q = 3.86 \times 10^{-6}$ m^3/s

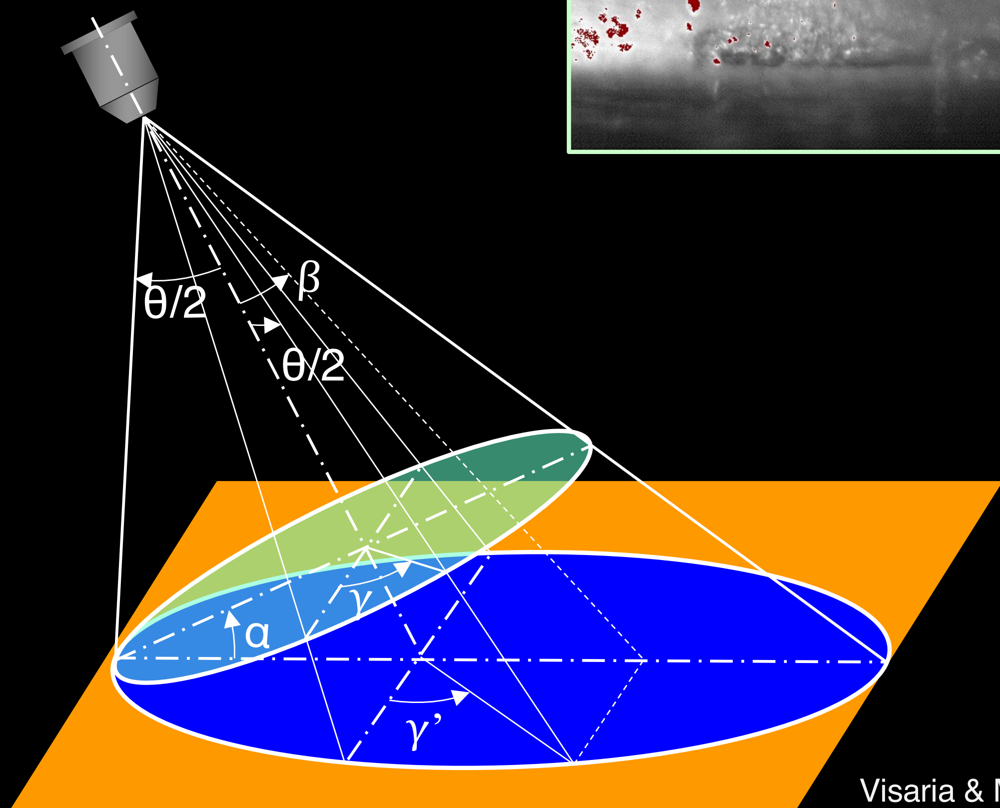
Recording speed: 6000 fps
Playback speed: 60 fps

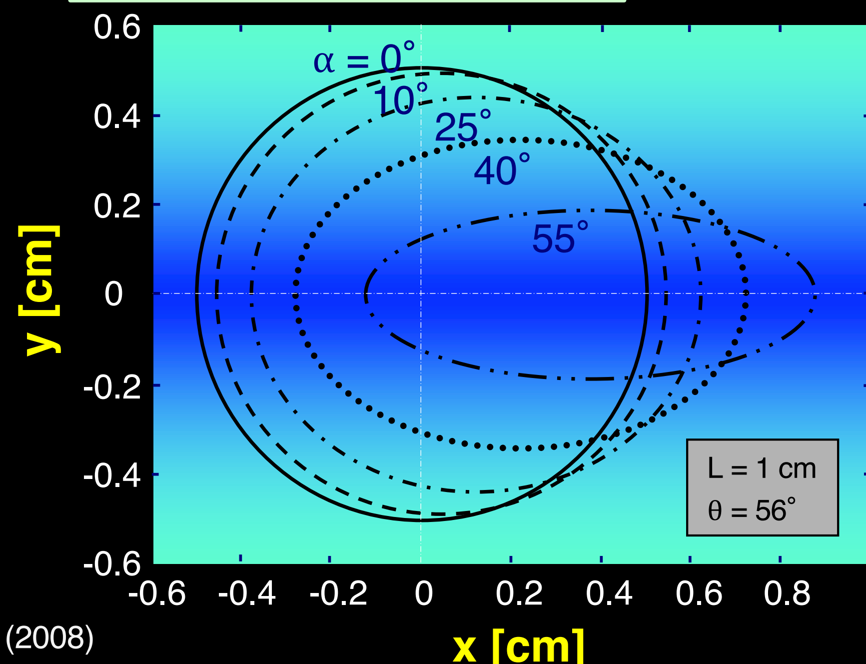
$\alpha = 0^\circ$



$\alpha = 50^\circ$







Visaria & Mudawar (2008)

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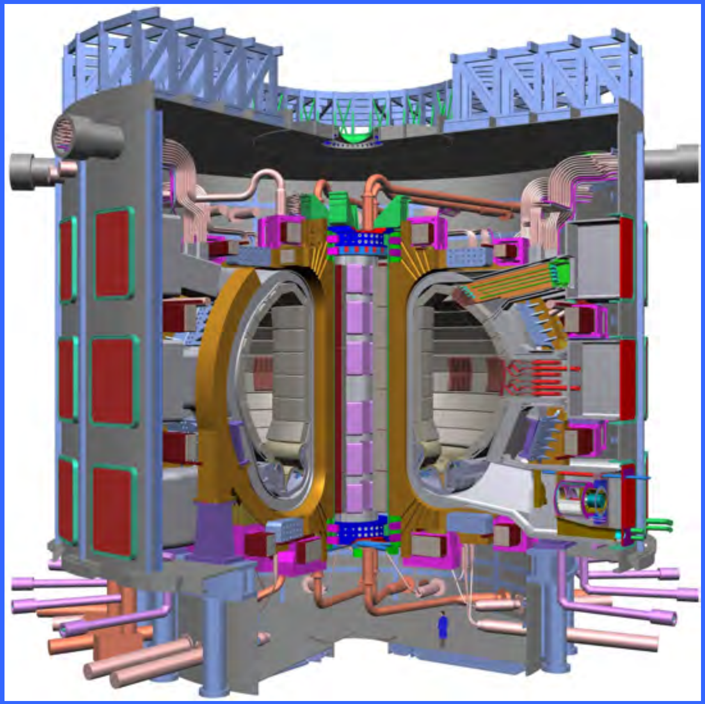
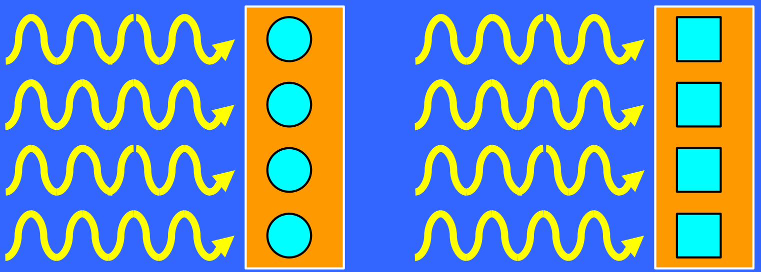
BTPFL Applications

Applications: Very-High-Flux Fusion Reactors, Particle Accelerators & MHD Generators

Fusion Reactor Blanket



International Thermonuclear Experimental Reactor (ITER)



Heat flux in cooling channels can exceed 10^4 W/cm^2

- Magnetic containment of plasma in donut-shaped vacuum vessel (tokomak)
- Fusion reactor blanket extracts fusion power to generate electricity
- Highly subcooled water cooling at high pressure and high mass velocity required to guard against CHF

Particle Accelerator Target

MHD Electrode Walls

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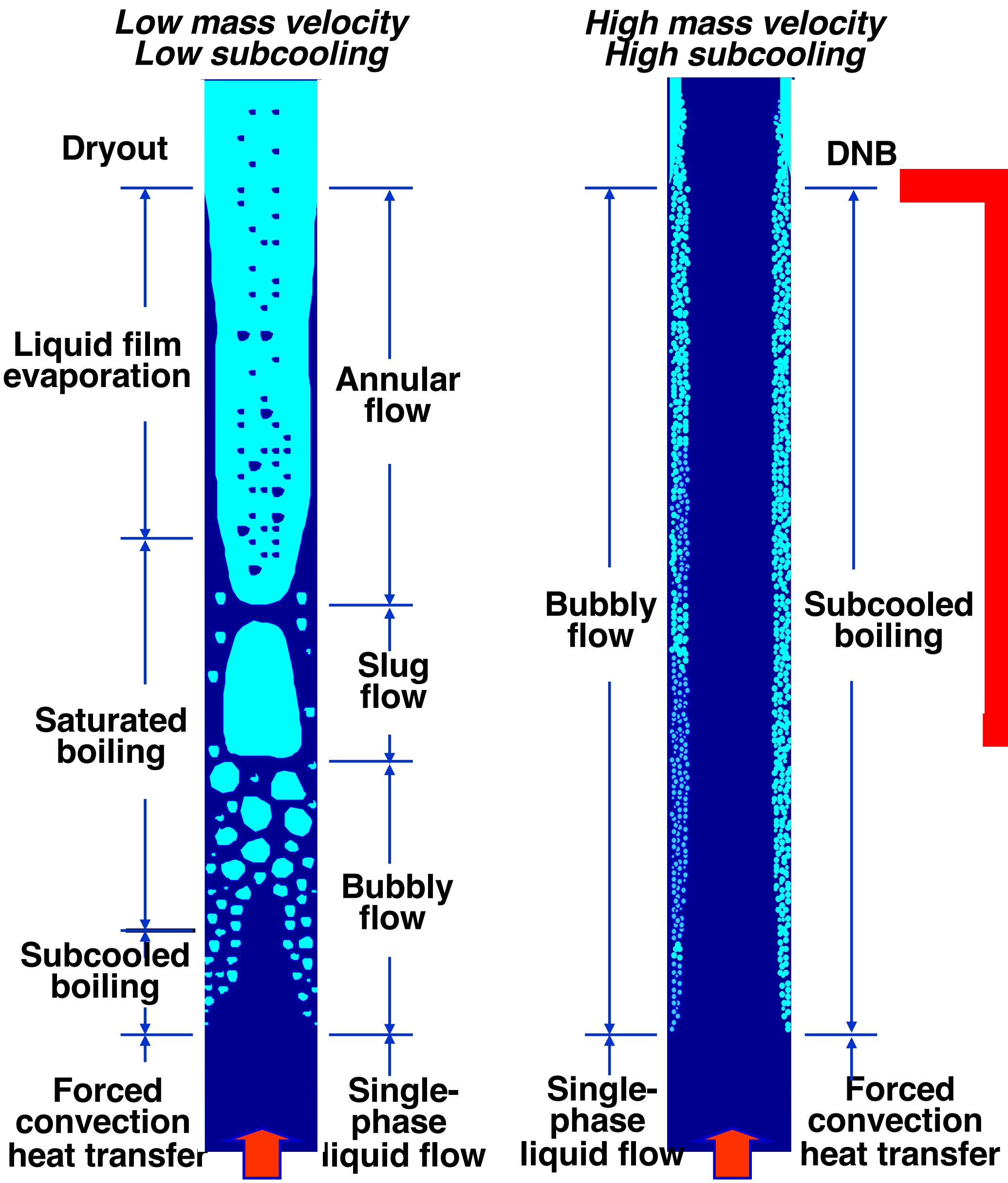
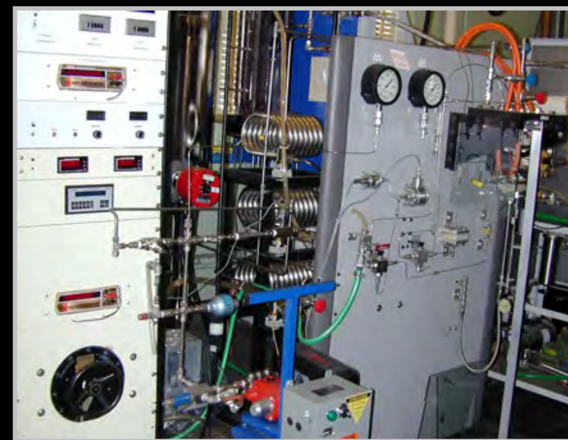
Applications: Very-High-Flux Fusion Reactors, Particle Accelerators & MHD Generators

Ultra-High-Flux Flow Boiling in Micro-Channels

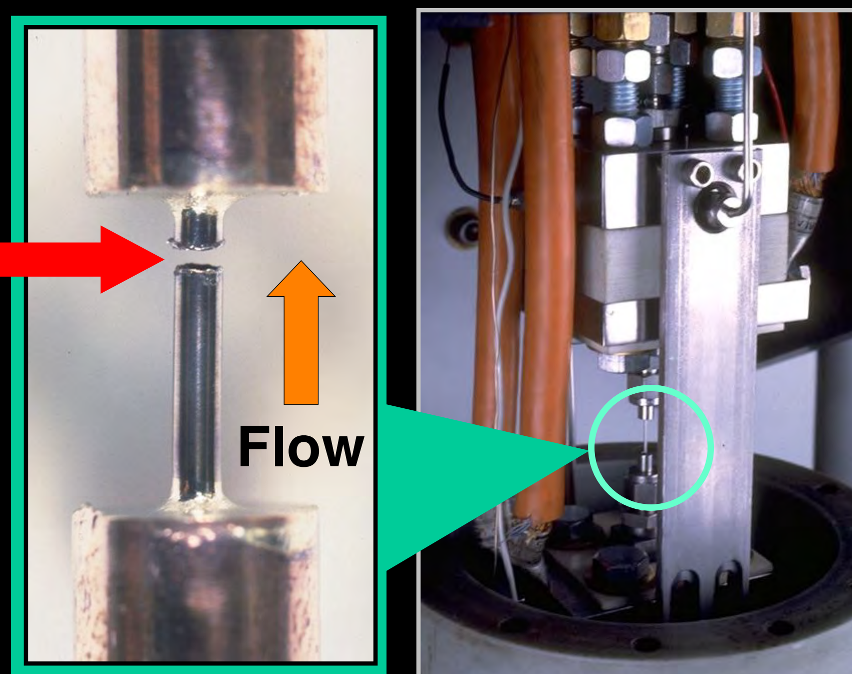


CHF = 27,600 W/cm^2 demonstrated experimentally



G = 120,000 kg/m^2.s

D = 0.406 mm



Mudawar & Bowers (1999)

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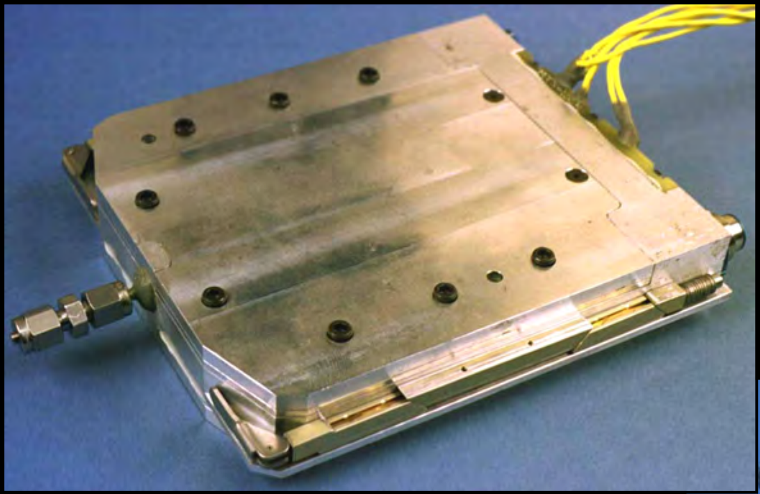
Applications: Avionics

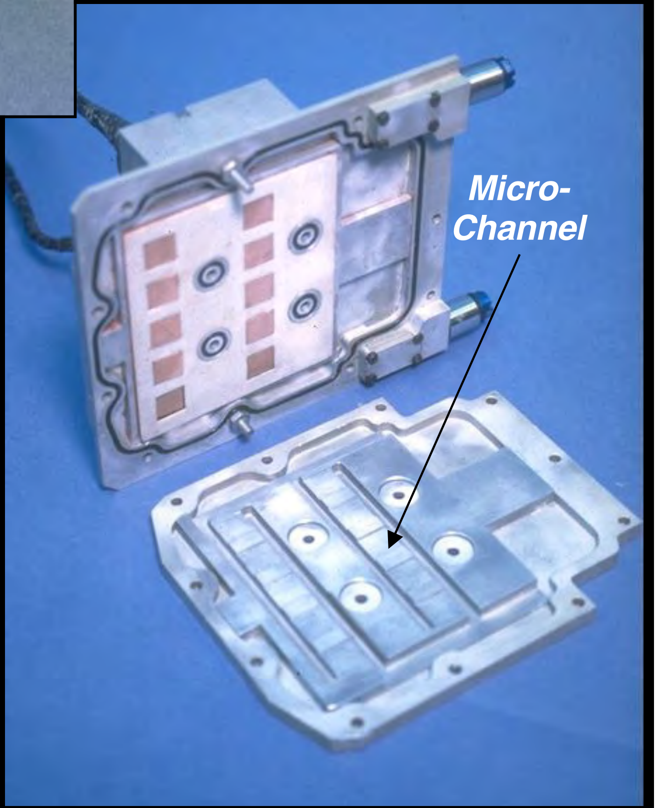
- **40 W cooling capacity for conventional 5.38 x 6.41 x 0.59 in^3 edge air-cooled module**
- **200 W capacity for equivalent flow-through polyalphaolafin (PAO) module**

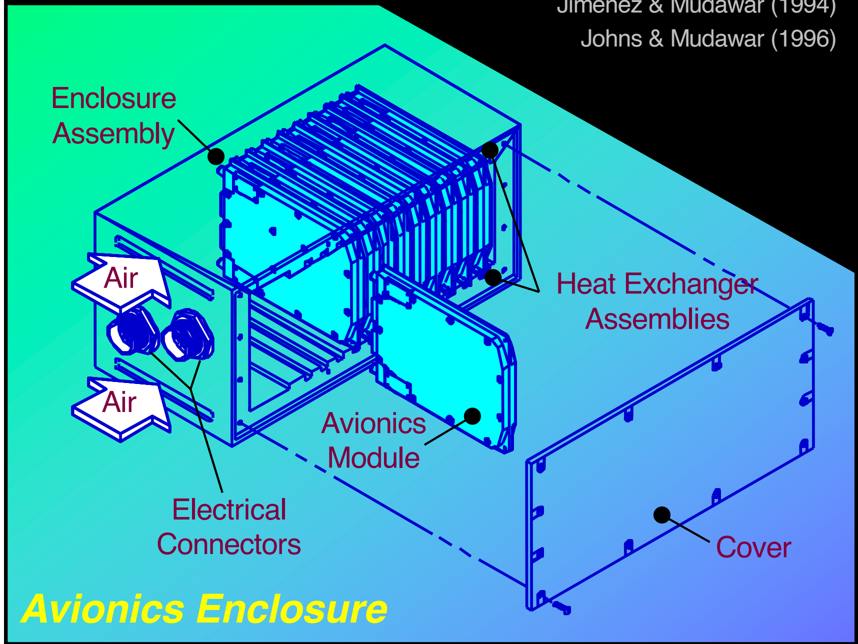
BTPFL-C3
12 kW Jet-Impingement
Clamshell Module



Mudawar, Jimenez & Morgan (1994)
Jimenez & Mudawar (1994)
Johns & Mudawar (1996)

BTPFL-C2
3 kW Micro-Channel
Clamshell Module





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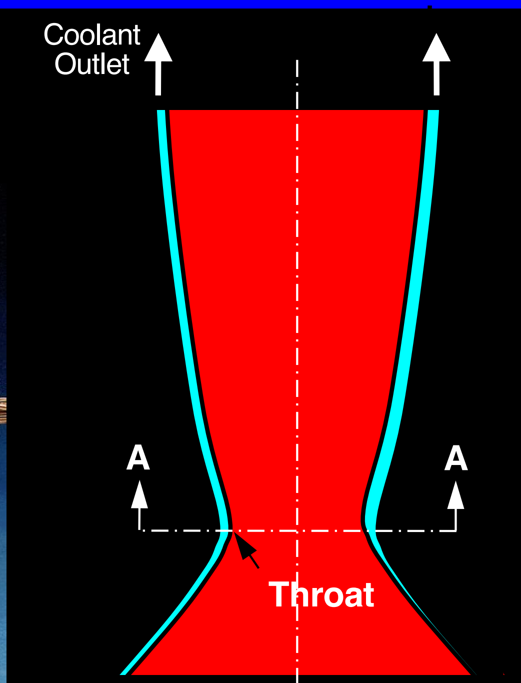
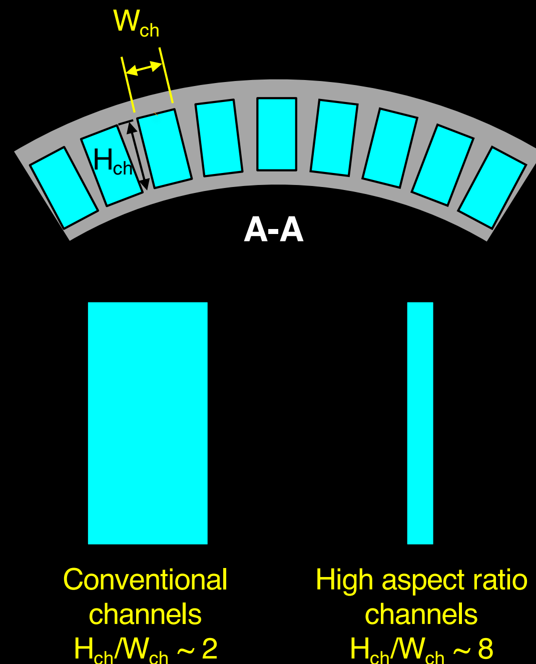
Applications: Boiling in Rocket Engines, Turbine Blades

NASA rocket engine with high aspect ratio cooling channels

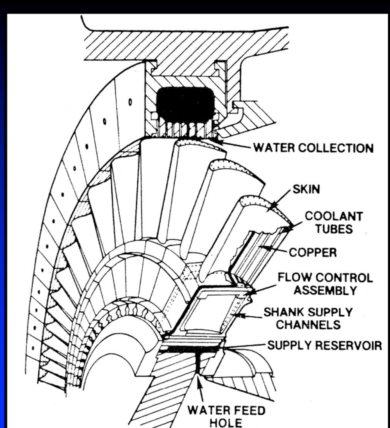


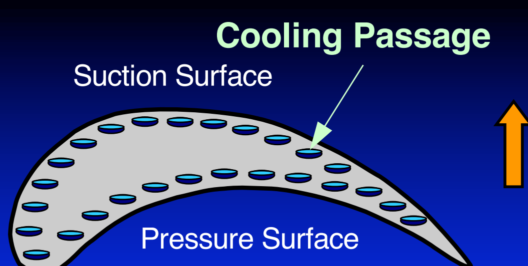
Hydrogen/oxygen liquid rocket engine with walls cooled by hydrogen



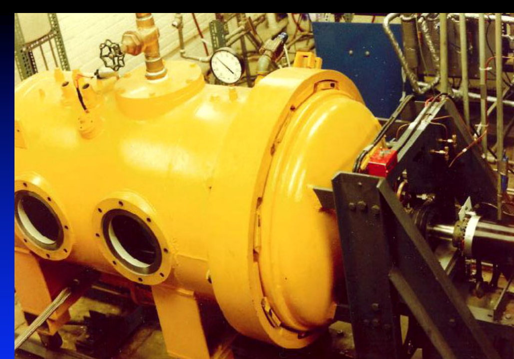
$$\varepsilon = (2k_w / h W_w)$$

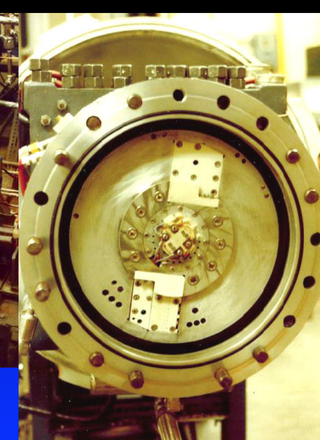
- Engine life doubled by decreasing wall temperature by 50-100° C
- Cooling performance in wall enhanced by using closely-spaced micro-channels separated by thin walls
- Depending on rocket engine type, boiling may or may not be desirable





Combined effects of centrifugal and Coriolis forces help achieve 4500 W/cm^2 inside blade





M.I.T. Gas Turbine Lab

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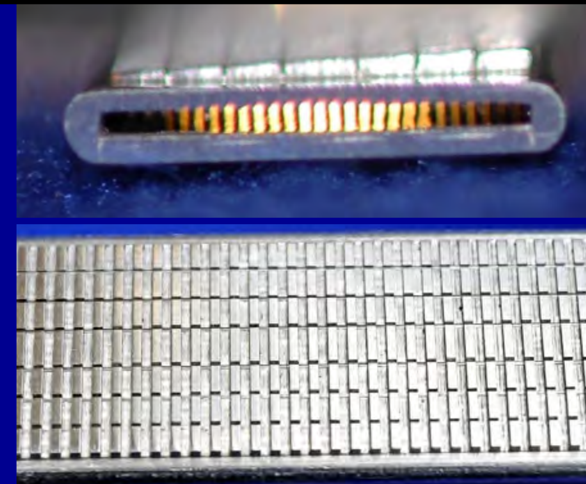
Applications: High Mach Turbine Engines, Radar, Laser & Microwave Systems

Nacke, Northcutt & Mudawar (2011)



Micro-Channel Cross-Flow Air-to Fuel (JP-8) Heat Exchanger

High-Power Laser, Radar and Microwave Systems

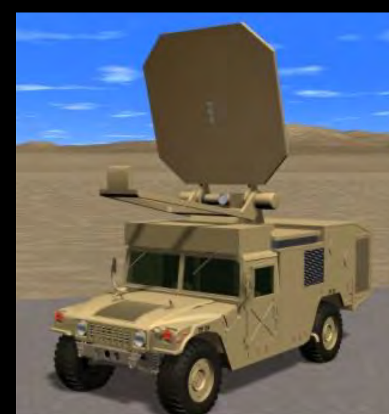
Power Supply
1 MW Total
→
Diode Array
50% efficient
500 kW Total
→
Solid State Crystal
20% efficient
100 kW Total
→ 100 kW Laser output

Diode Array ↓ 500 kW of Waste Heat

Solid State Crystal ↓ 400 kW of Waste Heat

Waste heat from high power diode pumped solid state laser

Mudawar (2001)



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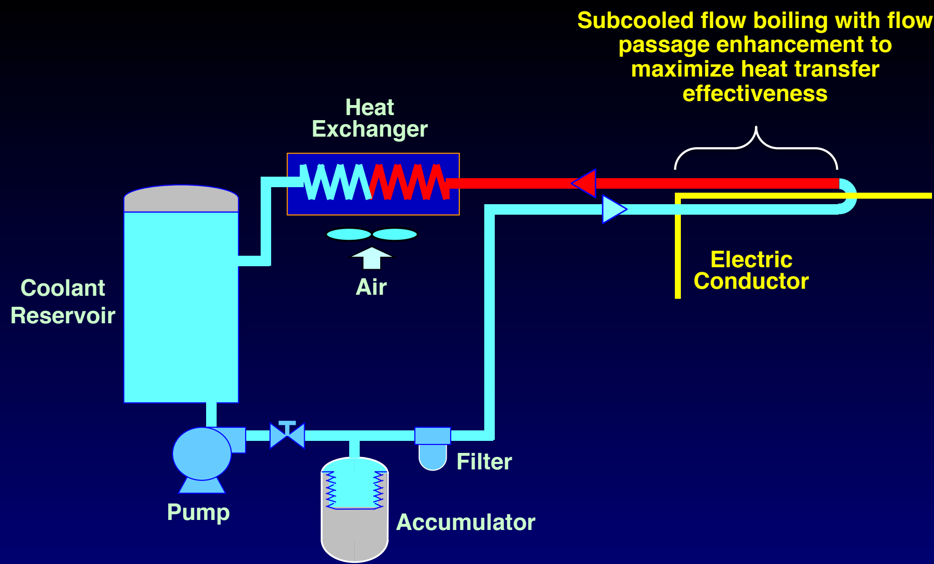
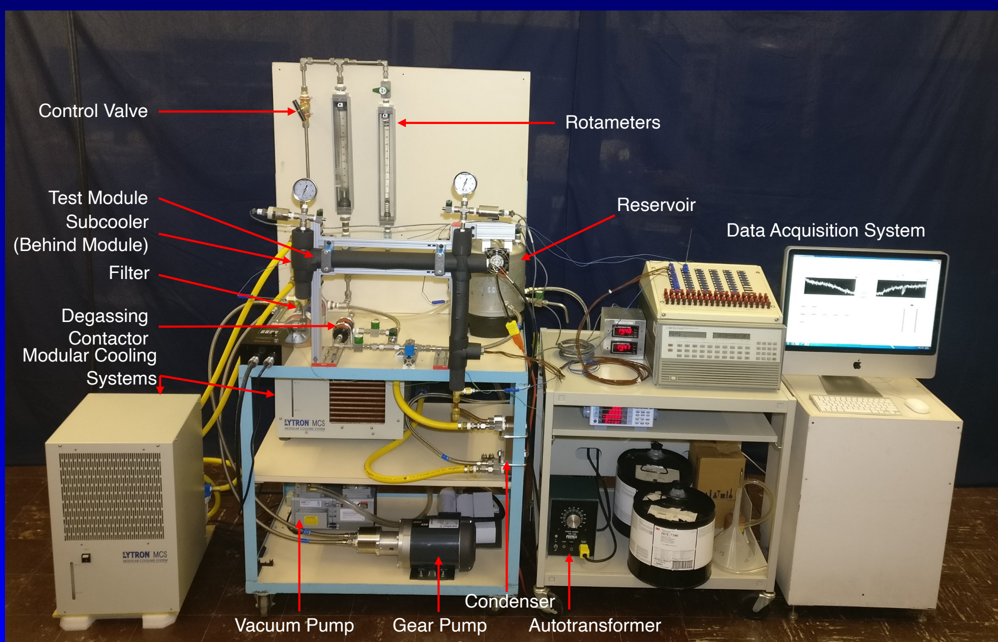
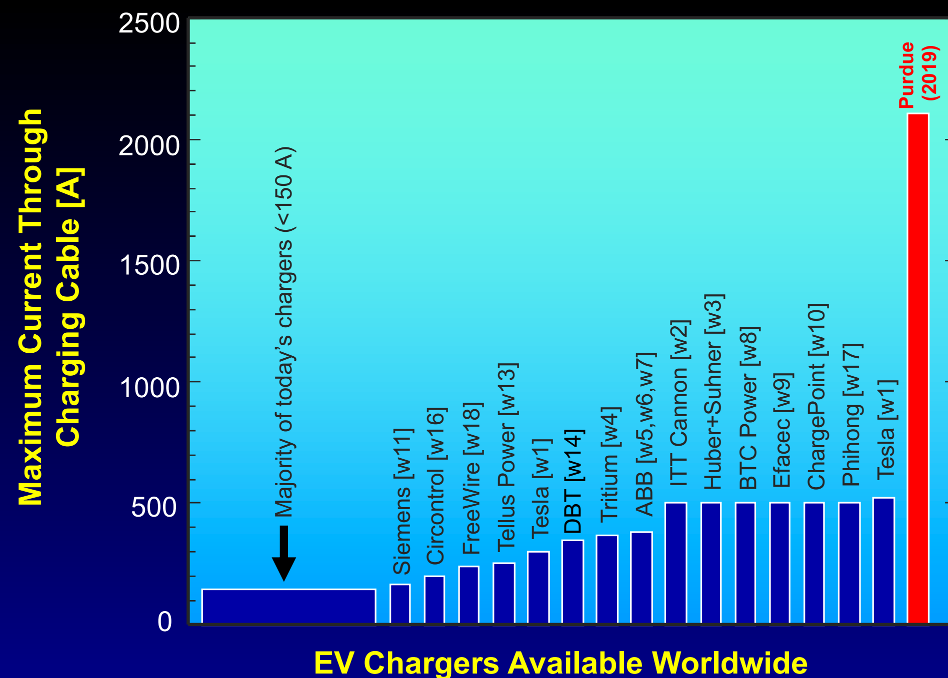
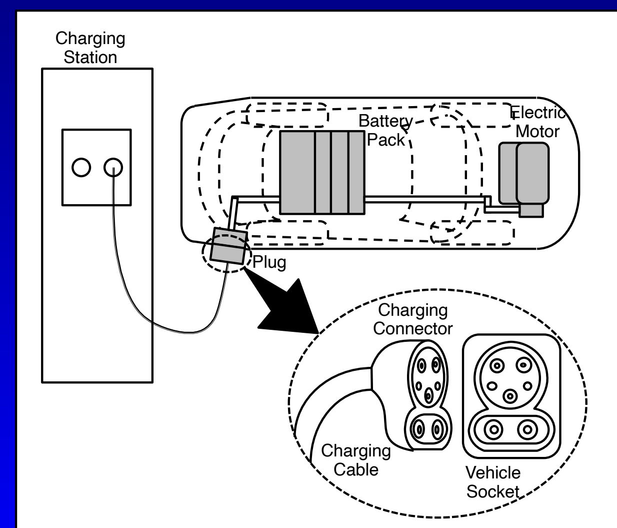
Applications: 5-Minute Charging of Electric Vehicles



