Controlled Temperature Packaging Using On-demand Cooling from Active Vacuum Insulation Panels

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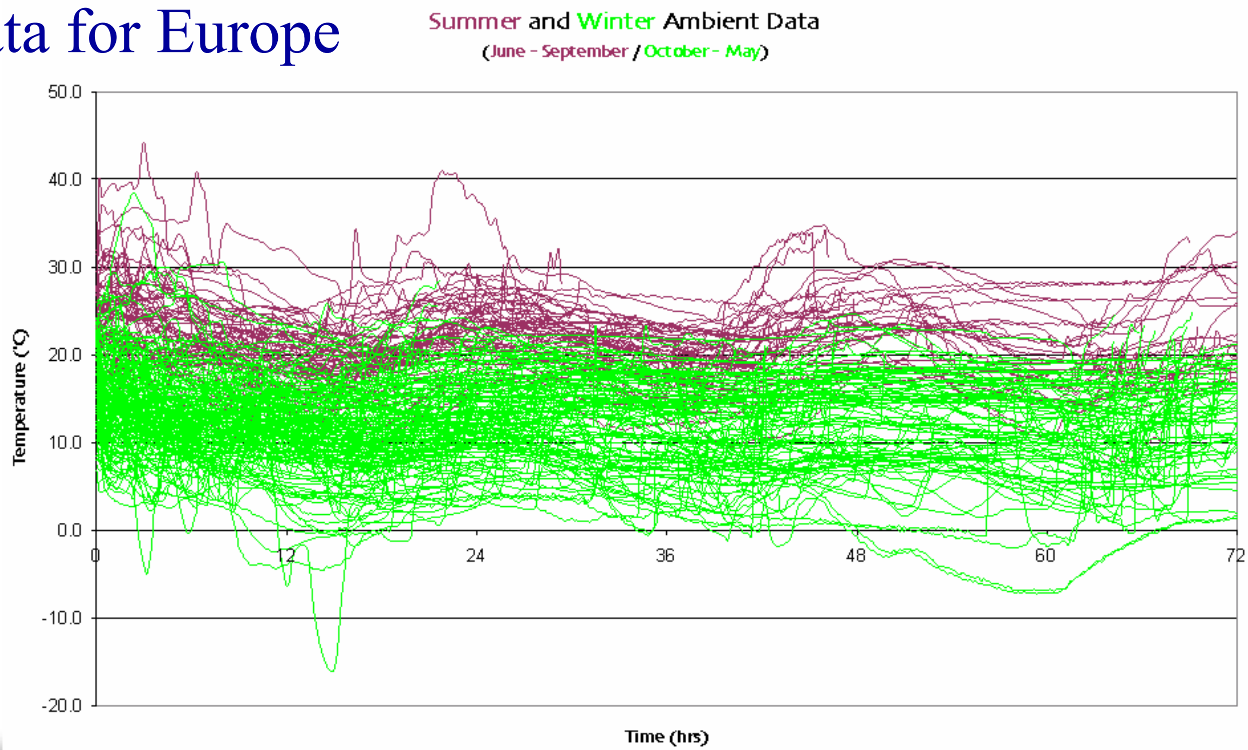
Transient Performance of Thermal Insulation

- Refrigeration:
  - Internal and external temperatures are essentially constant.
  - Key insulation property is thermal conductivity.
- Architectural and controlled temperature packaging:
  - Inside temperature is relatively constant but the outside temperature can vary by +/-20 ^{o}C. Timescale variation is diurnal.
  - Thermal diffusivity *and* thermal conductivity are important
  - Actual shipment data for Europe



