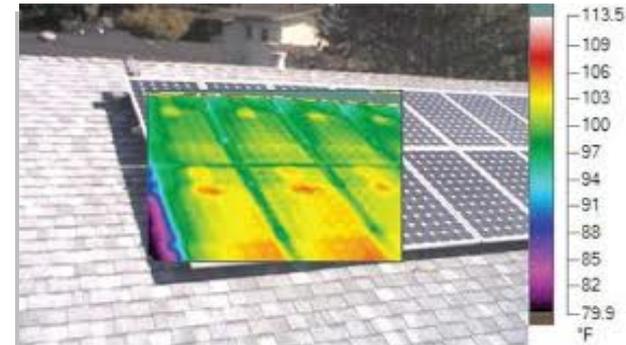
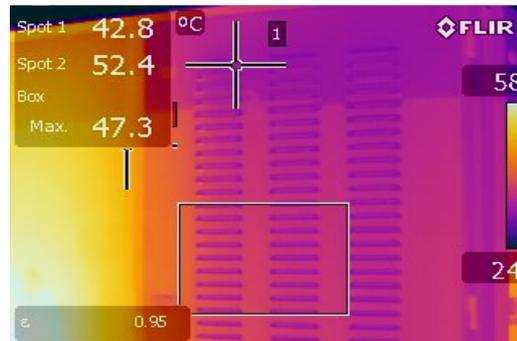
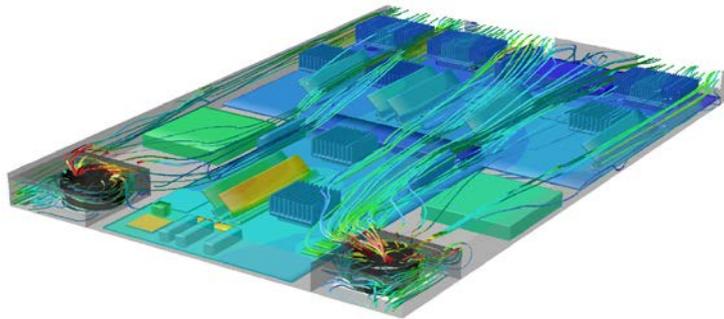


Exceptional service in the national interest



Reliability Thermal Management

Kenneth M. Armijo

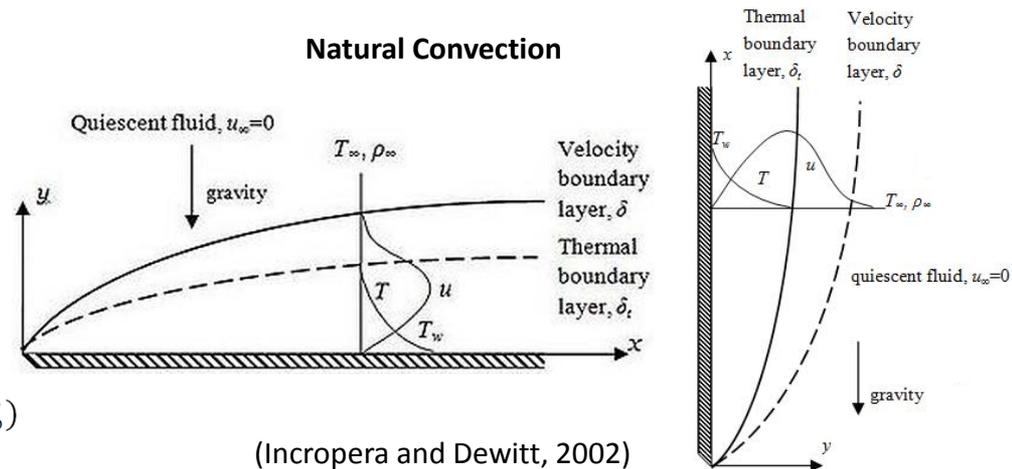
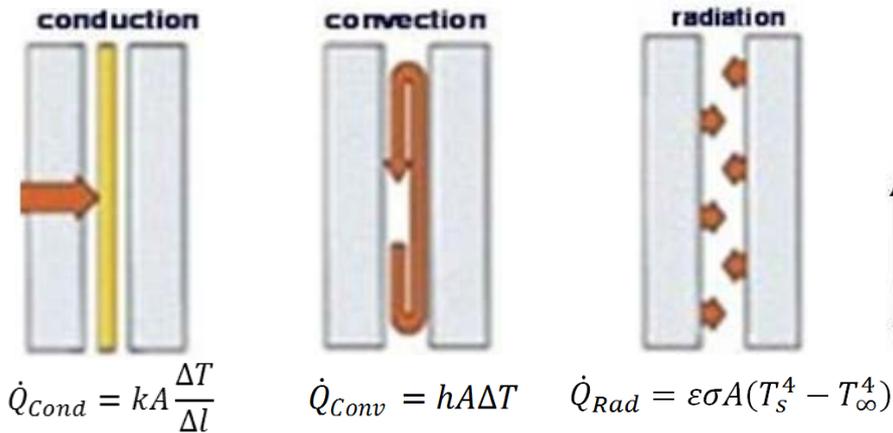


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Overview

Heat Transfer & Thermal Management

- Modes for Electronic Design: Conduction, Convection & Radiation



Inverter Thermal Considerations

- Thermally Sensitive Electronics
 - Passive vs. Active Cooling
- Solar Gain & Thermal Gain
 - Shading & Topology
- Temperature Sensing & Controls
 - Derates & Aging/Failure Modes

Process	h [W/m ² -K]
Natural Convection	
Gases	2-25
Liquids	50-1000
Forced Convection	
Gases	25-250
Liquids	100-20,000
Convection with Phase Change	
Boiling or Condensation	2,500-100,000

- Thermal cycling
 - Determines the ability of parts to resist extremely low and high temperatures, as well as their ability to withstand cyclical extremes. Stress resulting from cyclical thermo-mechanical loading accelerates fatigue failures.
- Humidity Freeze
 - This test serves as a mechanical strength test to ensure the reliability of a device/system from failure due to stress and water ingress
- High Temperature Operating Bias (HTOB)
 - It consists of subjecting the parts to a specified bias or electrical stressing, for a specified amount of time, and at a specified high temperature.

System Element	Failure Mechanism	Accelerated Test
Enclosure/Interconnect	Mechanical Deformation, Moisture Ingress, Corrosion, Dielectric Breakdown	Thermal cycling (TC)/Humidity Freeze (HF)/Damp Heat Test/UV Precondition
PCB/Solder system	TCE Mismatch, Electromigration, Corrosion	Thermal Cycling/humidity Freeze/ Damp Heat Test
Passive components	Dielectric/Insulation Breakdown	Humidity Freeze/Thermal Cycling/ UV Degradation
Active Components	Mechanical Wear-Out, etc.	Thermal Cycling/Damp Heat Test/Extreme Temperature Exposure/Integrated Power Cycling
Integrated Circuit Devices	Hot Carrier Injection (HCI), Time-Dependent Dielectric Breakdown (TDDB), etc.	Thermal Cycling/Humidity Freeze/Damp Heat Test

Thermal Design Considerations

■ Critical Thermal Management Components

■ IGBT's/MOSFET'S (Flicker et. al, 2012)

- Latch-Up
- Bond Lift-Off

(Saddik, 2013)

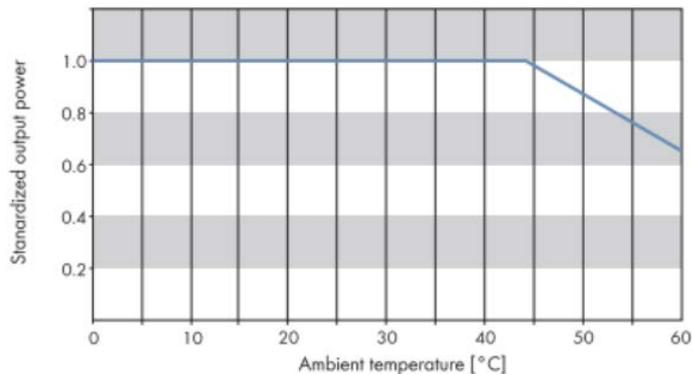
■ Capacitors

■ Direct Active Cooling Issues

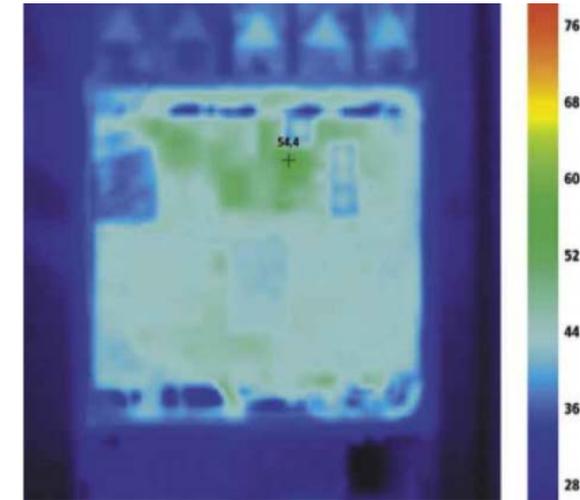
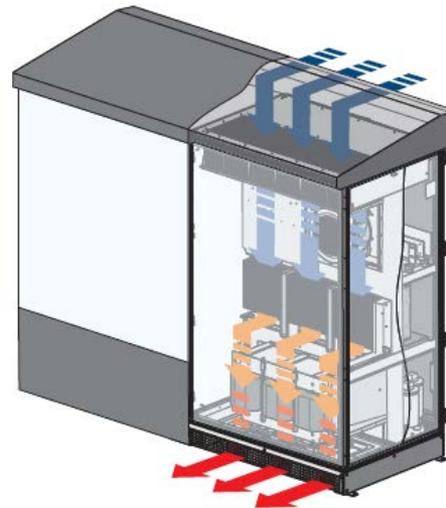
- Dust, Salt Build-Up and Fouling

■ Conjugate Heat Transfer

■ Derate Operation



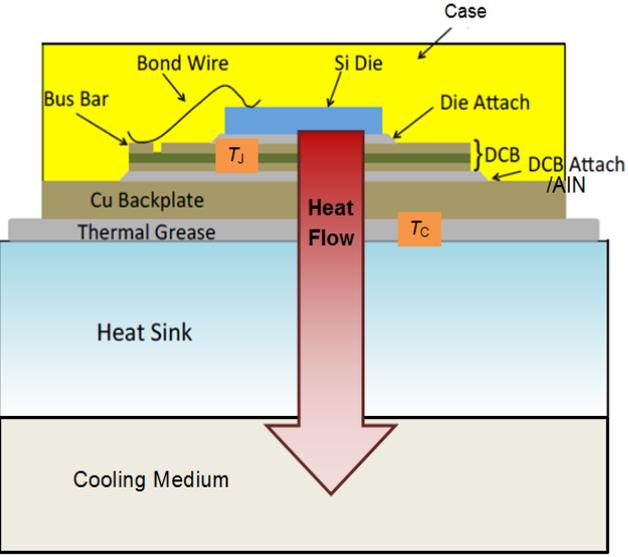
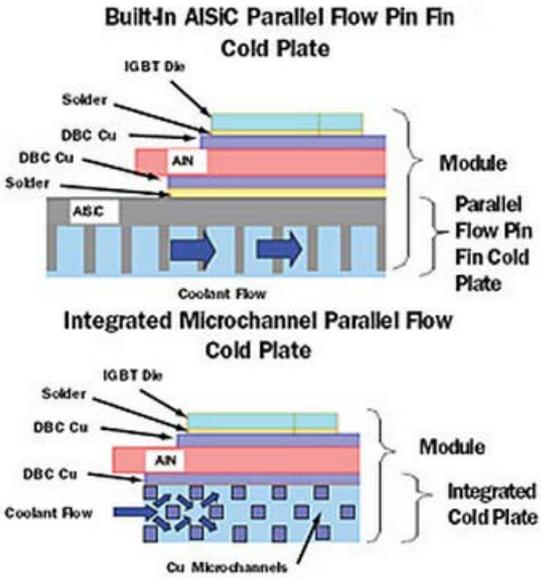
(Saddik, 2013)



(<http://www.sma.de>)