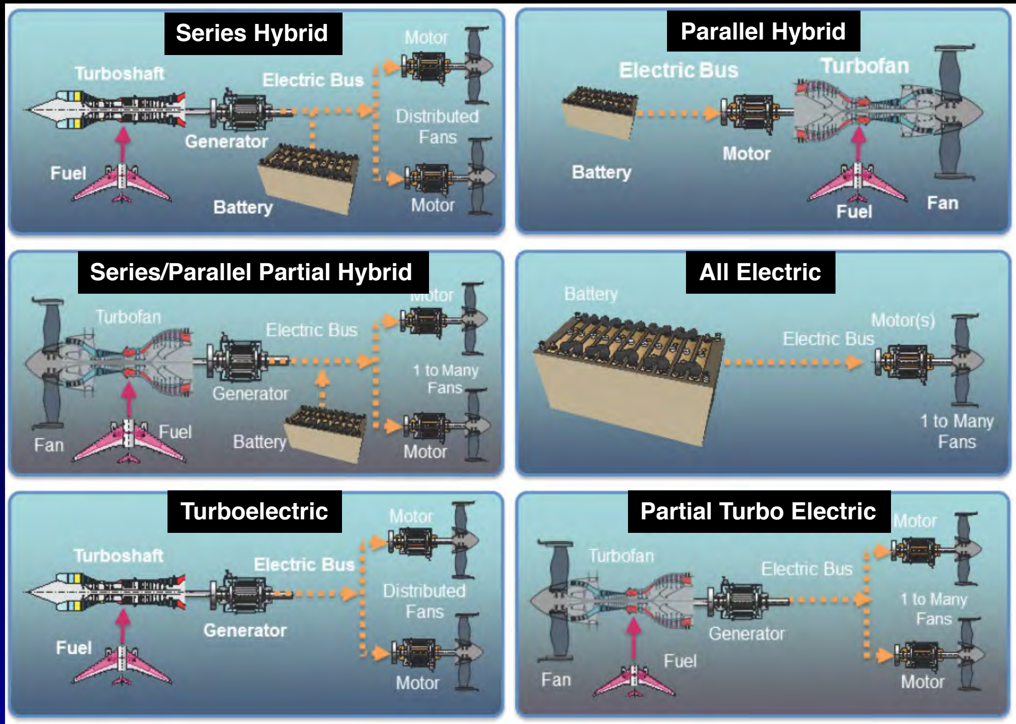


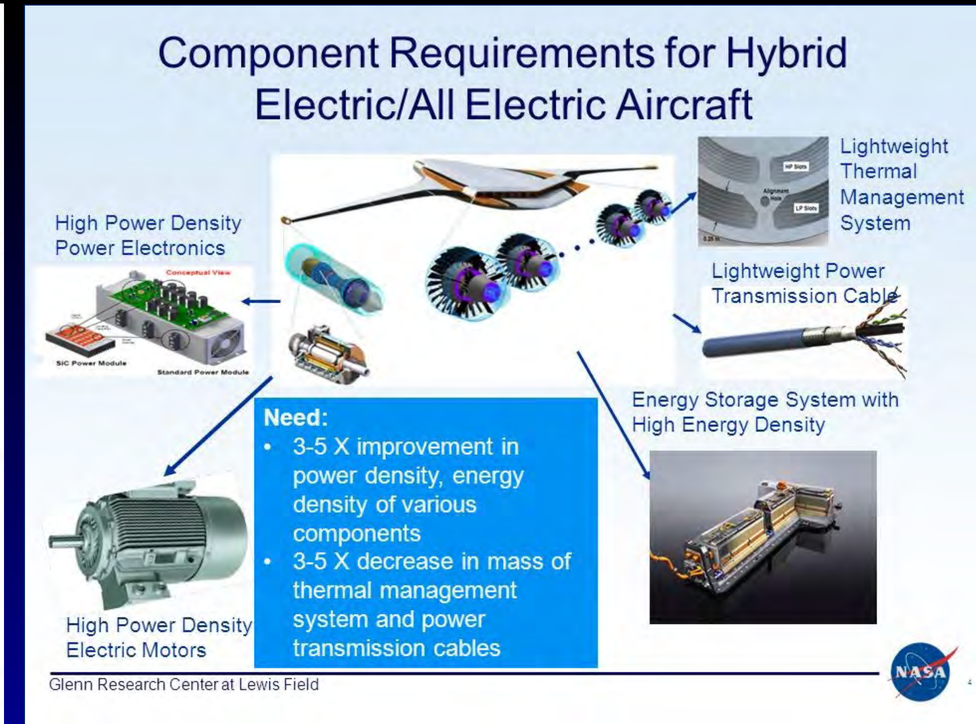




Research Presentation

Applications: Hybrid & All-Electric Aircraft



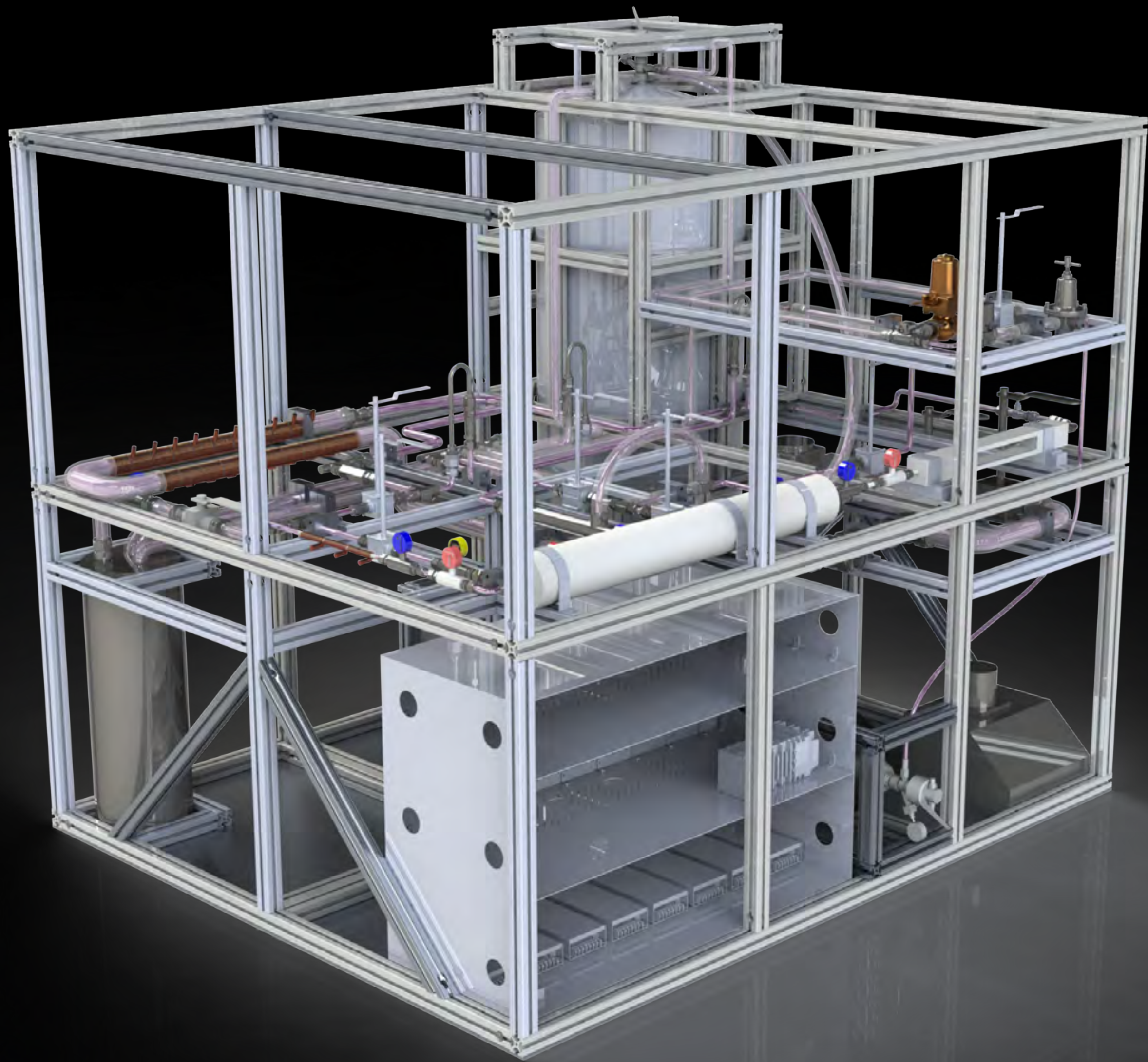


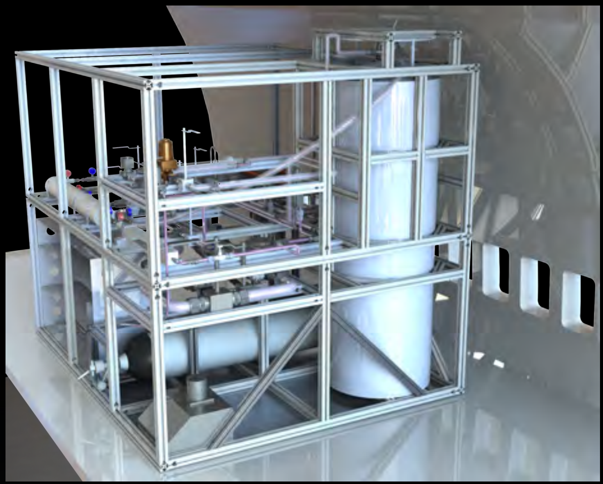
Immediate Goals: High-flux liquid cooling of

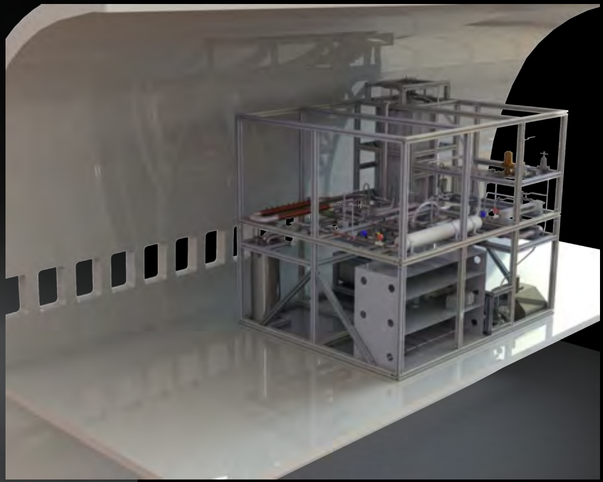
- Power electronics
- Motor
- Power transmission cable
- Other components important to industry partners

Research Presentation

Applications: Cryogenic Thermal Management







Research Presentation

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Flow Boiling & Condensation Experiment (FBCE) for the International Space Station (ISS)

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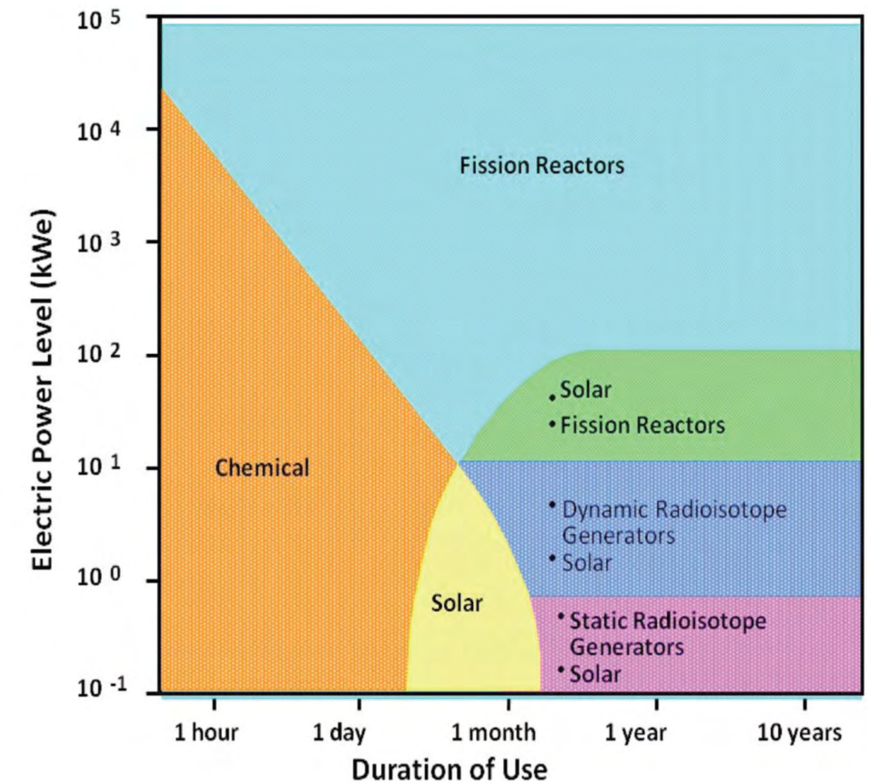
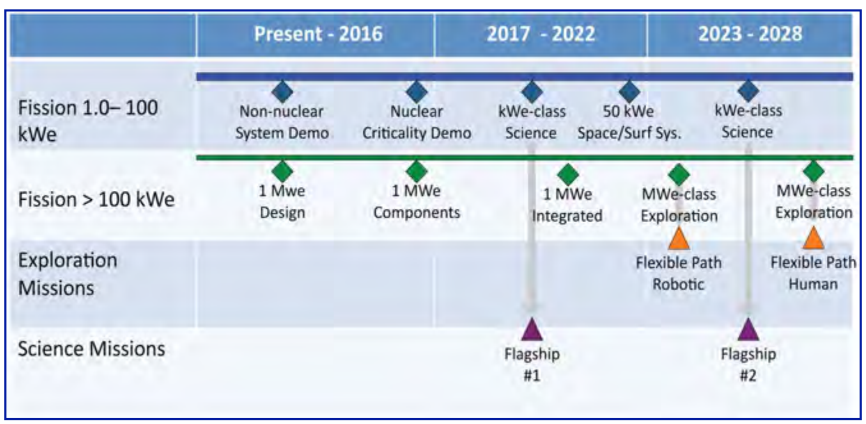
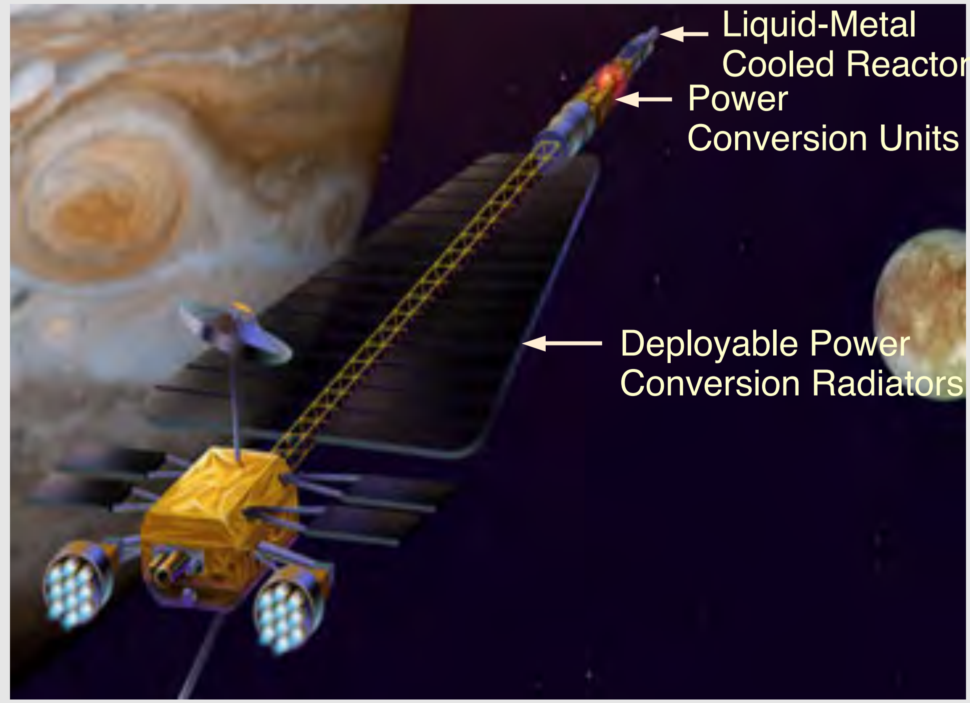
FBCE Applications: Nuclear Fission/Rankine Power Cycle for Future Space Missions



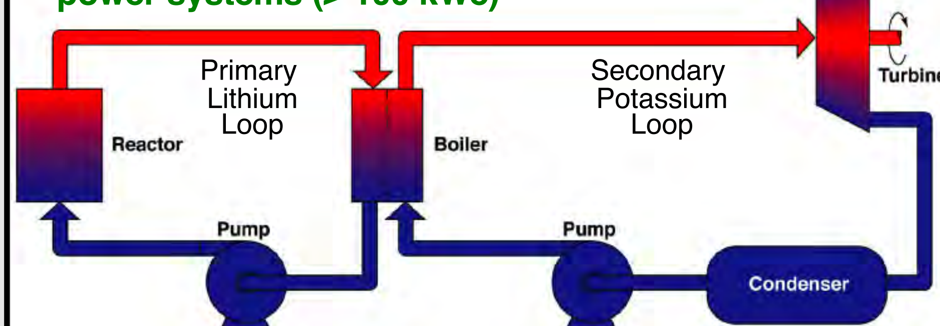


Project Prometheus:

Developing means to efficiently power advanced spacecraft for Solar System exploration



Rankine Cycle very attractive option for high power systems (> 100 kWe)



Research Presentation

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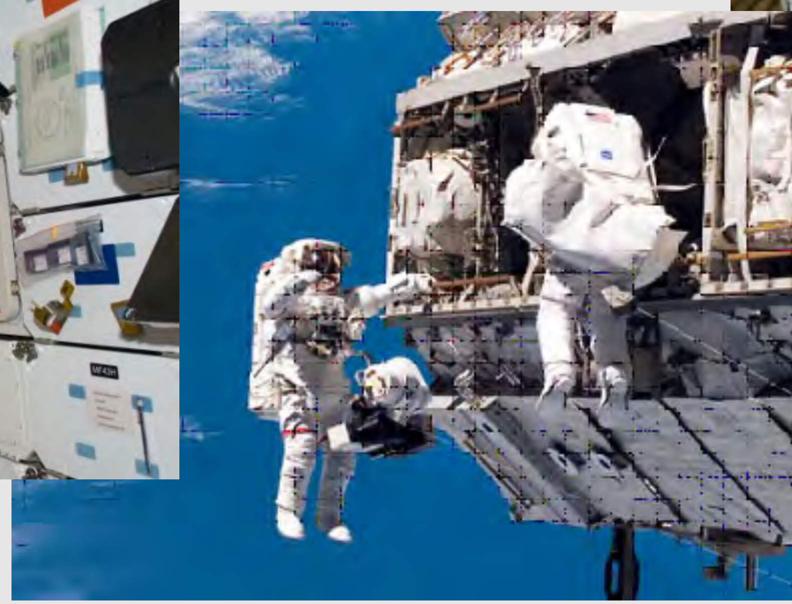
FBCE Applications: Thermal Control Systems (TCSs) & Life Support Systems for Future Space Space Missions

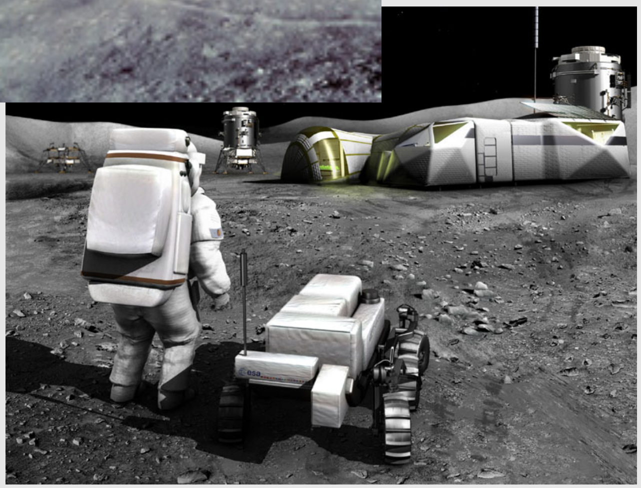
- **Thermal management systems responsible for controlling temperature and humidity using Thermal Control System (TCS) consisting of Heat Acquisition, Heat Transport and Heat Rejection hardware**
- **Refrigerator/freezer components provide cooling for science experiments and food storage**
- **Advanced water recovery systems transfer crew and system wastewater into potable water for crew and system reuse**

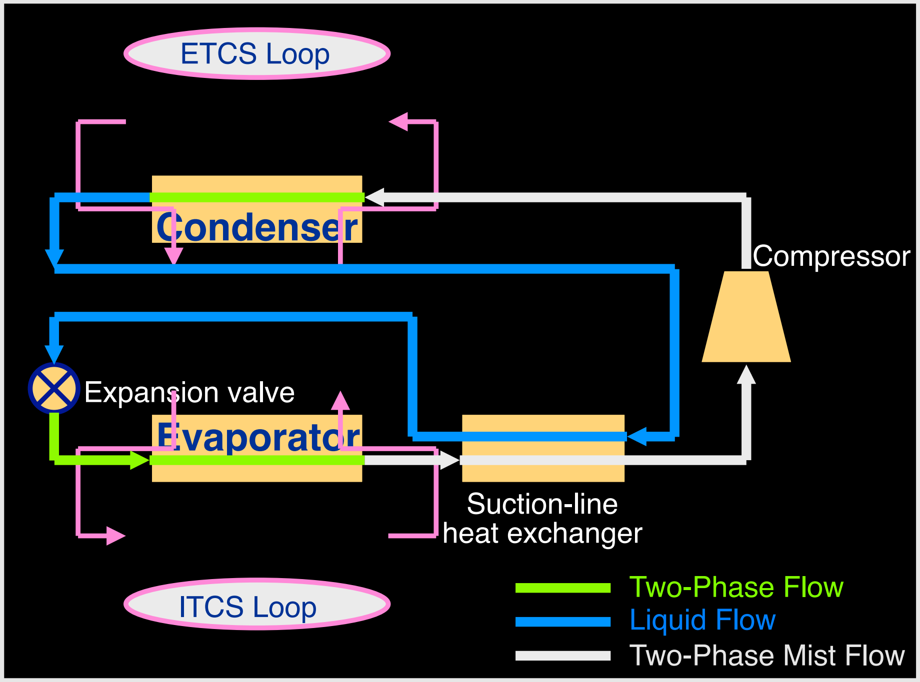


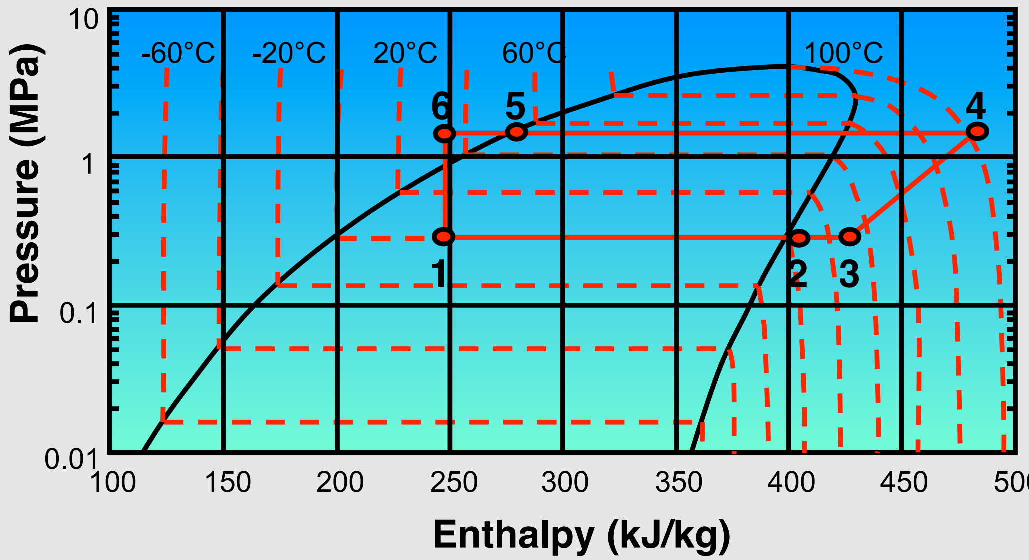
FBCE Applications: Vapor Compression Heat Pump for Future Space Vehicles Planetary Bases

NASA Johnson Space Center (JSC) Ground based Solar Heat Pump (SHP):

- Precursor to R134a vapor compression heat pump for future space vehicles and planetary bases
- Absorbs 5 to 15 kW
- Heat to evaporator provided by single-phase (liquid) Internal Thermal Control Cycle (ITCS)
- Heat from condenser by single-phase (liquid) External Thermal Control Cycle (ETCS)
- Evaporator and Condenser are SWEP Copper Brazed Plate (CBP) heat exchangers

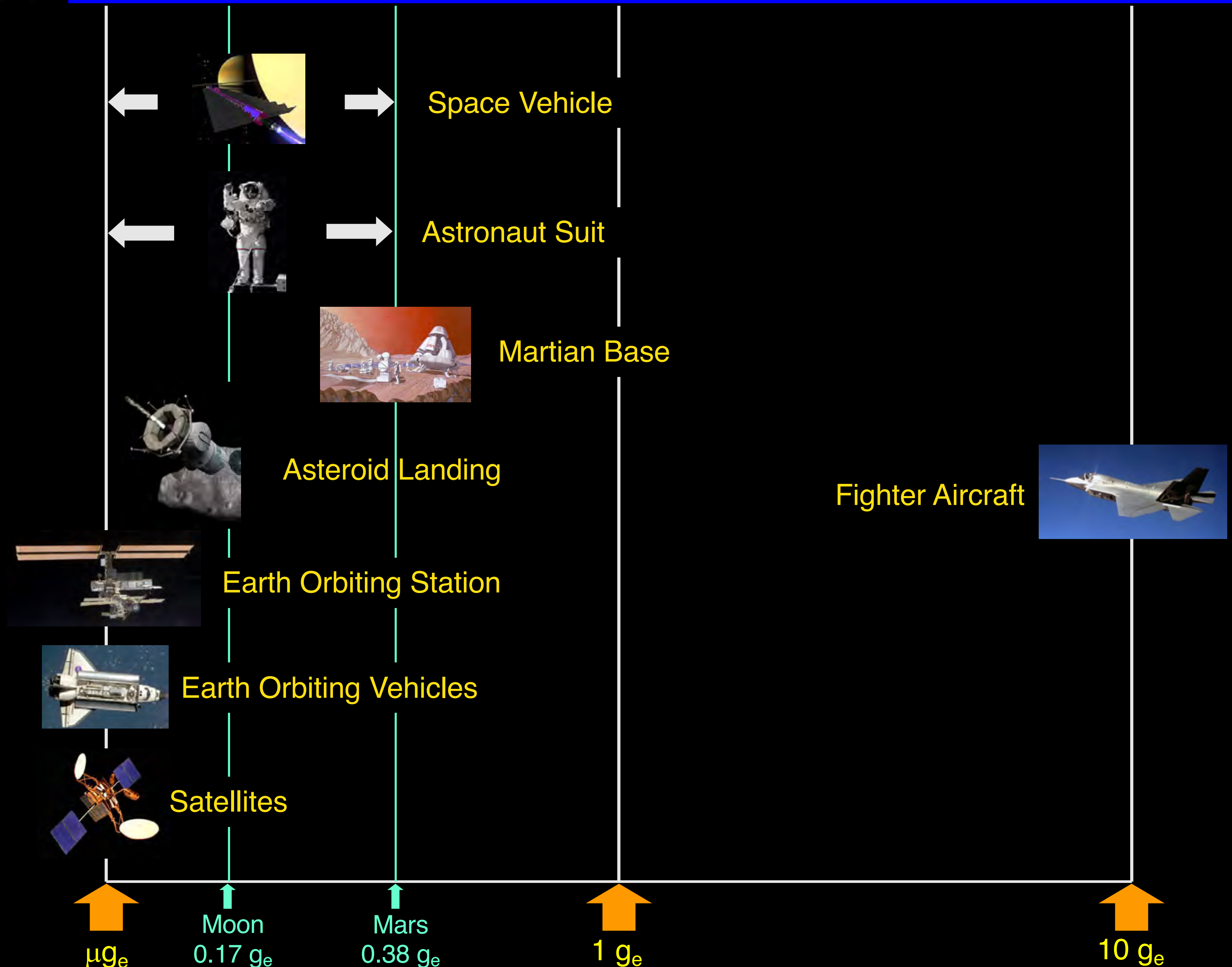




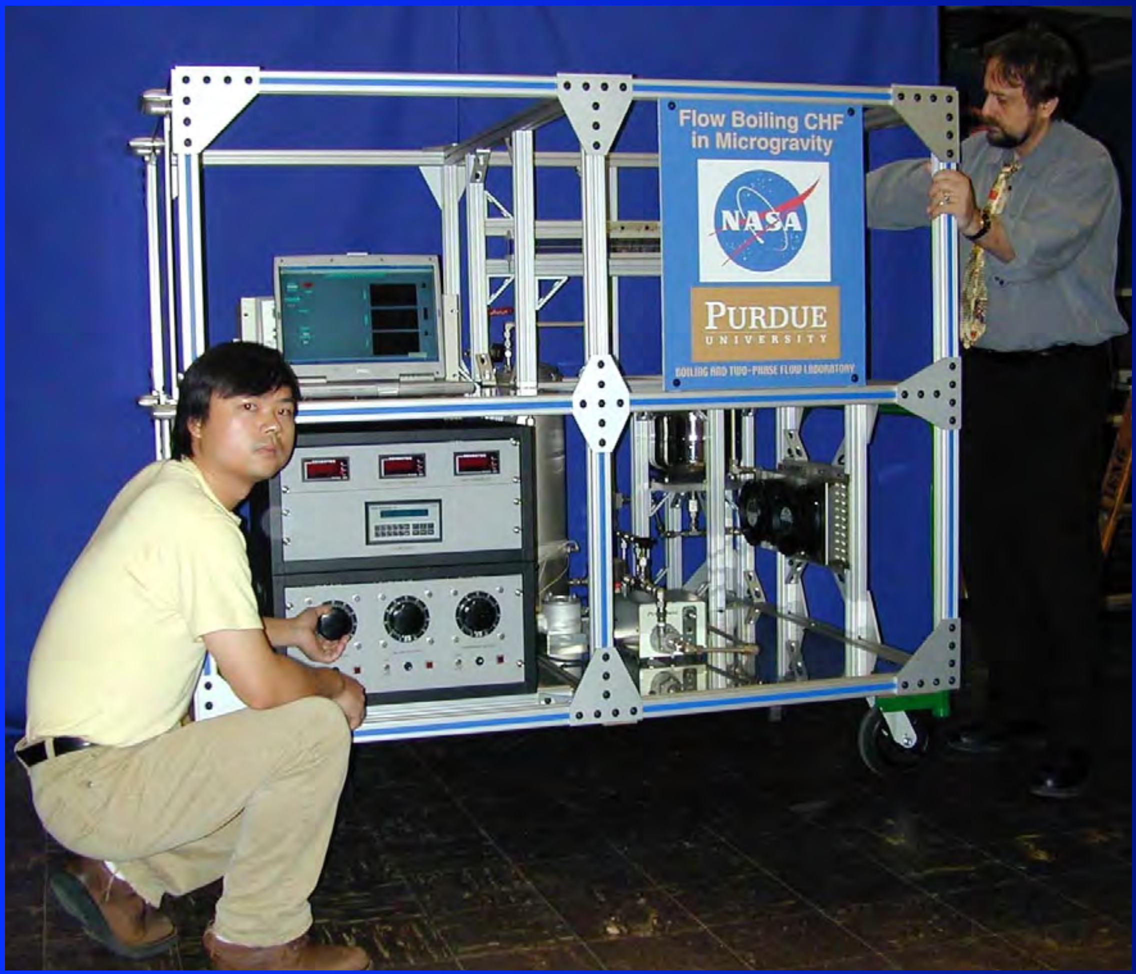


Research Presentation

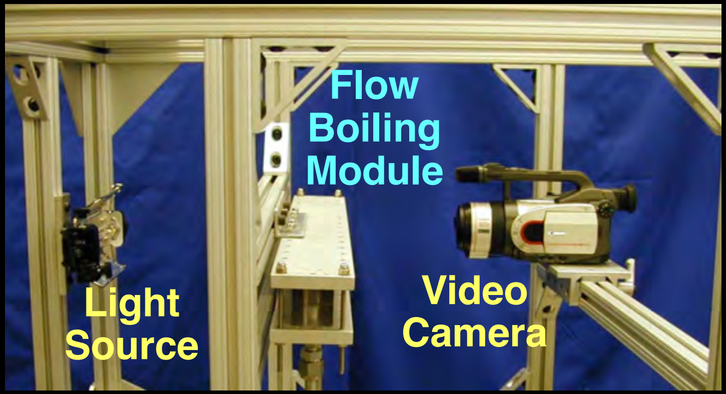
FBCE Applications: Gravity Effects on Two-phase Flow in Space Missions