Thermal Diffusivity of Insulation

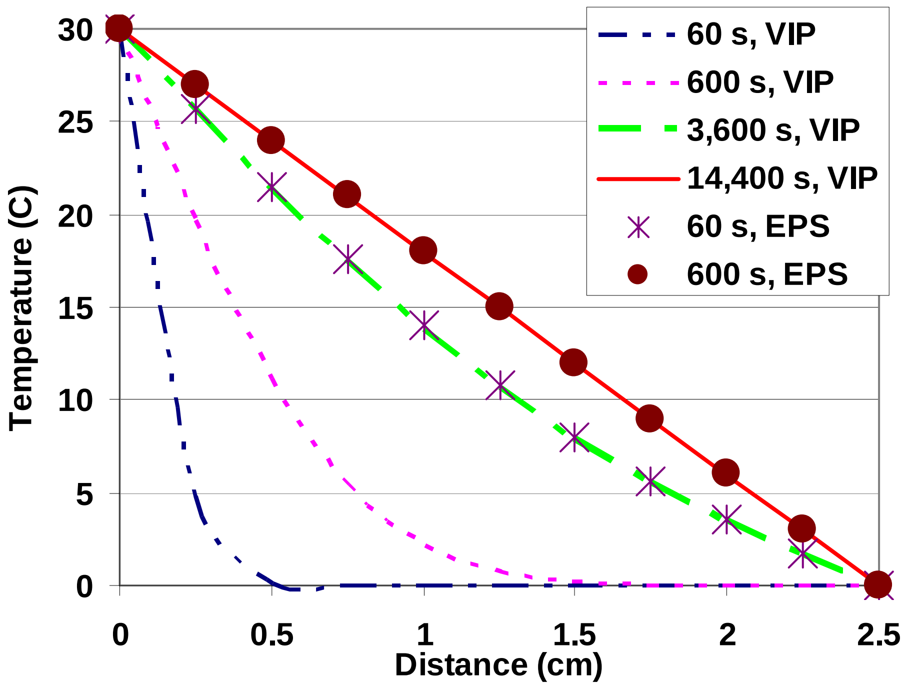
- Thermal diffusivity depends on mass, heat capacity and thermal conductivity ($\alpha=\lambda/\rho\, C_p$)
- Conventional foam insulation responds ~100 times faster to a temperature change than VIP's!!
- Thermal diffusivity of different VIP's are similar

VIP Type	λ (W/mK)	ρ (kg/m^3)	C_p (J/Kg K)	α (m^2/s)
Silica/carbon VIP	0.0036	165	835	2.6×10^{-8}
Silica/titania VIP	0.0040	200	835	2.4×10^{-8}
Fiberglass VIP	0.0036	220	830	2.0×10^{-8}
Foam VIP	0.0060	120	1,210	4.1×10^{-8}
EPS	0.040	20	1,210	1.7×10^{-6}

- For 25 mm thick foam insulation, the characteristic time is on the order of a few minutes but is hours for a VIP.
- The characteristic time (τ) increases with the square of the insulation thickness, $\tau=L^2/\alpha$.

Modeling of transient behavior

- Assume a 25 mm thick insulation slab is initially at 0 °C
- At time zero, one surface temperature is increased to 30 °C and the second is maintained at 0 °C.
- Temperature distribution calculated with an infinite series eigenvalue solution.
- In one minute the foam slab is almost to steady state and in 10 minutes, steady state is reached
- For a VIP, the "effect" of the change on one side is not felt on the other side for close to 1 hour.
- It takes ~4 hours for the VIP to reach steady state!



- How to extend to timeframes of 6-12 hours?
  - –Thicker; not usually practical
  - –More thermal mass: how?

