BERKELEY LAB

LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

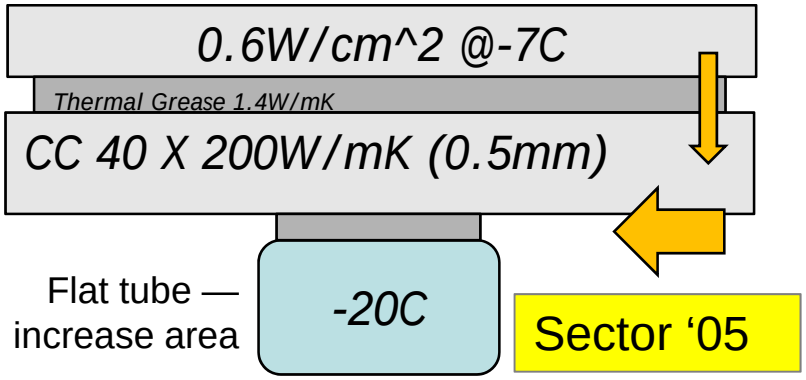
# Thermal modeling, interfaces, test results

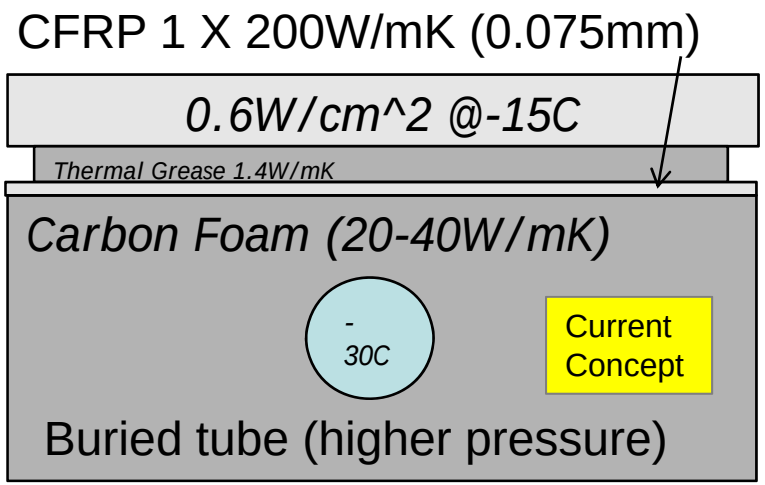
LBNL Composites Workshop

February 29-March 3, 2016

# Thermal modeling of our typical detector structures, like ATLAS pixel local supports, is *interesting*

- thermal-mechanical deflection
- steady-state heat transfer
- non-trivial thermal interfaces
- thin-wall and thick-wall
- convection
- 2 phase flow
- oh yes, and composite materials
  - fiber-reinforced
  - particle-reinforced
  - foam/filler hybrid



# High in-plane thermal conductivity can be achieved for CFRP

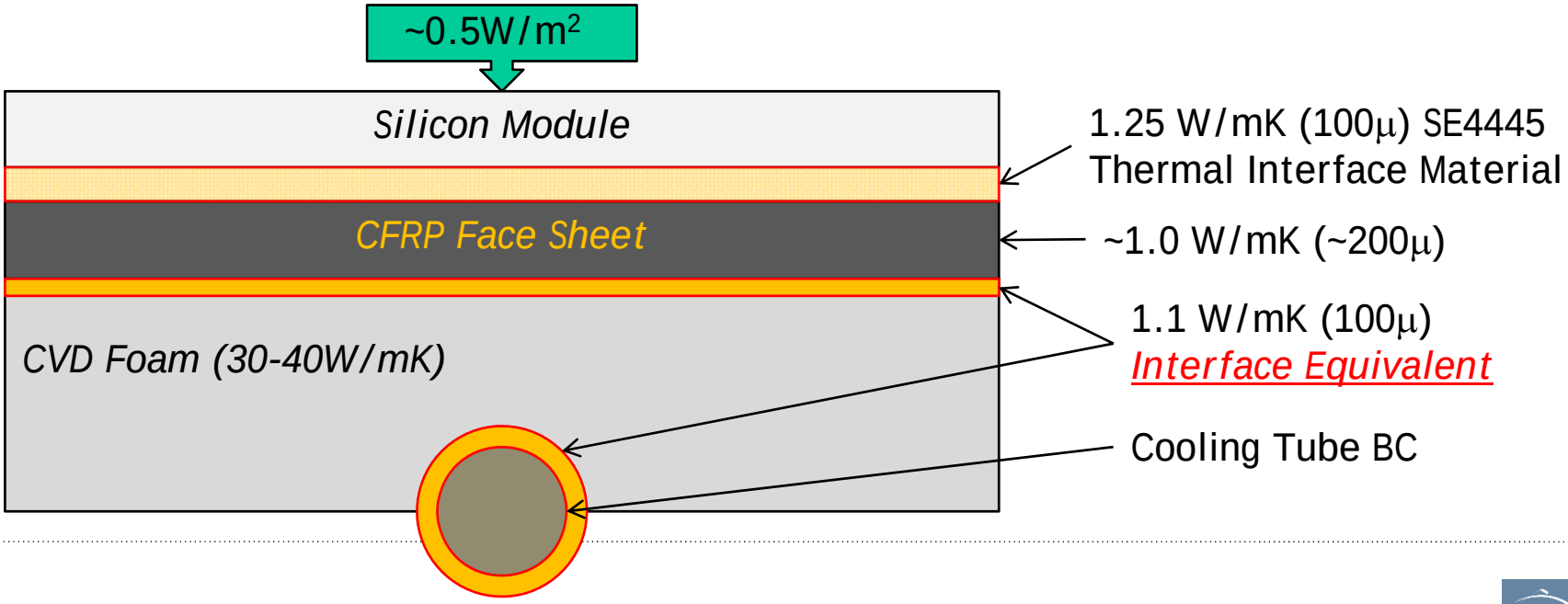
- Typically use pitch-based fibers with high thermal conductivity (K)
- $K_1$ of fiber itself can be extraordinary
  - K13D2U fiber is 800 W/m*K, which is 2x copper
  - this in the fiber direction (1-direction)
- $K_1$ of a unidirectional ply is ~½ that
  - rule of mixtures: $K_{1,ply} = K_{f1} * V_f + K_m * V_m$
- $K_1$ of a typical stackup is ~½ that again
  - tensor rotation of each ply $K_1$
  - weighted average by ply thicknesses
- So for the high-performance pitch fibers, we end up with aluminum-like thermal conductivity in-plane, ~200 W/m*K