Power Electronics

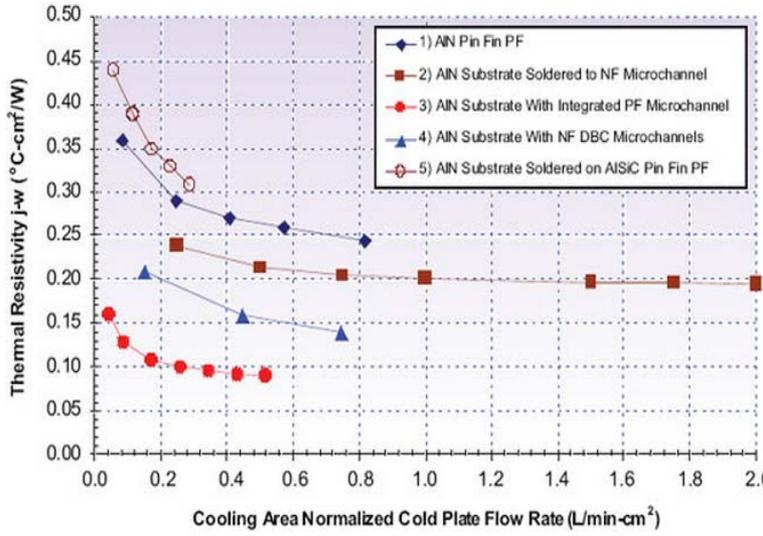
- Greater Number of Layers Increases R_{th} with Standard Configurations Capable of Thermal Dissipation Densities Up to 250-300 W/cm²
- Power Cycling Degradation Impacts
 - Material Degradation and Micro-Fracturing
- CTE Mismatch Impacts



Layer	Thermal Conductivity (W/mK)	Thermal Resistivity (°C-cm ² /W)
Silicon (100°C)	100	0.025
Solder	36	0.036
Top DBC on Aluminum Nitride	393	0.008
Aluminum Nitride	170	0.037
Bottom DBC on Aluminum Nitride	393	0.008
Solder	36	0.035

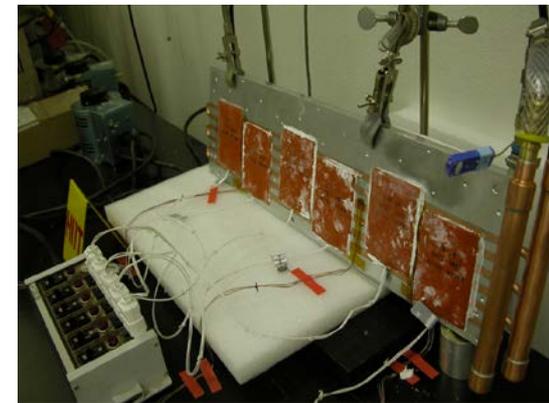
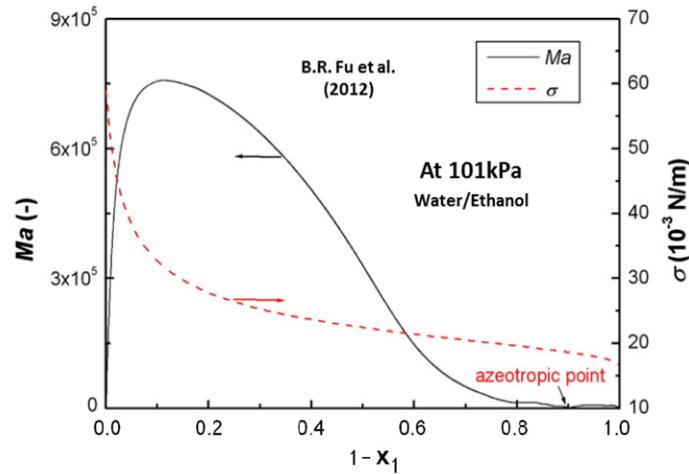
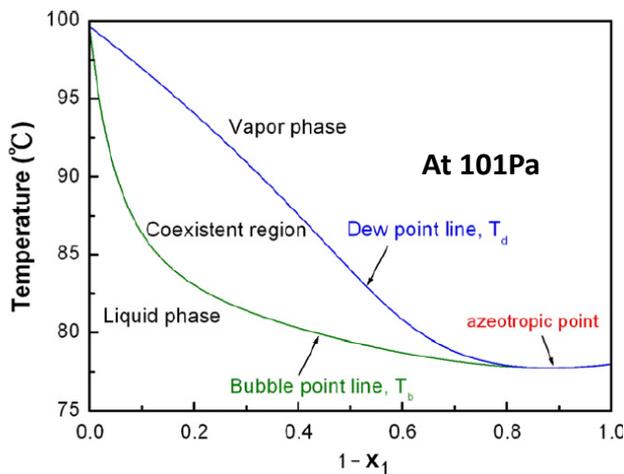
(Leslie et. al., 2013)

Standard Cooling System



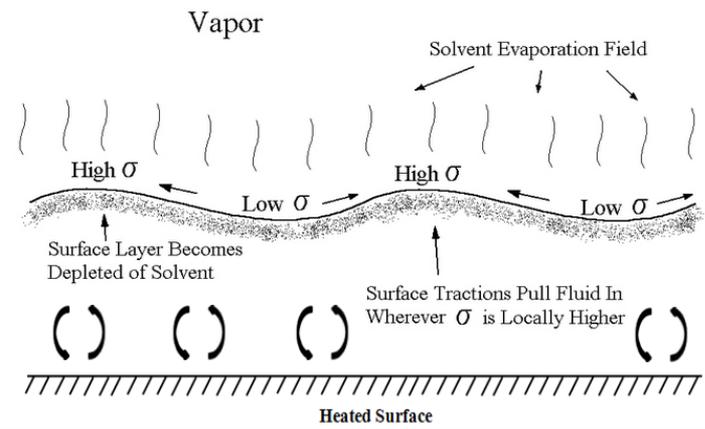
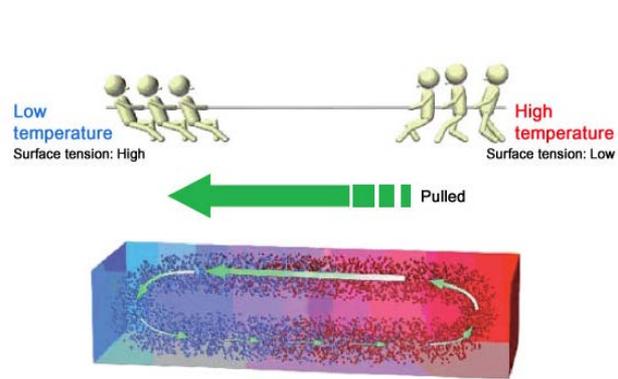
Heat Exchanger Cooling Plate

- Current Work Evaluating Heat Transfer Capability of Binary Mixture Working Fluids to Improve Heat Exchanger Performance
 - Propylene-Glycol (PPG)/Water
 - Ethanol/Water
 - Pure Components
- Alternative Adhesives Durability/ Performance Evaluation

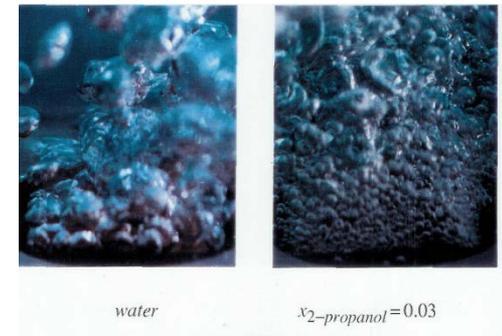


Equilibrium Phases of Mixtures

- Equilibrium Phase Diagrams for Binary Mixtures
 - For low-concentration binary mixtures, Marangoni Effect potentially and likely responsible for Increased Temperature and Heat transfer at low alcohol, x_1 concentrations (Armijo & Carey, 2010, 2012 & 2013).
- Marangoni Effect (*Previous Slide*): Mass transfer due to mixture surface tension & concentration gradients.
 - High surface tension fluids pull more strongly than those with lower surface tension
- More volatile alcohols have lower surface tension than water.
 - Region with lower alcohol concentration (greater surface tension) will pull on surrounding fluid more strongly than a region with higher alcohol concentration (lower surface tension).
 - Preferential evaporation of the more volatile component occurs at the thinner, higher surface-tension l-v interface facilitating fluid motion over a heated surface.

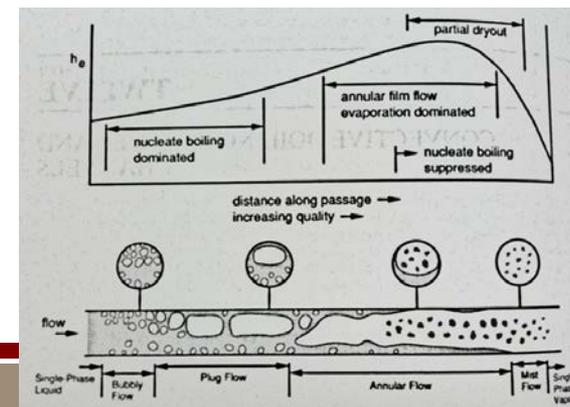
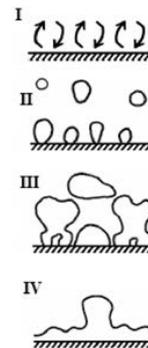
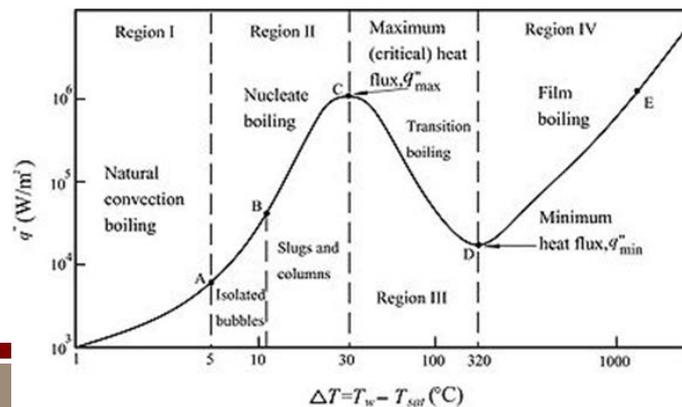


Ex. Of low-conc alcohol/water Mixture Boiling



Heat Transfer & Boiling

- Boiling Curve of a Fluid - A transition diagram depicting the different phases of heat transfer as bubble nucleation increases with superheat
 - Provides the phase-change processes of heat transfer from a heat surface (or wall, “w”) and a liquid (“sat”), for a given heat flux q ”.
 - The Critical Heat Flux (CHF) condition is the point where dryout occurs, whereby the heat surface begins to be severely covered by vapor and heat transfer becomes exceedingly limited.
 - **Superheat** \equiv The temperature gradient between the heated wall temperature and the saturation temperature of the bulk fluid
 - $q'' \equiv$ the heat flux that passes between the heated surface and the bulk fluid



Flow Heat Transfer Modeling

- V.P. Carey (2008) as there are no direct heat transfer correlations for flow boiling at varying mixture concentration

- $q''_{tot} = q''_{NB} + q''_{CB}$ Liquid-vapor phase change analytical mixture models

- PPG/Water Mixtures

- E.V. McAssey & S.G. Kandlikar [2000]

- Volatility Parameter: A relative measure of Mass Diffusion:

- Total Heat Transfer Coeff: $\alpha_{tot} = (\alpha_{NB}^2 + \alpha_{CB}^2)^{1/2}$

$$V_1 = \frac{c_{pL}}{\Delta h_{LG}} \left(\frac{\kappa}{D_{12}} \right)^{1/2} \frac{dT}{dx_1} (x_1 - y_1)$$

$$q'' = \alpha \Delta T$$

- Heat Transfer Coeff.: $\alpha_{CB} = 1.136 Co^{-0.9} (1 - x_1)^{0.8} \alpha_l + 667.2 Bo^{0.7} (1 - x_1)^{0.8} F_{D,l} \alpha_l$

- Mass Diffusion factor: $F_D = 0.678 \left(1 + \left(\frac{c_{p,l}}{\Delta h_{lv}} \right) \left(\frac{\kappa}{D_{12}} \right)^{1/2} (x_{1,s} - y_{1,s}) \frac{dT}{dx_1} \right)^{-1}$