Thermal Mass Materials

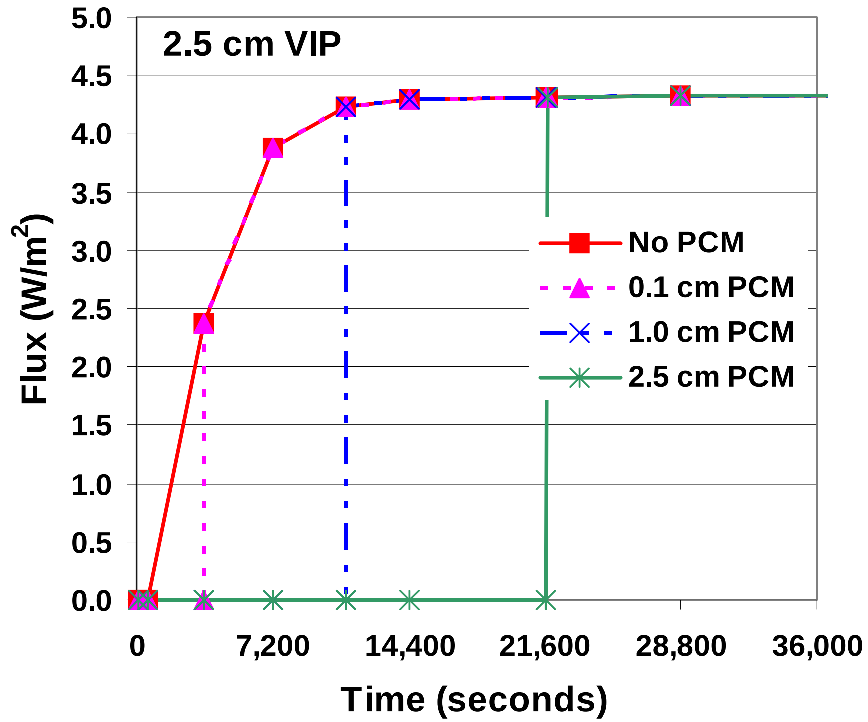
- Use specific heat (no phase change)
  - Advantages: works over a wide temperature range, better reproducibility, low cost
  - Disadvantages: water is about the best and it is only ~4.18 J/g K
- Use latent heat (phase change) and specific heat:
  - Advantages: much higher energy density
  - Disadvantages: transition temperature must be matched to application, limited range of practical materials, high cost, reproducibility
  - Common phase change materials for building and controlled temperature packaging:

PCM	Melting point (^{o}C)	ΔH_f (J/g)	ΔH_f (J/cm^3)	ρ(g/cm^3)
Ice	**0**	**333**	**306**	**0.917**
Tetradecane	**5**	**165**	**126**	**0.764**
Octadecane	**28**	**244**	**189**	**0.814**
$CaCl_2 \cdot 6H_20$	**30**	**171**	**256**	**1.71**
$Na_2SO_4 \cdot 10H_20$	**32**	**254**	**377**	**1.48**

- For water cycling between:
  - 5 to 15 ^{o}C, **42** J/g
  - -5 to 5 ^{o}C, **375** J/g

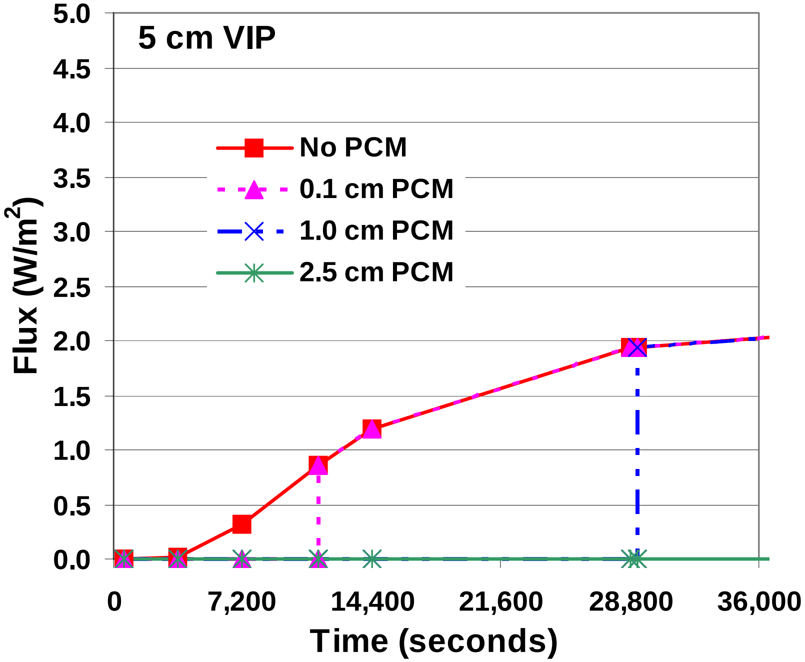
Transient response with a PCM

- Transient thermal modeling with a PCM (water) added:
- Assume:
  - 25 mm VIP initially at 0 °C
  - Layer of ice at 0 °C on the inside
  - Outside surface is changed to 30 °C
  - Calculate heat flux at inside surface
  - There is no heat influx until the ice has completely melted



- With no PCM, after 1 hour, the surface flux is ~50% of the steady-state value and 90% of the SS value after 2 hours
- With 1 cm of ice, there is no heat influx until three hours
- With 2.5 cm of ice, there is no influx for six hours!