# Thru-thickness thermal conductivity is generally 2-3 orders of magnitude lower

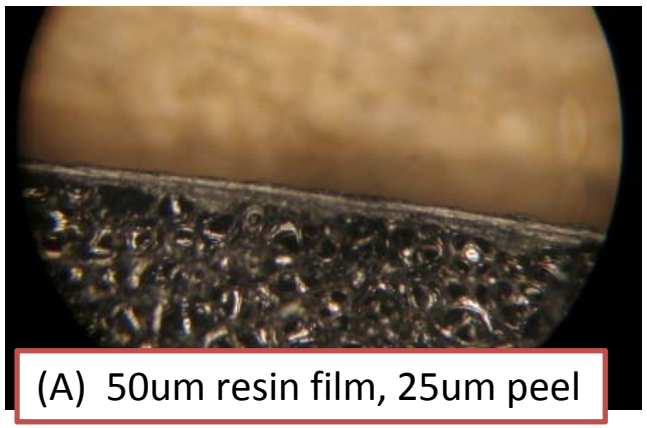
- This is the out of plane direction ($K_3$)
- $K_3$ ~ 1 W/m*K
- $K_1$ / $K_3$ ~ $10^2$ to $10^3$
- In special cases we can do a bit better than $K_{11}$ = 200 W/m*K, but it often doesn't matter:
  - In many practical applications the limiting factor is getting the heat into or through the thickness of the laminate
- For a ply, $K_2 = K_3 \sim (V_f / K_{f2} + V_m / K_m)^{-1}$
- Typical $K_{f2}$ ~ 2-10 W/m*K
- Typical $K_m$ ~ 0.2 W/m*K

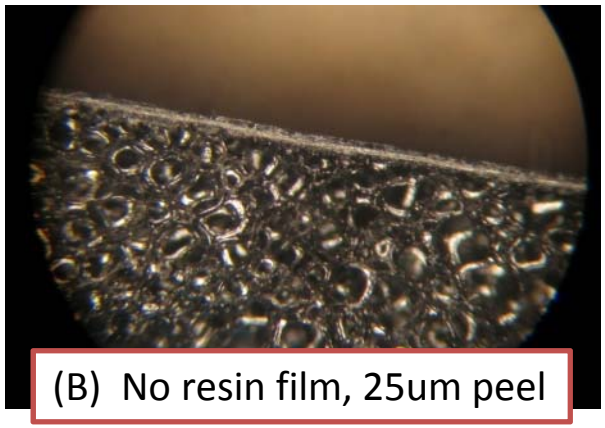
# The *interfaces* are important resistors in our typical geometries

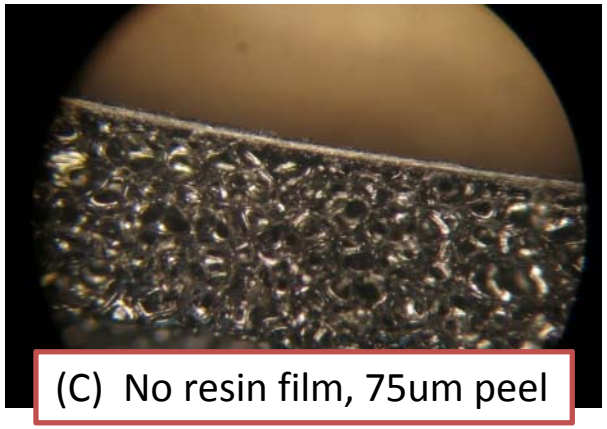
- They certainly cannot be ignored.
- Generally need to modeled as discrete solids, with finite thickness.