- Convection Number: $Co = (\rho_v / \rho_l)^{0.5} ((1 - x_1) / x_1)^{0.8}$

- Bond Number: $Bo = \frac{g(\rho_l - \rho_v) d_d^2}{\sigma}$

- Ethanol/Water Mixtures

- General Correlation b

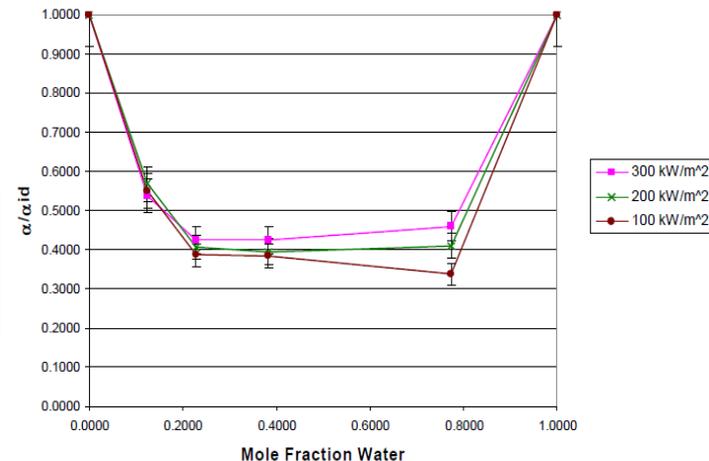
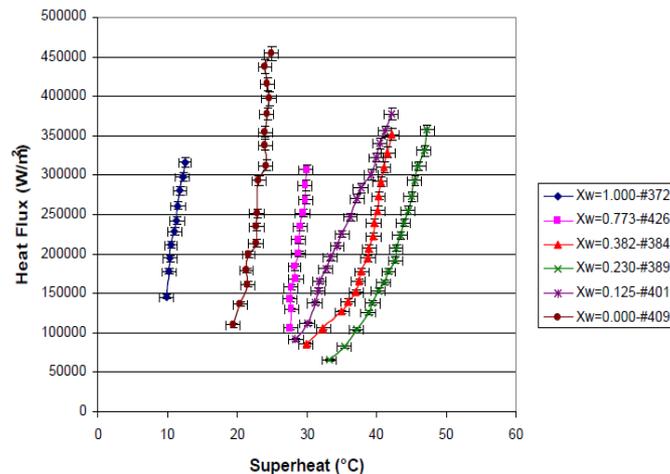
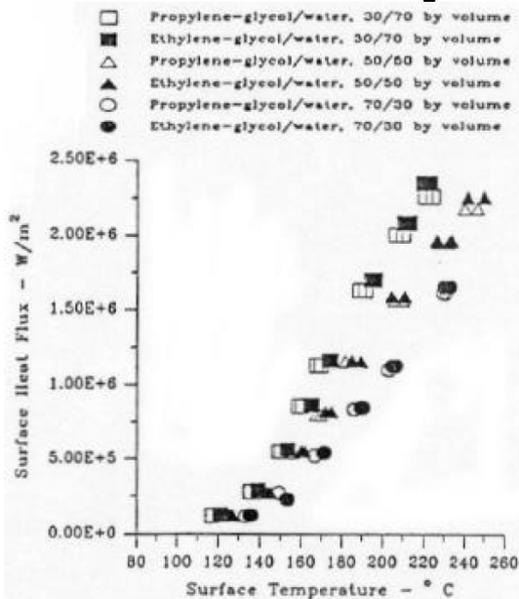
- $q''_{NB} = \alpha_l [T_w - T_l]$,

$$q''_{CB} = \mu_l h_{lv} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} Pr_l^{-s/r} \left[\frac{C_{p,l}(T_w - T_{sat}(P_l))}{C_{sf} h_{lv}} \right]^{1/r}$$

Literature Work on Flow Boiling

(Propylene Glycol/Water)

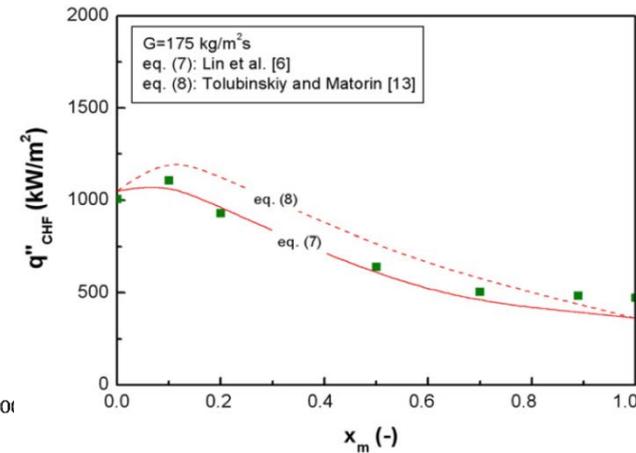
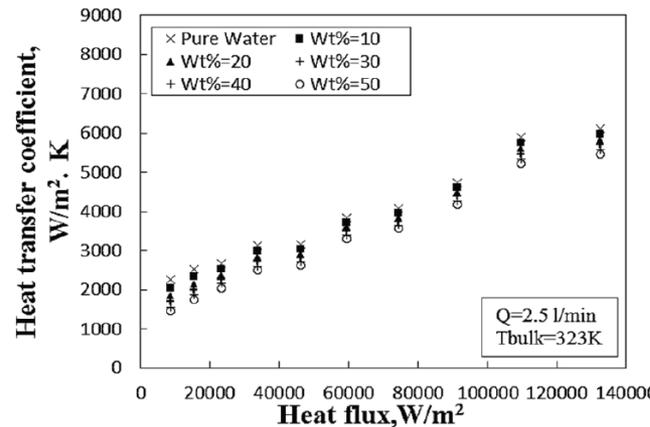
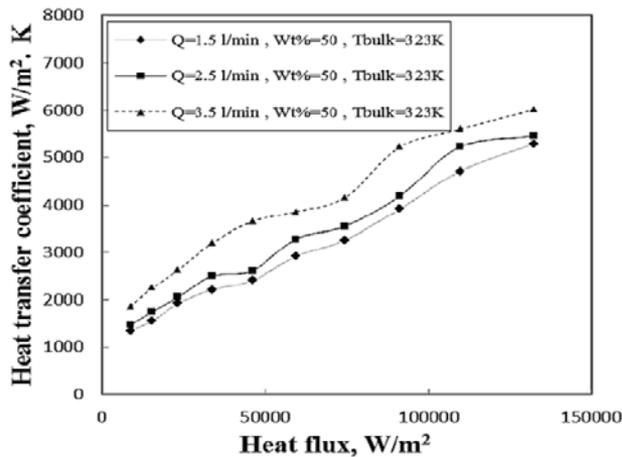
- S.M. Bajorek & S. Schnelle (2001)
 - A mixture concentration of $x_1=0.3$ (through a smooth tube) had the lowest surface temperatures and higher surface heat flux results
 - Further experimentation found the lowest mixture superheat for a mixture conc. of $x_1=0.227$ through a smooth tube
 - However, large conc. also found low superheat values, up to a concentration of $x_1 = 0.77$
 - However, data suggests the heat transfer coefficient, α could increase further with decreasing x_1 beyond $x_1=0.3$.



Literature Work on Flow Boiling

(Ethanol/Water)

- M.M. Sarafranz et. al. (2012)
 - This research considered a constant 323K bulk fluid temperature over a short 40cm test section of smooth 14mm inner diameter pipe
 - Volumetric flow rates 3.51 L/min found an average 25% and 33% heat transfer improvement for respective flow rates of 2.51 L/min and 1.51 L/min
 - Found highest heat transfer coefficients for varying input heat flux, for mixture conc. $x_1=0.1$, due to greater Nu number (heat transfer/fluid metric) resultant values



Rifled Tubing vs. Smooth Tubing

- To improve the heat transfer rate from the heated wall to the flowing bulk fluid, rifled tubing designs have demonstrated increased turbulence.
- S.M. Bajorek and J. Schnelle (2002):
 - The increased internal surface area was found to improve the heat transfer coefficient as the convection effective area (Nu number) was greater than that of a smooth tube.
 - For an PPG/water, $x_1=0.3$ concentration an approximate 39% heat transfer coefficient improvement was observed using the Turbo Bill over a smooth pipe

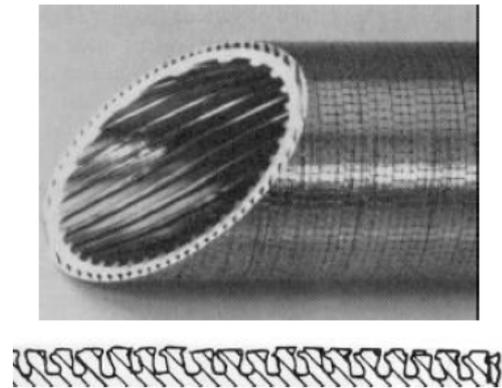
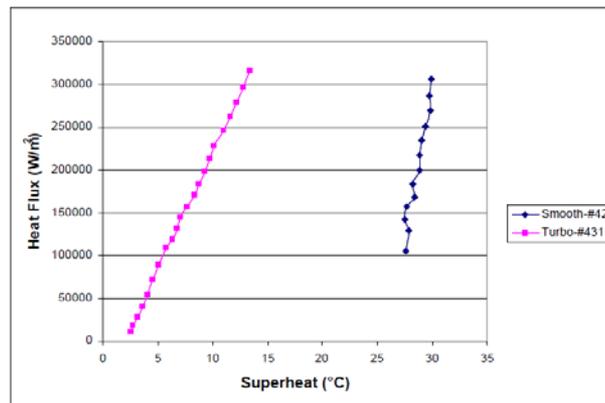
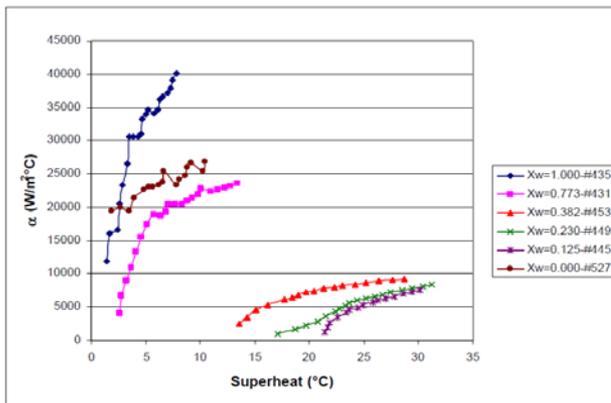


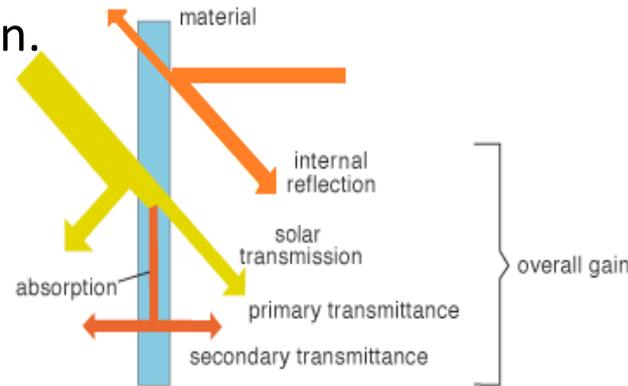
Figure 6.2-Heat transfer coefficient vs. superheat boiling curves for water/propylene glycol mixtures at saturation at 1.0 bar on the Turbo Bill tube.

Figure 7.4-Boiling curve comparison between smooth and Turbo Bill tubes in $X_w=0.773$, $X_{pg}=0.227$ at saturation at 1.0 bar.

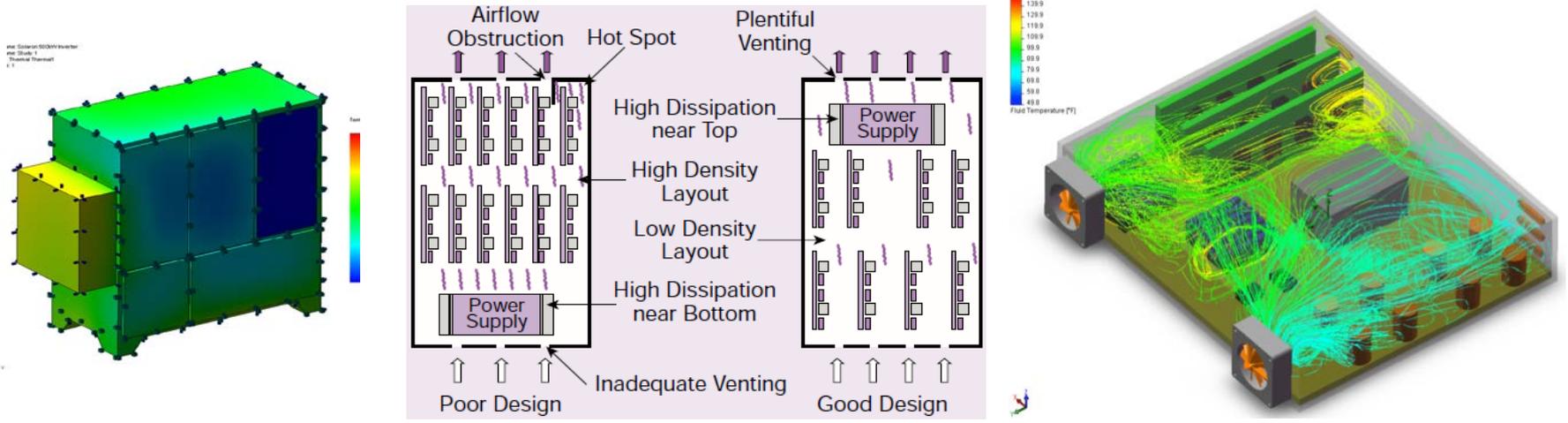
Solar Gain & Thermal Gain

- Thermal gain from solar radiation in an object, space or structure, which increases with the strength of the sun, and with the ability of any intervening material to transmit or resist radiation.