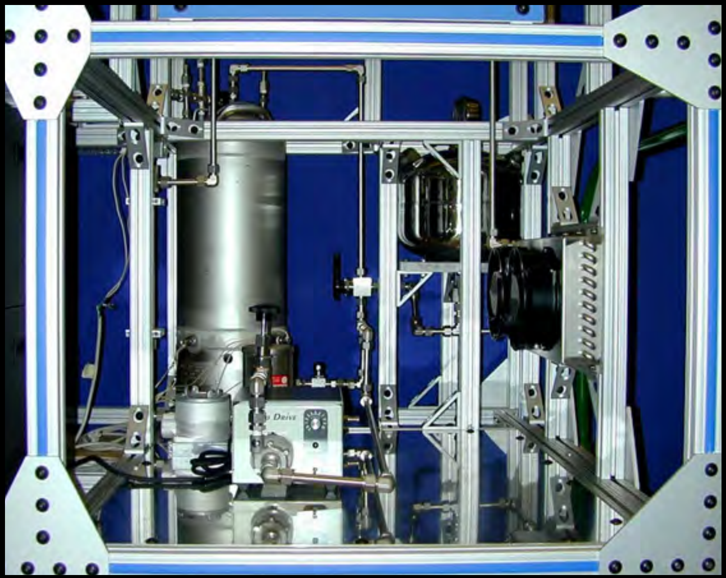


Purdue Microgravity Flow Boiling Apparatus



Flight Rack

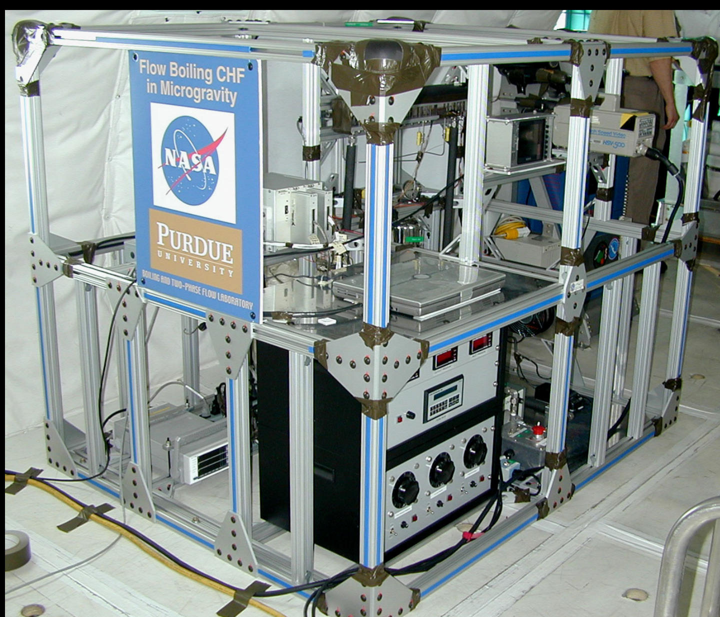


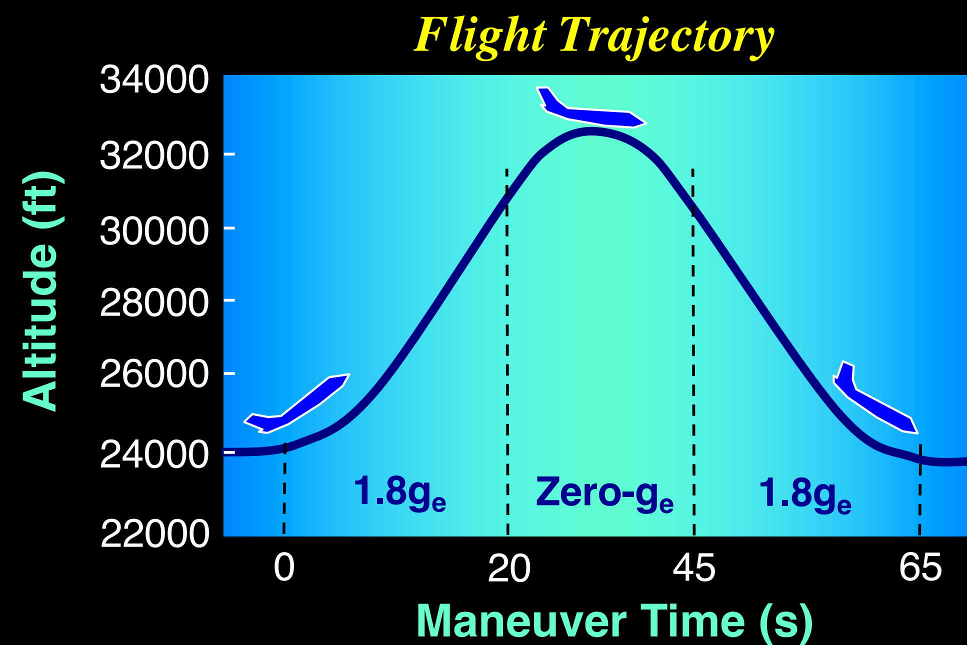


Two-Phase Flow Loop

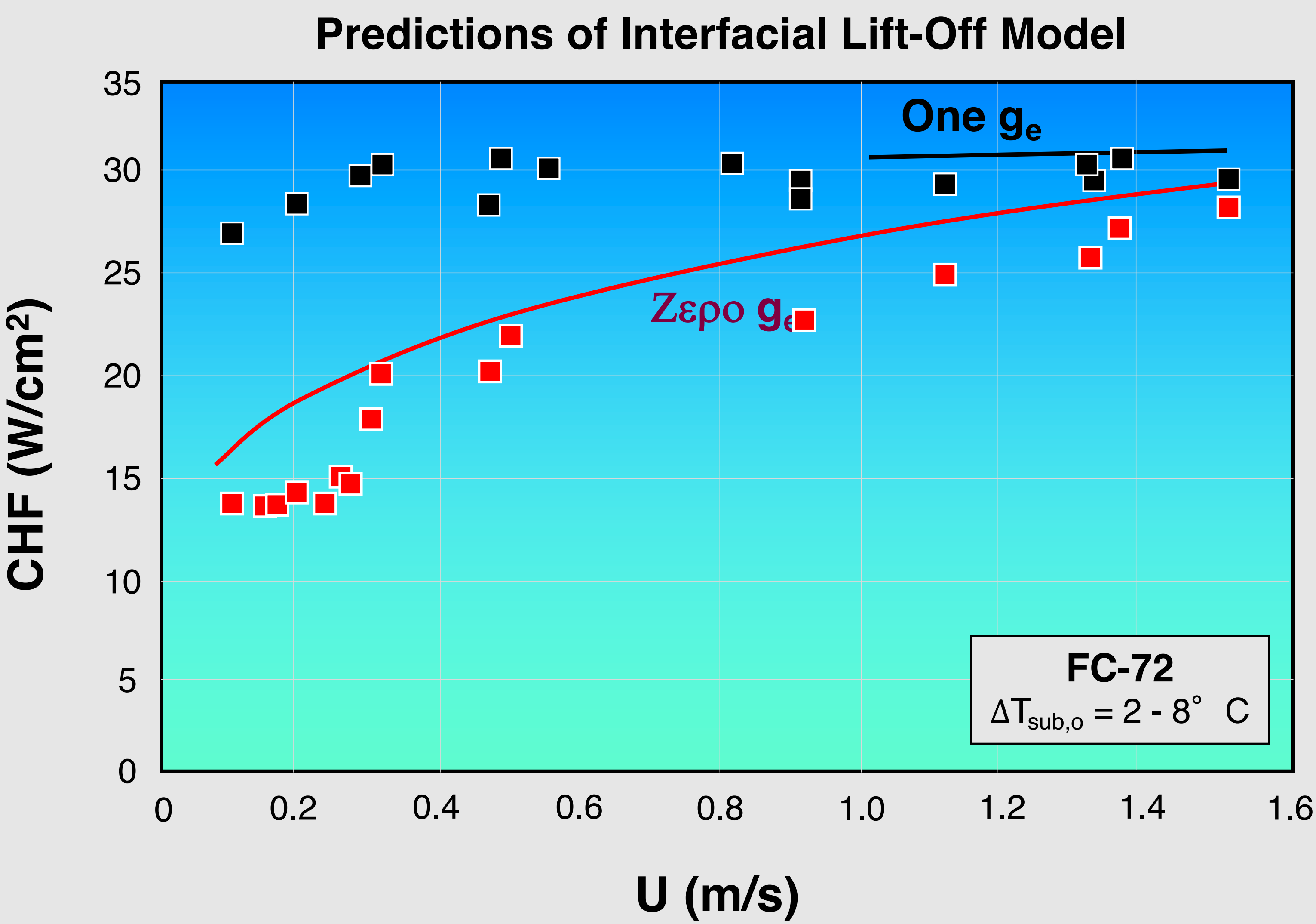
Research Presentation

KC-135 Tests performed at NASA Glenn Research Center

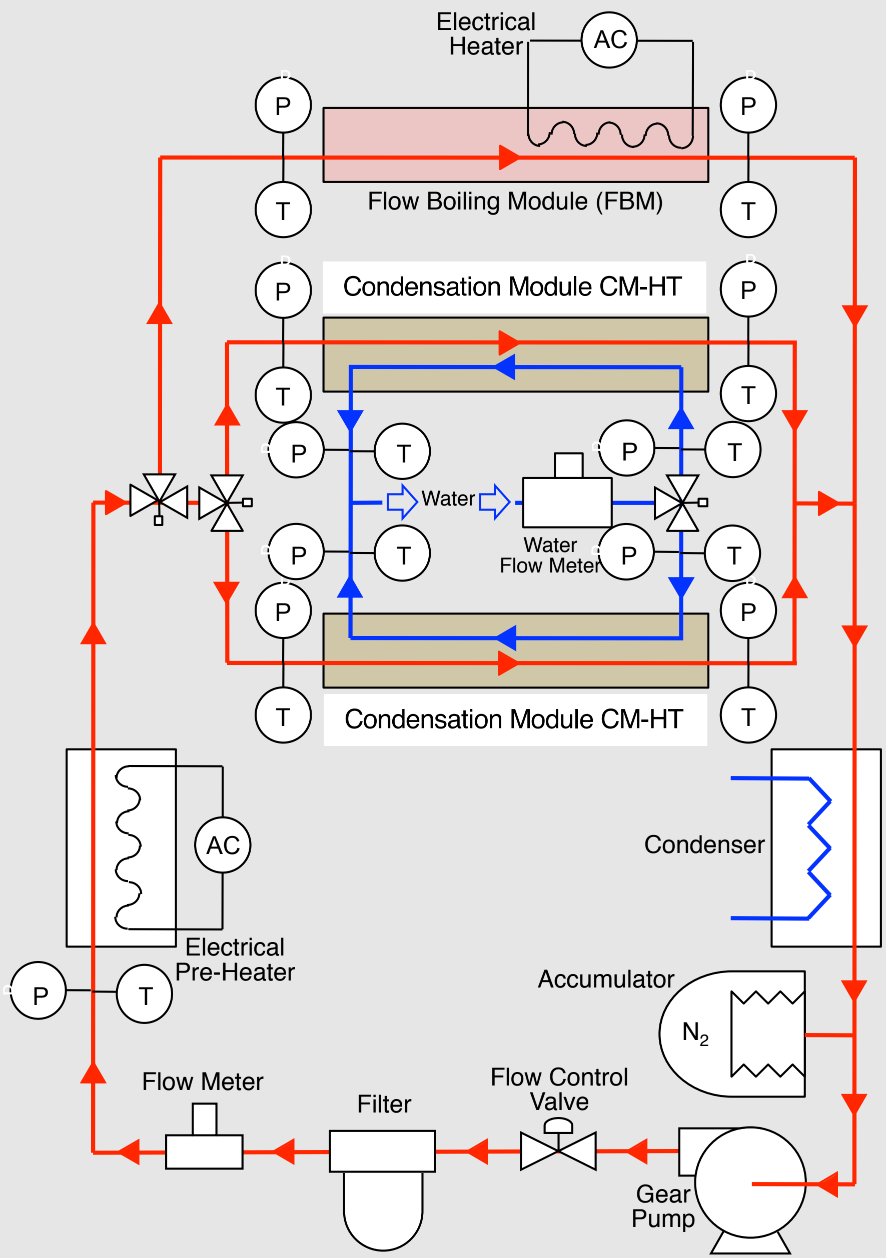




Phase Change Photo Library
(Mudawar, 1984 - 2014)


Predictions of Interfacial Lift-Off Model
One g_e
Zερο g_e
CHF (W/cm²)
U (m/s)
FC-72
$\Delta T_{sub,o}$ = 2 - 8° C
0
5
10
15
20
25
30
35
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

FBCE: Simplified Loop Schematic



Consists of:

- **nPFH sub-loop**
- **Water sub-loop**

Contains three test modules:

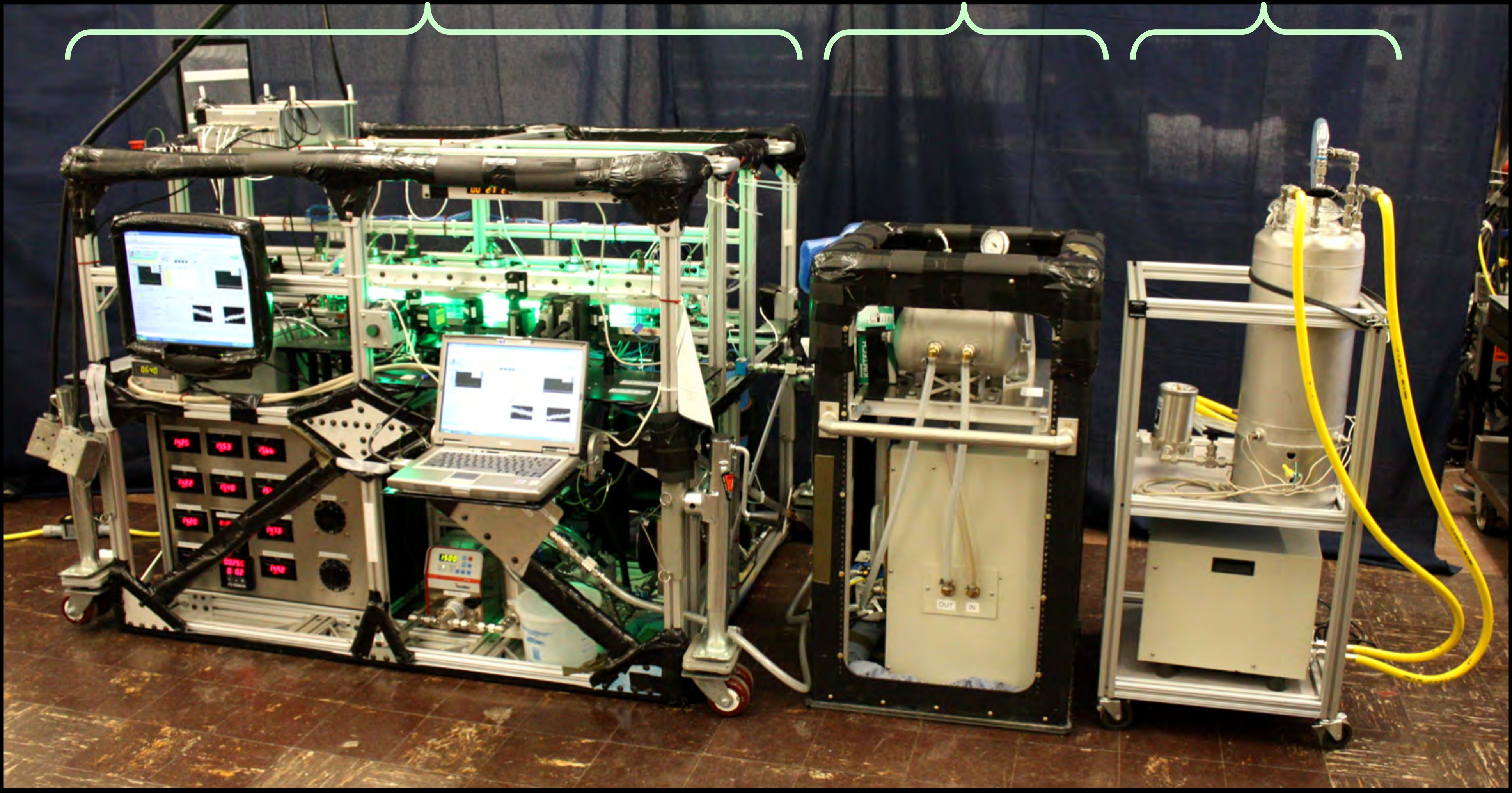
- **Flow Boiling Module (FBM)**
- **Condensation Module CM-HT for heat transfer measurements**
- **Condensation Module CM-FV for flow visualization**

FBCE: Parabolic Flight Condensation Rig

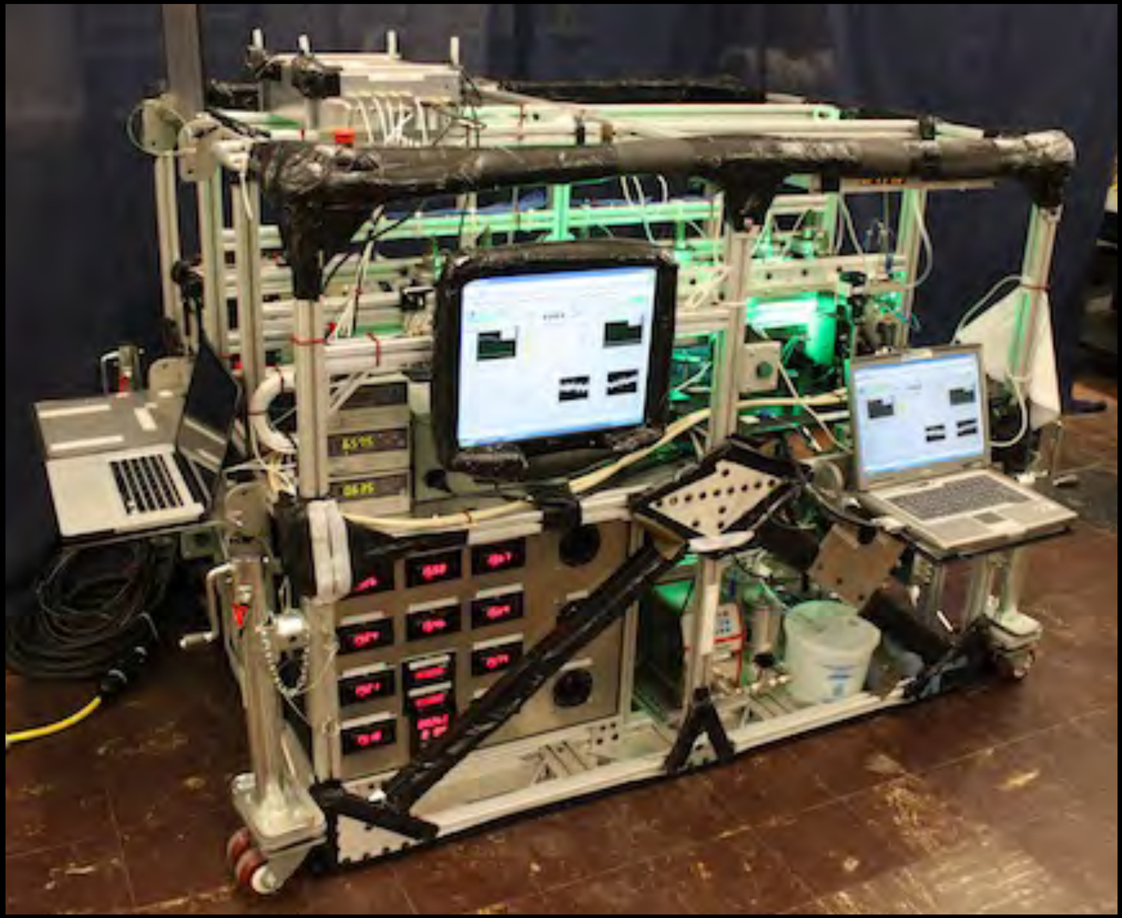
Condensation Rig

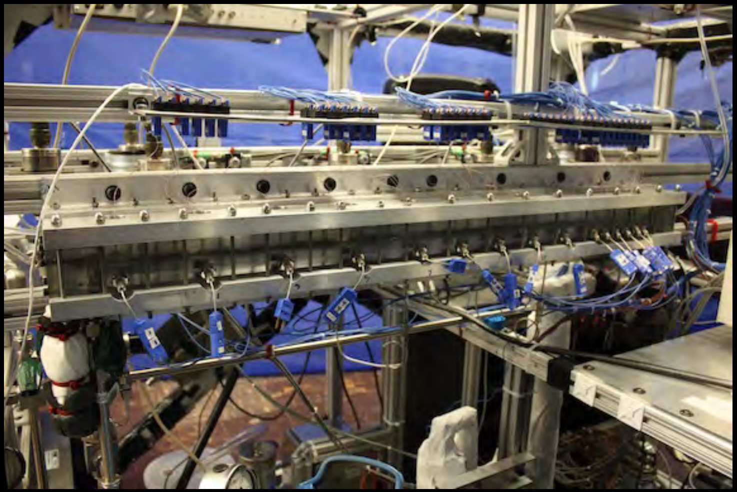
Water Conditioning Rig

Deaeration Rig

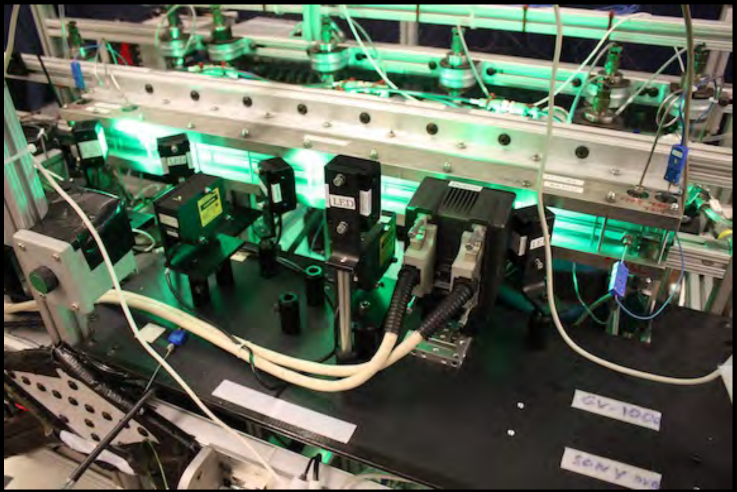


FBCE: Parabolic Flight Condensation Rig





CM-HT: Condensation Module for Heat Transfer Measurements



CM-FV: Condensation Module for Flow Visualization

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FBCE: Parabolic Flight Condensation Apparatus

zero G
the weightless experience

Flight Campaigns:

- **May 2012**
- **August 2012**

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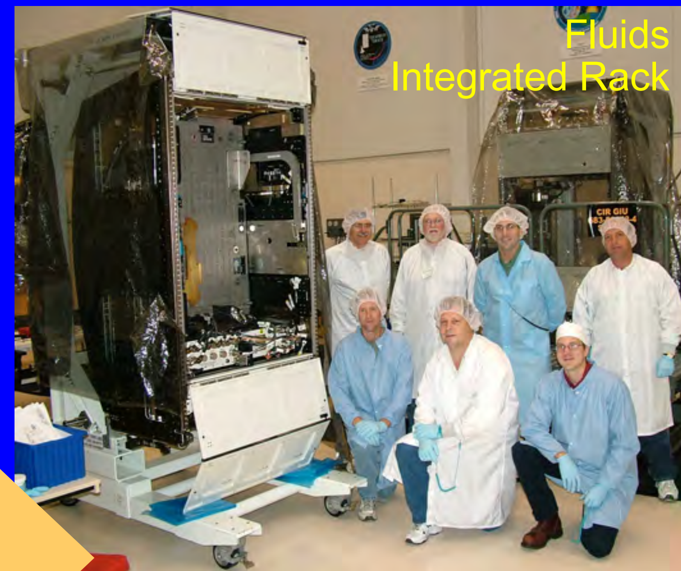
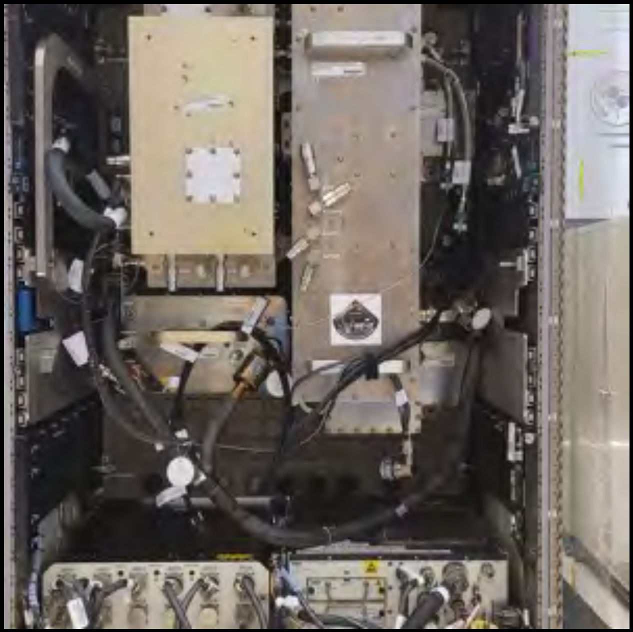
FBCE: From Parabolic Flight to the ISS



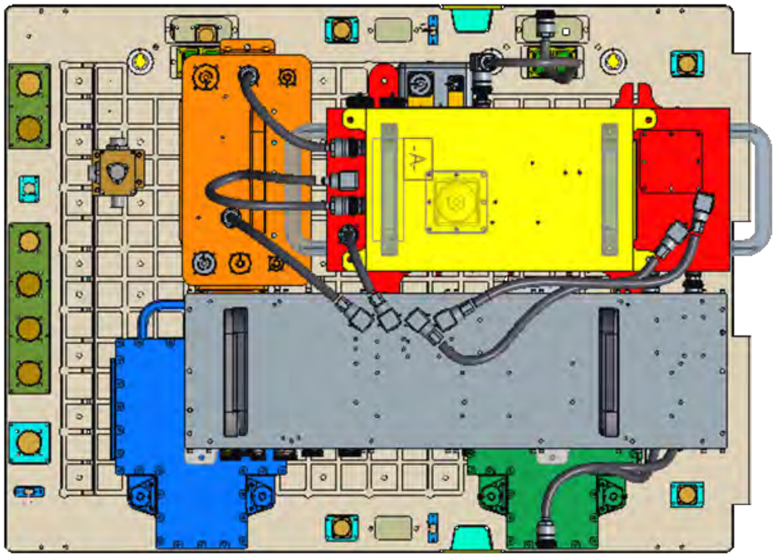
Research Presentation

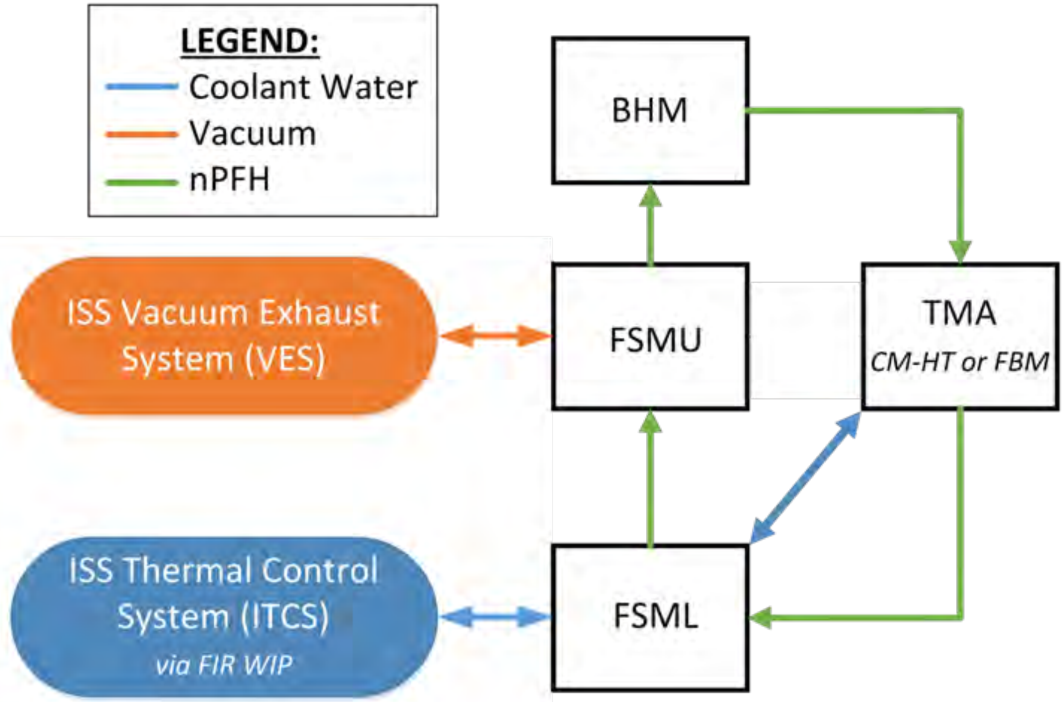
FBCE: The Final Configuration!



