Local Supports Critical Design Issues

September 9, 2008
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Topics

- **Pixel Stave Thermal Estimate**
  - Influence of material choice under chip thermal load $0.5 W/cm^2$
- **Carbon and Graphite Foam Properties**
  - Elastic and Thermal Properties
- **Foam and Adhesive Thermal Strains in Stave Sandwich Structure**
  - Room temperature to -35ºC
  - One compliant adhesive and one semi-rigid

Pixel Stave Thermal Study

- **Objective: Material and Geometry Sensitivity Analysis**
- **Variables**
  - Double-pass coolant tube (U-Tube): Symmetry places tube at transverse quarter points
  - Single Tube: on stave center
  - Tubes: Al, 2.8mm OD with 0.3048mm wall
  - Sandwich core
    - Carbon foam, 10 to 20W/mK
    - POCO Foam Insert around perimeter of cooling tube
  - Facings: K13D2U and CC
  - Integrated Chip Circuit on CVD diamond substrate
  - Cable (estimated to be 79/0.28/79 W/mK): Assessed effect if thickness value was 1.0W/mK
  - Adhesives: Two values 0.8W/mK and 1W/mK, thickness depends on location

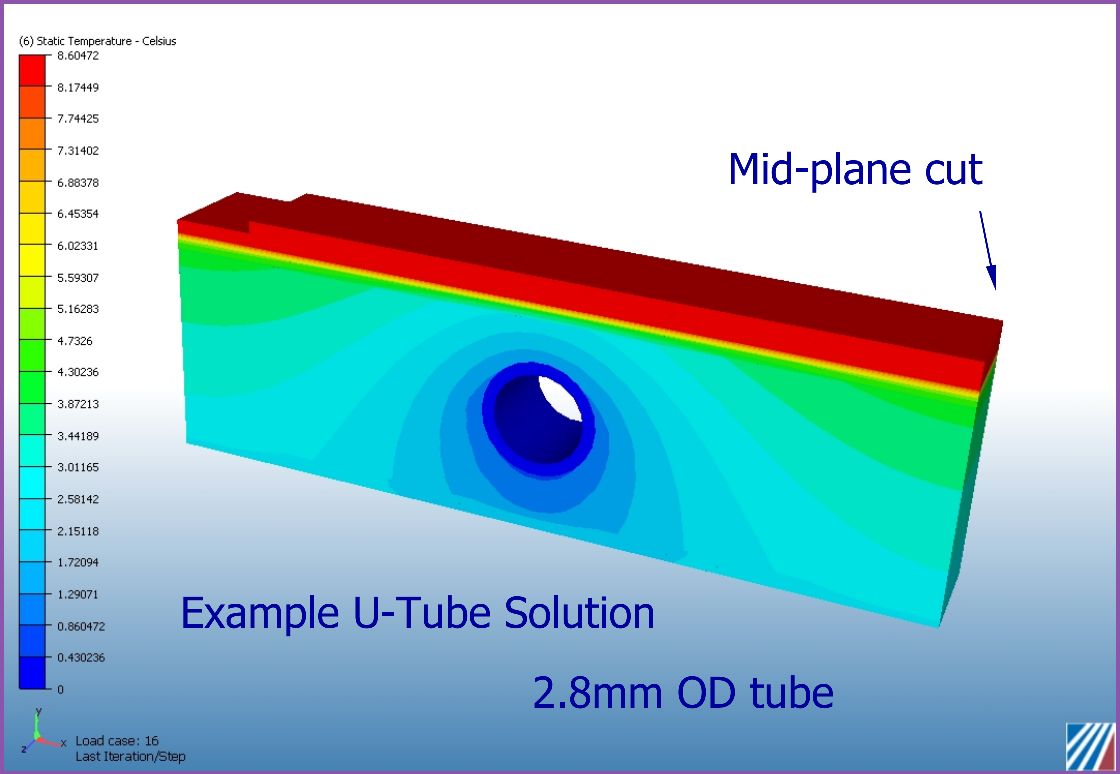
Adhesive Breakdown-(K Conservative)

- **Chip to Cable**
  - 0.8W/mK with thickness of 0.1mm (4mils)
- **Cable to Facing**
  - 0.8W/mK with thickness of 0.05mm (2mils)
- **Facing to sandwich foam core**
  - 1.0W/mK with thickness of 0.075mm (3mils)
- **Foam core to cooling tube**
  - 1.0W/mK with thickness of 0.1mm (4mils)