Radiative Energy Balance:

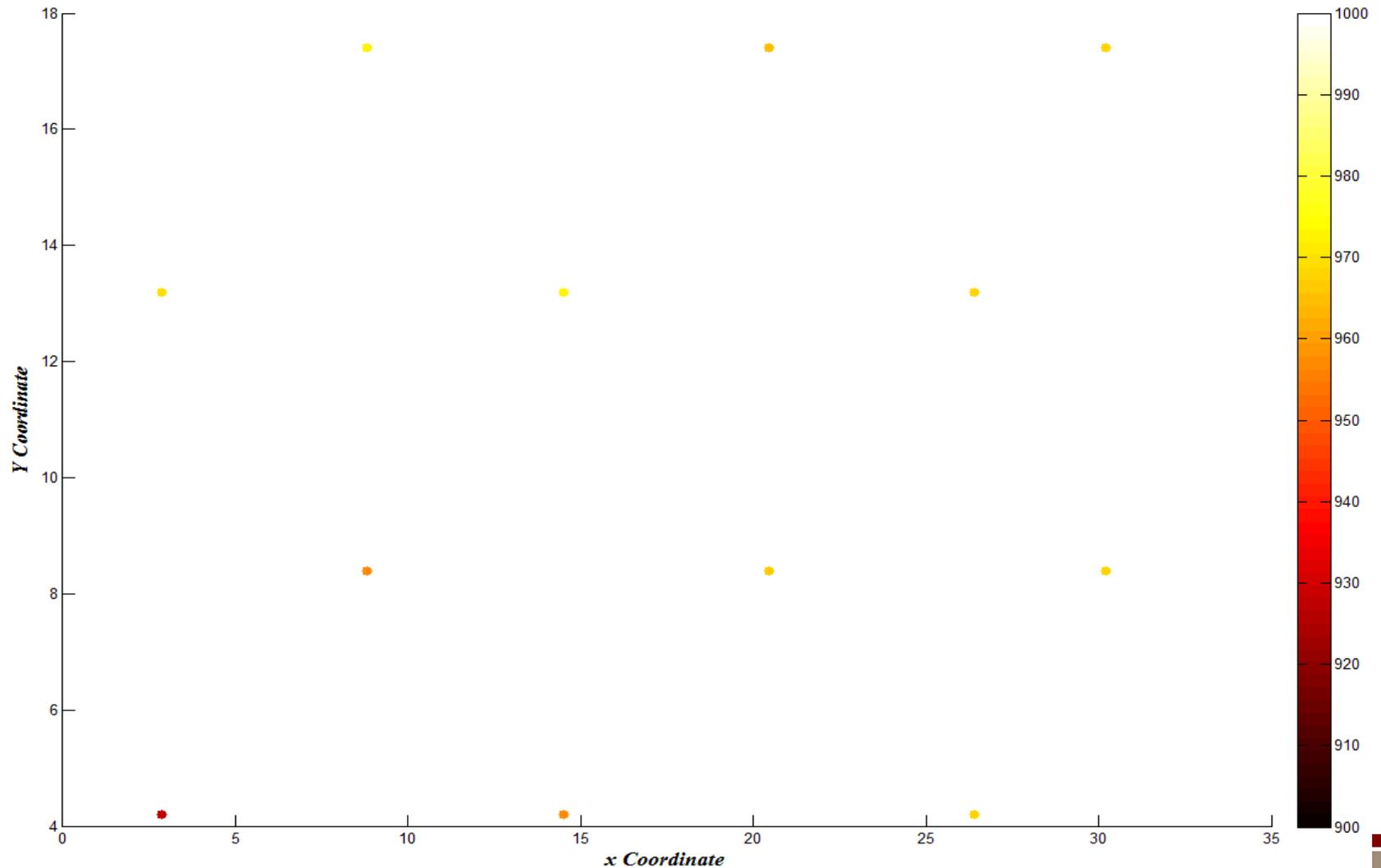


- FEA/CFD Impact Analysis of Internal Comps.



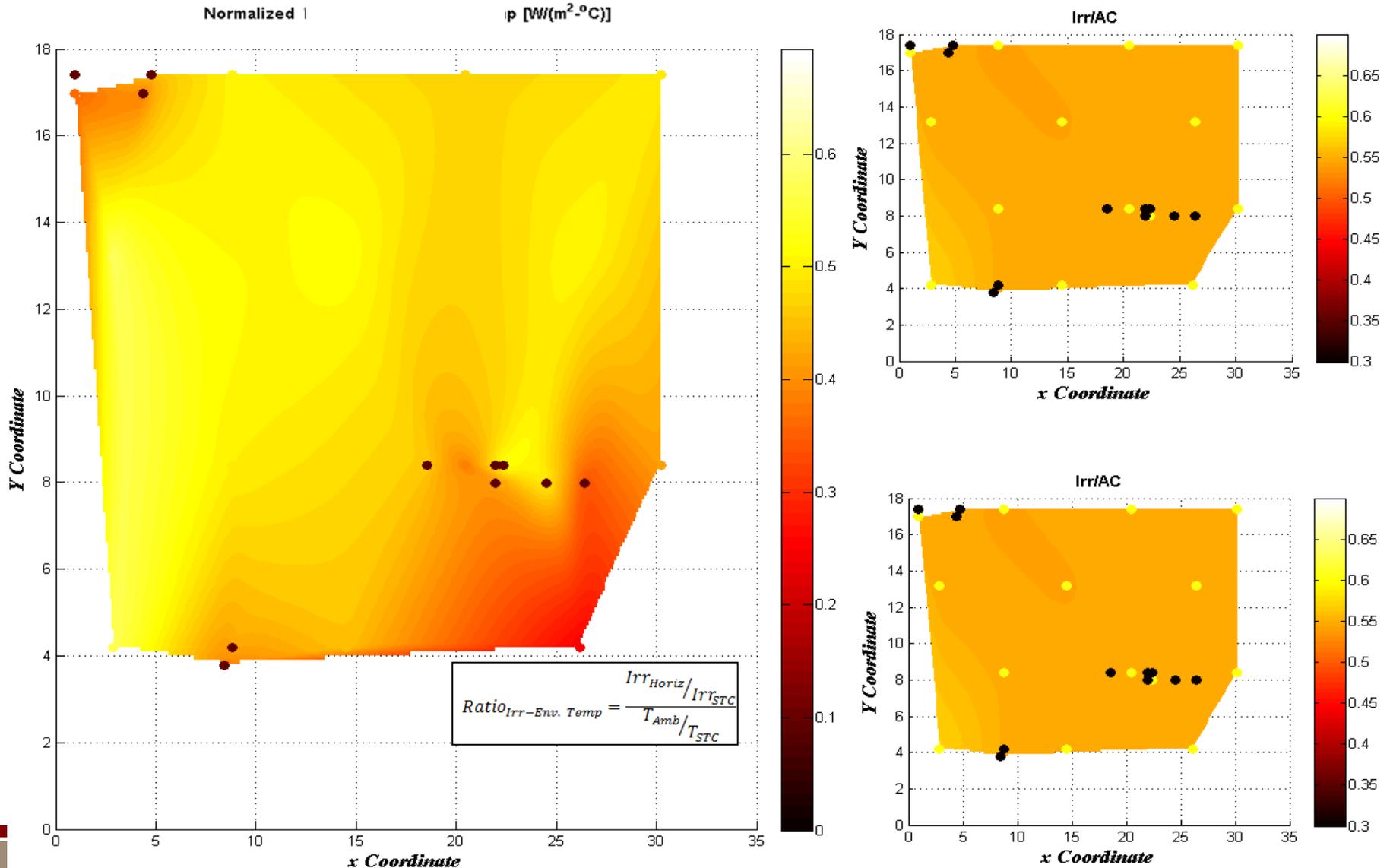
Spatial Site Data Analysis

- Nearest Neighbor interpolation algorithms – Adapted from Sibon [1981]



Performance Ratios

- Normalized Parametric Analysis – Adapted from Haeberlin and Beutler [1995], was adapted based on IEC standard 61724 [1998]



- **Environmental Param's and Inverter Temperatures**

- Cabinet Temperature
- Line Reactor Temperature
- Inverter Ambient Temperature
- Ambient Pressure
- POA and Horiz. Pyranometer Irradiance
- Wind Velocity
- Wind Direction

- **Inverter Performance**

- VARS
- Ground Current
- DC Bus Voltage

$$\text{Cumulative Energy Loss} = \frac{DC_{\text{Power}} - AC_{\text{Power}}}{\# \text{ Operating Days}}$$

- **Performance Ratio's**

- (DC/AC) / Irradiance
- (DC/AC) / Cabinet Temp.
- Coolant Temp. / Irradiance
- Line Reactor Temp. / Irradiance
- Coolant Temp. / AC Power
- Coolant Temp. / DC Power

- **Other Analysis I am Considering**

- Gradient Analysis: 1. Across the Site, 2. Across the Skid
- Skid-Level Solar Gain/Thermal Gain Analysis, wrt. To Transformer
- Inverter Ambient Temperature
- Analysis performed 3 Days prior to failures
- Parametric Analysis of Cloudy vs. Clear Day and vs. Season: (Spring, Summer, Fall, Winter)
- Performance Ratio: AC / POA Insolation