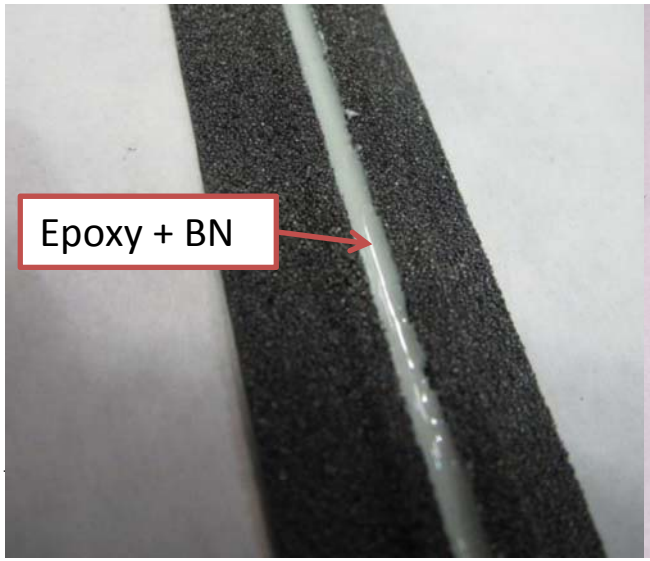


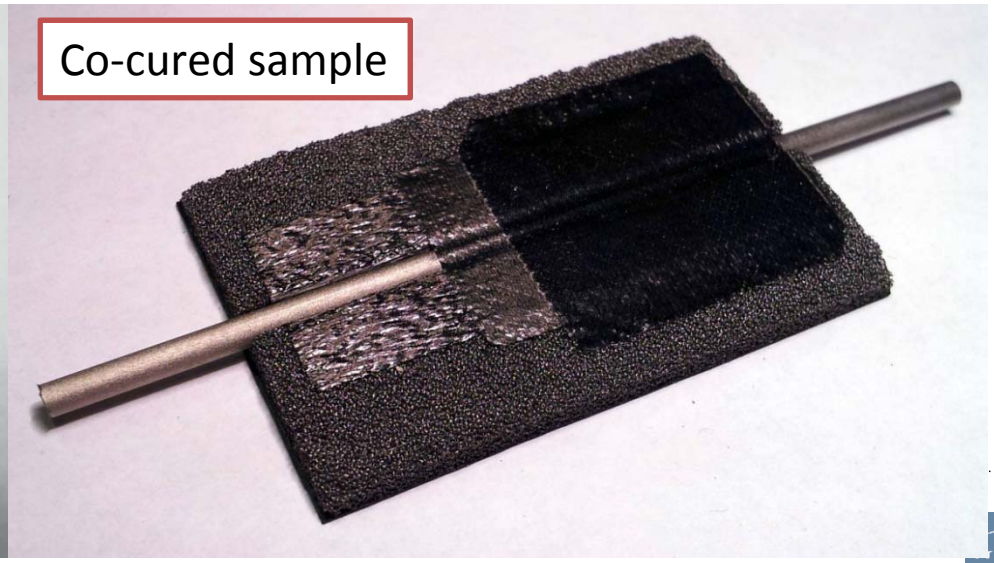
# Our interfaces at foam-facesheet or foam-tube depend deeply on fabrication details



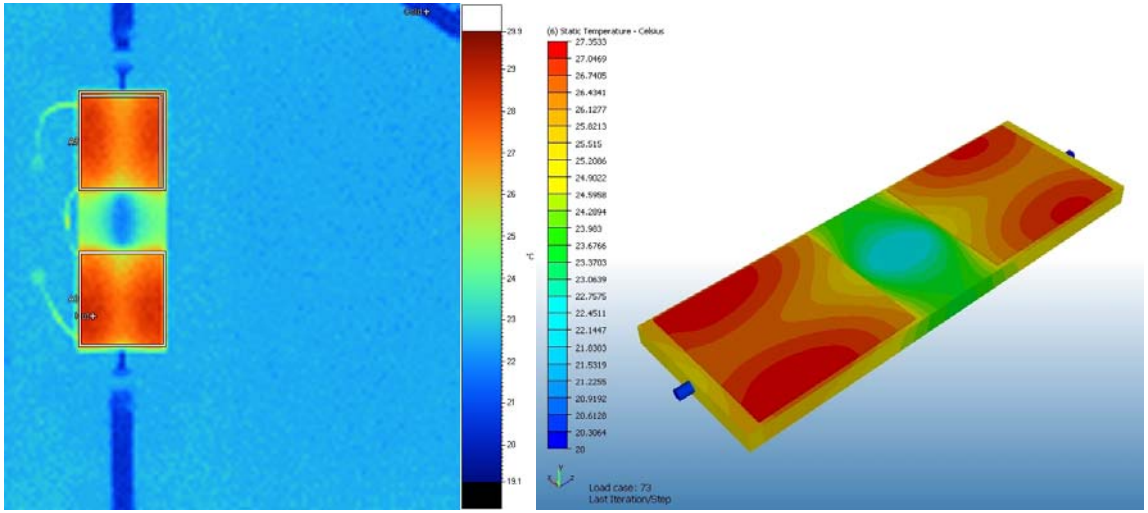



# We need to use solids for thermal models in FEA

- For structural FEAs, we often use shell bodies (2D) to represent composite laminates
  - This works because the thru-thickness loads (shear and out-of-plane modulus) are negligible
- For thermal FEAs, the thru-thickness conductivity is *essential*
  - So we have to model 3D bodies of finite thickness
  - This adds overhead to model setup
    - more contact surfaces to define
    - may need a discrete body for every *ply*
    - and each ply body needs a discrete coord system to define its orientation
    - some FE pre-processors (such as ACP) can make this work much faster (for complex geometries, read “possible”) to do

# We've more or less standardized on a typical method for assessing thermal performance of staves for detectors



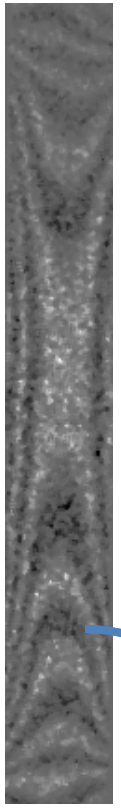
- Stave has all fab processes and materials
- 2+ Si/Pt dummy module heaters
- IR camera images heaters on and off
- $\Delta T = T_{on} - T_{off}$ , typical spec $\Delta T < 8\text{-}10^{\circ}$ C
- This type of test includes the *interfaces*.