PCM and thicker VIP's



- Employing a 50 mm VIP reduces the steady-state flux by 50%.
- The "breakthrough" time for a 1 cm ice layer increases to 8 hours with a 50 mm VIP from 3 hours for the 25 mm VIP
- For a given breakthrough time (on the order of 6-12 hours for buildings and packaging), there is a range of VIP and PCM thicknesses.
- For minimizing *weight*, one should employ more insulation relative to the PCM
- For minimizing *volume*, use more PCM.
- Weight and volume could be significantly reduced if the PCM had higher energy density

Other phase change approaches?

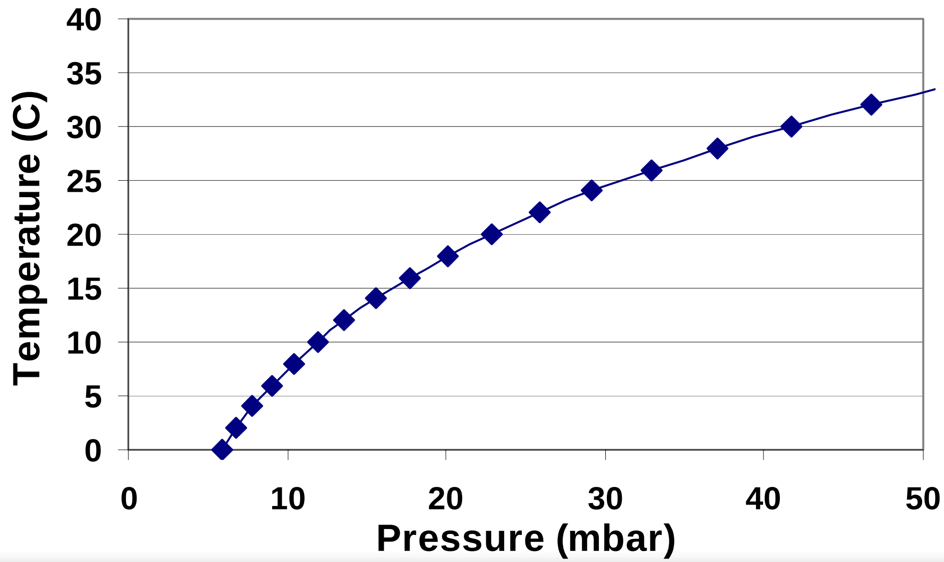
- Conventional PCM's have limited energy density
- Conventional PCM's have a *fixed* transition temperature

PCM	Transition point (°C)	ΔH_f (J/g)	ΔH_f (J/cm^3)	ρ (g/cm^3)
Ice melting	0	333	306	0.917
Water evaporation	Depends on pressure	2,502*	2,502*	1.00*

* at 0 °C

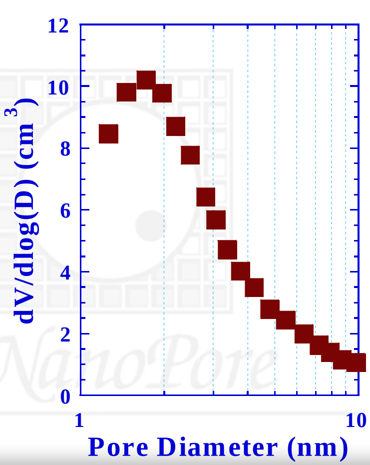
- Evaporating water has ***7.5 times*** the energy density of ice!
- Phase change temperature simply ***varied*** by the pressure

But the water vapor must be "removed"!