Haeberlin and Beutler [1995] Analytical Parameters

Reference Yield: $Y_r = \frac{G_{meas}}{G_o}$

Array Yield: $Y_a = \frac{E_{DC}}{P_o}$

Final Yield: $Y_f = \frac{E_{AC}}{P_o}$

Performance Ratio: $PR = \frac{Y_f}{Y_r}$

Inverter Efficiency: $\eta_{eff, inverter} = \frac{Y_f}{Y_a}$

Inverter System Losses: $L_s = E_{AC} - E_{DC}$

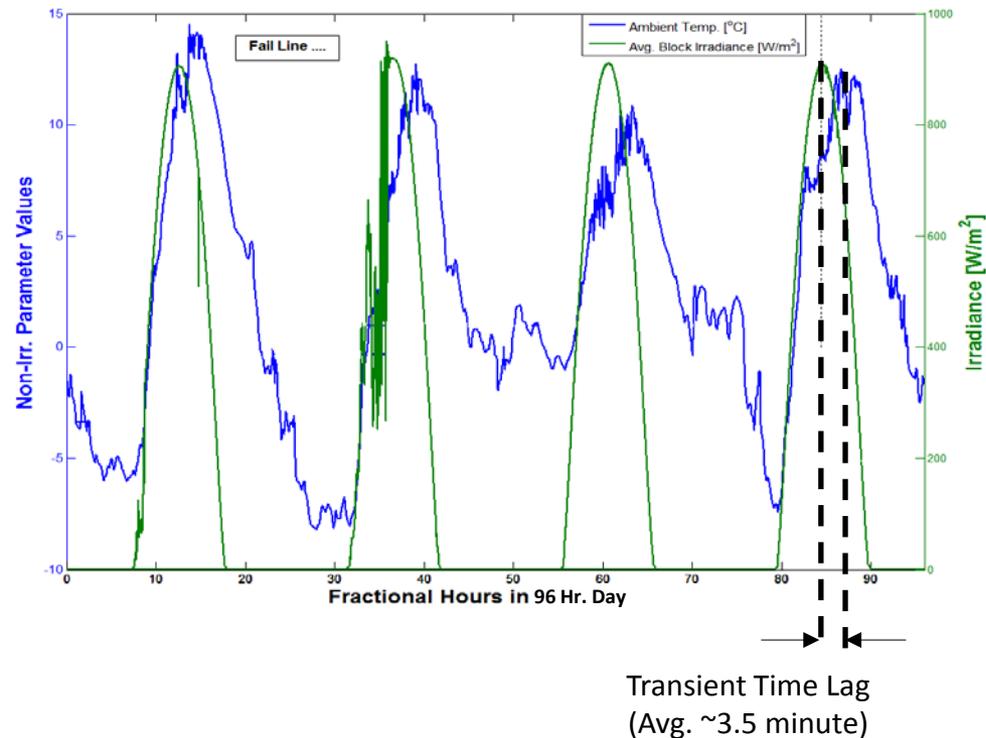
$$L_c = L_{ct} + L_{cm}$$

Captured Losses: $L_{ct} = Y_r(1 - P_{OT})$

$$L_{cm} = Y_r \frac{P_{OT}}{P_o} - Y_a$$

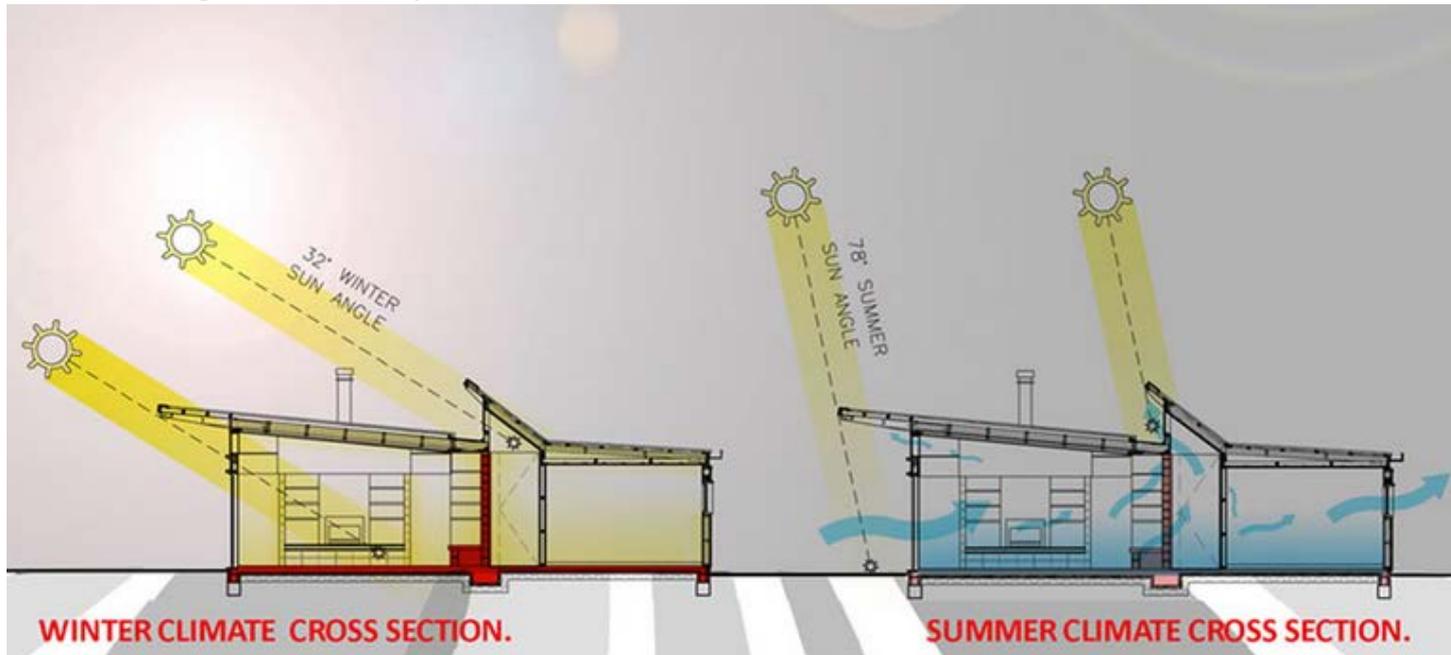
Transient Thermal Lag

- Transient time variation accounting with measurements that vary differently with time
 - Moving average algorithm based on Spearman “Best-fit” correlation coefficient [1973]
 - FEA Analysis will later be implemented for more accurate Time Factor Correction
- A transient thermal lag was found between peaks of irradiance and respective external inverter ambient temperatures.
 - The time lag was not consistent for all inverter failure dates and prior 3-Day data, across all blocks and skids.



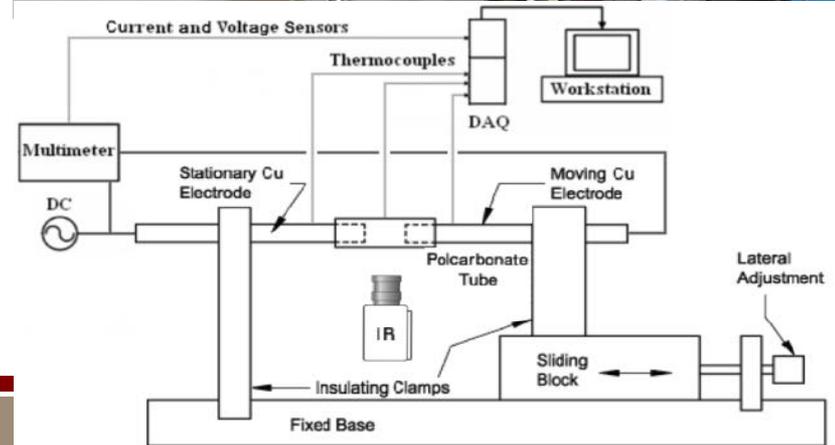
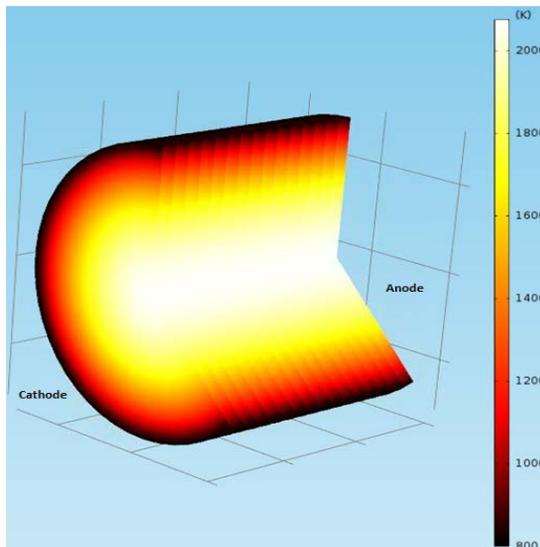
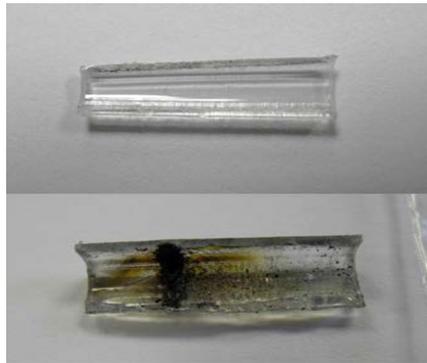
Shading Studies

- Shading variations, due either to clouds, soiling, etc., can influence DC power spikes which can have failure implications on inverters
- Performance studies will include:
 - Shading magnitude
 - Shading patterns – Shading coverage factor: $S = \frac{\%A_{Shaded}}{A_{Total}}$
 - Cloud lensing and ramp rate evaluation



Thermal Arc-Fault Research

- Arc-fault events arise due to PV cabling degradation & other reliability issues.
- Investigate arc-faults with arcing power in the 50-150 W range to determine the potential for low power arcs to establish fires and to determine appropriate AFCI trip times for these arcs.
- Analysis was performed with experimental tests and numerical simulations of arc-faults in close proximity to three polymer materials common in PV systems, e.g., nylon, PET, and polycarbonate.



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Extra Slides

Criteria for the Onset of Boiling

- In general, to determine the onset of any bubble nucleation (micro boiling), system thermodynamic conditions must allow for the critical radius of a bubble to be reached, where a bubble's interface will be stable enough not to collapse or burst, within the respective bounds prescribed by the following equation by Carey (2010):

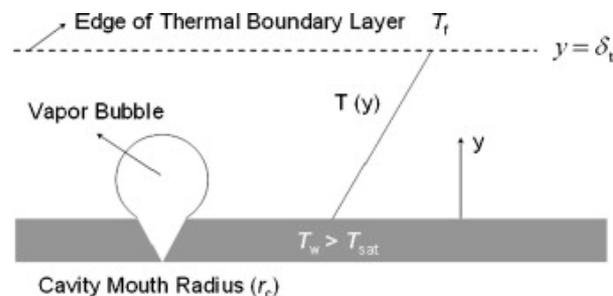
$$\left(\frac{2r_c}{\delta_t}\right)_{min} \leq \frac{2r_c}{\delta_t} \leq \left(\frac{2r_c}{\delta_t}\right)_{max}$$

- The radius of curvature (shown graphically in Fig. 1) of a nucleated bubble, r_c is determined from thermodynamic properties of the heated wall surface, “ w ” and bulk fluid conditions within the bounds of the thermal boundary layer (denoted by “ sat ”), with the liquid and vapor states denoted by “ l ” and “ v ” respectively, and the subscript “ $fluid$ ” refers to thermodynamic conditions that satisfy $y > \delta_t$

$$\left\{ \begin{array}{l} r_{c, min} \\ r_{c, max} \end{array} \right\} = \frac{\delta_t}{4} \left[1 - \frac{\theta_{sat}}{\theta_w} \left\{ \begin{array}{l} + \\ - \end{array} \right\} \sqrt{\left(1 - \frac{\theta_{sat}}{\theta_w}\right)^2 - \frac{12.8\sigma T_{sat}(P_l)}{\rho_v h_{lv} \delta_t \theta_w}} \right]$$

where: $\delta_t \equiv$ Thermal Boundary Layer Thickness, $\theta_w \equiv T_w - T_{bulk}$, $\theta_{sat} \equiv T_{sat} - T_{bulk}$, $\sigma \equiv$ Surface Tension, $\rho \equiv$ Density, $h_{lv} \equiv$ Latent Heat, $P \equiv$ Pressure, $T \equiv$ Temperature

(Fig. 1):



- To use the analytical models, thermodynamic properties for the mixture have to be determined, which need to be developed for these particular mixtures:
- Binary Mixture Properties
 - Activity Coefficients, α provide a metric for assessing a properties departure from an ideal mixture, or one that does not have linearly-varying properties.

- Currently using ideal mixture properties where the activity coefficient: $\gamma=1$ for computing thermodynamic properties

Ex. For Saturation Pressure:
$$P_{tot} = x_1 \alpha_1 P_1 + x_2 \alpha_2 P_2$$

- Current Work: Accurate Novel Saturation Pressure/Temperature Property Correlation Development

- Propylene Glycol/Water Binary Mixture

- Margules Method/Wilson Method of Activity Coefficient Determination

$$\ln \alpha_k = -\ln \left(\sum_{j=1}^m x_j \Lambda_{jk} \right) + 1 - \sum_{i=1}^m \frac{x_i \Lambda_{ik}}{\sum_{j=1}^m x_j \Lambda_{ij}}$$

$$\Lambda_{ij} \equiv \frac{v_j}{v_i} \exp \left(-\frac{\lambda_{ij} - \lambda_{ii}}{RT} \right)$$

$$\Lambda_{ji} \equiv \frac{v_i}{v_j} \exp \left(-\frac{\lambda_{ji} - \lambda_{jj}}{RT} \right)$$

- Method by A.C. Compostizo et. al. (2001)

- $P^* \equiv$ Spinodal Temp, $\gamma \equiv$ surface tension, $\kappa \equiv$ isothermal compressibility factor, $V \equiv$ Molar Volume

$$P_{\kappa T, 0} = (\rho^\delta - 1) / \delta$$

$$\rho = \rho_0 / \{1 - B_4 \ln[(B + P)/(B + P_0)]\}$$

$$\kappa_T = \kappa^* (P - P^*)^{-\gamma}$$

$$P^* = P^{\text{sat}} - 1.323 \frac{\gamma^{3/2}}{(k_B T)}$$

$$\rho_0 = B_1 + B_2 T + B_3 T^2$$

$$B = B_5 \exp(-B_6 T)$$

$$V/V_0(0.1 \text{ MPa}) = \frac{\exp \left[-\left(\frac{\kappa^*}{1 - \sigma} \right) (P - P^*)^{1 - \sigma} \right]}{\exp \left[-\left(\frac{\kappa^*}{1 - \sigma} \right) (0.1 - P^*)^{1 - \sigma} \right]}$$

Flow Boiling Literature

- For PPG/Water mixtures, heat transfer experimentation has been conducted for limited mixture concentrations and system pressures.
- E.V. McAssey & S.G. Kandlikar (2000)
 - Low surface heat flux variation between various mixture concentrations was found for wall temps lower than 150°C.
 - For single (liquid only) phase fluids: Investigators used $x_1=0.5$, and found little heat transfer coeff. Variation at low system pressures
 - Slightly larger superheat values were found for significant increases in mass flow, however the inlet temperatures were higher than that of the current AE heat exchanger system
 - Model predictions had superheat inaccuracies of approximately ~40% were found at the higher tested system pressure of 205kPa, versus ~18% for the lower 129kPa system pressure.