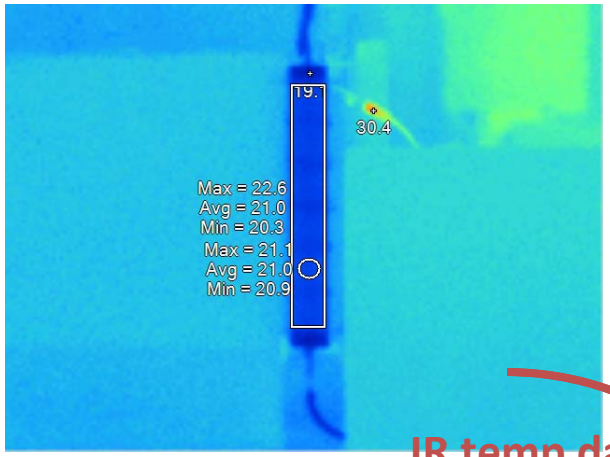
# Thermal-mechanical behavior is pretty straightforward to do in FEA

1. Solve the thermal problem
2. Pass temperature data as input to structural
3. Solve the structural problem

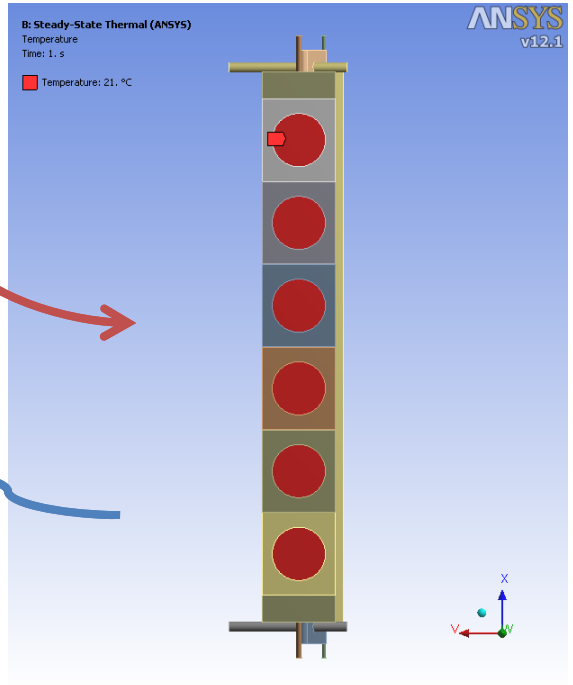
It is *not* straightforward to test.