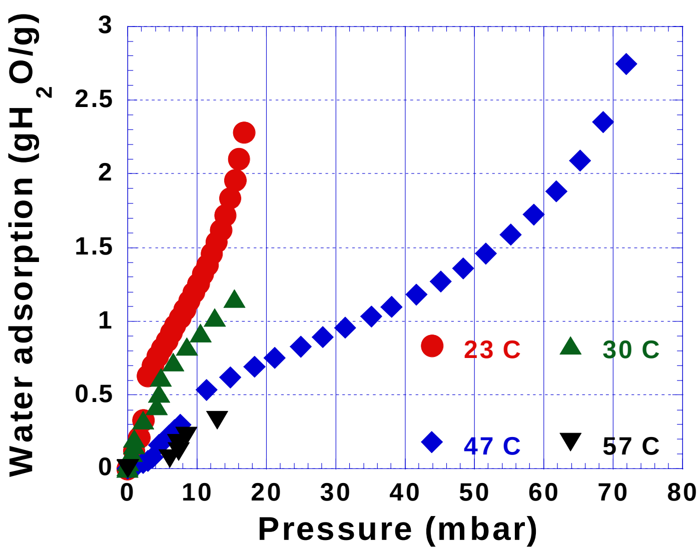
Water vapor control

- "Conventional" Desiccants
  - Pore volumes are 0.2 to 0.5 cm^3/g which limits capacity – pore size less than 2 nm to enable adsorption at low humidity
  - Small pore size yields high ΔH_{ad} (heat which must be rejected)
- NanoPorous Carbon Desiccants
  - High pore volumes (1-3 cm^3/g) and high surface area (>1,500 m^2/g)
  - Use surface functionality for high uptake at low humidity and moderate heat generation. (US # 6,559,096 and others pending)
  - Uptake is 10x greater than zeolites!
  - ΔH_{ads} ~46 kJ/mole. 1.18 $\Delta H_{vap} << \Delta H_{zeolites}$