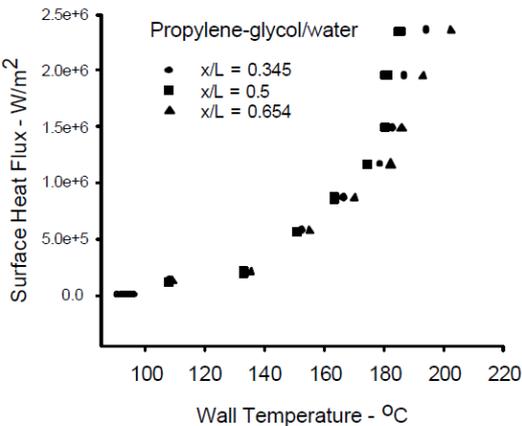


Figure 3 Surface heat flux versus wall temperature for propylene-glycol/water mixture at an inlet velocity = 1.33 m/s, $T_{inlet} = 85\text{ }^{\circ}\text{C}$ and $P_{exit} = 205\text{ kPa}$

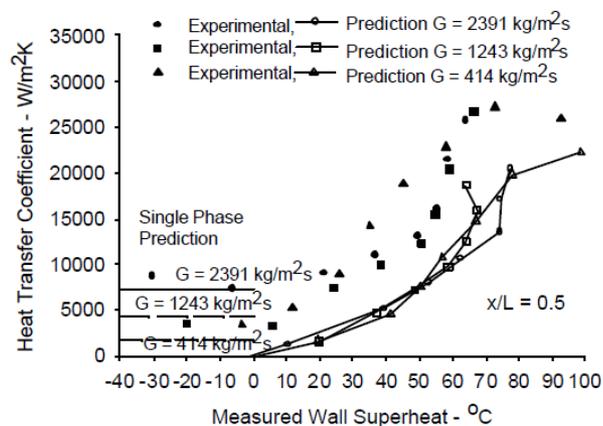


Figure 11 Comparison between equation (9) correlation and experimental data for propylene-glycol/water mixture for $T_{inlet} = 85\text{ }^{\circ}\text{C}$, and $P_{exit} = 205\text{ kPa}$

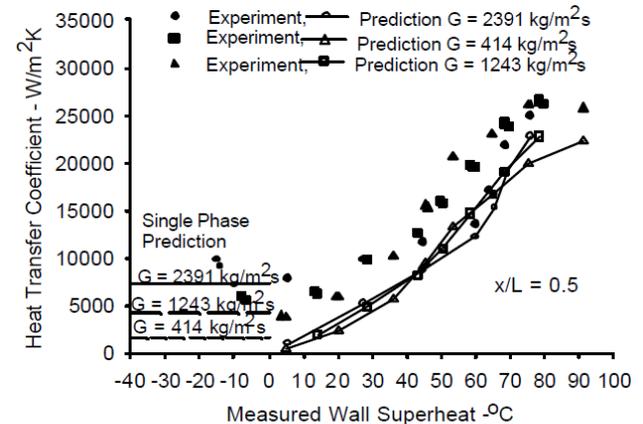
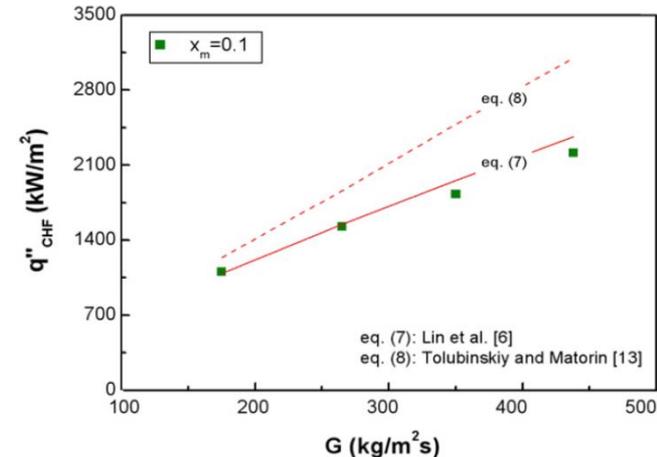
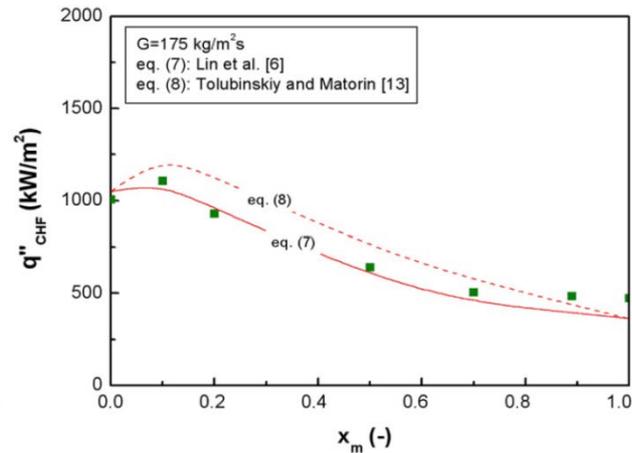
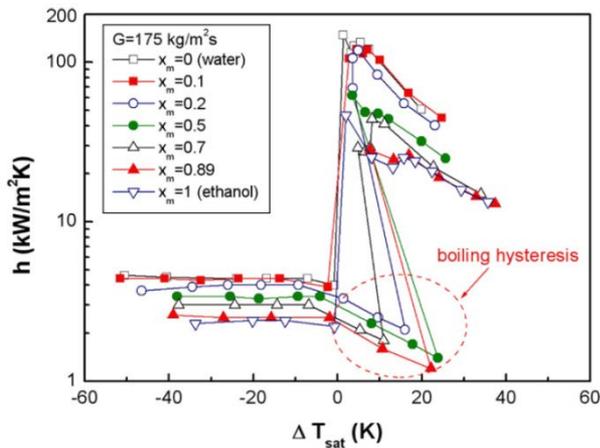


Figure 12 Comparison between equation (9) correlation and experimental data for propylene-glycol/water mixture at $T_{inlet} = 85\text{ }^{\circ}\text{C}$, and $P_{exit} = 129\text{ kPa}$

Literature Work on Flow Boiling

(Ethanol/Water)

- For Ethanol/Water mixtures, heat transfer experimentation has been conducted for limited mixture concentrations and system pressures.
- B.R. Fu et. al. (2012)
 - Increasing CHF values were found for increasing mass flow rates
 - The highest critical heat flux was found for a low ethanol/water concentration of $x_1=0.1$
 - Subsequent research found the highest Ma number, and the highest heat transfer coefficient, for a mixture concentration of $x_1=0.1$
 - Boiling hysteresis was observed in heat transfer coefficient experimentation, whereby delayed boiling occurred



Tube Turbo Bill Literature Results

(w/ Propylene-Glycol/Water)

- S.M. Bajorek & S. Schnelle (2001)

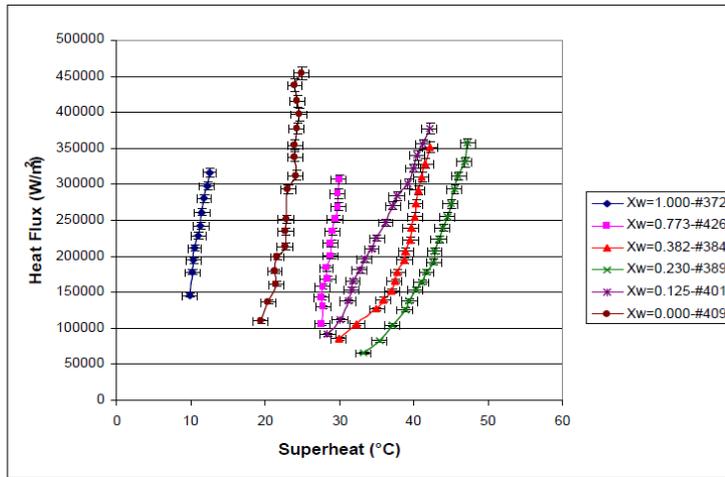


Figure 5.1-Heat flux vs. superheat boiling curves for water/propylene glycol mixtures at saturation at 1.0 bar on the smooth tube.

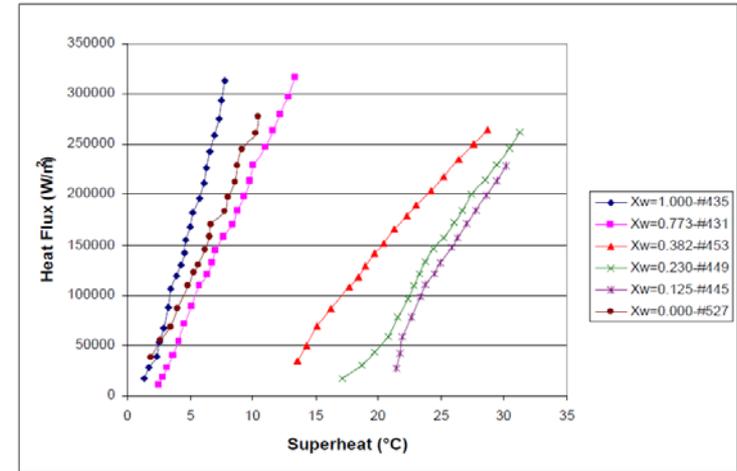


Figure 6.1-Heat flux vs. superheat boiling curves for water/propylene glycol mixtures at saturation at 1.0 bar on the Turbo Bill tube.

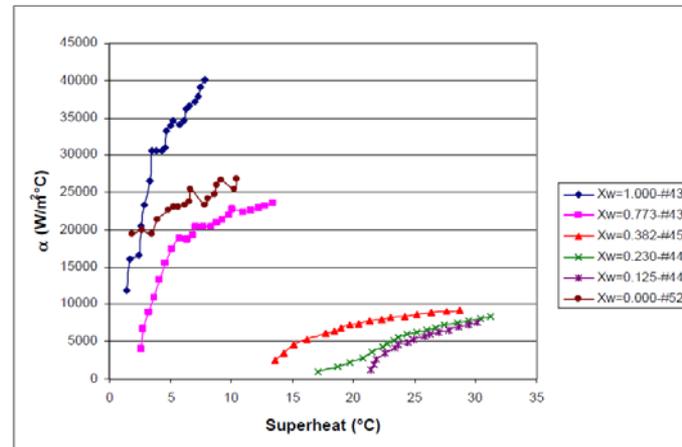


Figure 6.2-Heat transfer coefficient vs. superheat boiling curves for water/propylene glycol mixtures at saturation at 1.0 bar on the Turbo Bill tube.

Tube Turbo Bill Literature Results

(w/ Propylene-Glycol/Water)

- S.M. Bajorek & S. Schnelle (2001)

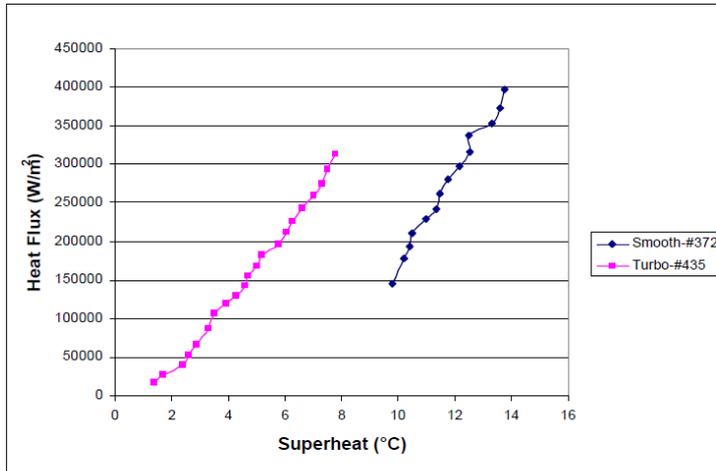


Figure 7.3-Boiling curve comparison between smooth and Turbo Bill tubes in $X_w=1.0$, $X_{pg}=0.0$ at saturation at 1.0 bar.