# We've used combined IR (thermal) + TVH (interferometry) to do this on I-beam





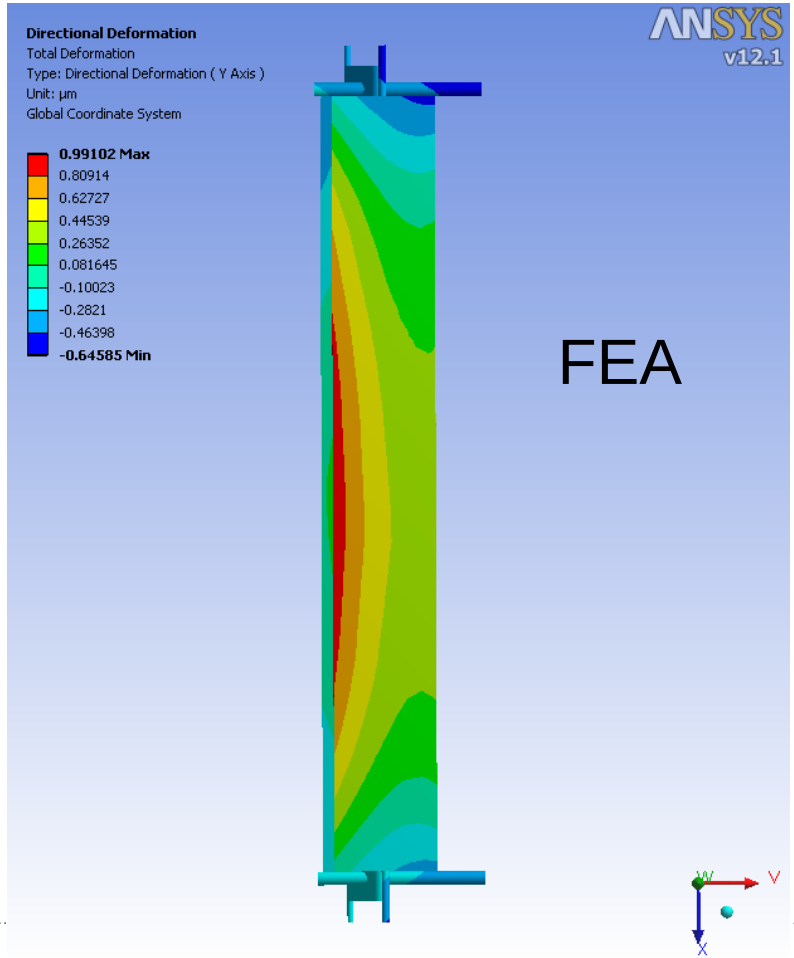

IR temp data
→ B.C. for FEA

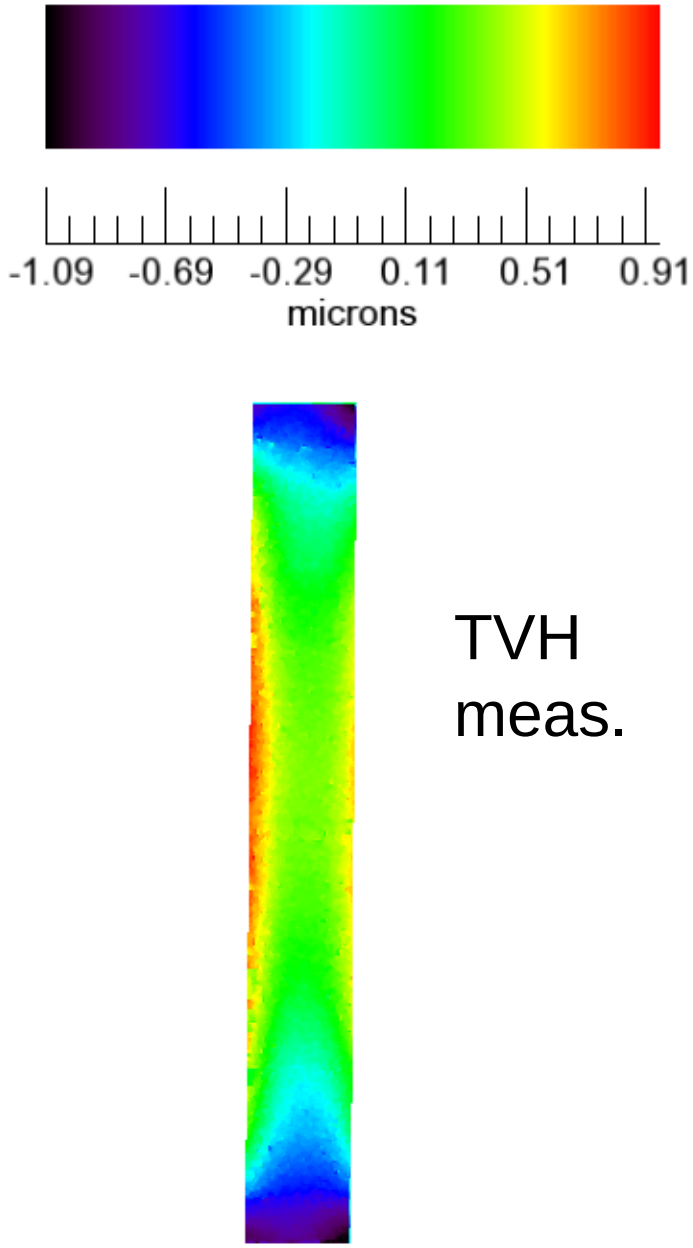



Solve two thermal-stress analyses at the two setpoints and then compare to TVH data

TV holography data
→ Differential deflection between 2 setpoints
(2 different power inputs to silicon)

# It is highly effective at validating FEA, but takes some work to do

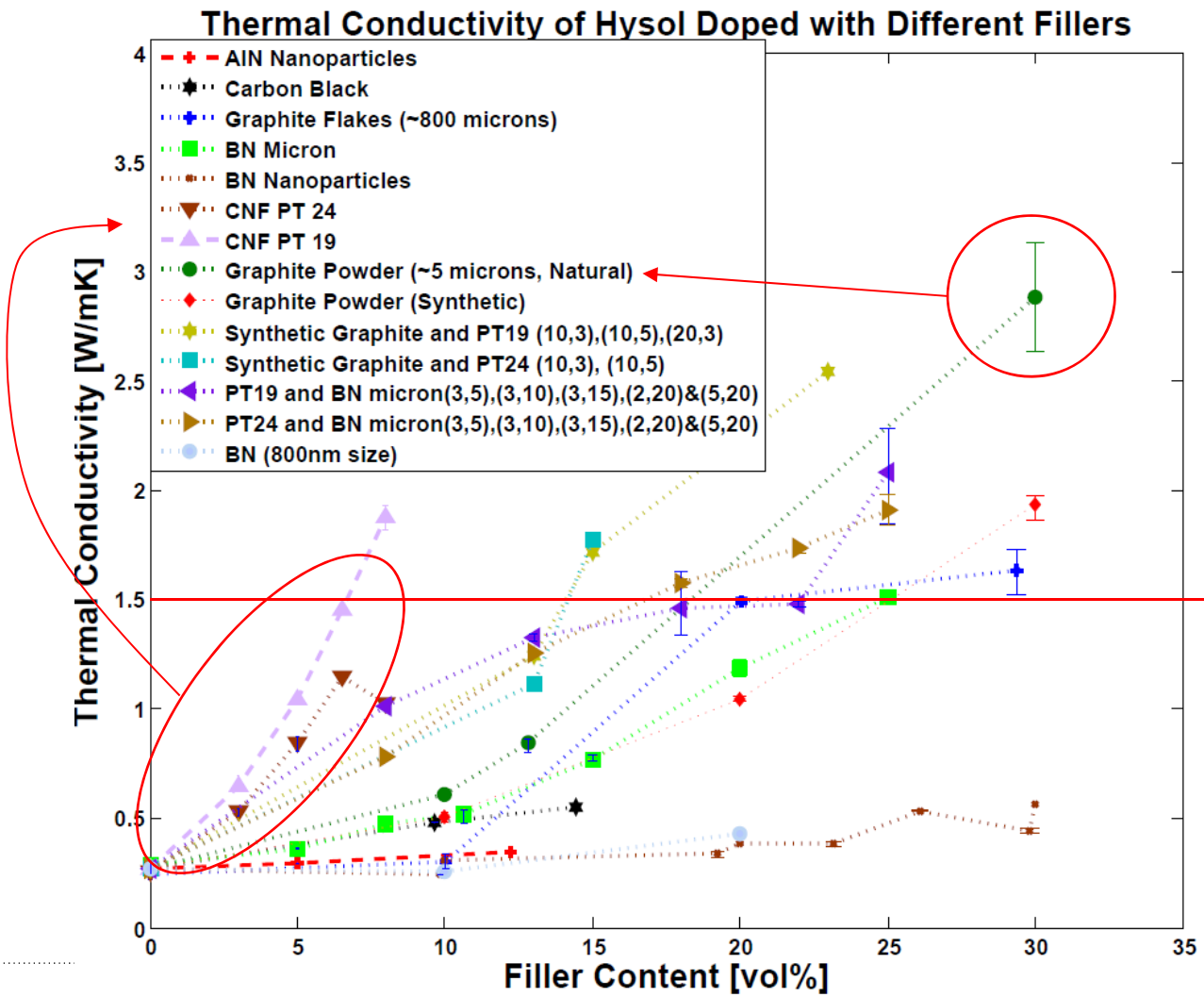


# We typically fill our epoxies with particles to enhance $K_m$

- Typical unfilled epoxy (Hysol 9396), K = 0.2 W/m*K
- Baseline filler for most of our applications is micron-sized BN, which gets you to K ~ 1.1 W/m*K at 20-30% mass fraction
  - easy to use, safe, gives nice viscosity
- Another typical filled material is SE4445, with K = 1.25 W/m*K
  - frequently used to mount Si modules
  - proprietary filler, Dow material