- **POCO Foam Insert-(variant on design of single tube geometry)**
  - HC core 3W/mK, but de-coupled from POCO by thermal block of 0.2W/mK and 0.125mm (5mils)

U-tube (Variant "A")

- **Peak differential temperature =8.6ºC for chip surface flux of 0.5W/cm² and foam K=10W/mK**



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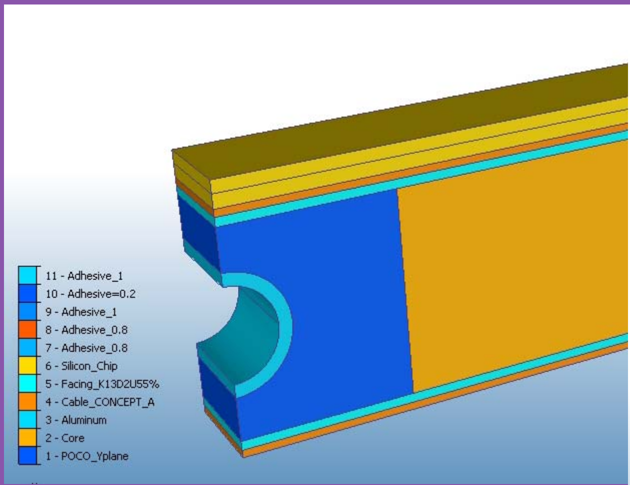
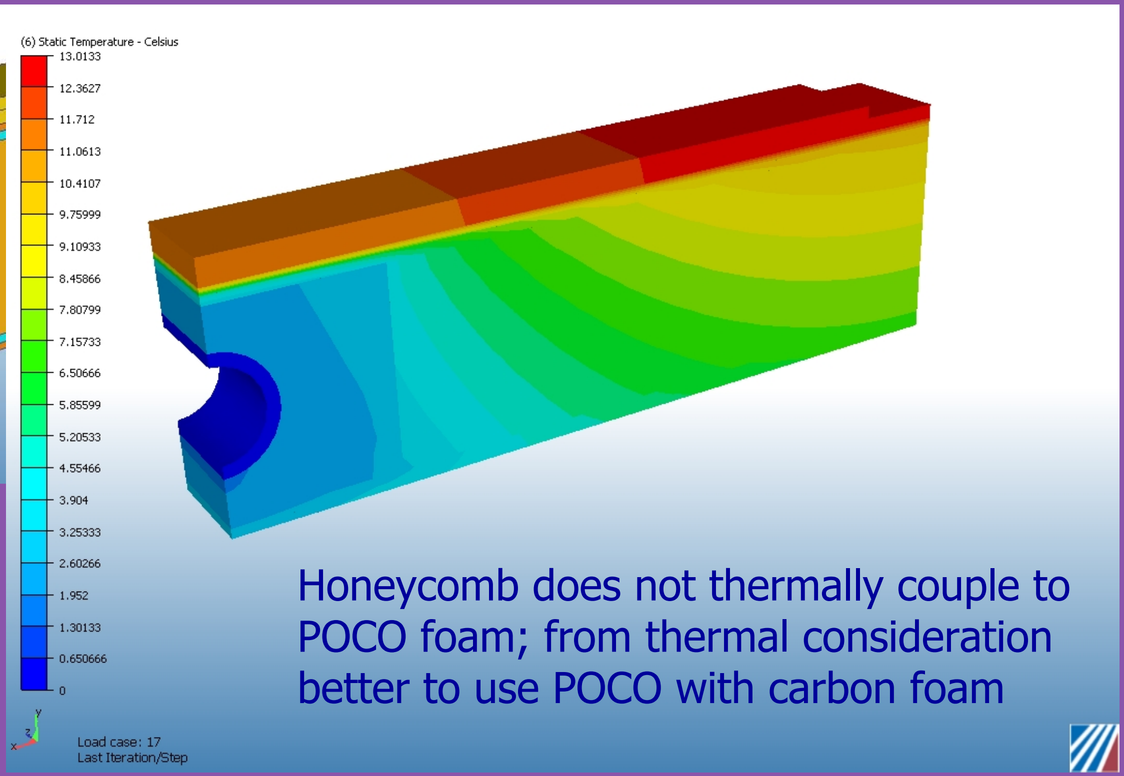
Single Tube (POCO Foam Variant)