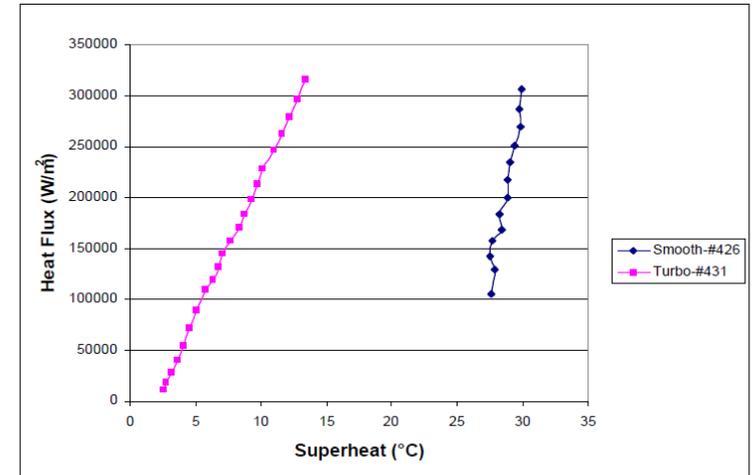


Figure 7.4-Boiling curve comparison between smooth and Turbo Bill tubes in $X_w=0.773$, $X_{pg}=0.227$ at saturation at 1.0 bar.

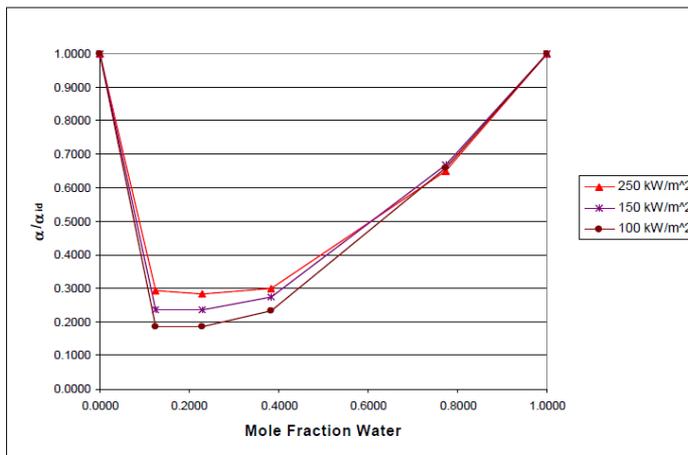


Figure 6.3- α/α_{id} vs. mole fraction water in a water/propylene glycol mixture at saturation at 1.0 bar on a Turbo Bill tube.

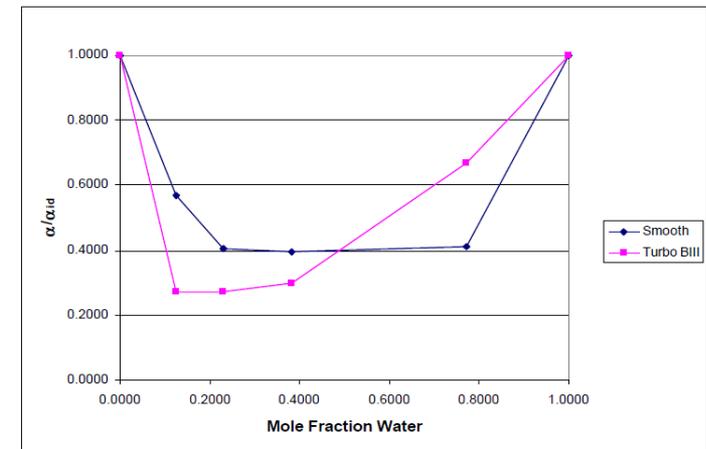


Figure 7.9- α/α_{id} vs. mole fraction water comparison between smooth and Turbo Bill tube for Water-Propylene Glycol Mixtures at saturation at 1.0 bar at 200 kW/m^2

Tube Turbo Bill – Other Mixtures

- Despite lower α values for lower PPG/water concentration ratios using the Turbo Bill design, ethylene-glycol/water mixtures, studied by S.M. Bajorek and j. Schnelle (2002), found heat transfer improvement over their respective smooth tube tests for concentrations greater than $x_1 = 0.2$.
- This study however did not evaluate ethanol/water mixtures, and to date little literature evidence suggests that any exists for this binary mixture.

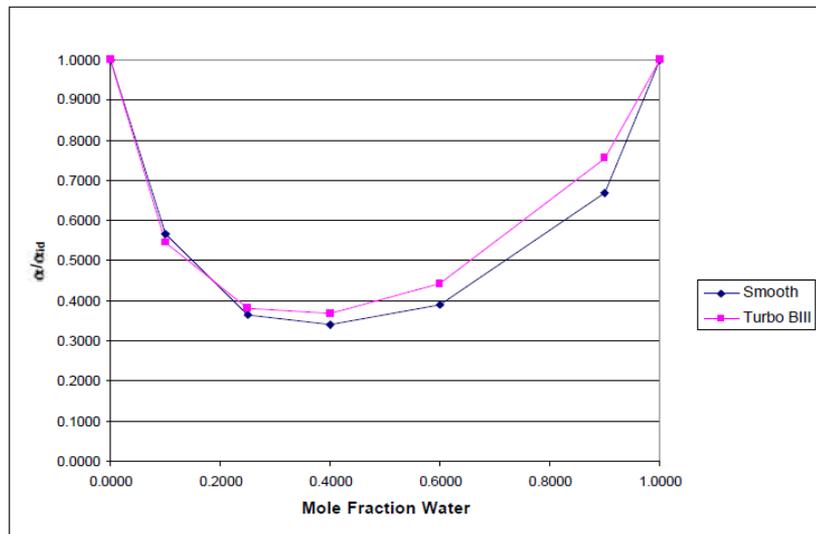


Figure 7.17- α/α_{id} vs. mole fraction comparison between smooth and Turbo Bill tube for water-ethylene glycol mixtures at saturation at 1.0 bar at 200 kW/m²

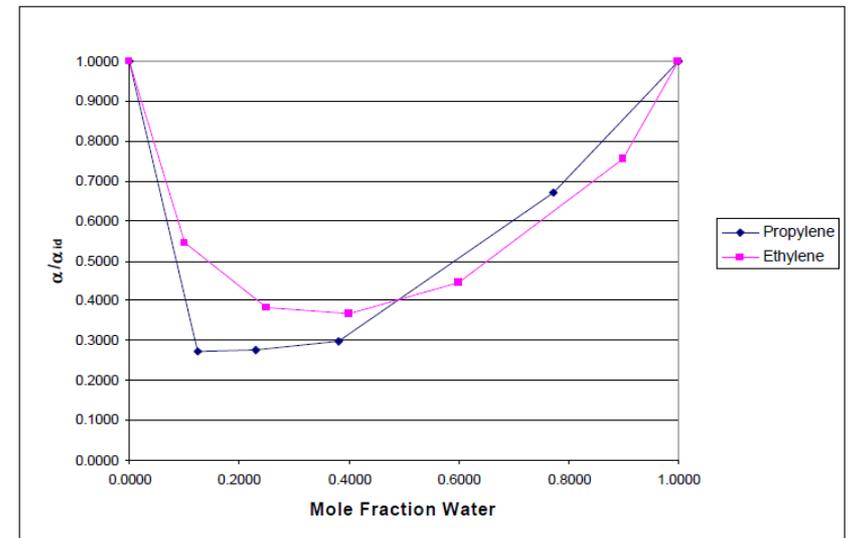
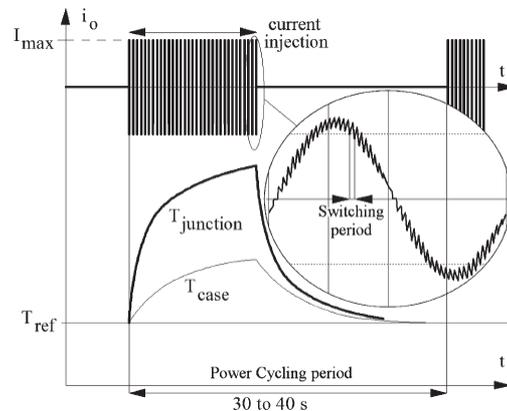


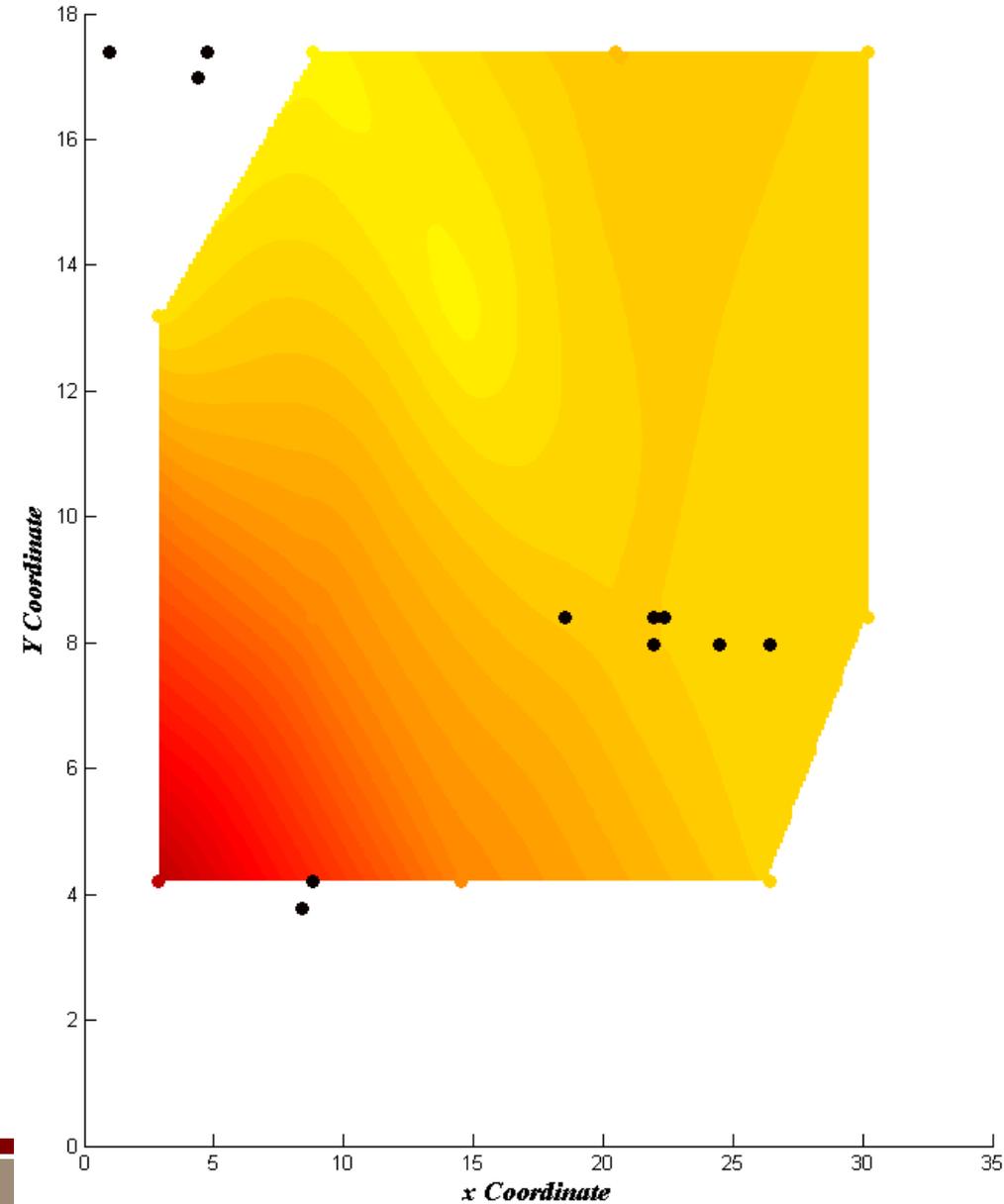
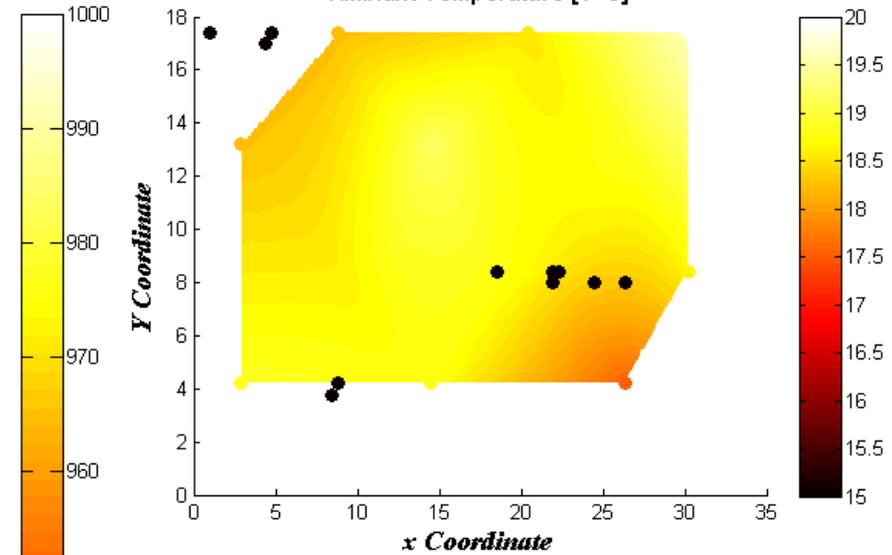
Figure 7.2- α/α_{id} vs. mole fraction water comparison of water-propylene glycol mixtures to water-ethylene glycol mixtures at saturation at 1.0 bar on a Turbo Bill tube at 200 kW/m²