Research Presentation

FBCE: System Overview





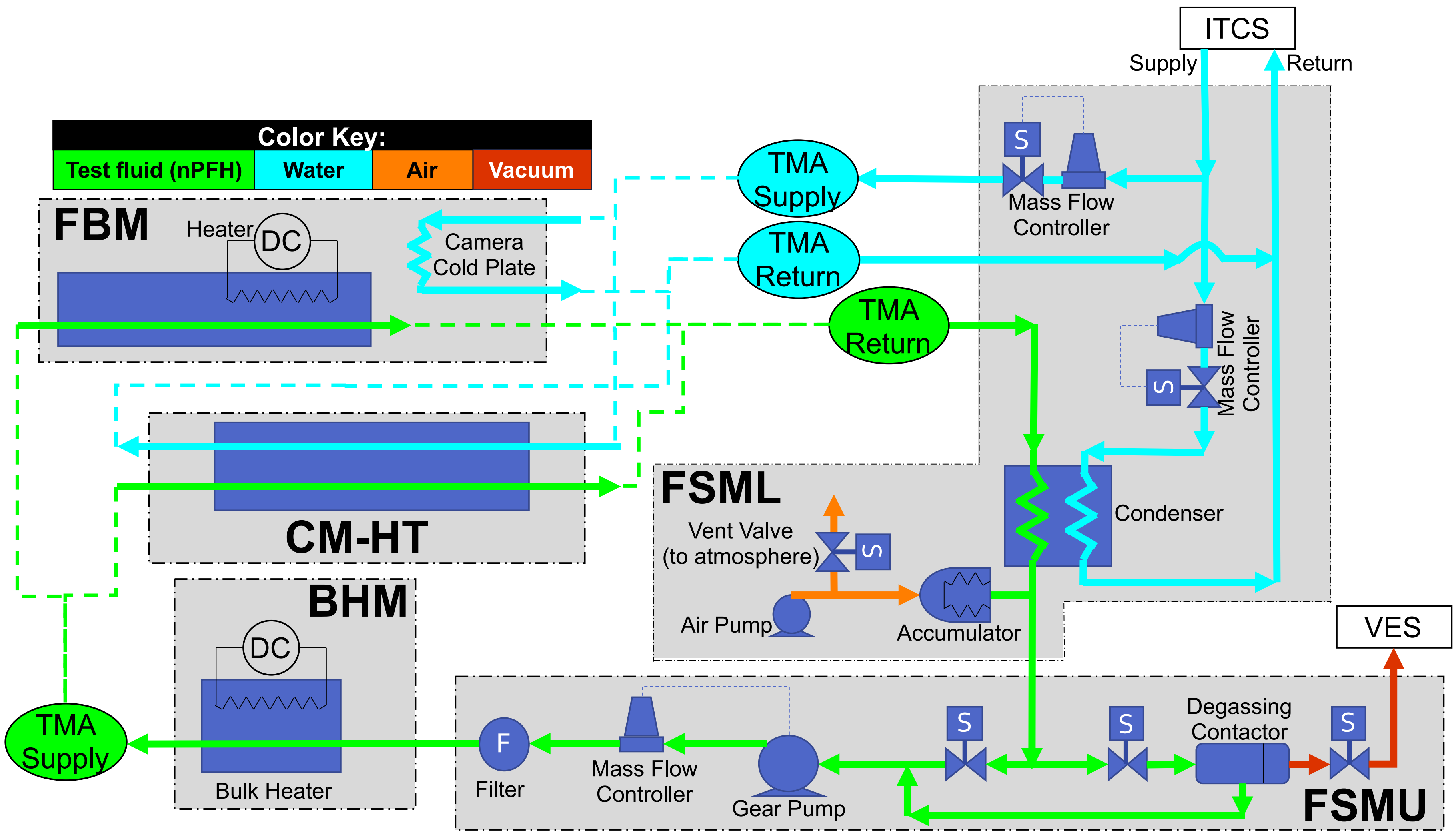
FBCE Modules:

- **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

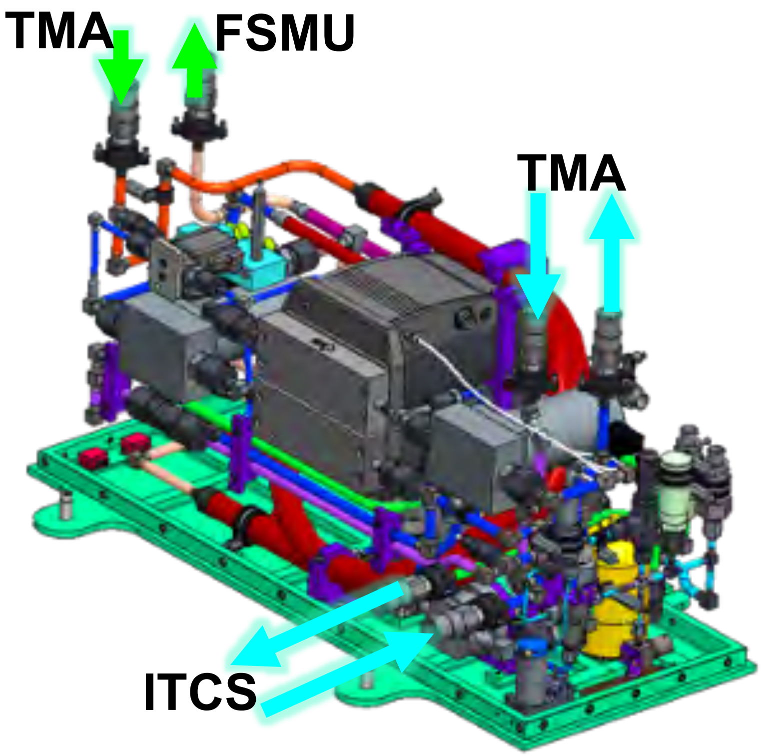
FIR Provided Hardware:

- 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)

FBCE: Fluid System Overview

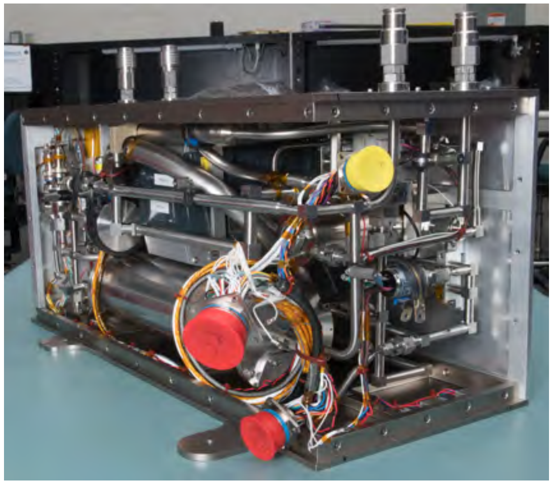


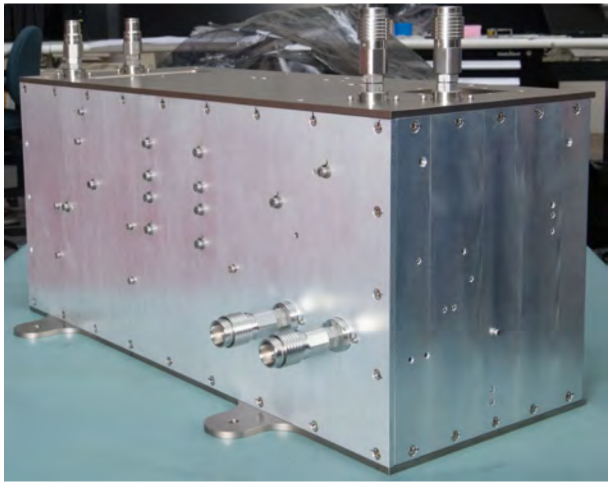
FBCE: Fluid System Module - Lower

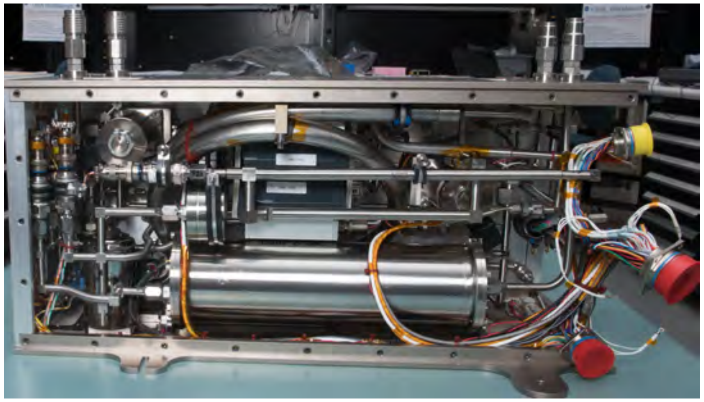


Color Key:		
Test fluid (nPFH)	Water	Air

- **Provides primary cooling for the test fluid exiting the test section, and the test section itself**
- **System pressure set by pressurizing or venting the air-side of a bellows accumulator**

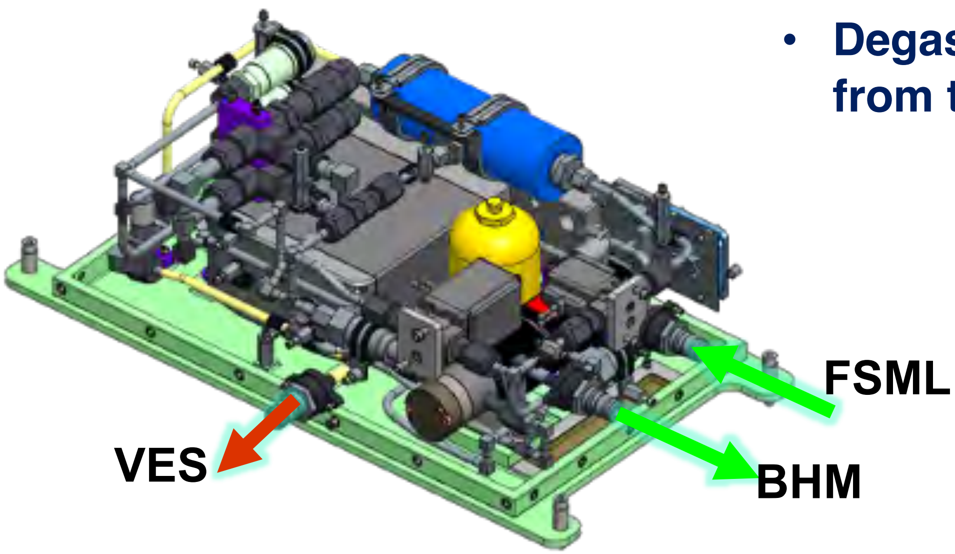




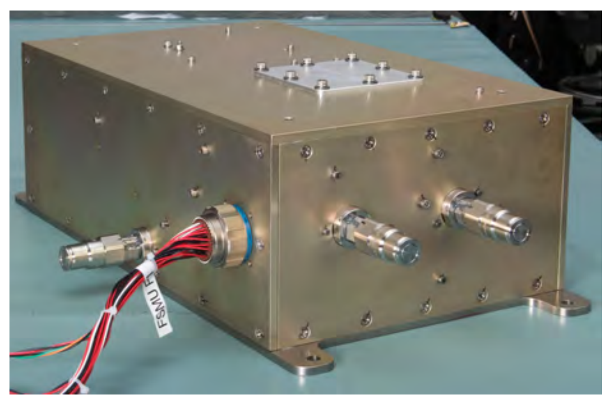


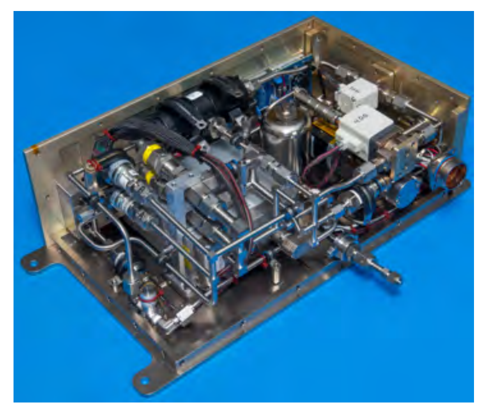
FBCE: Fluid System Module - Upper

- Mass flow controller drives a gear pump to provide flow throughout the closed loop system
- Multiple controls in place to prevent over-pressurization
- Degassing contactor removes dissolved gases from test fluid when membrane exposed to vacuum

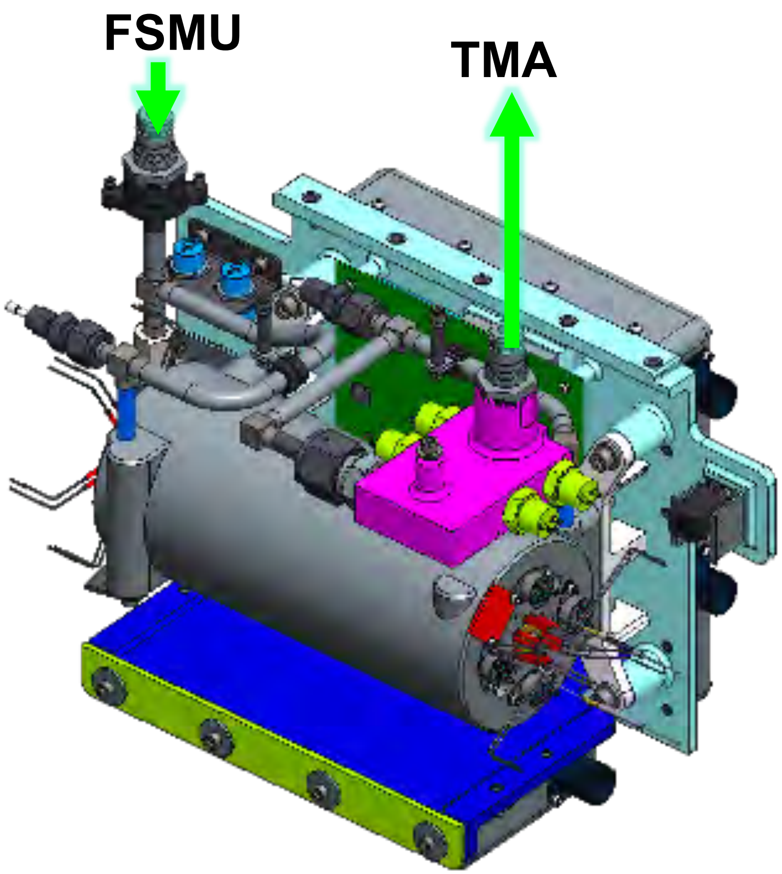


Color Key:	
Test fluid (nPFH)	Vacuum



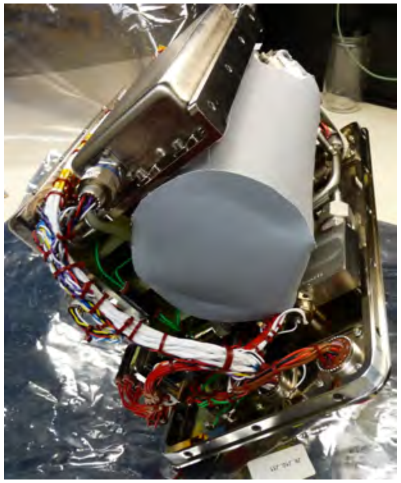
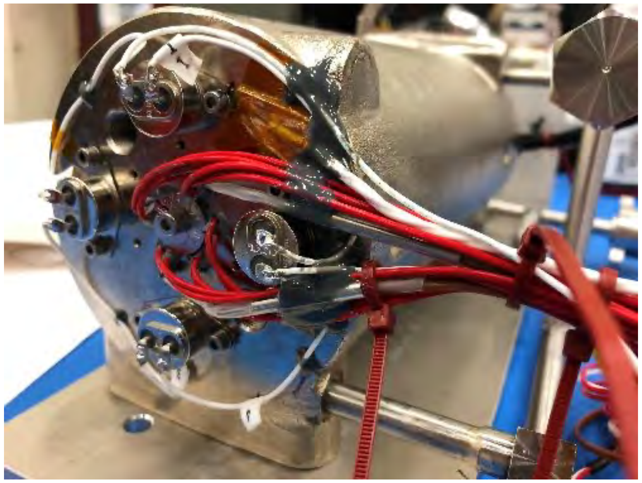
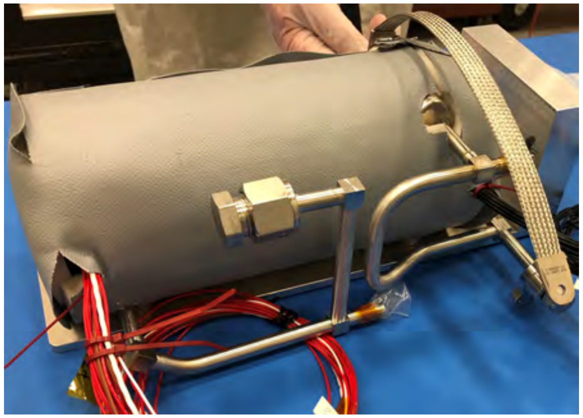


FBCE: Bulk Heater Module



Color Key:
Test fluid (nPFH)

- Primary source of heating to condition test fluid to required test section inlet conditions
- Three 120V primary heaters and three 28V booster heaters can be operated at any time, with backup heaters available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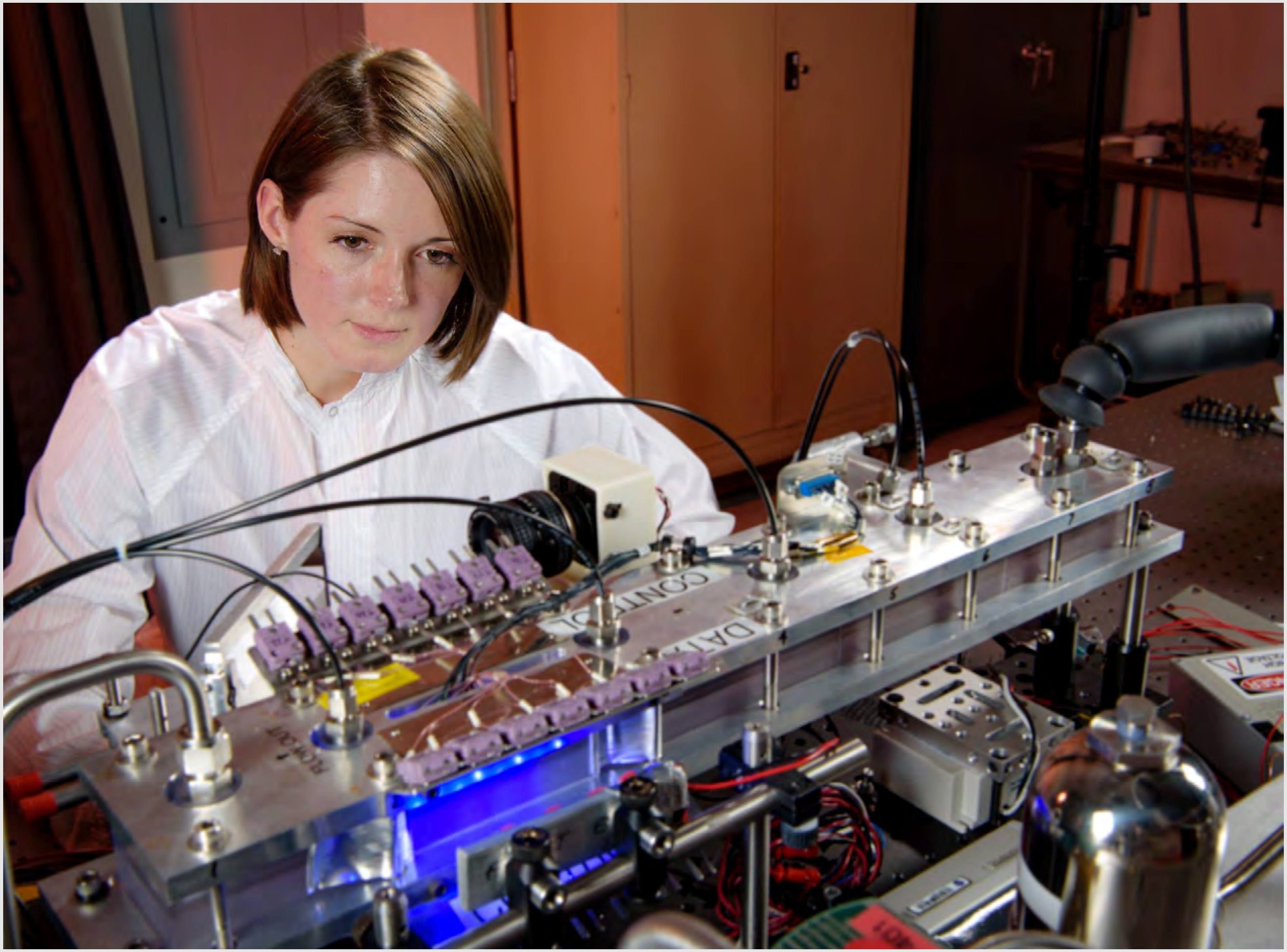
FBCE: Flow Boiling Module (FBM)



Research Presentation

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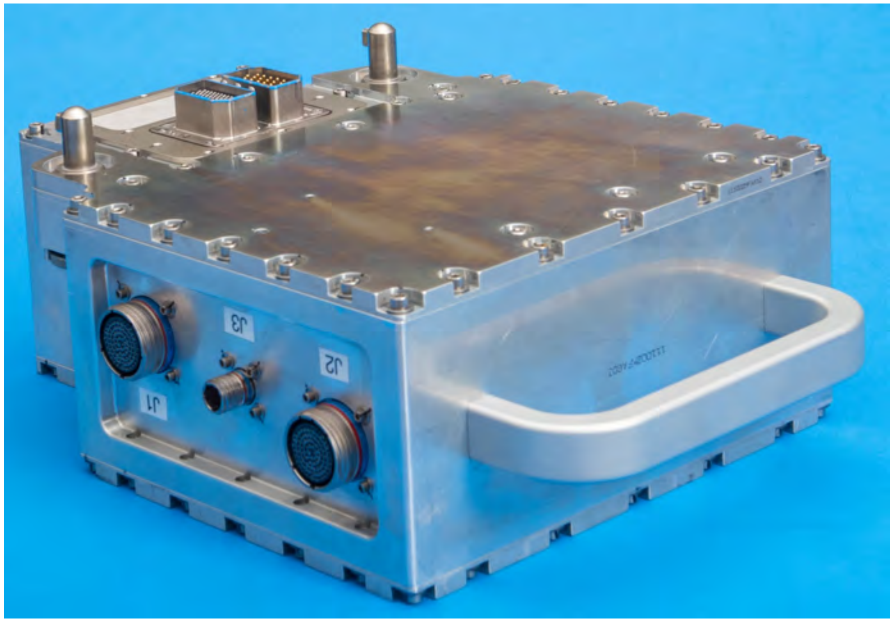
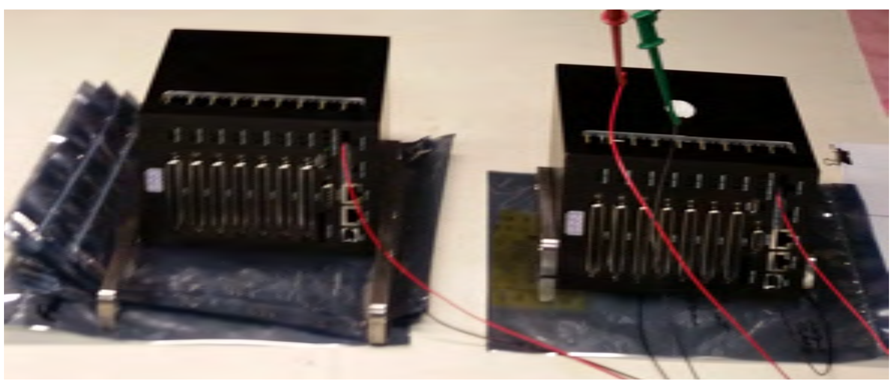
FBCE: Remote Data Acquisition Modules

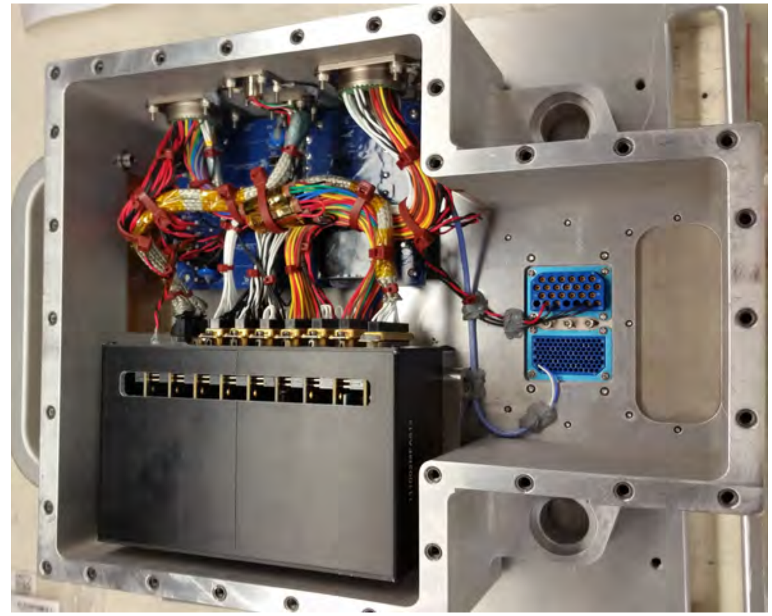
Remote Data Acquisition Module 1 (RDAQM1)

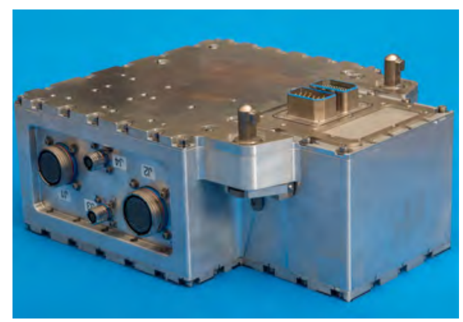




UEI Data Cubes (Thermocouple Signal Conditioning)

Remote Data Acquisition Module 2 (RDAQM2)



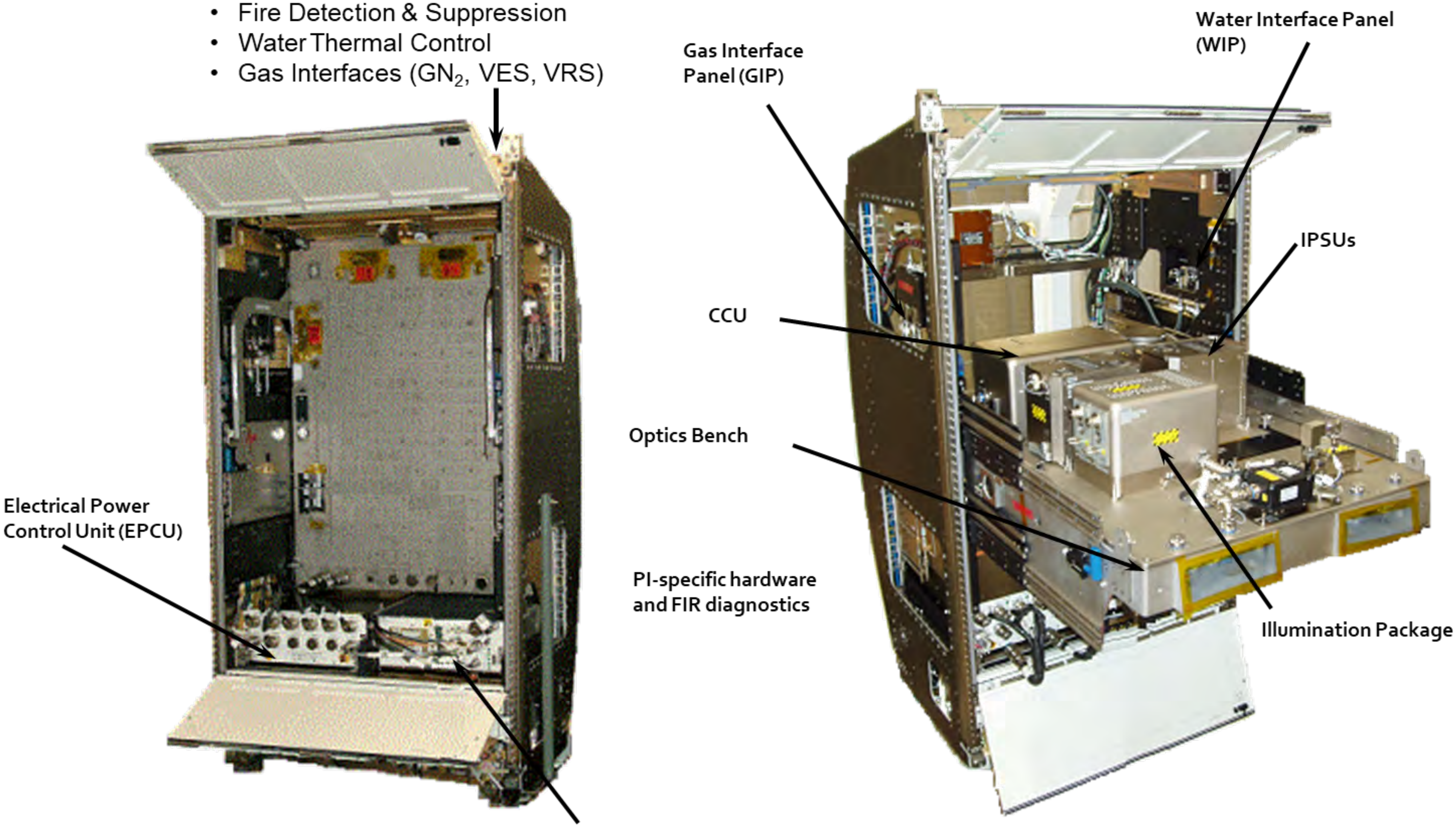


UEI Data Cube and Custom Sensor Supply Printed Circuit Board
(Signal Conditioning and Power Distribution)

FBCE: Fluids Integrated Rack (FIR)

Environmental Control (ECS)

- Air Thermal Control
- Fire Detection & Suppression
- Water Thermal Control
- Gas Interfaces (GN_2, VES, VRS)



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FBCE: Preparations for Launch

Research Presentation

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FBCE: August 10, 2021 Launch from NASA's Wallops Flight Facility in Virginia

Largest Cygnus cargo ever launched to ISS (3,723 kg)

Launch (August 10, 2021, 6:01 pm ET)

Arrival at ISS (August 12, 2021, 6:10 am ET)

Research Presentation

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Predictive Methods

Predictive Methods for Liquid-Vapor Two-Phase Systems

- **Computational methods:** computationally very intensive; predictions very sensitive to numerical and phase change model used
- **Theoretical models:** very few exist!
- **Semi-empirical models:** mechanistic models with specific constants determined from empirical data
- **'Universal' experimental correlations:** based on large databases for many fluids and broad ranges of geometrical or flow parameters; few exist; most desirable in industry
- **Narrow-range experimental correlations:** applicable to one or very few fluids and limited ranges of geometrical or flow parameters; often extrapolated resulting in erroneous predictions
- **Replication:** performance based on specific fluid, geometry, and operating conditions of given device