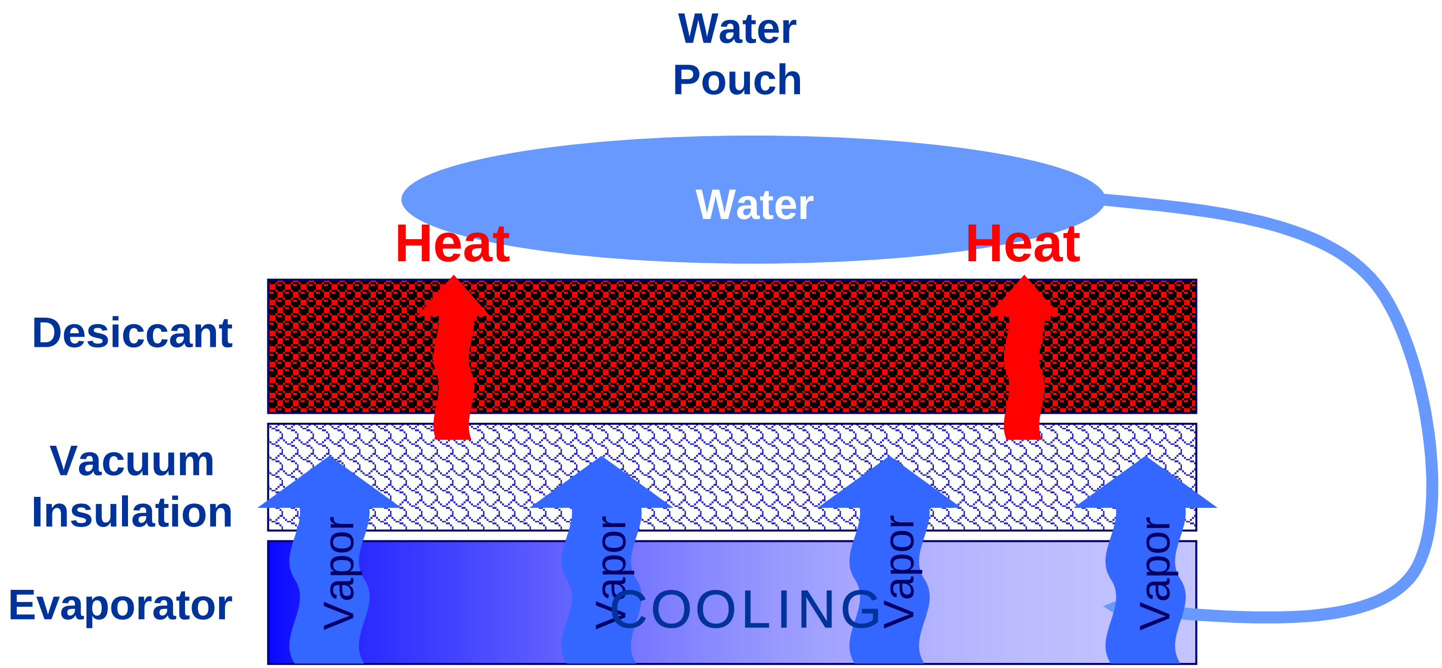


N_2 pore size distribution

Water adsorption isotherms



NanoCool Technology: How it works



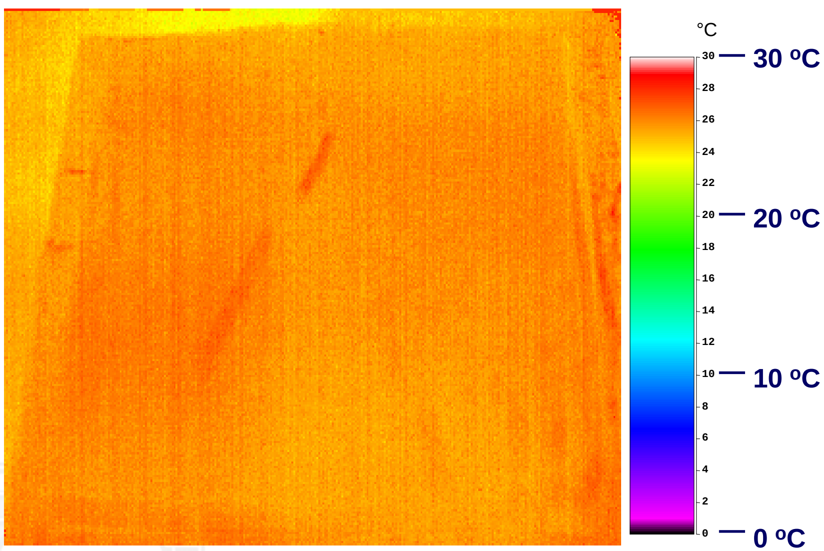
- Insulation layer is key to separating the hot and cold sides (reducing “thermal leakback”)
- Insulation core choice represents a trade-off between thermal conductivity, water permeation, and water adsorption

NanoCool System

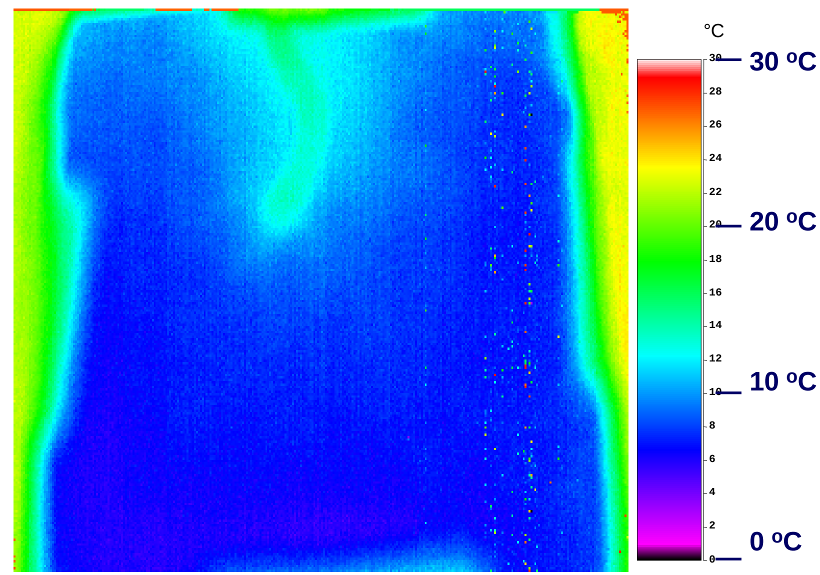
- •One active vacuum panel on top
- •Box made with 5 conventional vacuum panels
- •The payload is only for product, not product plus ice packs
- •Active panel activated by depressing dome
- •Performance feedback from thermochromic label

Quick Cool Down Time

In less than five minutes, the surface temperature of the cooler's inside surface has reached operating temperature as shown in these infrared imaging photographs.