Coldplate Type	Cooling System Design	Liquid Flow Type	Generation Area (cm ²)	Total Cooling Area (cm ²)	Notes	References
1	AlN Substrate Pin Fin	Parallel	1.0	4.6	Pin Dia. = 1 mm Pin Height = 3 mm Pin Spacing = 2 mm Alternating Rows Measurements made with 1.0 mm thick AlN were reduced by 0.022°C-cm ² /W to simulate 0.635 mm AlN	[1]
2	AlN Substrate Soldered on Cu NF Microchannel	Normal		6.7 (For comparison purposes only with Type 4)	Die/AlN Rth = 0.149°C-cm ² /W was added to datasheet values for NCP-A-10-20 cold plate	[8]
3	AlN Substrate with Integrated PF Microchannel	Parallel	4.0	11.6	Reported measurements for AlN QUA structure with 11 layers used	[3]
4	AlN Substrate with Integrated NF DBC Microchannels	Normal	2.9	6.7	Reported measurements used	[7]
5	AlN Substrate Soldered on AISiC Pin Fin	Parallel	34.8	34.8	Pin Dia. = 4 mm Pin Height = 4 mm Pin Spacing = 4.3 mm Alternating Rows Die/AlN Rth = 0.149°C-cm ² /W was added to reported measurements	[2]

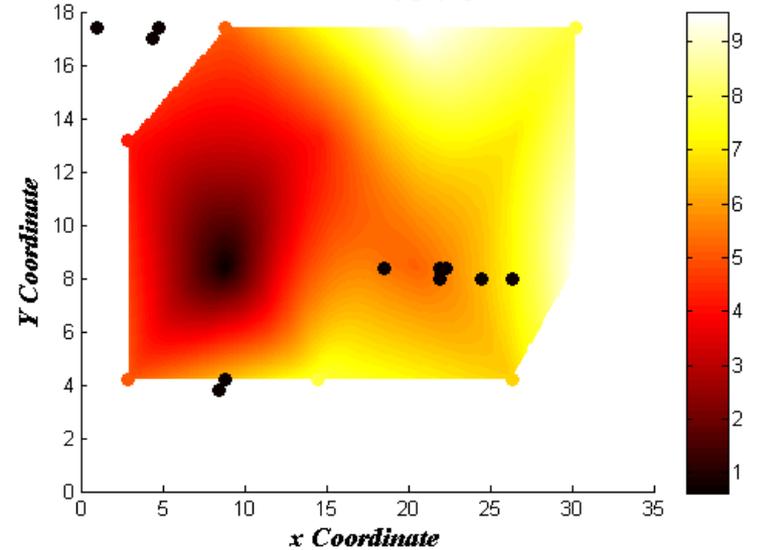


(Smet et. al., 2011)
JED _____

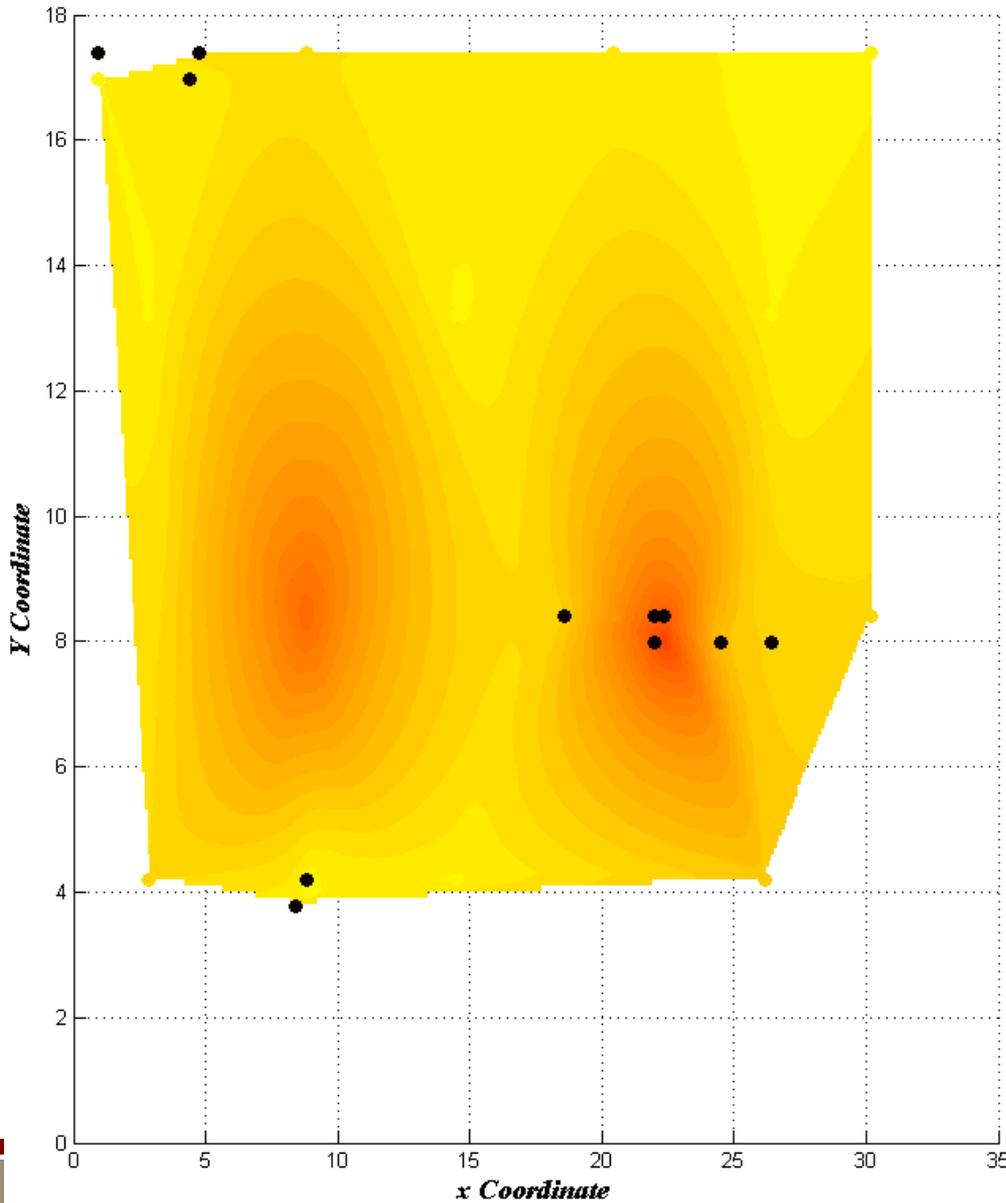
Layer	Thermal Conductivity (W/mK)	Layer Thickness (mm)	Thermal Resistivity (°C-cm ² /W)
Silicon (100°C)	100	0.250	0.025
Solder	36	0.127	0.036
Top DBC on Aluminum Nitride	393	0.305	0.008
Aluminum Nitride	170	0.635	0.037
Bottom DBC on Aluminum Nitride	393	0.305	0.008
Solder	36	0.127	0.035

Irradiance [Wm^2]Ambient Temperature [$^{\circ}\text{C}$]

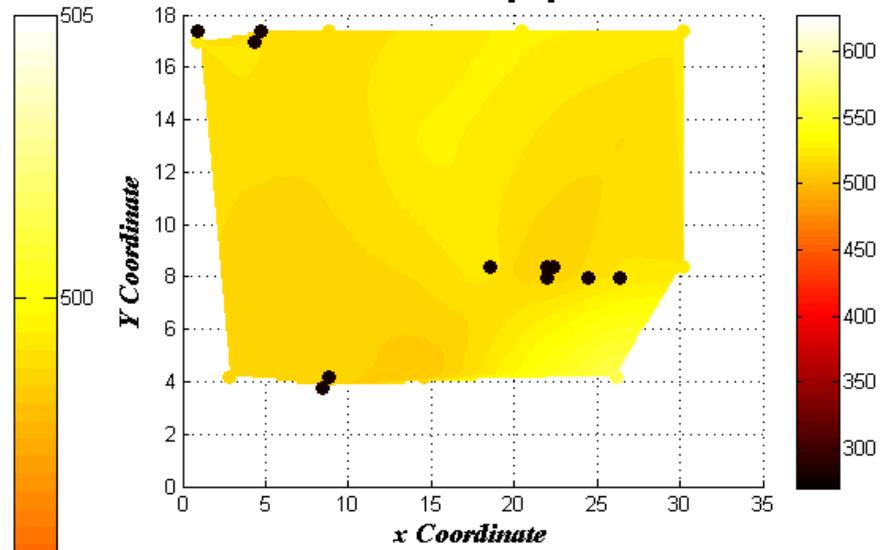
Wind Velocity [mph]



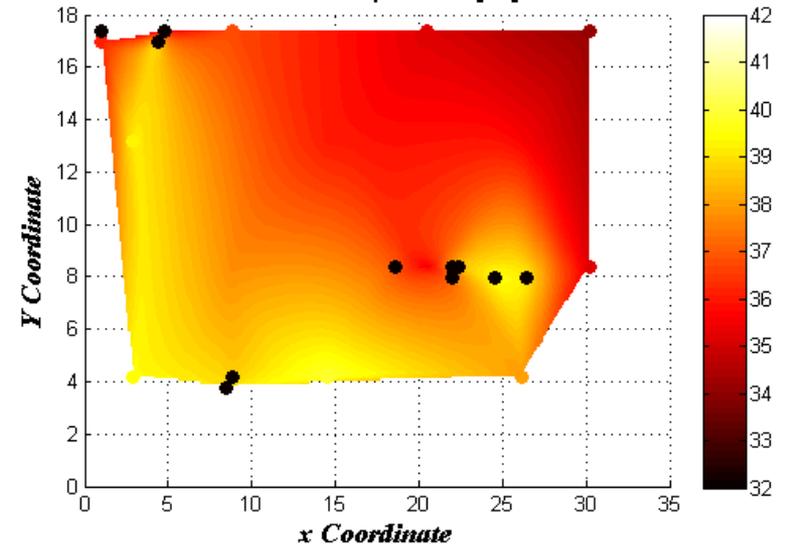
AC Power [kW]



DC Power [kW]

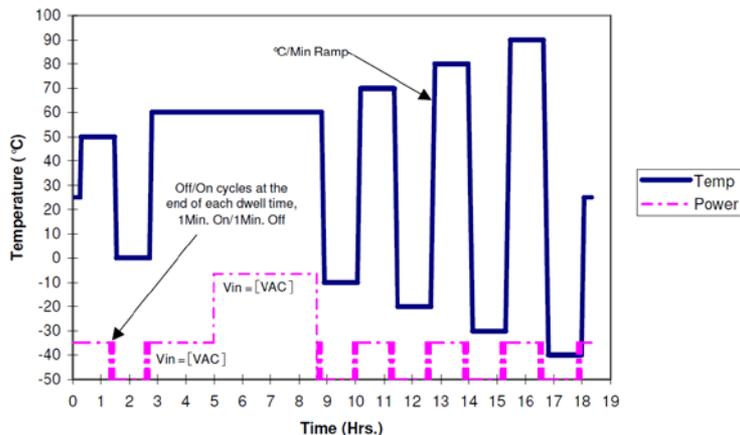


Coolant Temperature [°C]



Accelerated Testing

- HALT – Highly Accelerated Life Testing
 - Stress tests not meant to simulate the field environment, but find weaknesses in design
 - Stresses are stepped up to well beyond the expected field environment until “fundamental limit of the technology” is reached
 - General Procedures for HALT Testing:
 - 1. Attach thermocouples, & monitor line input Vac, output Vdc, and other signals.
 - 2. Perform temperature cycling
 - 3. Perform functional test
 - 4. Determine root cause of any failures, implement corrective action (if required), and repeat test (if required).



$$A.F. = e^{\left(\frac{E}{K}\right)\left(\frac{1}{T_1} - \frac{1}{T_0}\right)}$$

T_1 = Normal Ambient Temp. (298 °K)

T_0 = Elevated Ambient Temp (°K)

E = Activation Energy (eV, Typ.)

K = Boltzman's constant