Recent Challenges:

- Reluctance to develop large, complex phase-change facilities
- Studies focused on development of narrow-range correlations or simply data trends
- Findings very incremental
- Avoidance of mechanistic models

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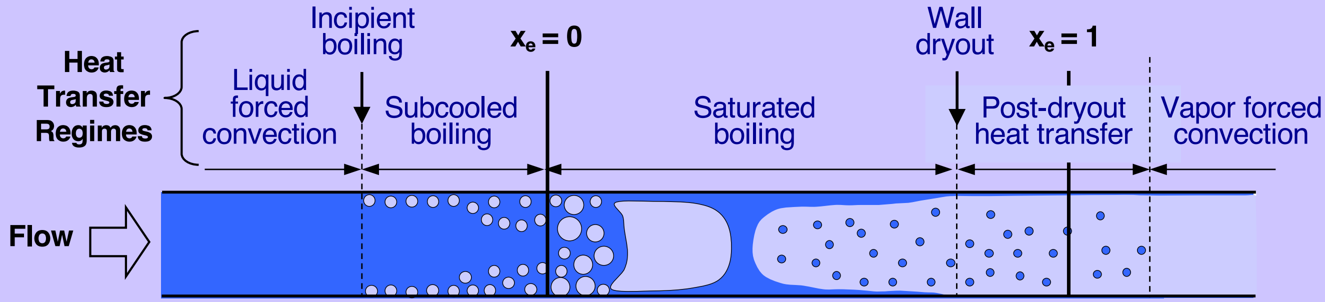
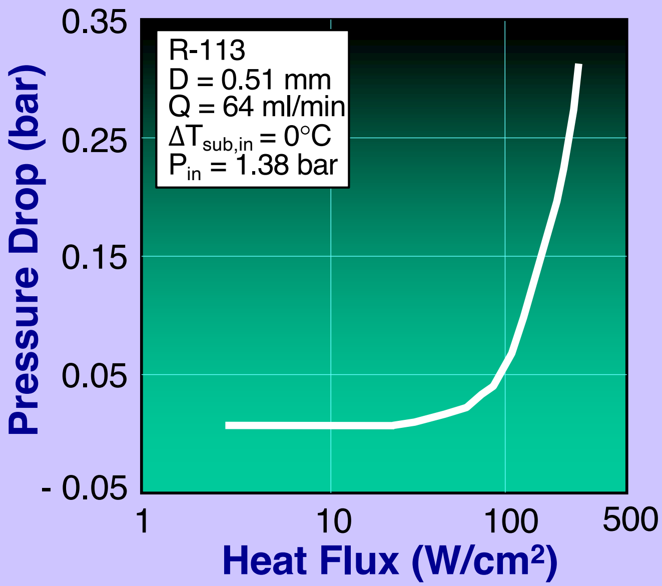
Fundamental Physics of Flow Boiling and Heat Transfer

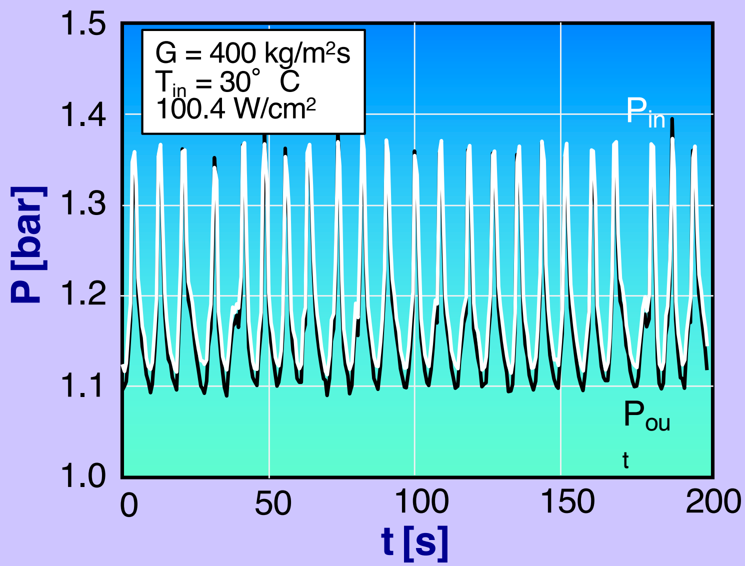
Two-Phase Flow and Heat Transfer Regimes



- Heat transfer regimes
- Regime boundaries
- Pressure drop components
- Heat transfer coefficients
- Dryout versus CHF

Flow Constrains and Instabilities

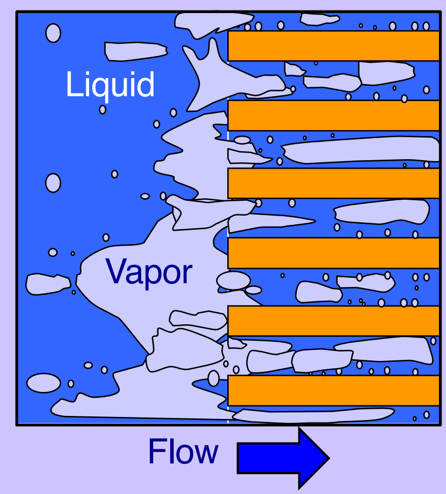




- Compressibility
- Flashing
- Two-phase choking

- Instabilities

Heat Transfer Limits and Anomalies



- CHF
- Premature CHF

Research Presentation

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Consolidated World Databases and Correlations for Flow Boiling Critical Heat Flux of Water in Tubes

Research Presentation

Flow Boiling Heat Transfer Transfer Coefficient

Universal Heat Transfer Correlation for Saturated Boiling in Small Channel

Consolidated database:
10,805 saturated boiling heat transfer coefficient data points from 37 sources

- FC72, R11, R113, R123, R1234yf, R1234ze, R134a, R152a, R22, R236fa, R245fa, R32, R404A, R407C, R410A, R417A, CO_2, water
- $0.19 < D_h < 6.5$ mm
- $19 < G < 1608$ kg/m²s
- $57 < Re_{fo} = GD_h/\mu_f < 49{,}820$
- $0 < x < 1$
- $0.005 <$ *Reduced pressure* < 0.69

$$Bo = \frac{q''_H}{G\, h_{fg}}$$

$$h_{tp} = \left(h_{nb}^2 + h_{cb}^2\right)^{0.5}$$

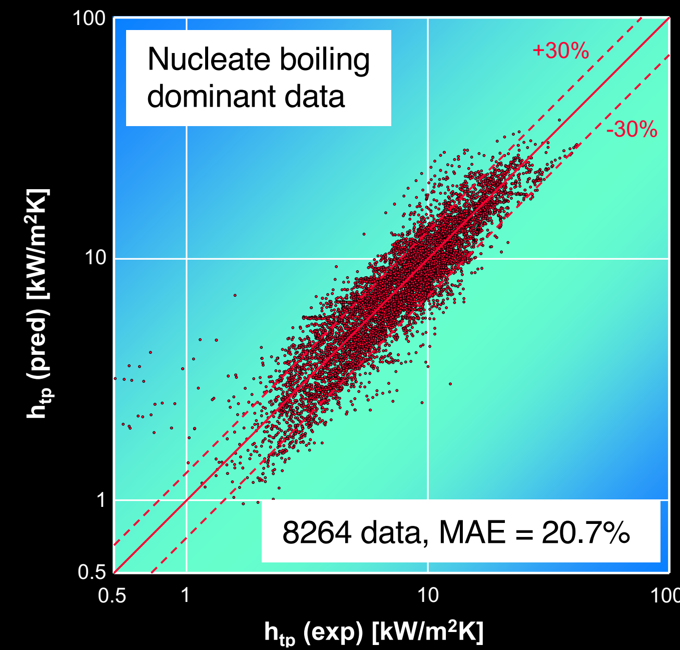
For nucleate boiling dominant regime :

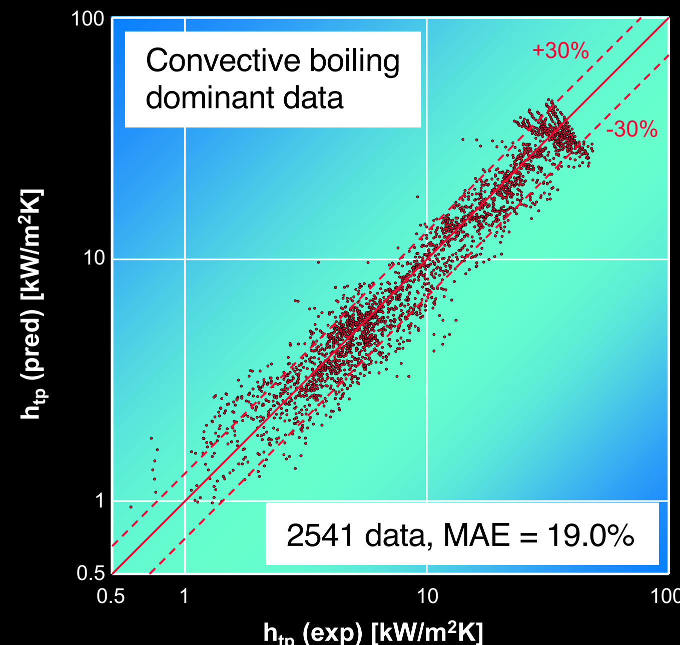
$$h_{nb} = \left[2345\left(Bo\frac{P_H}{P_F}\right)^{0.70} P_R^{0.38}(1-x)^{-0.51}\right]\left(0.023Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$$

For convective boiling dominant regime :

$$h_{cb} = \left[5.2\left(Bo\frac{P_H}{P_F}\right)^{0.08} We_{fo}^{-0.54} + 3.5\left(\frac{1}{X_{tt}}\right)^{0.94}\left(\frac{\rho_g}{\rho_f}\right)^{0.25}\right]\left(0.023Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$$

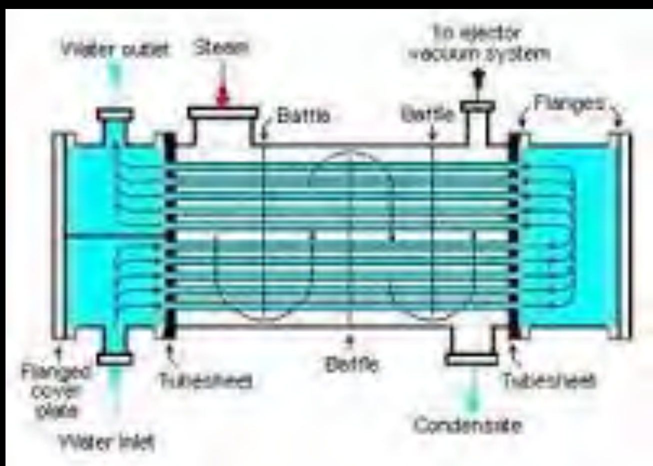
Kim & Mudawar, *Int. J. Heat Mass Transfer*, 2013



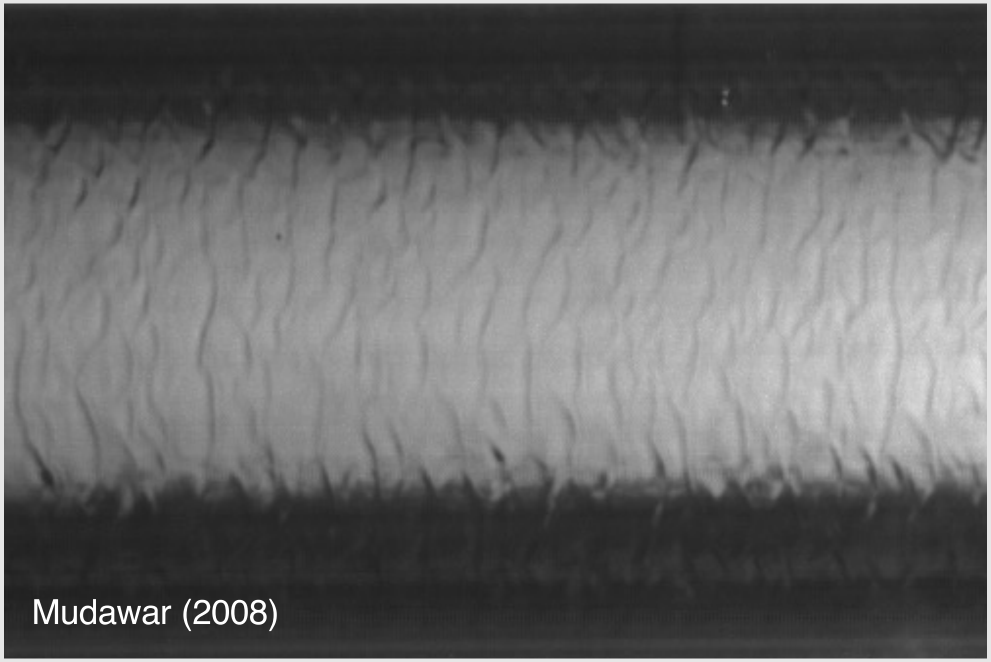


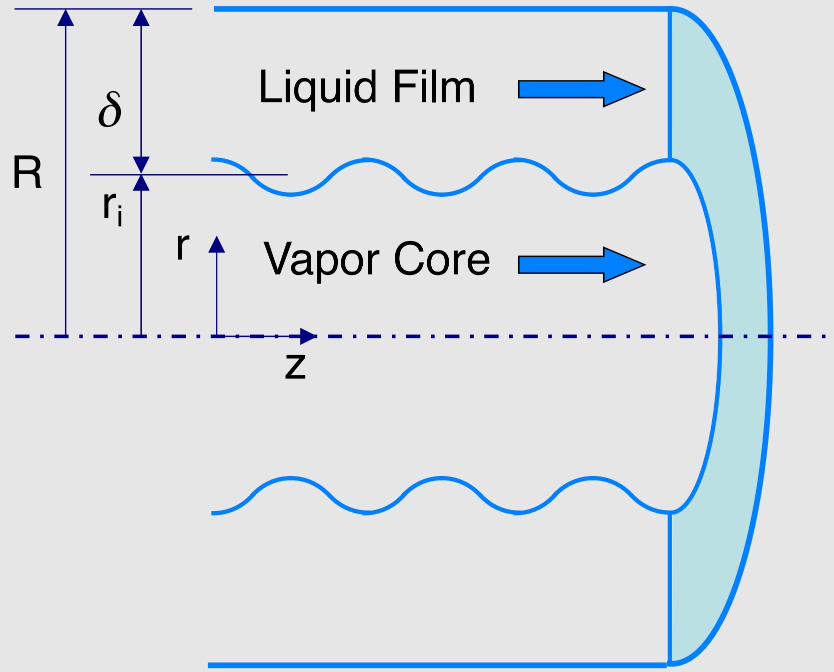
Air Cooled Condensers for Refrigerant

Shell-and-Tube Condensers



Condensation in Tubes



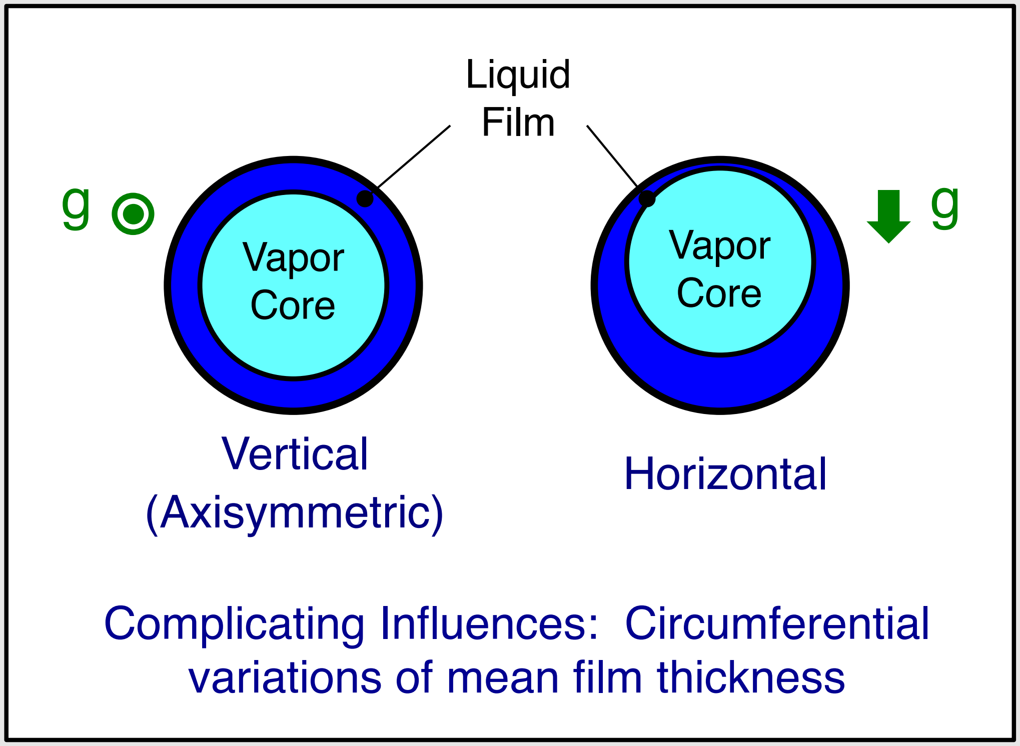


- Different flow regimes: pure vapor, annular, slug, bubbly and pure liquid
- Annular regime most prevalent … separated two-phase flow consisting of thin shear-driven liquid film along tube wall and central vapor core
- Thin annular film responsible for high condensation heat transfer coefficients

Fundamental Challenges to Modeling Annular Condensation

Common perception:

Separated flows presumed convenient to model because they can be represented by two predominantly single-phase flows



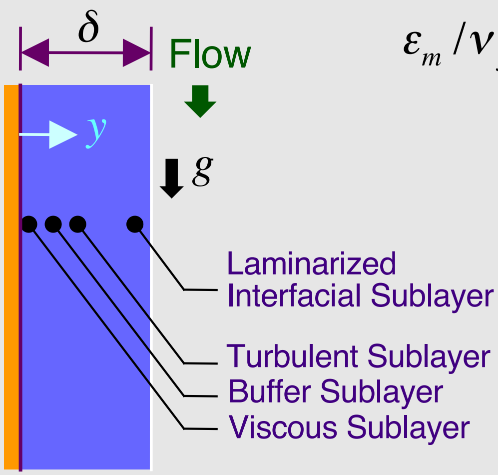
Complicating Influences (Fluid Physics):

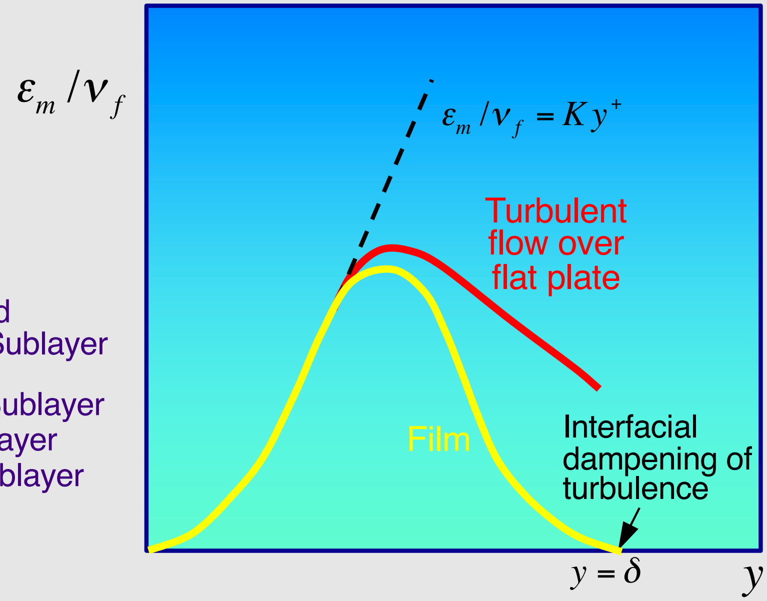
1. **Circumferential variations of mean film thickness due to transverse body force**
2. **Complex transitional characteristics of condensation films**
3. **Turbulence dampening near film interface**
4. **Interfacial waves**
5. **Droplet entrainment and deposition**

Challenges:

1. **Develop fundamental understanding of all above**
2. **Incorporate all above influences into robust predictive model**

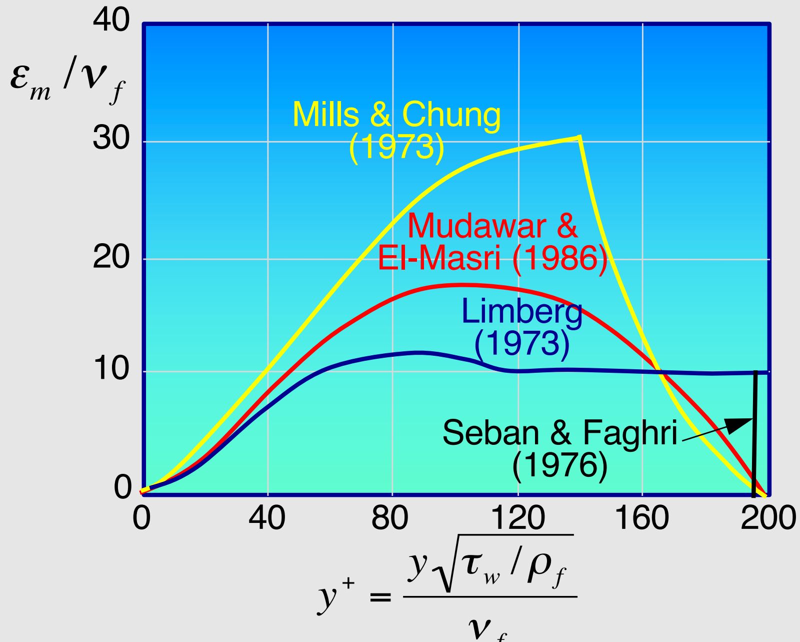
Complicating Influences: Turbulence Dampening near Film Interface



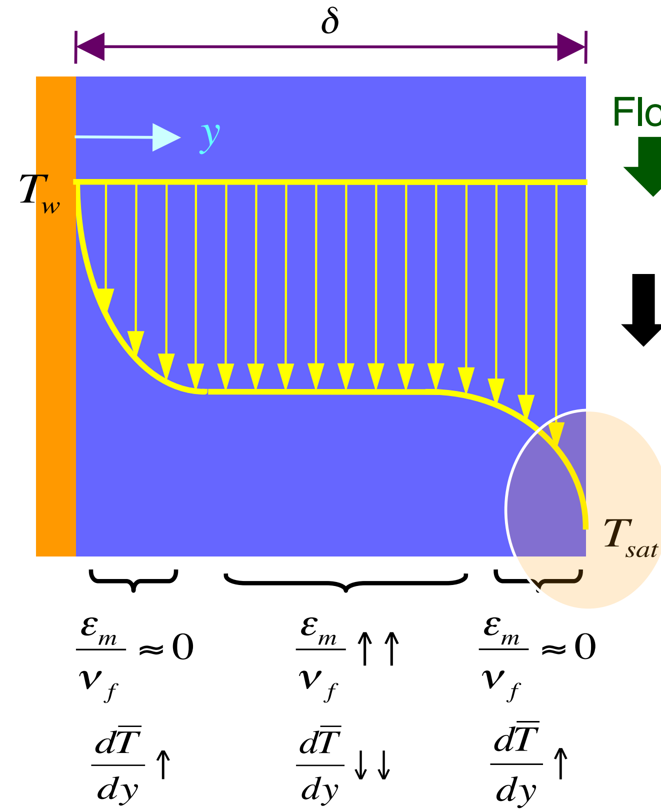


- Near-wall region: Most use Van Driest (1956) function
- Mudawar & El-Masri: Ueda et al. (1977) experimental profile in middle, and a function of Kapitza number near interface:

$$Ka = \frac{\mu^4 g}{\rho \sigma^3}$$



$$-q'' = k_f \left(1 + \frac{Pr_f}{Pr_{f,t}} \frac{\varepsilon_m}{\nu_f}\right) \frac{d\bar{T}}{dy}$$



Failure to account for interfacial dampening of turbulence near the interface and large interfacial temperature gradient has been shown to produce significant errors in predicting heat transfer across films!!

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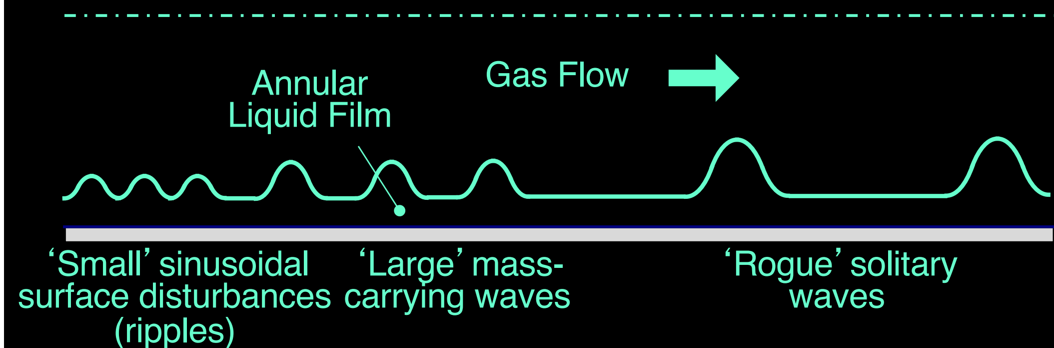
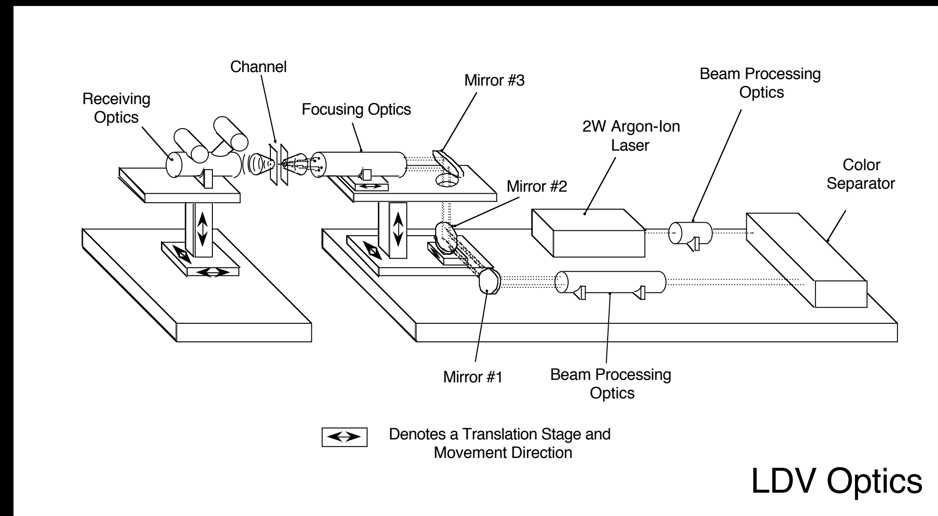
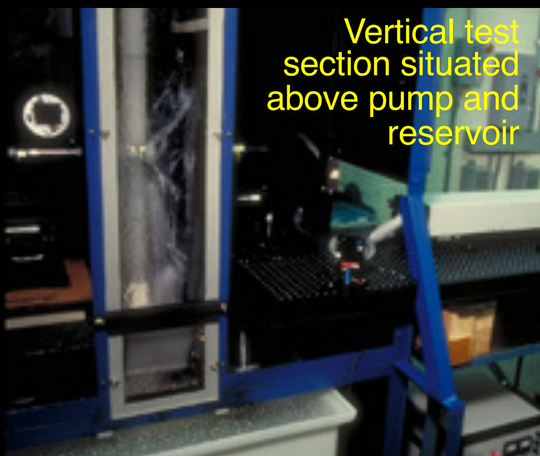
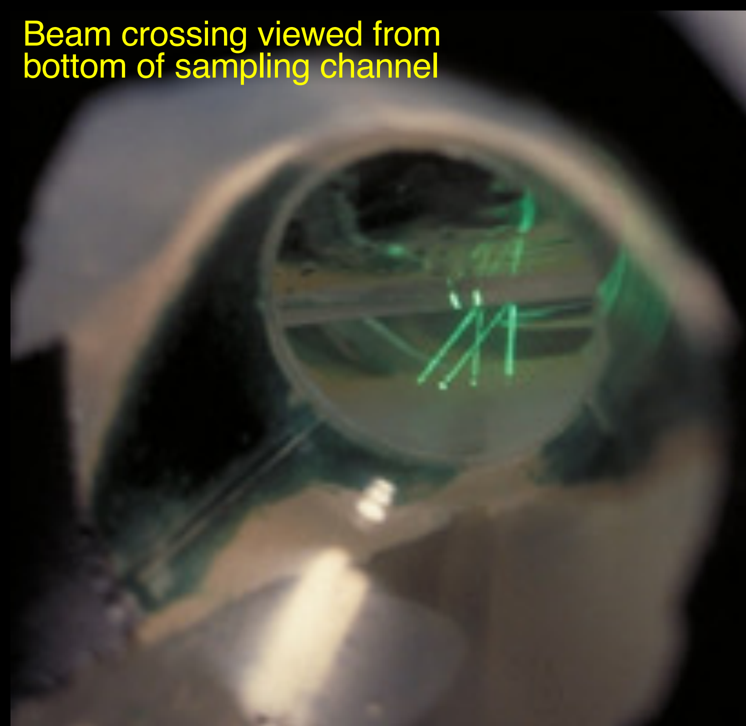
Complicating Influences: Interfacial Waves

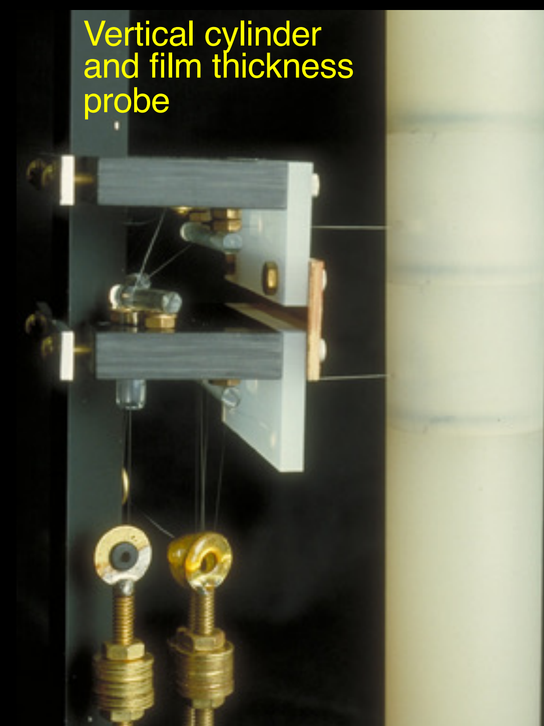




Mudawar & Houpt (1993a,b)