# There's been a lot of activity recently on finding new fillers for resins, to enhance K



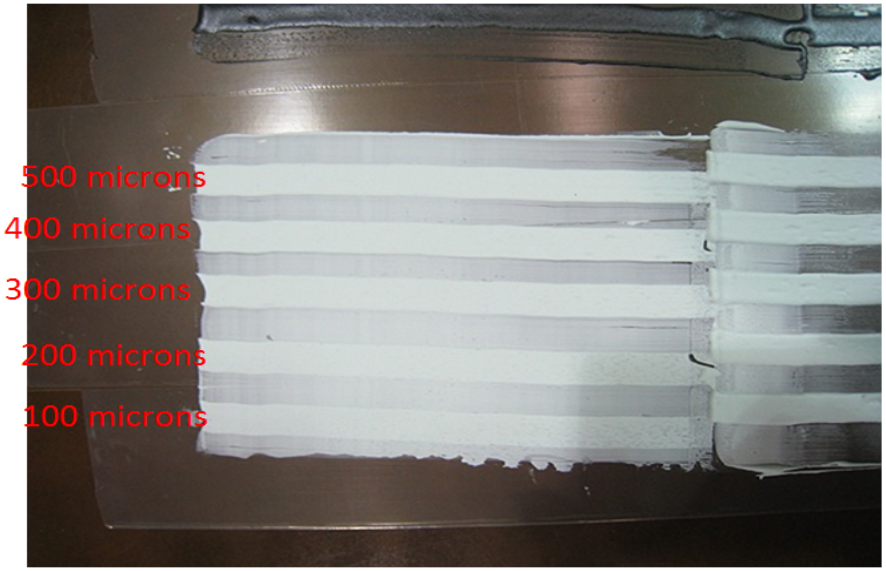

We should be able to reliably get above ~1.5 W/m*K in practice with Hysol.

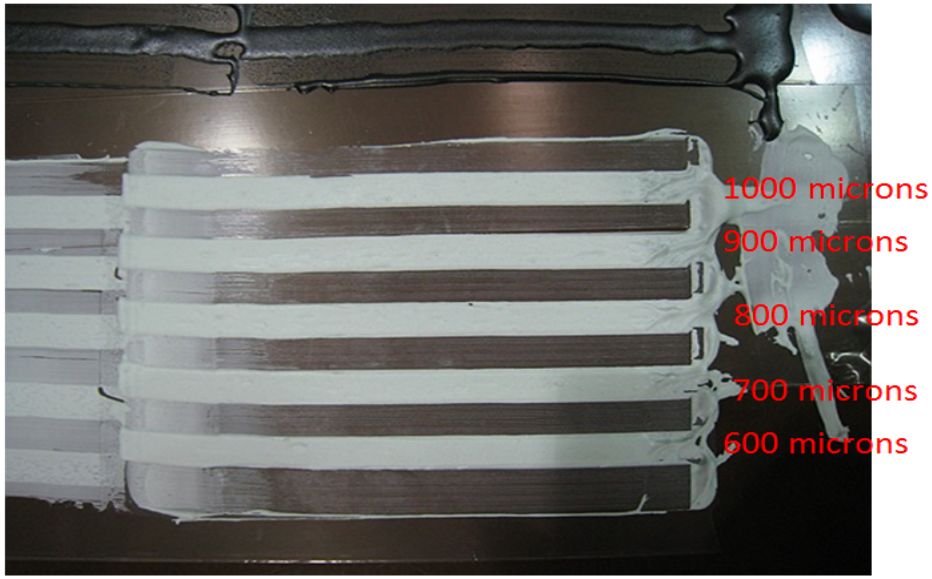
3 W/m*K is about the conceivable limit.

(and "nano" was not magical)

# Thermal conductivity is important, but filled adhesives still need to be used as *adhesives*

Micron BN 20% vol (~1.185 W/mK)