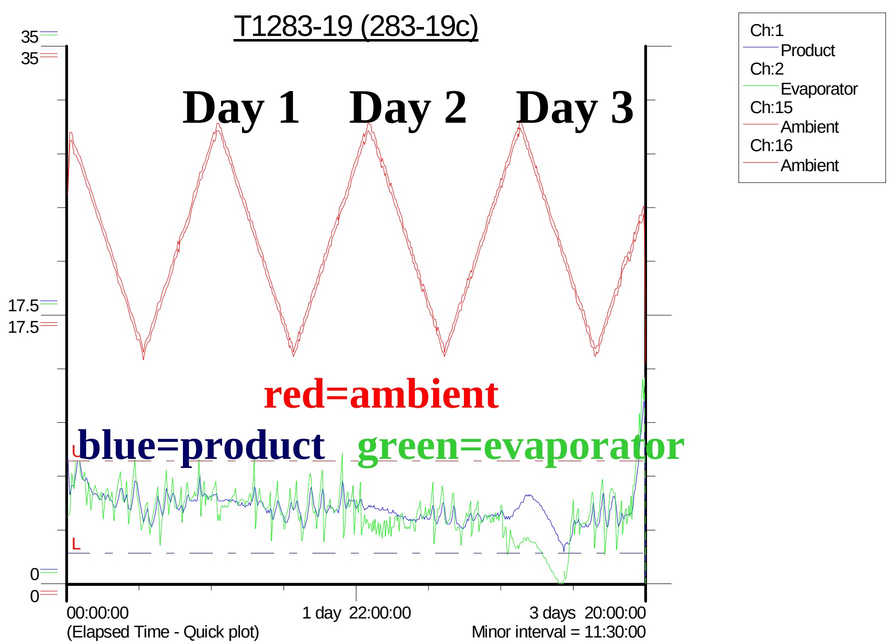
Internal surface of cooler prior to activation