Research Presentation

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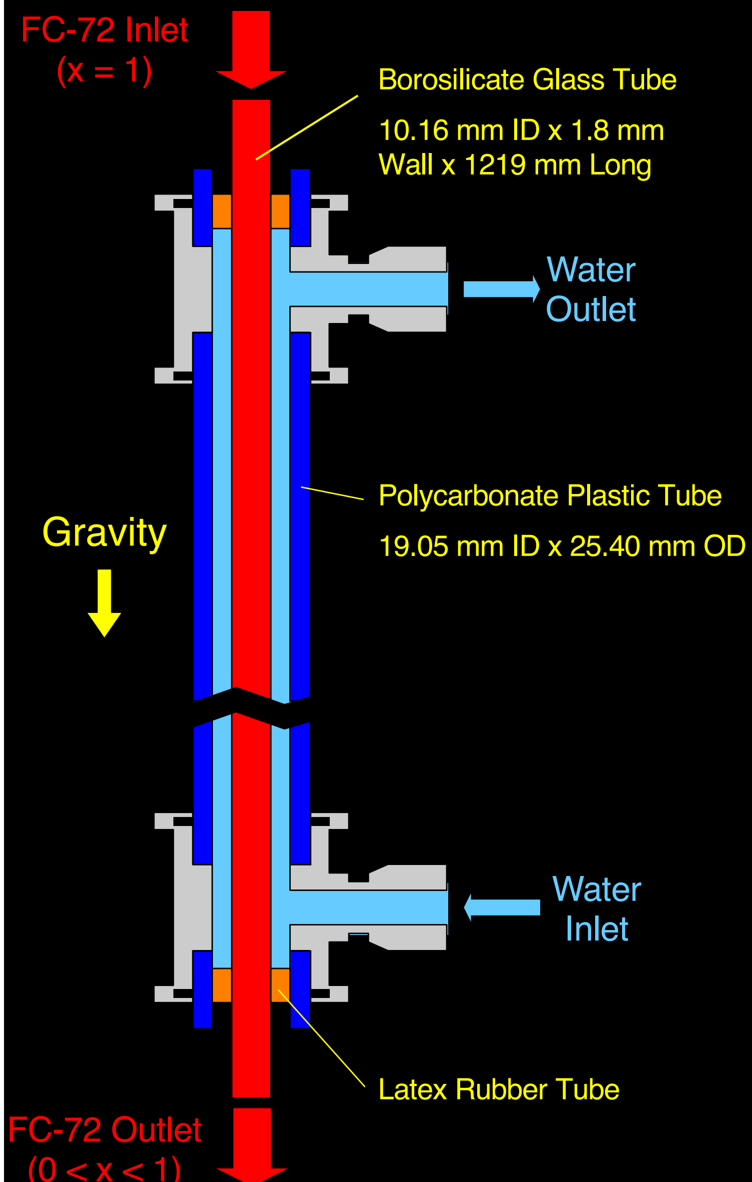
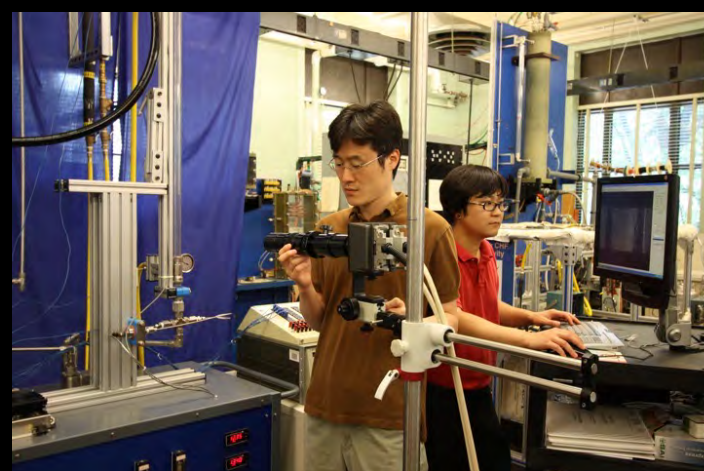
Condensation Measurements



Condensation Module for Flow Visualization

Purdue High Capacity Condensation Facility



High-Speed Video Motion Analysis System:

- Photron FASTCAM-Ultima camera with shutter speeds up to 1/120,000 s
- Infinity K-2 high magnification lenses
- PerkinElmer Xenon source fitted with Olympus fiber optic cable

Research Presentation

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Condensation Measurements – Large Tubes

$\dot{m}_{FC\text{-}72}$ = 19.5 – 19.6 g/s

Flow ↓

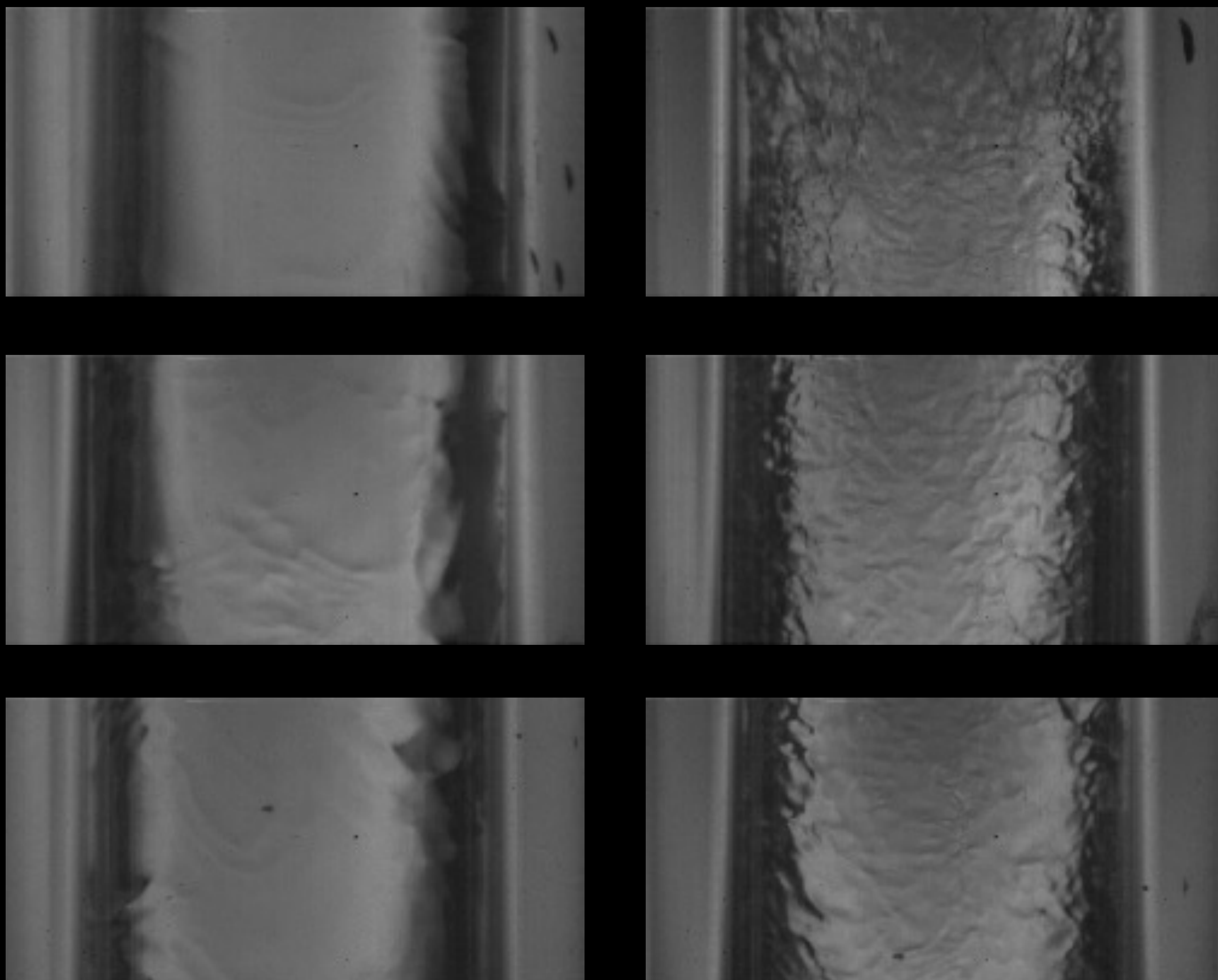
1/267 speed | Video: 4000 frames/s

Video: 4000 frames/s | 1/133 speed

Inlet

Middle

Outlet



$Re_{f,\ FC\text{-}72,\ exit}$ = 179 – 181

q_{out} [W] = 77.5 – 78.3

$Re_{f,\ FC\text{-}72,\ exit}$ = 927 – 960

q_{out} [W] = 392 – 406

Purdue High Capacity Condensation Facility

For $Re_{f,FC\text{-}72,exit} < 200$

- Smooth Laminar in inlet
- Wavy Laminar in middle and outlet

For $Re_{f,FC\text{-}72,exit} > 200$

- Flow appears to turn turbulent
- Wave structure more complex

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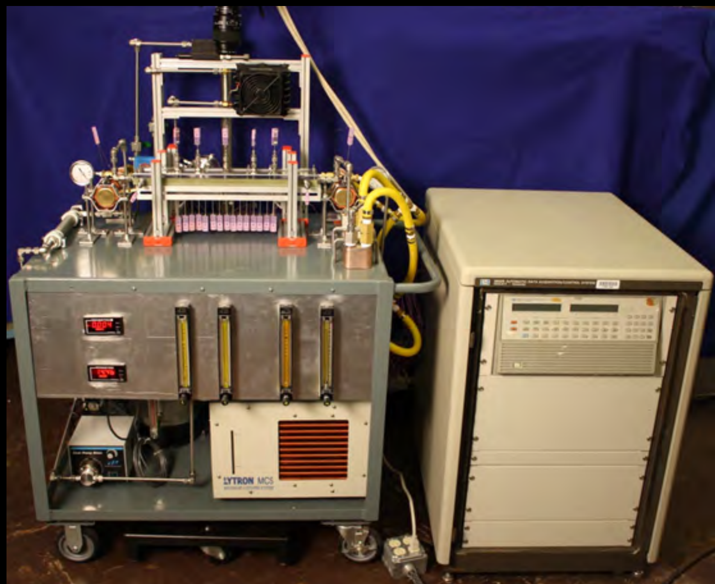
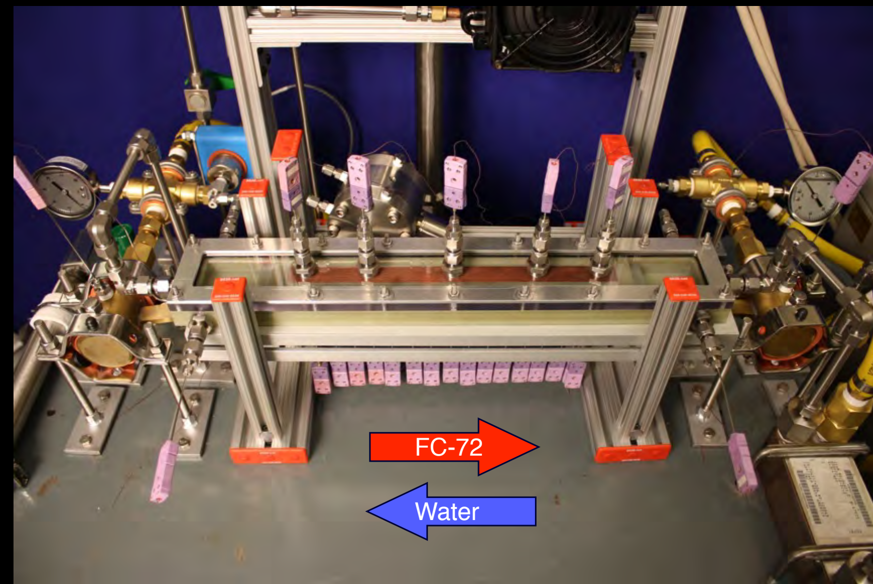
Condensation Measurements – Small Channels

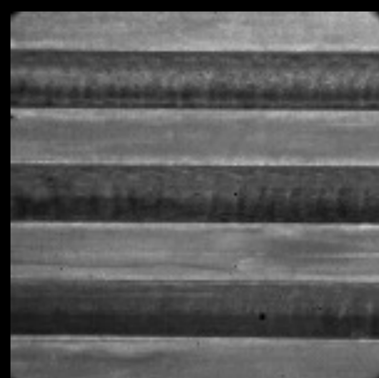




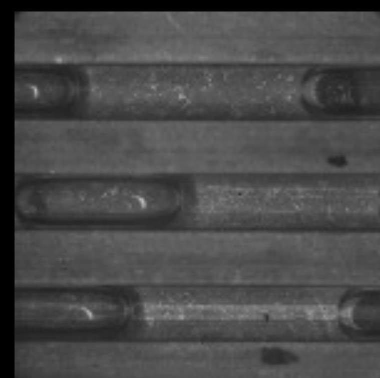
Flow

Annular

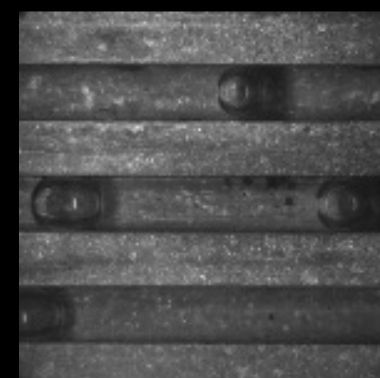
Wavy-Annular



Slug



Bubbly



Purdue Small Channel Condensation Facility

Regime	FC-72 (g/s)	Water (g/s)	Video Rate
Annular	1.51	5.06	1/66.6
Wavy-Annular 1.51	2.97	1/66.4	
Slug	0.55	2.97	1/66.4
Bubbly	0.55	5.06	1/66.4

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In Pursuit of More Efficient, Renewable and Cleaner Energy …

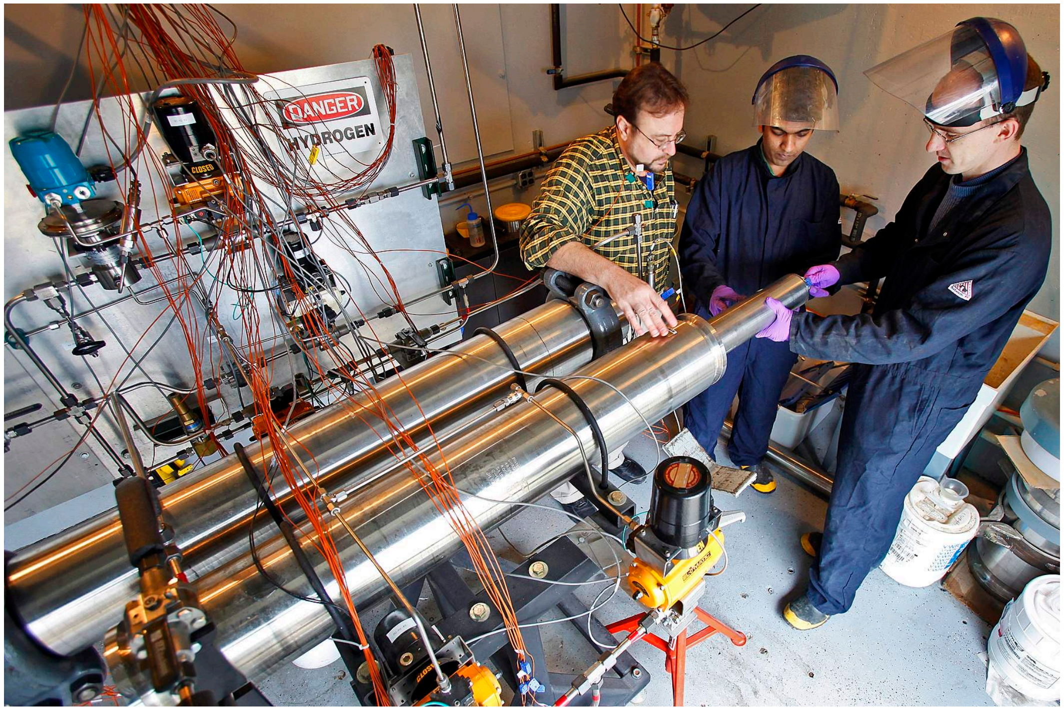
1. *Hydrogen Fuel Cells*

2. *Hybrid Vehicles*

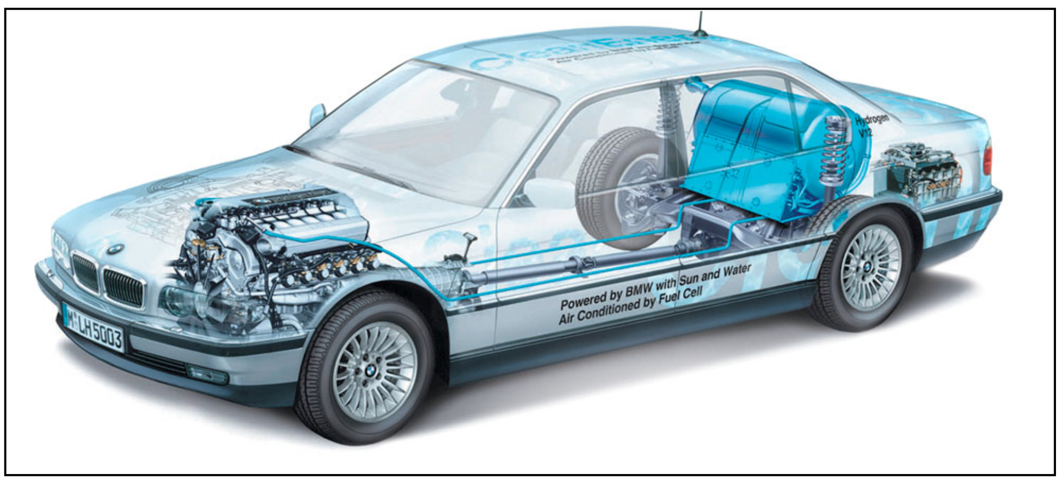
3. *Solar Receivers*

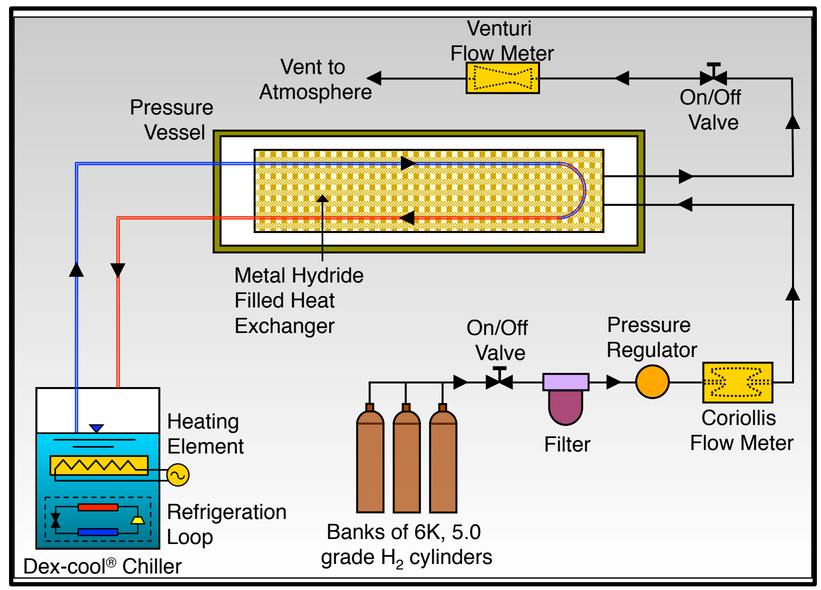
4. *Intelligent Heat Treating of Metal Alloys*

1. Heat Exchanger for Hydrogen Storage Fuel Cell Systems



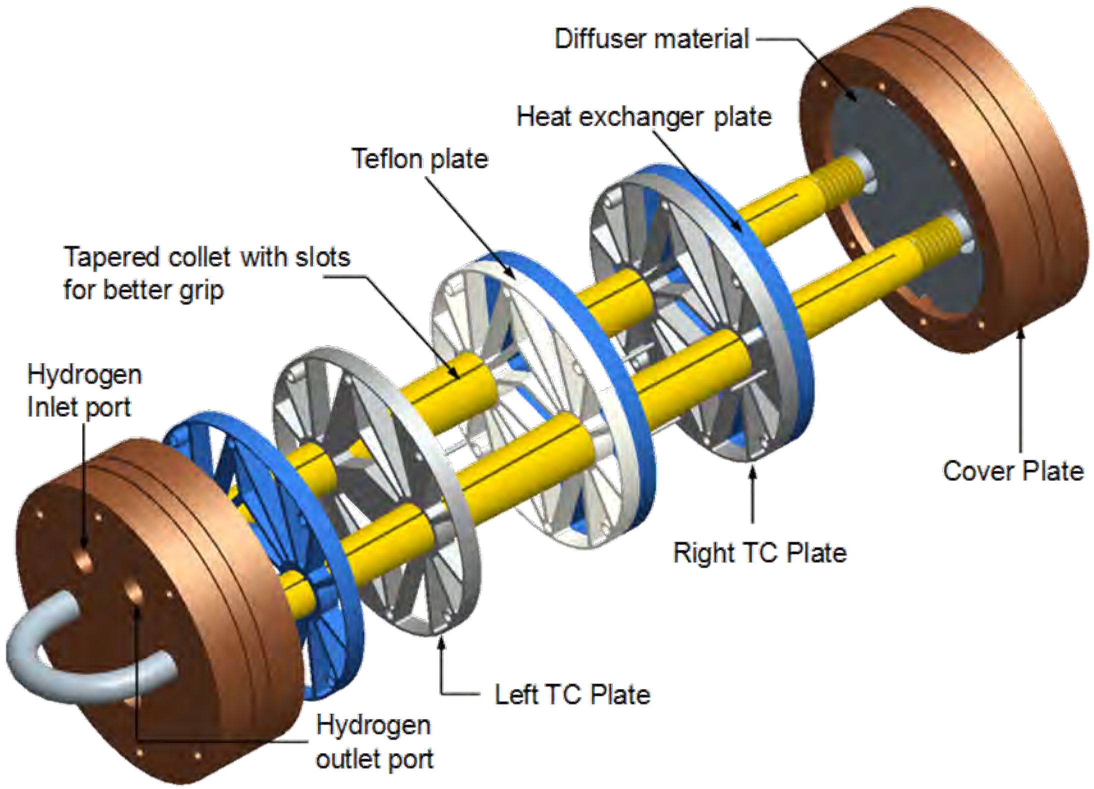
- Developed for high-pressure metal hydride (e.g., $Ti_{1.1}CrMn$) storage systems
- Used to remove large amount of heat dissipated from hydriding reaction when H_2 is charged into storage vessel

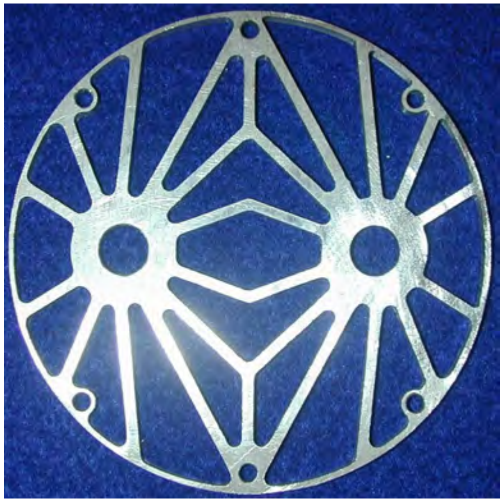




Research Presentation

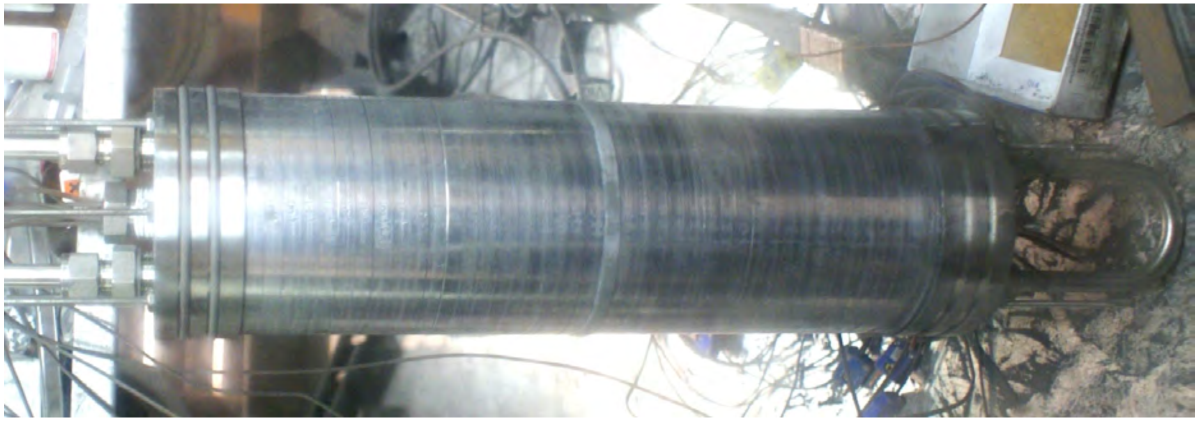
1. Thermally-Optimized Heat Exchanger





US Patent 8,636,836 B2
January 28, 2014

Assembled Heat Exchanger



1. Transient Contours of Temperature, Fraction of Reaction Completion and Volumetric Heat Generation Rate during Hydriding

P = 100 bar

P = 200 bar

P = 300 bar

P = 300 bar

P = 300 bar

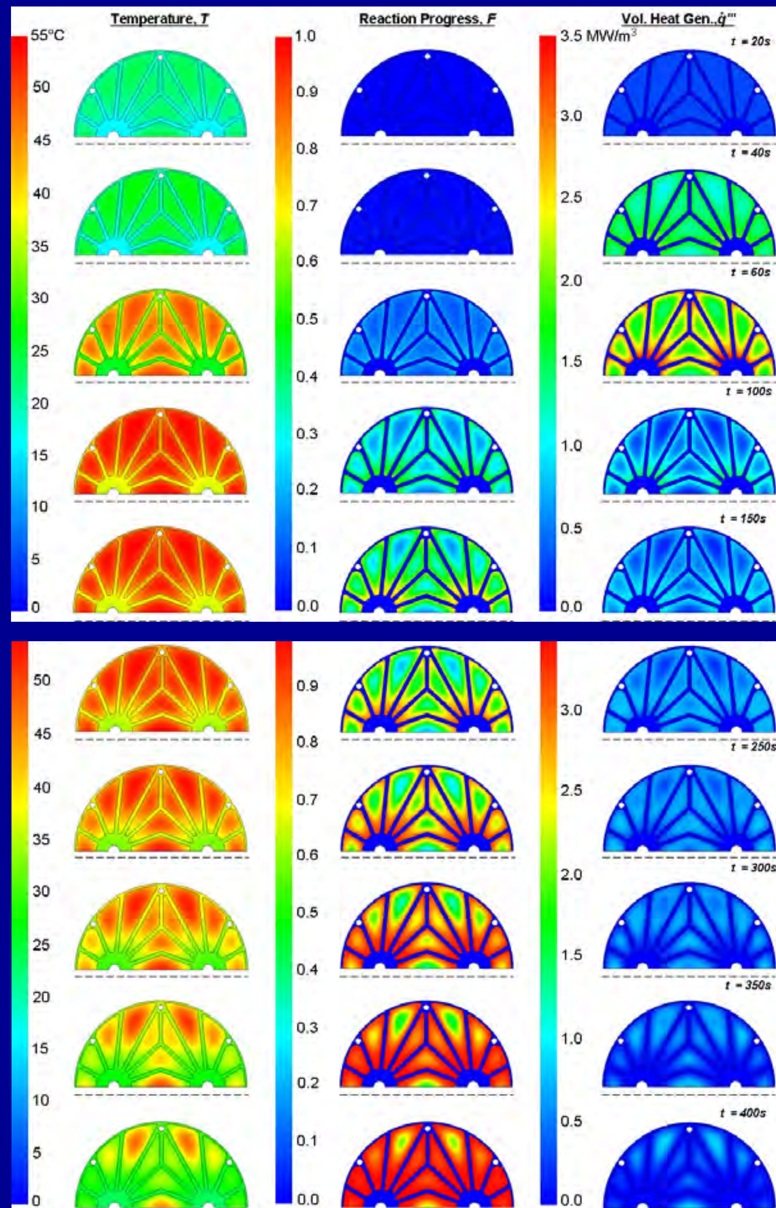
P = 300 bar

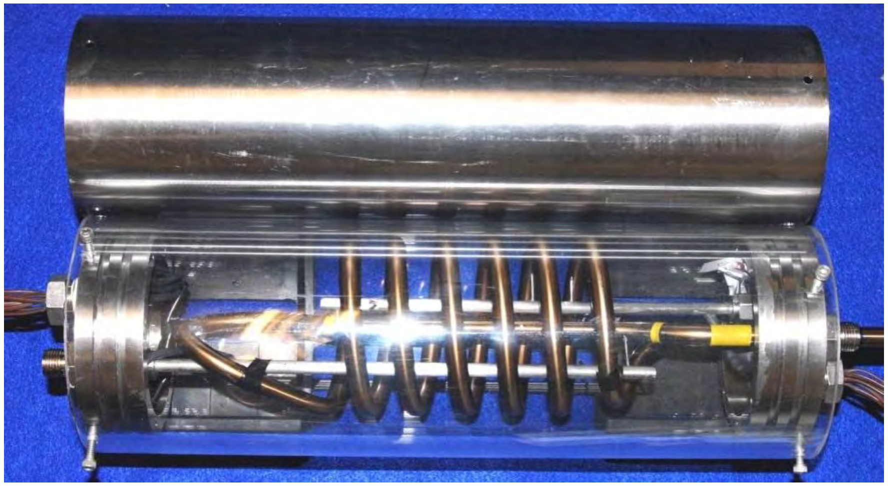
P = 300 bar

P = 300 bar

P = 300 bar

P = 300 bar

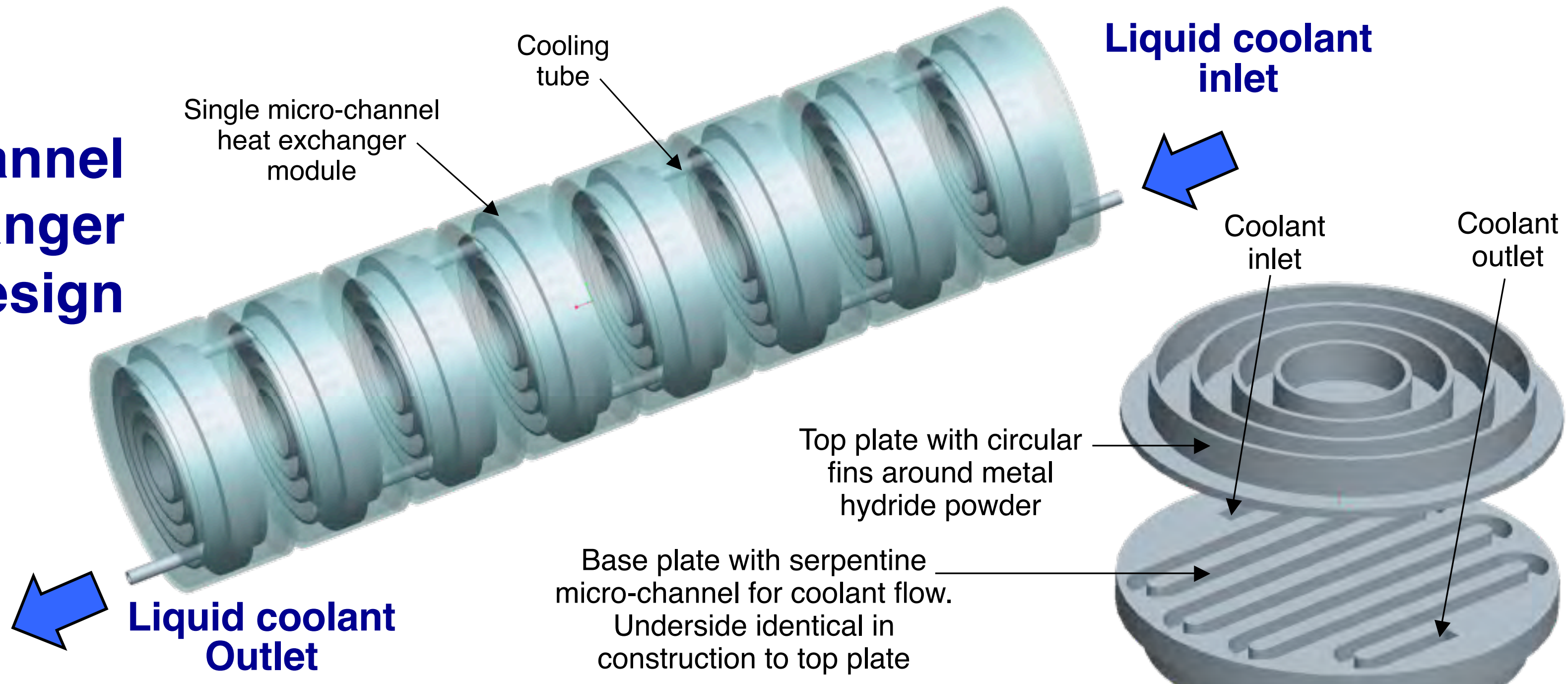




Coiled Heat Exchanger Design

US Patent 8,778,063 B2
July 15, 2014

Micro-Channel Heat Exchanger Design



Mudawar (2009)