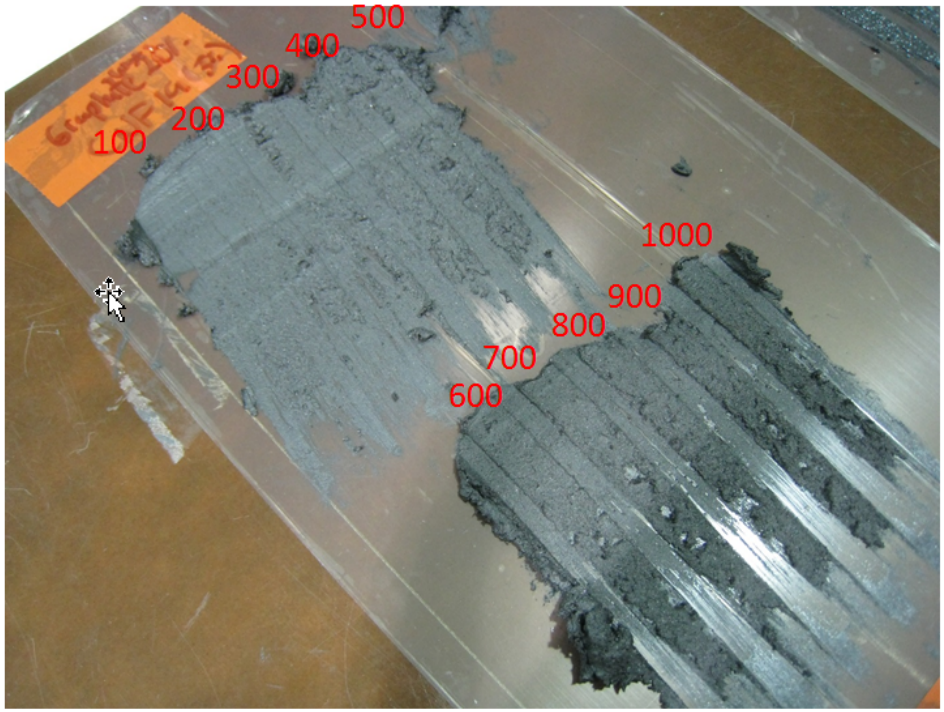


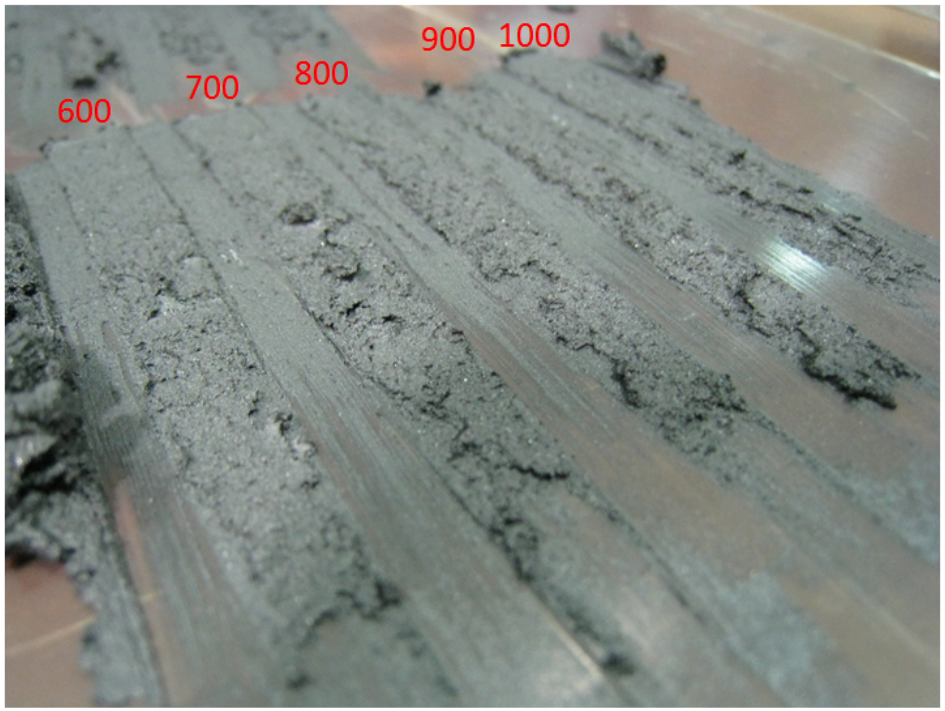




Here is a nicely-spreadable typical BN-filled epoxy.

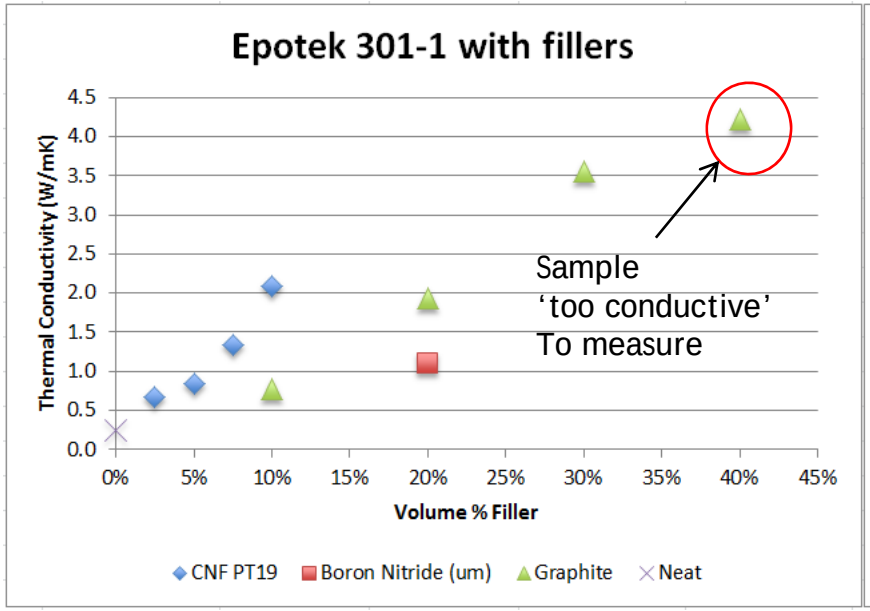
# Here is an example of an unusable mixture.