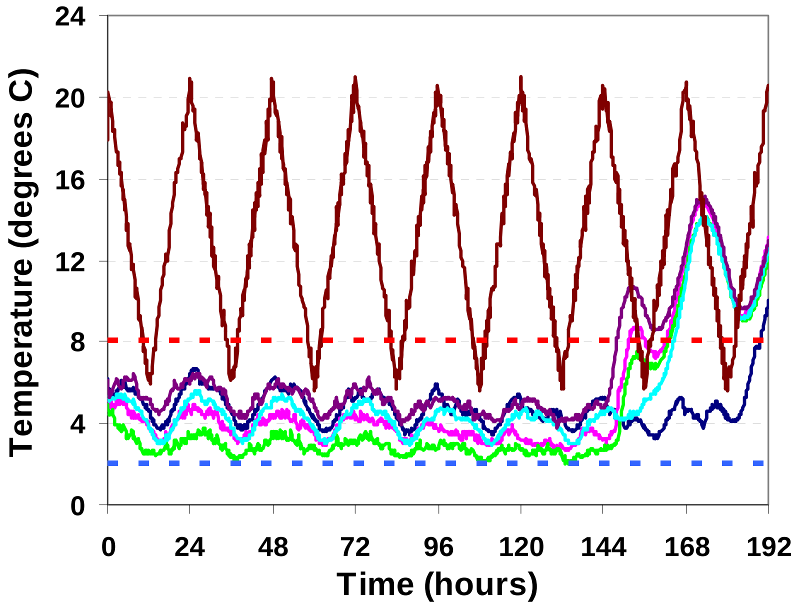


Cooler 5 minutes after activation

NanoCool Testing With Variable Ambients

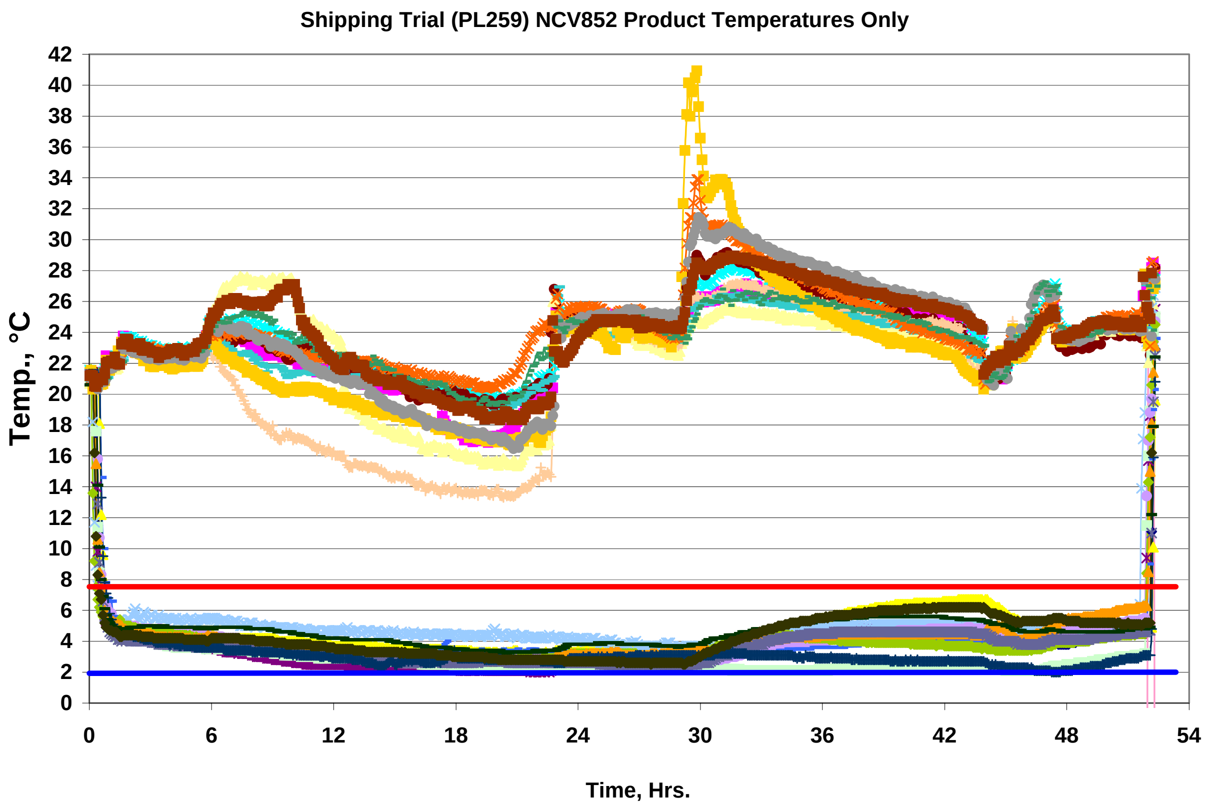
- The “*real CTP world*” is not constant temperature – even in the summer, ambient temperature is lower in a plane or warehouse
- “Active” nature of NanoCool™ technology serves to control product temperature (note: green temperature oscillation illustrates control function on cooler surface) – lower average ambients = longer lifetimes
  - Average temp/duration: 30 ºC is >2 days, 25 ºC is >3 days, 15 ºC >6 days





NanoCool Trial Shipments

- May 2005 shipping trial of 13 standard NCV852 systems from Charleston SC to Albuquerque, NM
- 51-hour duration trial
- Ambient temperature range was 13 to 41 ^{o}C
- Product temperature range was just 2.1 to 6.8 ^{o}C



NanoCool Controlled-Temperature Packaging Benefits

- Reduced Package Size – up to 70% reduction as compared to conventional foam/ice pack systems
  - Lower shipping costs
  - Reduced inventory space
  - Reduced waste
- Take anywhere on-demand cooling
- Simplified pack out – no gel packs
- Performance and reliability
- Commercial status: Pilot production approaching 5,000 systems (30,000 VIP's!) per week

Active VIP's for building applications?

- If 20 °C is the average temperature and 50% is the average RH
- At 10 °C and the same water vapor pressure, RH is 96% (winter)
- At 30 °C and the same water vapor pressure, RH is only 27% (summer)
- Performance of most adsorbents is RH based (~temperature independent).
- High capacity adsorbents at intermediate RH
- Cycle water vapor from one side of the VIP to the other with day/night T/RH swings to dramatically reduce thermal flux on 24 hour timescale?