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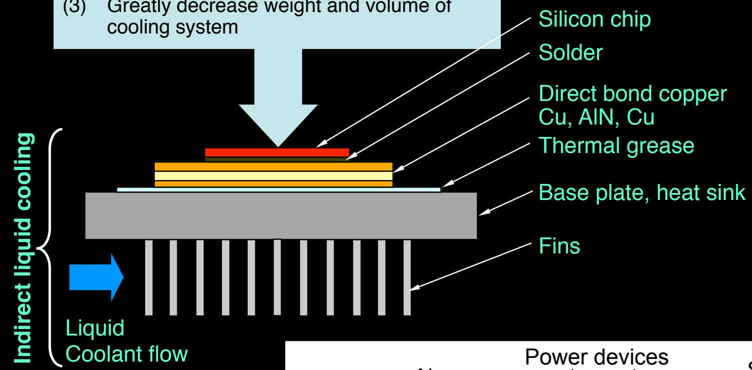
2. Hybrid Vehicle Power Electronics

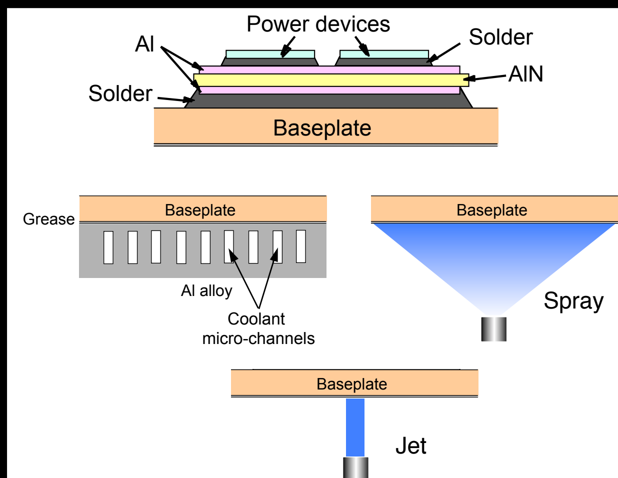
Alternative **direct liquid cooling** of chip to:

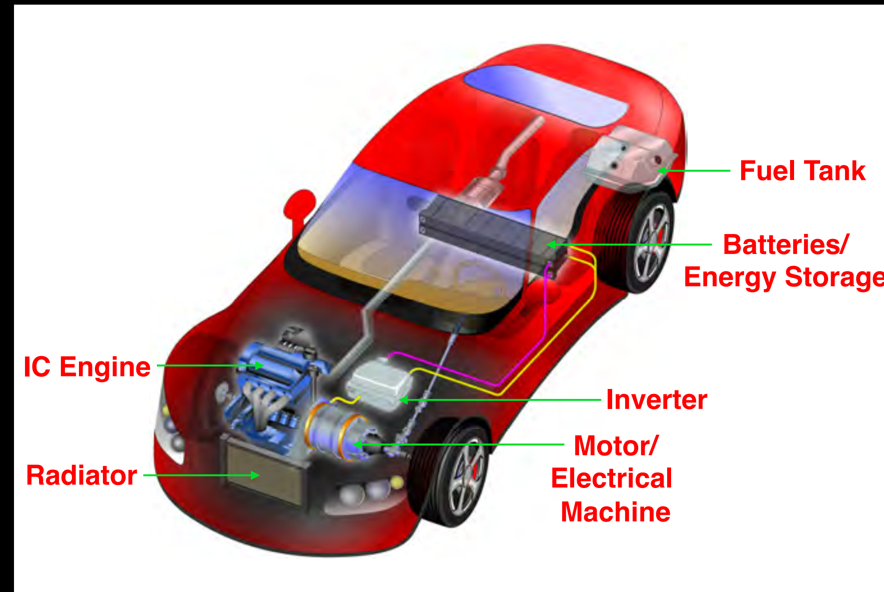
(1) Eliminate conductive resistances of intermediate layers

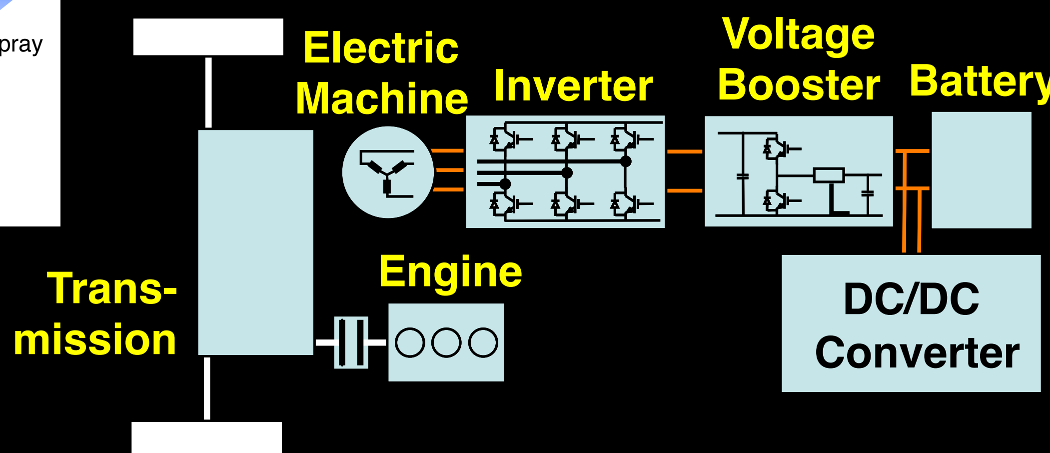
(2) Allow closer packaging of high-flux chips

(3) Greatly decrease weight and volume of cooling system









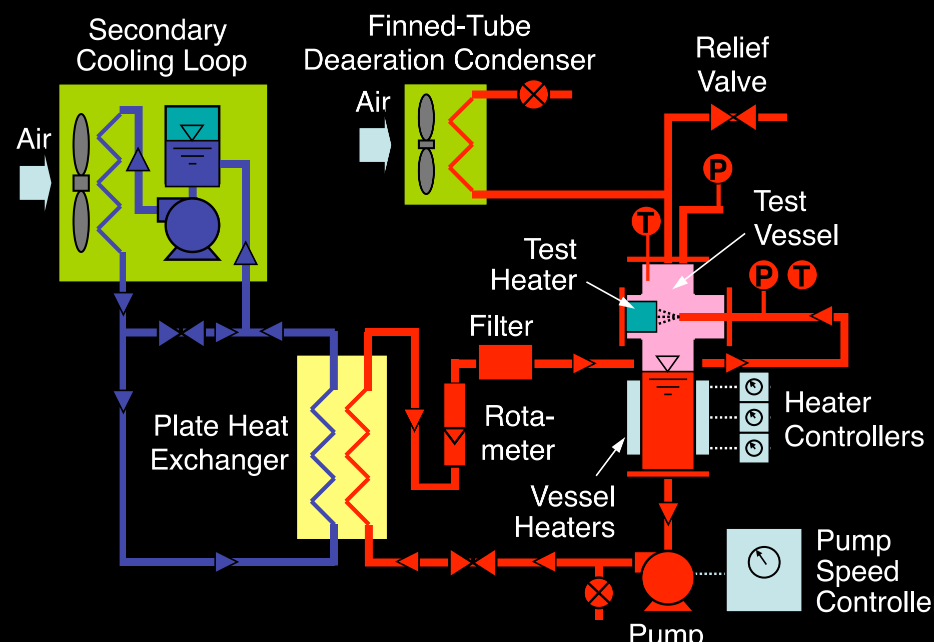
- Goal: dissipate over 250 W/cm^2 while maintaining device temperature below 125° C for silicon devices
- Two-phase cooling options: R134a loop that taps into vehicle's refrigeration loop, or separate HFE 7100 cooling loop

Research Presentation

2. NREL Hybrid Vehicle Power Electronics Thermal Test Laboratory

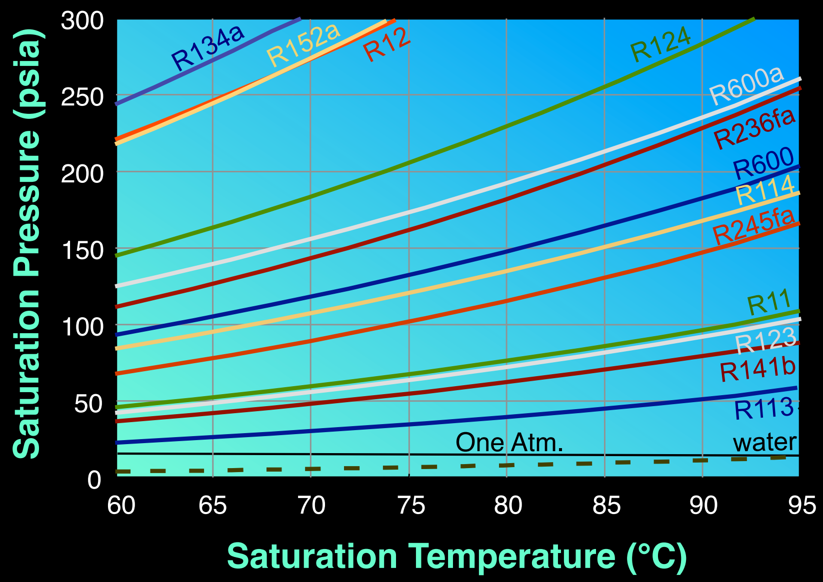
Mudawar, Bharathan, Kelly & Narumanchi (2009)

Power Supply and Instrumentation Rack

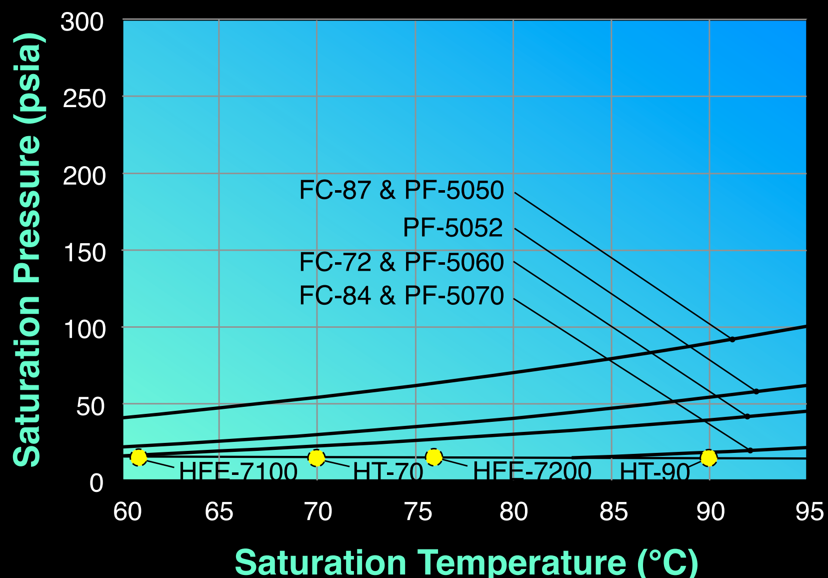


2. Coolant/Refrigerant Thermal/Environmental Study

Refrigerants



Liquid Coolants



Refrigerants

Chlorofluorocarbons (CFCs) (*e.g.*, R11, R12, R113 and R114) composed of chlorine, fluorine and carbon; they are nontoxic and inert, but highly ozone-depleting and contribute to global warming.

Hydrochlorofluorocarbons (HCFCs) (*e.g.,* R123, R124 and R141b) constitute a more recent alternative to CFCs, given their somewhat similar inertness and cooling characteristics but less than 10% of the ozone-depleting effects of CFCs.

Hydrofluorocarbons (HFCs) (*e.g.,* R134a and R143a) provide essentially zero ozone depletion and reduced global warming effects; R134a has good ratings in most performance categories.

Liquid Coolants

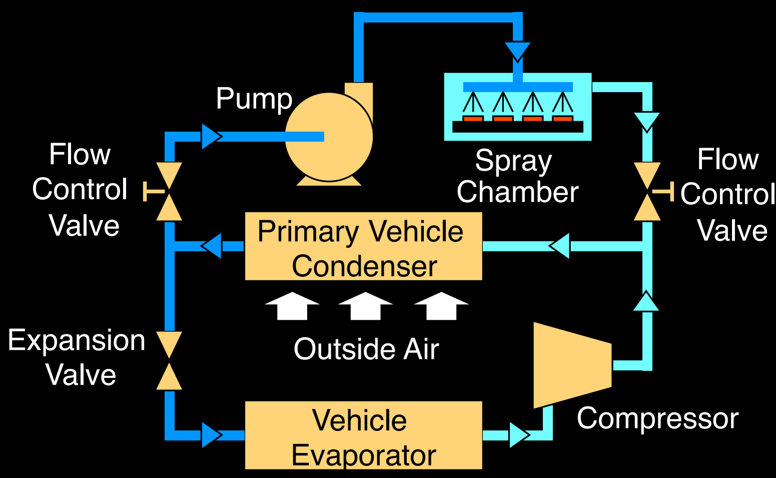
3M perfluorocarbons (PFCs) (*e.g.,* Fluorinerts FC-72, FC-87 and FC-84, and Performance Fluids PF-5050, PF-5052, PF-5060 and PF-5070) have *average* environmental ratings because of their relatively high GWP

3M HFCs (*e.g.,* Novec fluids HFE-7100 and HFE-7200). HFE-7100 has *good* ratings in all performance categories but HFE-7200 carries a low LEL. HFE-7100 has a freezing point of -135° C, which is well below any expected automobile application range of temperatures.

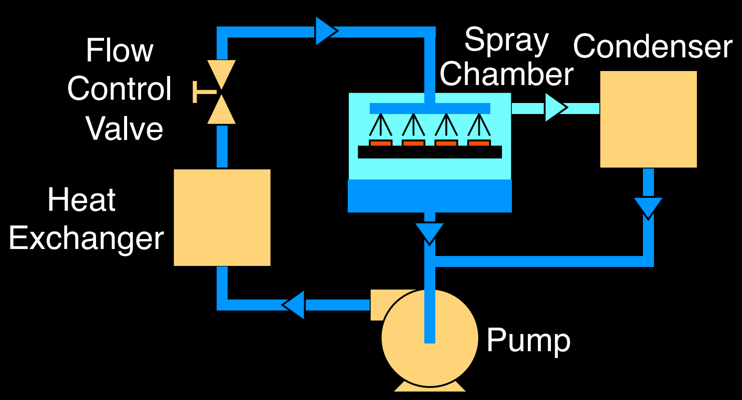
Most promising: R134a and HFE-7100

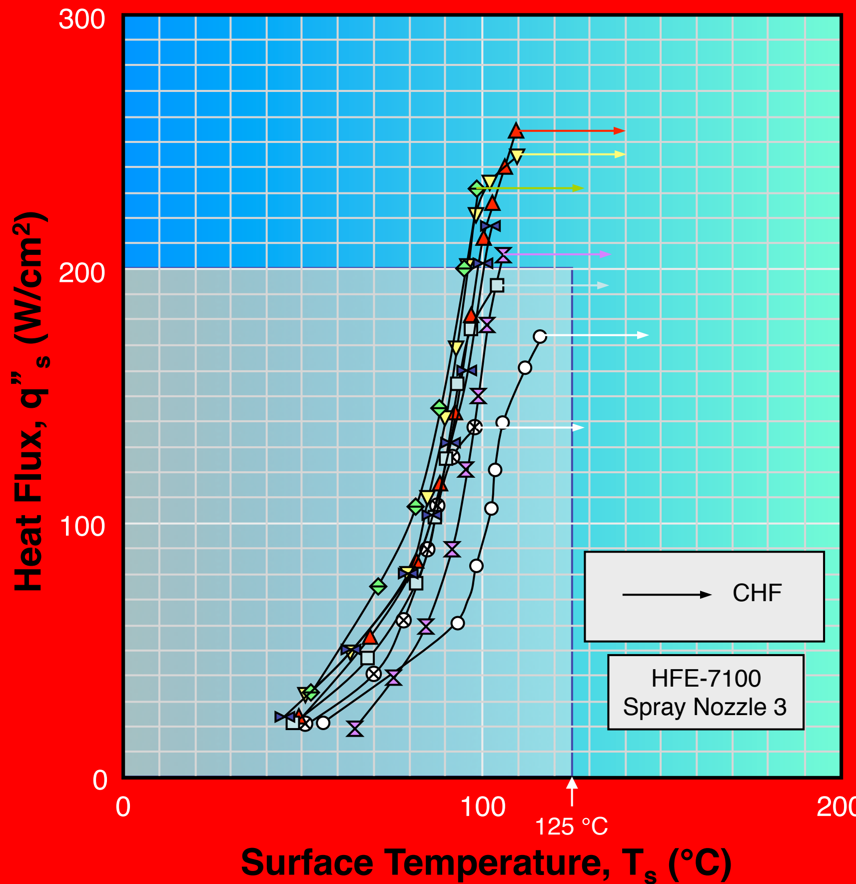
2. Cooling Loop Options for Hybrid Vehicle Power Electronics

Modified R134a Air-Conditioning Refrigeration Loop



Separate Cooling Loop with Appropriate Coolant



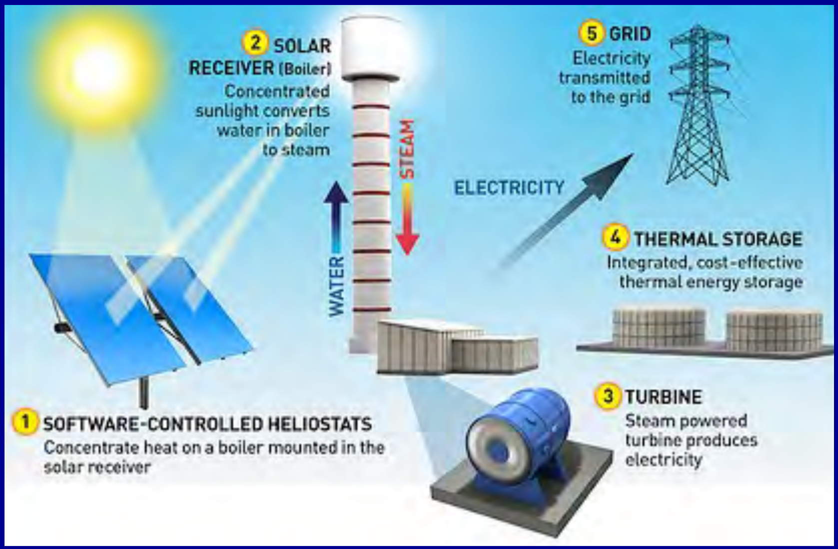


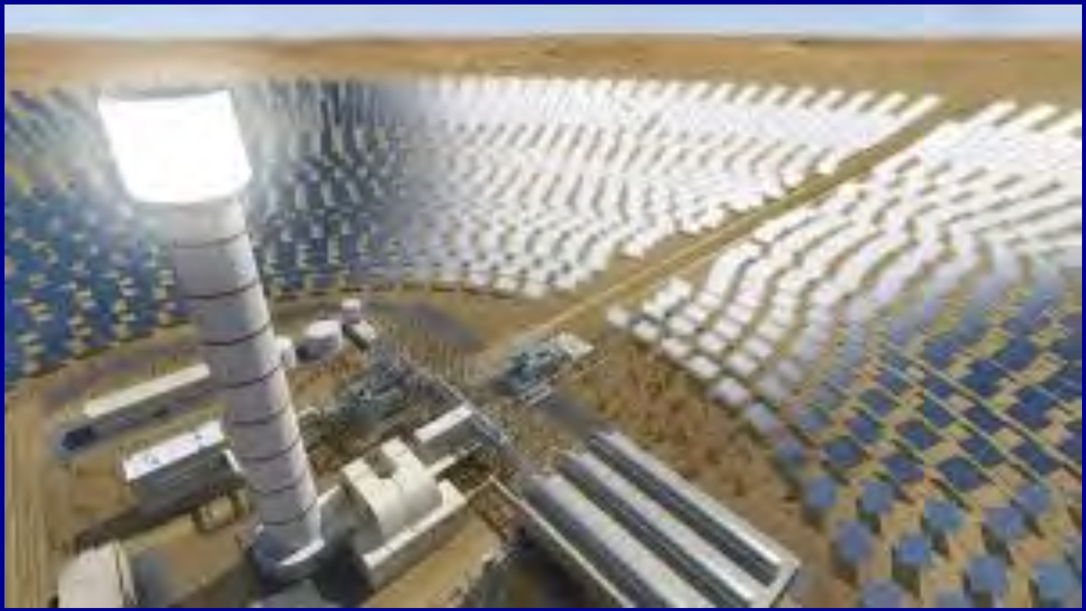
- R134a can yield high CHF values, but cannot maintain low device temperatures.
- HFE-7100 can yield CHF values in excess of 200 W/cm^2 at surface temperatures below 125° C.
- Two-phase HFE-7100 spray cooling is effective at meeting thermal management requirements of hybrid vehicle electronics.

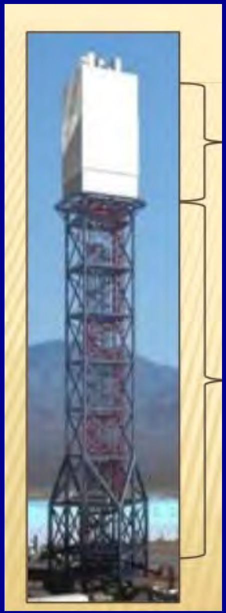
3. Solar Receiver Steam Generator

Ivanpah Solar Power Facility

- World's largest solar thermal project
- California Mojave Desert
- 3,600 acres (3 units)
- 370 MW power output
- 173,500 heliostats
- Serves 140,000 homes

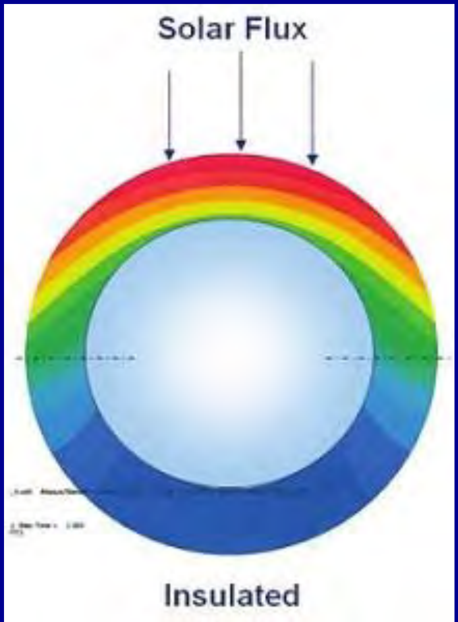






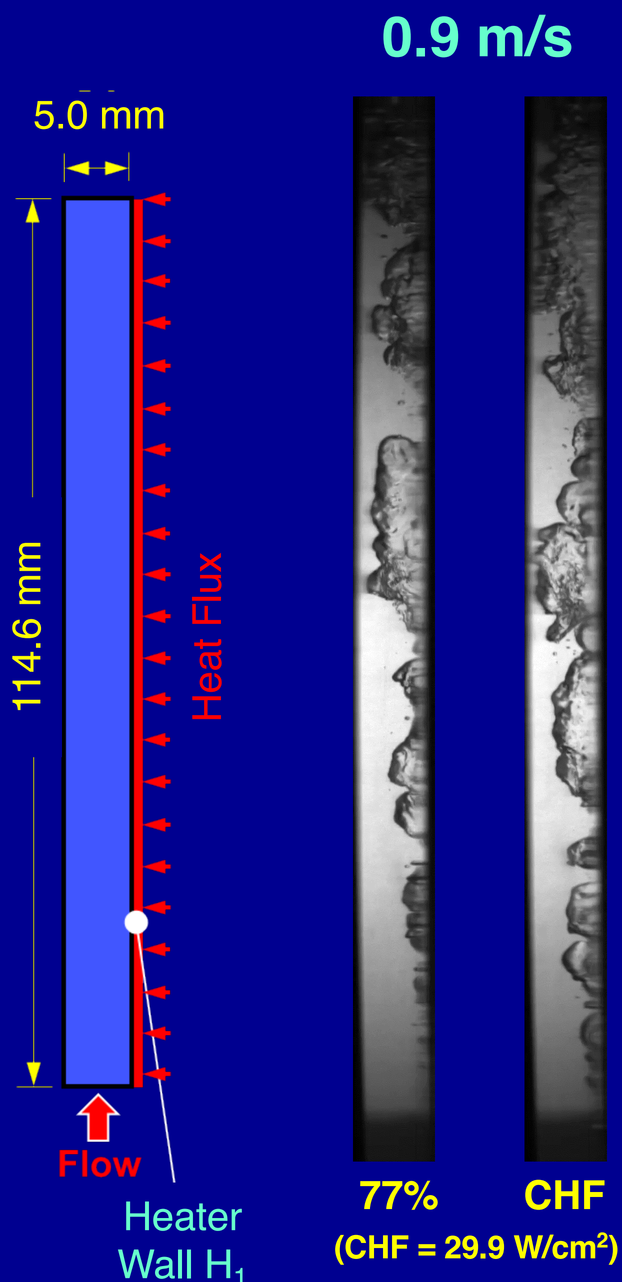
120' Solar Receiver Steam Generator

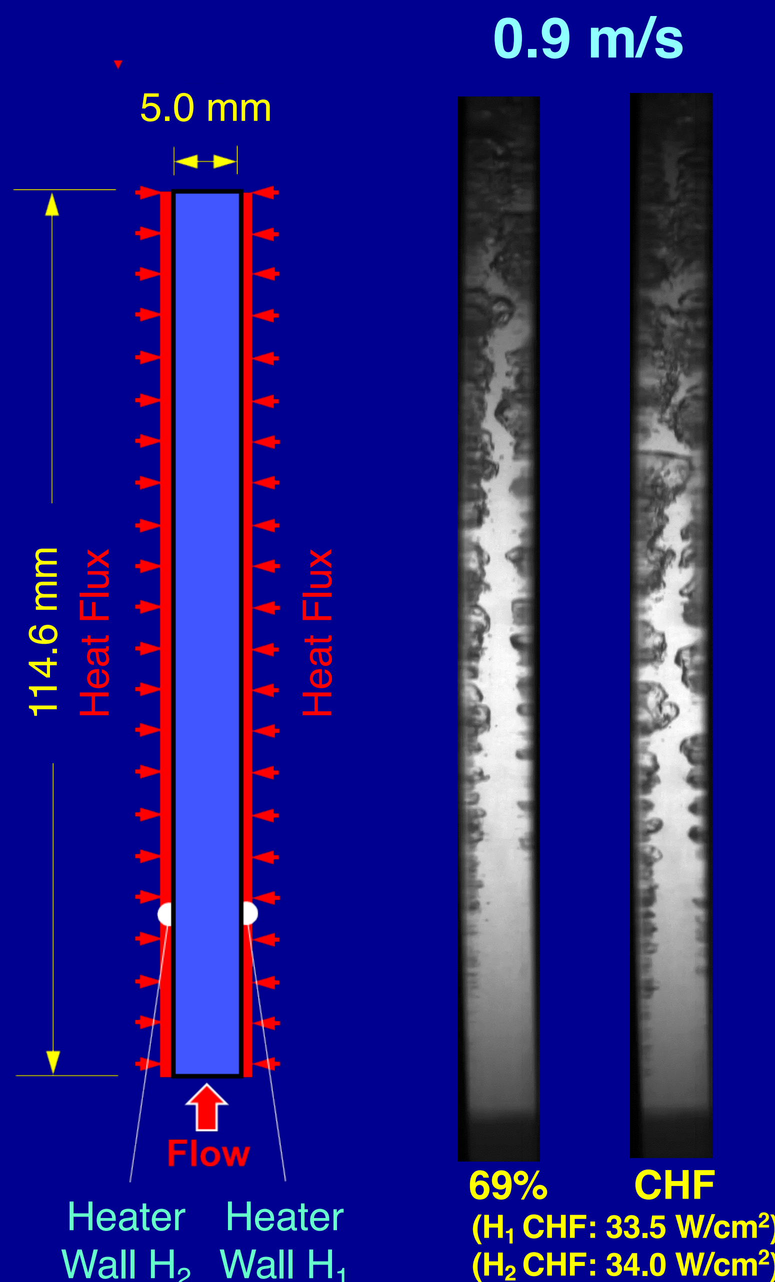
339' Tall Tower



- Evaporator heats subcooled water to boiling temperature to produce steam-water mixture at high pressure and temperature
- Heat flux one-sided and much higher than in fossil boilers

3. Single-Sided versus Double-Sided Heating





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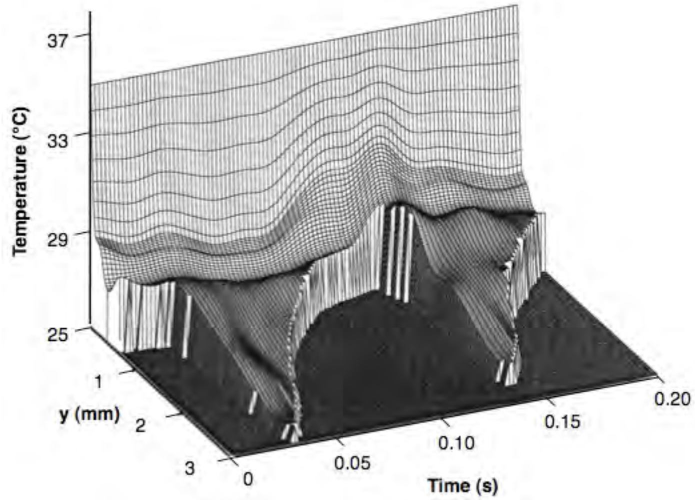
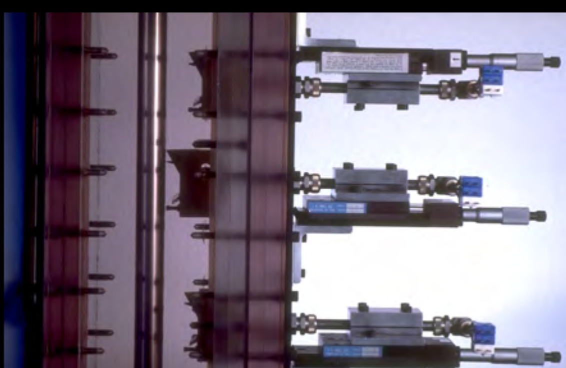
3. Measurement of Effects of Waves on Wavy Heated Liquid Layers