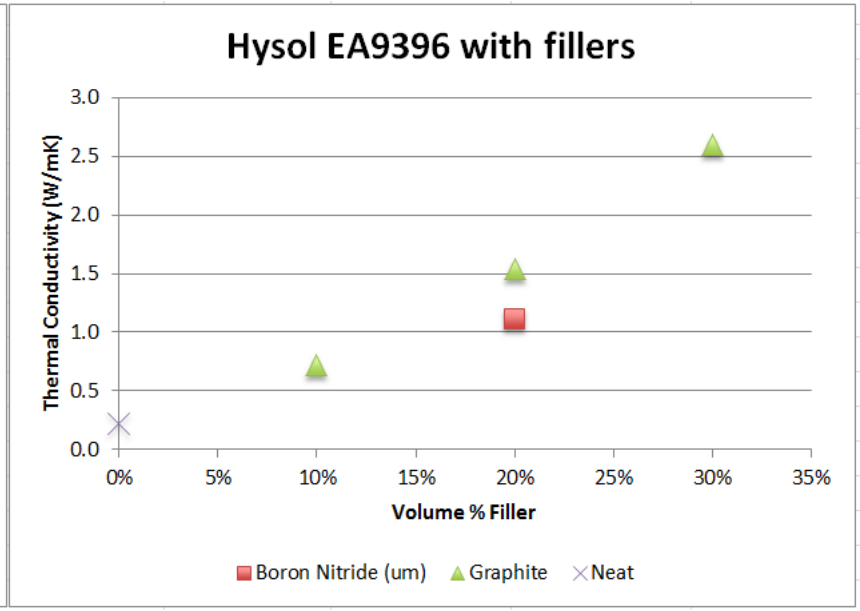
Graphite(Natural, “low” Purity) (20%) & CNF PT19 (3%)



# A lower viscosity resin allows more filler, and perhaps better exfoliation / distribution

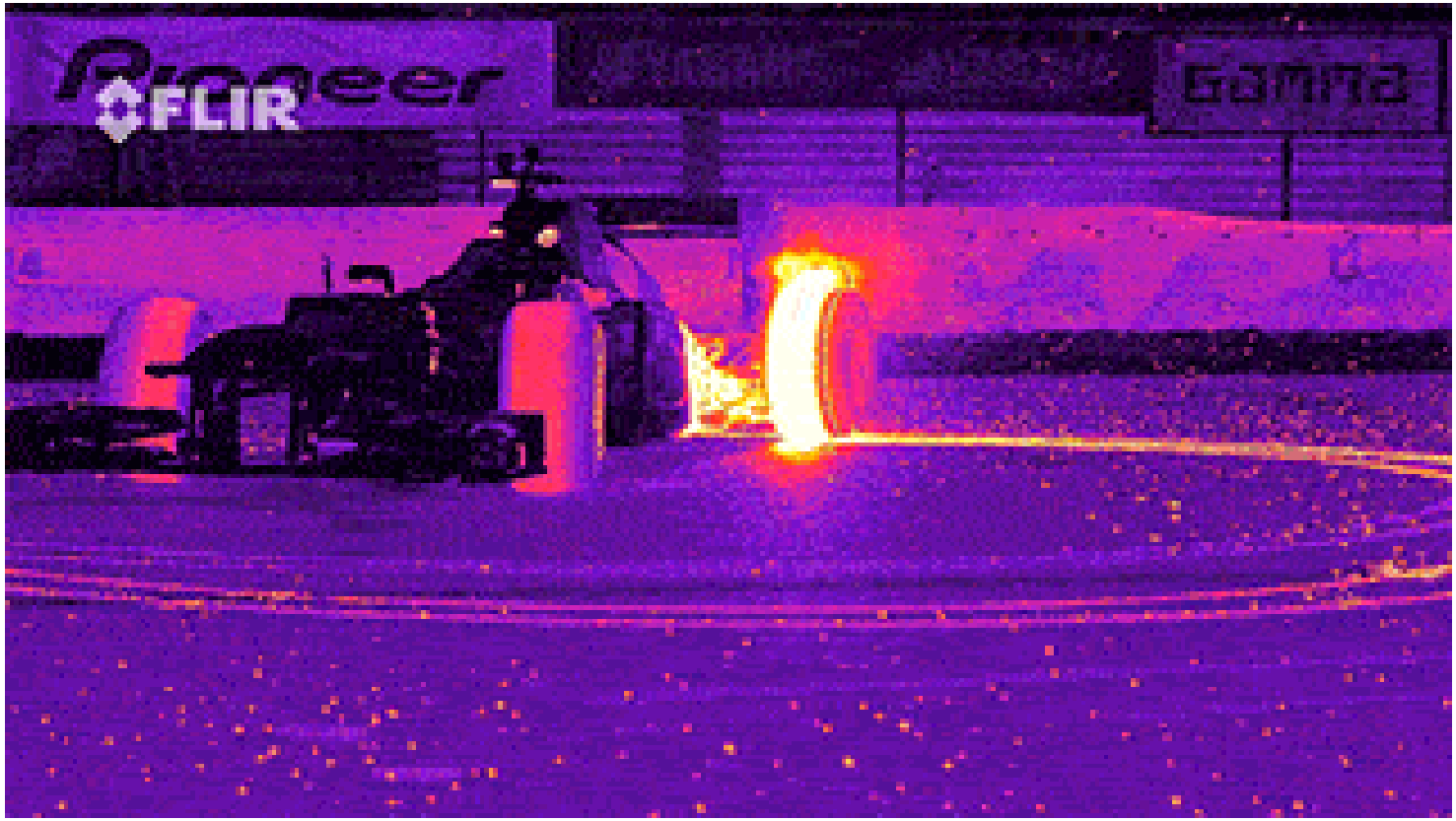



- This also highlights the importance of mixing quality.
- A mixing machine with 2 spin axes (centrifugal + local) is an essential piece of equipment.

# Thermal modeling is about intimate investigation of the materials and interfaces

- Interfaces must be modeled discretely
- K is often fabrication process-dependent
- Testing properties and validating FEAs is generally not-so-simple:
  - accuracy and cross-calibration of temperature sensors
  - thermal interfaces to temperature sensors
  - thermal interfaces to heat sources
  - natural convection or other losses
  - cost of producing many samples
  - variability of samples
  - combining thermal and mechanical
  - plumbing is required
- It takes a lot of iteration.
- A good IR camera is really helpful.


FLIR