Vertical Evaporation Facility

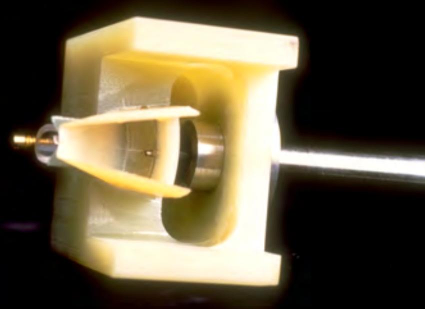


Temperature fluctuations across wavy, turbulent water film falling on vertical heated cylinder at Re = 5700 (Lyu & Mudawar, 1991)

Thermocouple Knife-edge for Measurement of Temperature Profile across Wavy Liquid Layer



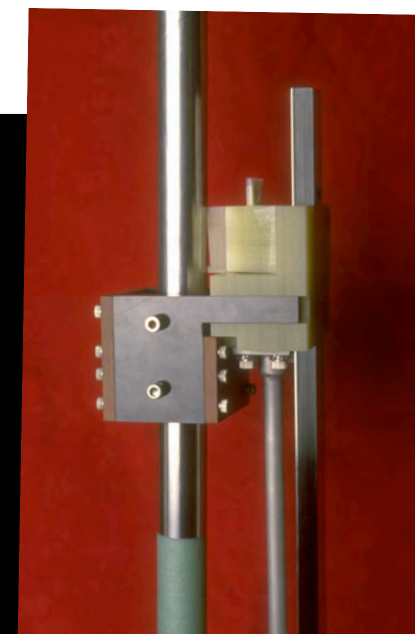
Translation stages for liquid layer probes



Scoop for measurement of mean liquid layer temperature

Probe for simultaneous measurement :

- Temperature profile across liquid layer
- Liquid layer thickness
- Interfacial wave speed

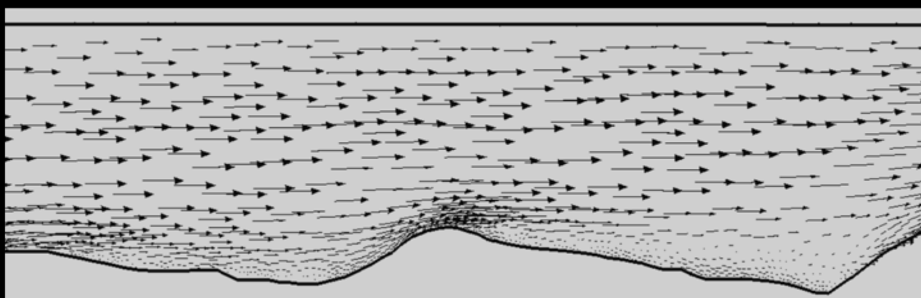
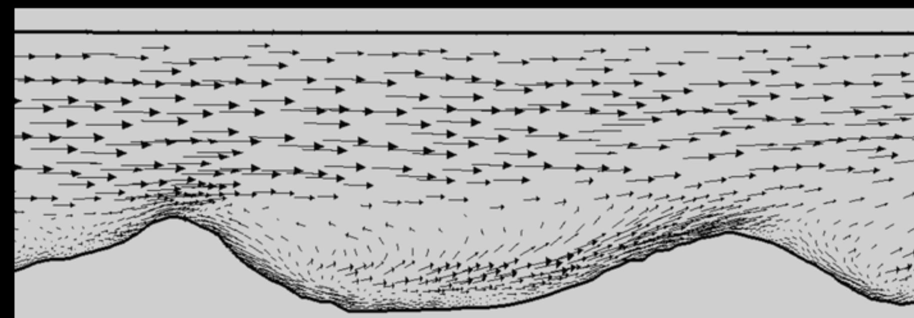


Research Presentation

3. Computed Nitrogen Velocity Vector and Contour Plots along Stationary Wavy Interface

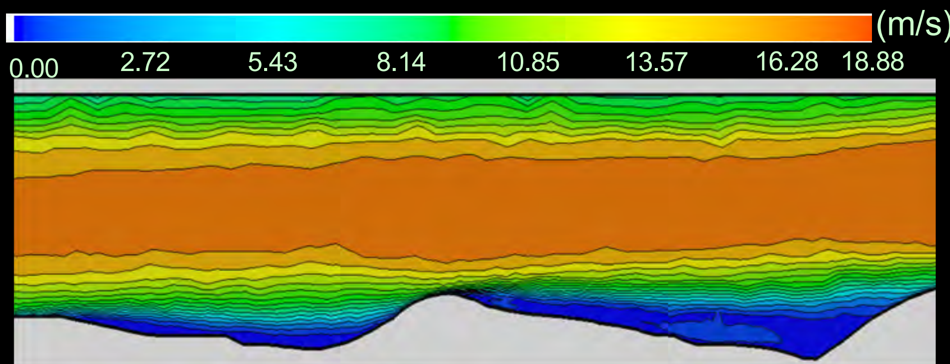
Re_g = 3450 Re_g = 6100

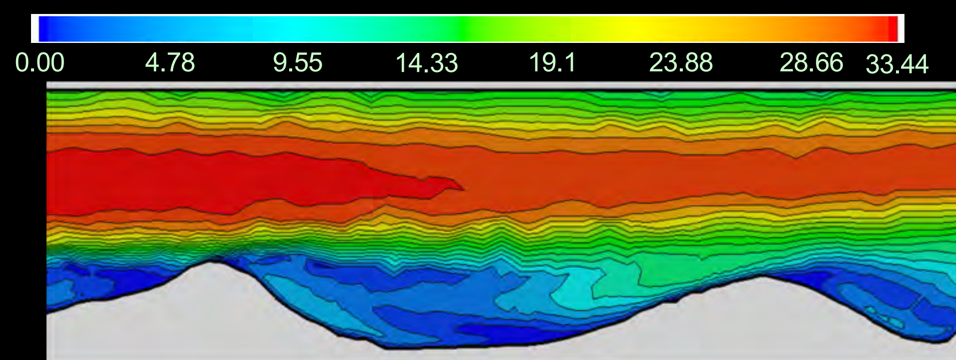
⟶ 24 m/s ⟶ 40 m/s

(m/s)

Nitrogen velocity vector plots at *z* = 0





Nitrogen velocity contour plot at *z* = 0

FLUENT, k - ω model

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4. *Intelligent Heat Treating of Aluminum Alloy Parts*

Enormous Energy Consumption

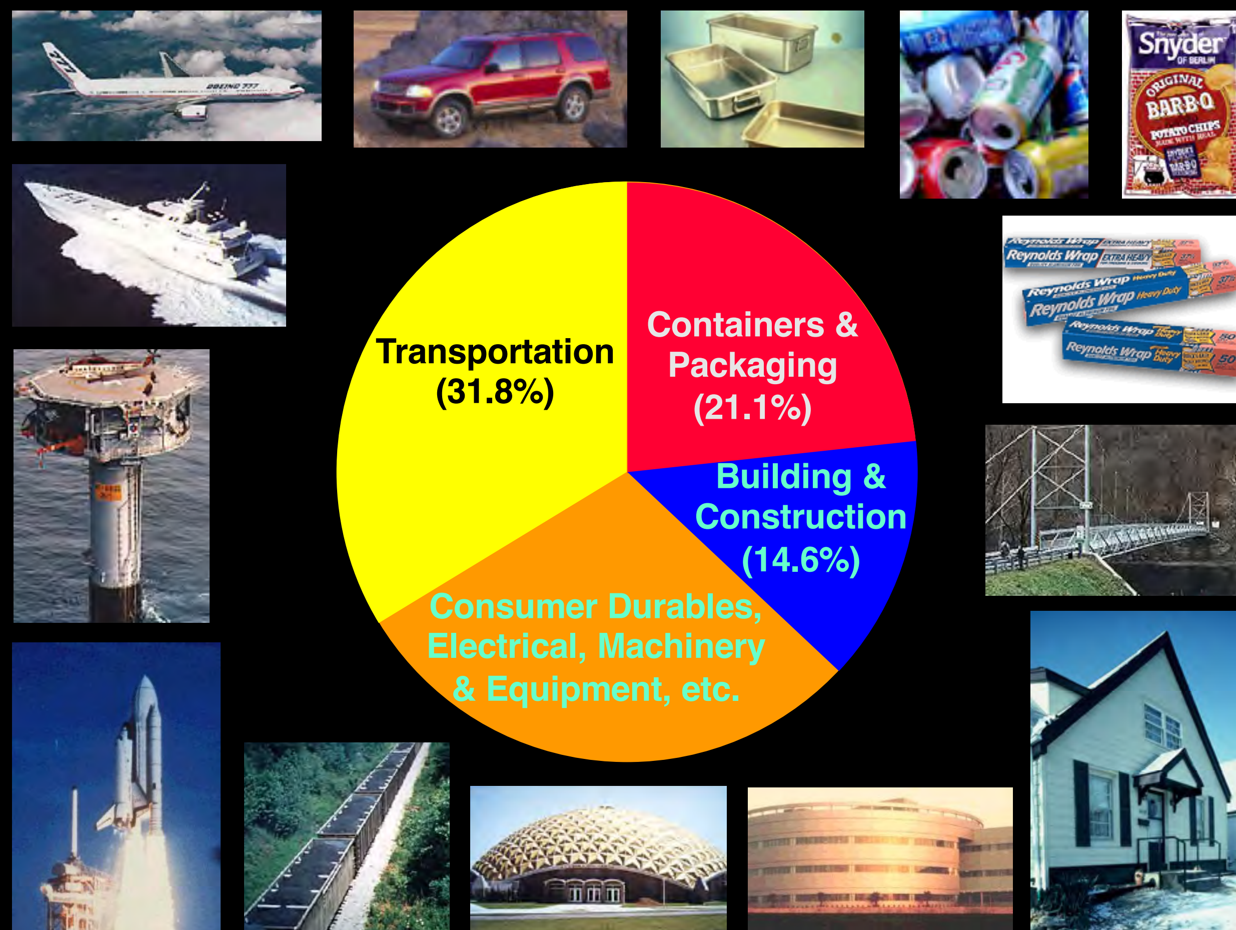
Poor Productivity

High Scrap Rate

High Water Consumption

High Emissions & Greenhouse Gases

Up to 50% of Cost of Aluminum Production associated with Post-Processing of Poorly Produced Parts



U.S. Aluminum Industry Profile

Energy Consumption: 200,000 Trillion BTU
23.0 B lbs Annual Production Volume
Generates $65 Billion (plus $87 B indirect)
155,000 Employees (plus 517,000 Indirect)
Source: Aluminum Assoc.

Large Residual Stresses

Warping

Cracking

Soft Spots

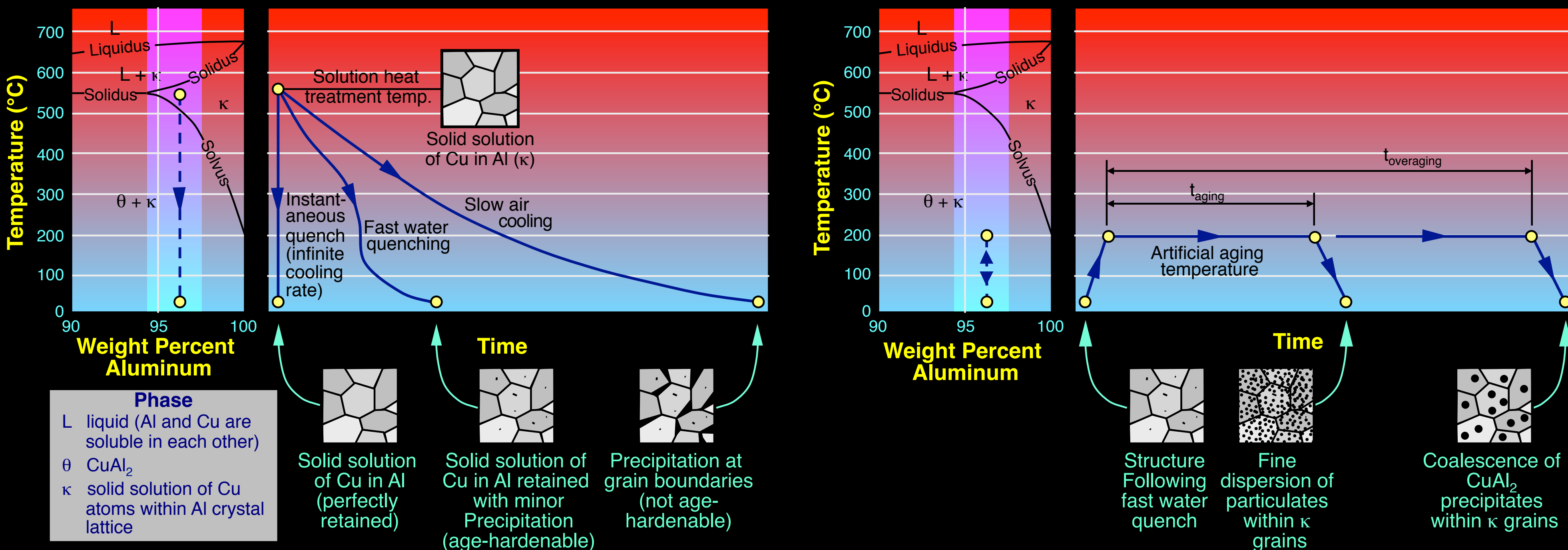
Poor Corrosion Resistance

Poor Hardness

Poor Strength

Research Presentation

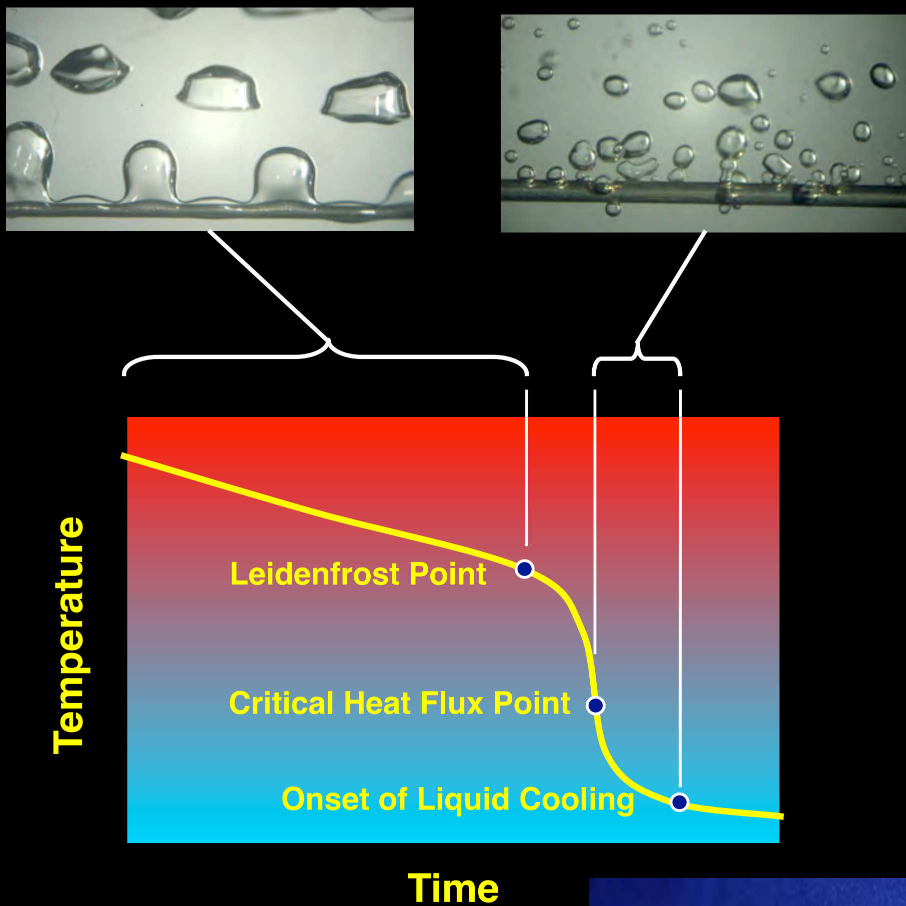
4. Microstructural Development of Aluminum Alloy during Quenching Phase of Heat Treating

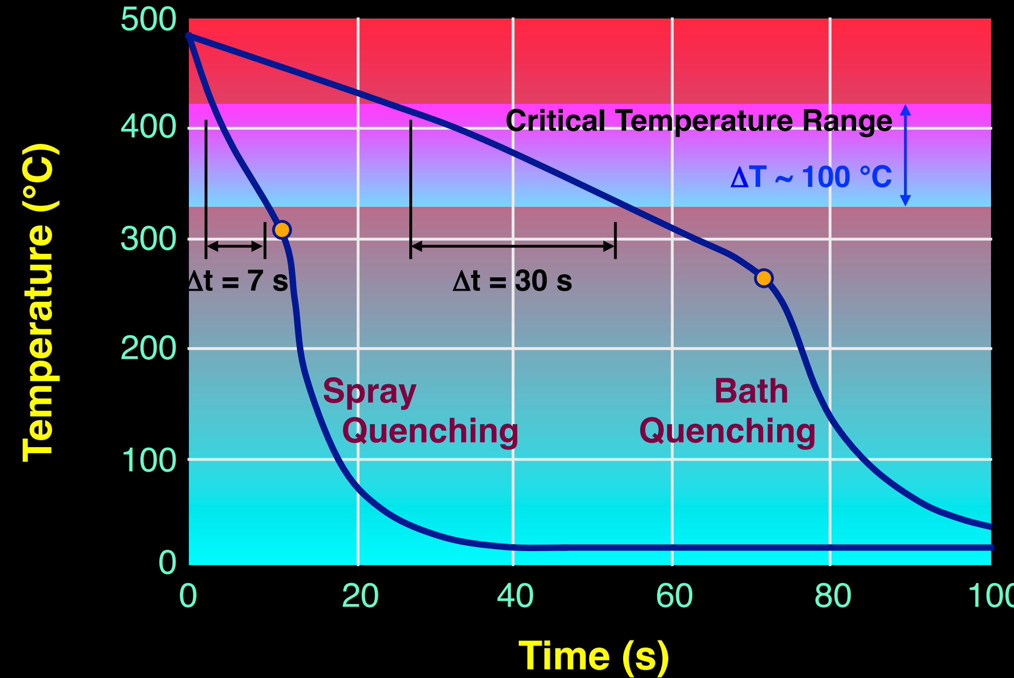


Heat treating of Al-Cu (4.4 wt %) alloy (Hall & Mudawar, 1996)

Research Presentation

4. *Cooling Curve for Liquid Bath Quenching versus Spray Quenching*





Distortion induced by Poor Quenching

4. *Fundamental Physics of Spray Cooling*

Mudawar & Valentine (1989)

Surface Analysis Facility

Krüss Tensiometer

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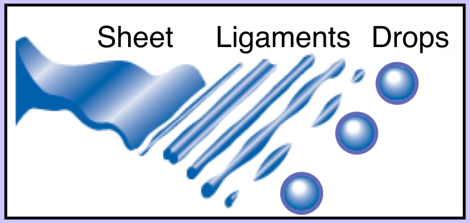
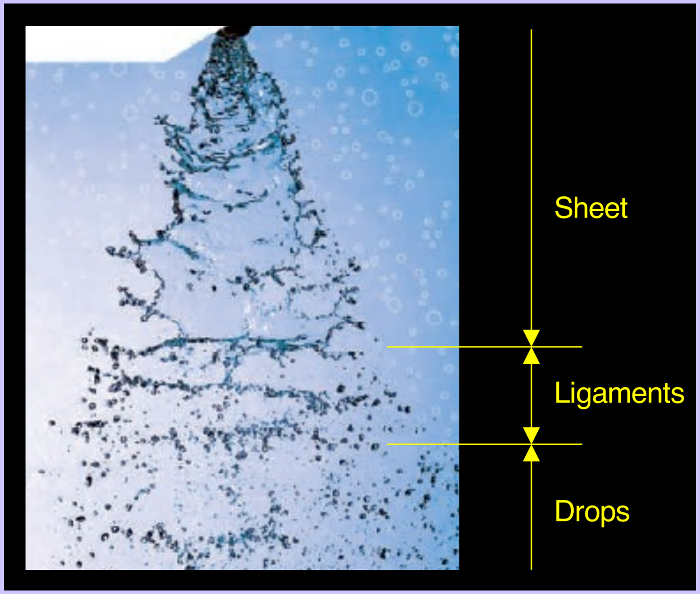
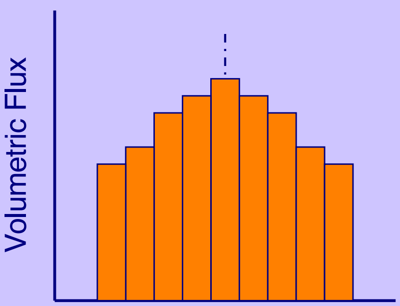
4. Fundamental Physics of Spray Cooling

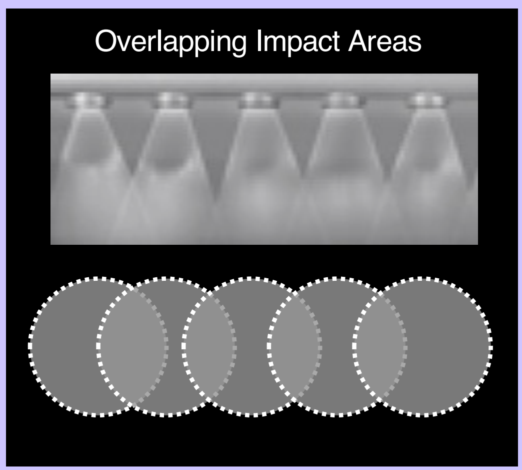
Nozzle Region: Droplet Breakup Physics



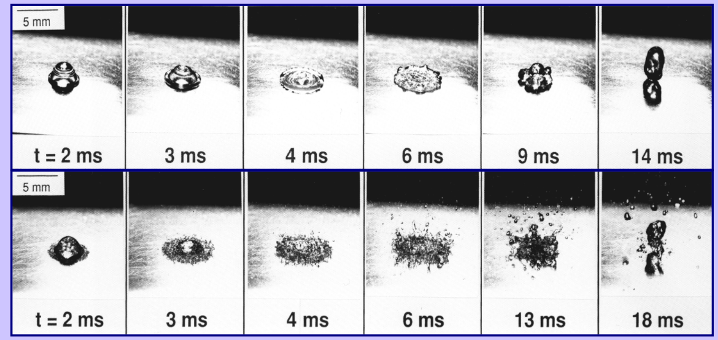


Surface Region: Global Impact Physics

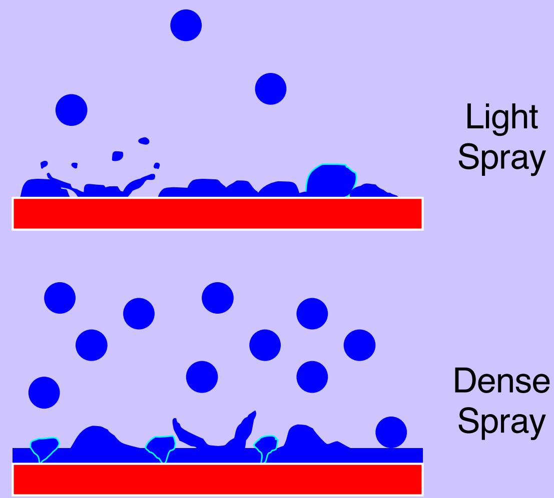




Surface Region: Local Impact Physics



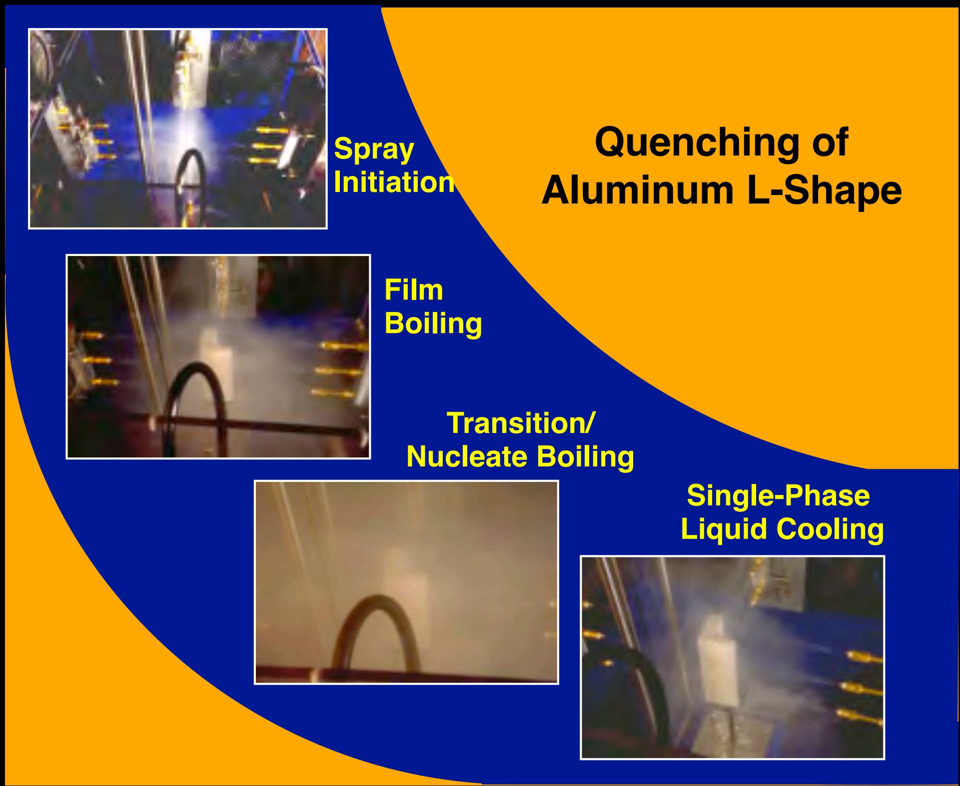
Individual Droplet Impact:
- Weber number
- Surface temperature



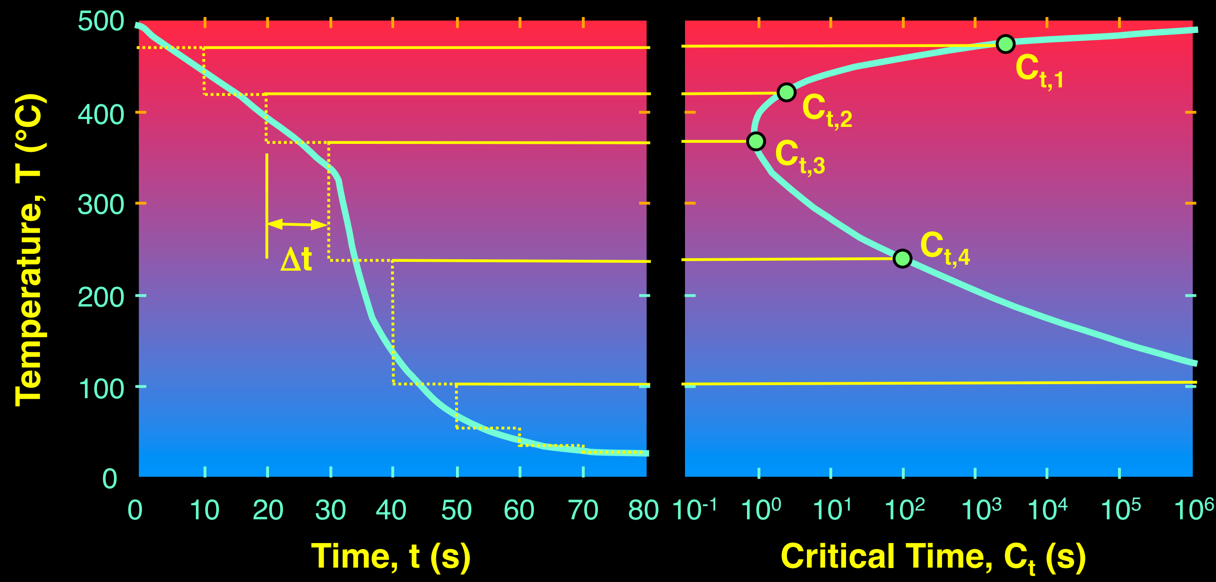
Liquid Film Formation, Evaporation & Boiling:
- Volumetric flux

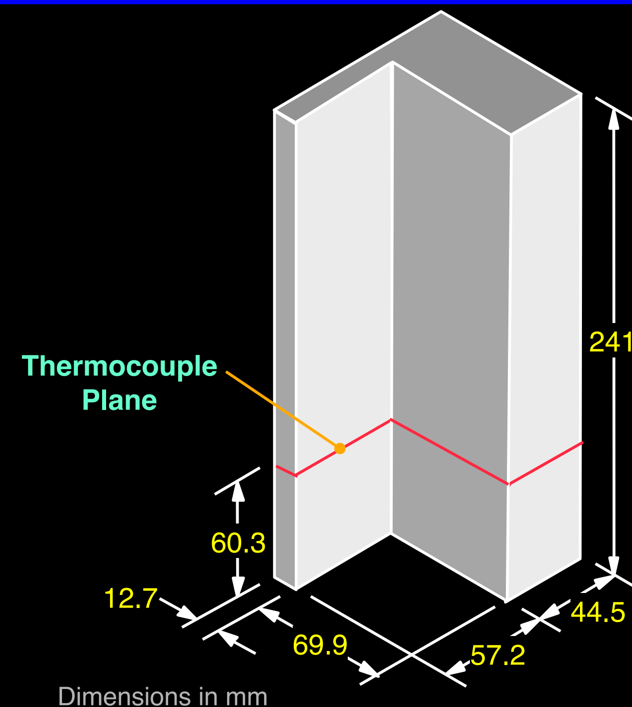
Research Presentation

4. Purdue Quenching Facility



4. Determination of Quench Factor and Hardness





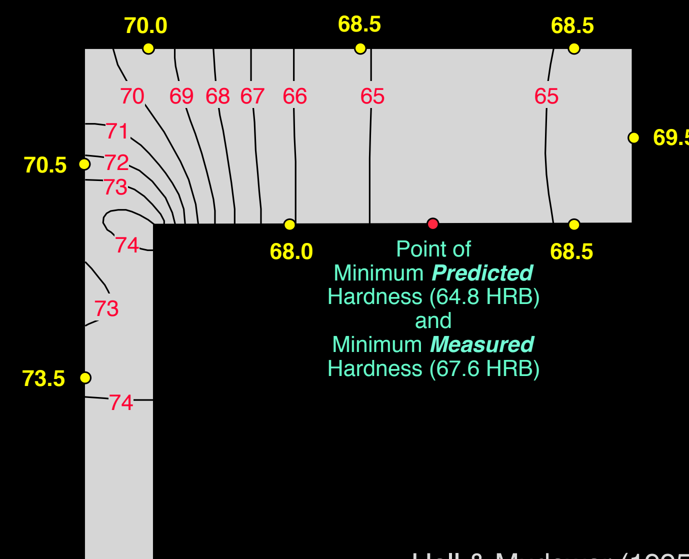
Quench factor:

$$\tau = \int_{t_1}^{t_2} \frac{dt}{C_t} \cong \frac{\Delta t_1}{C_{t,1}} + \frac{\Delta t_2}{C_{t,2}} + \cdots + \frac{\Delta t_n}{C_{t,n}} = \sum_{i=1}^{n} \frac{\Delta t_i}{C_{t,i}}$$

where $C_t = -k_1 k_2 \exp\left(\frac{k_3 k_4^2}{RT(k_4 - T)^2}\right) \exp\left(\frac{k_5}{RT}\right), T \text{ in Kelvins}$

Hardness:

$$H = H_{min} + (H_{max} - H_{min}) \exp(k_1 \tau)$$



Hall & Mudawar (1995)

H ○ Rockwell B hardness (average of three *measurements* near thermocouple plane rounded to nearest 0.5 HRB, all three measurements were within ±1 HRB)

—H— Rockwell B hardness contours *predicted* using quench factor technique with *predicted* temperature-time history)