- **Tube encased in POCO foam**
  - Sandwich Core is honeycomb, with adhesive resistance between two materials
  - Peak temperature is 13ºC (compare to variant B in Solution Summary Table)



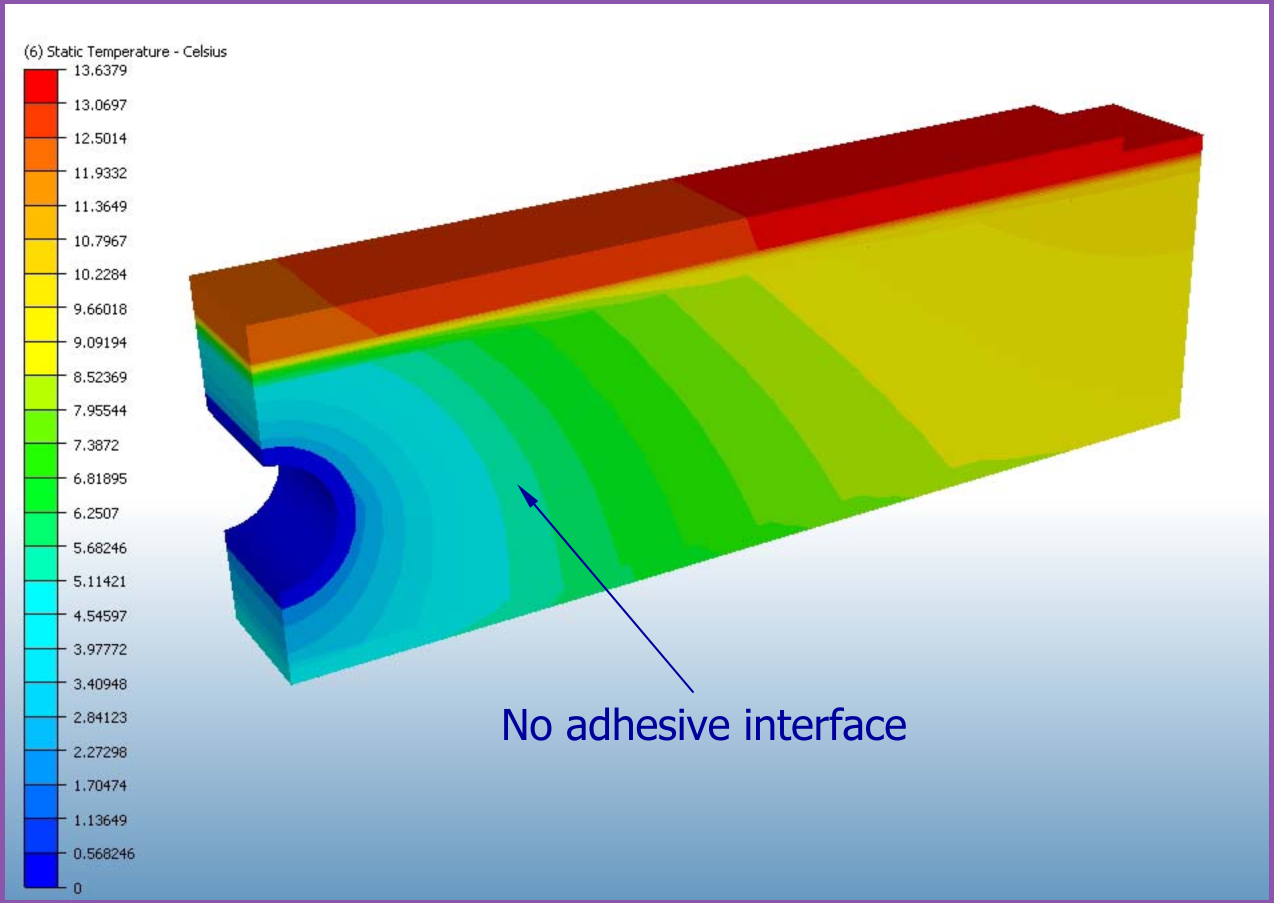
POCO foam, in conjunction with 15W/mK carbon foam would be 10.4ºC



Honeycomb does not thermally couple to POCO foam; from thermal consideration better to use POCO with carbon foam

Single Tube (Variant B)

- **Entire core is carbon foam with 10W/mK conductivity**
  - Realizing 20W/mk in core reduces gradient from 13.6ºC to 11.2ºC



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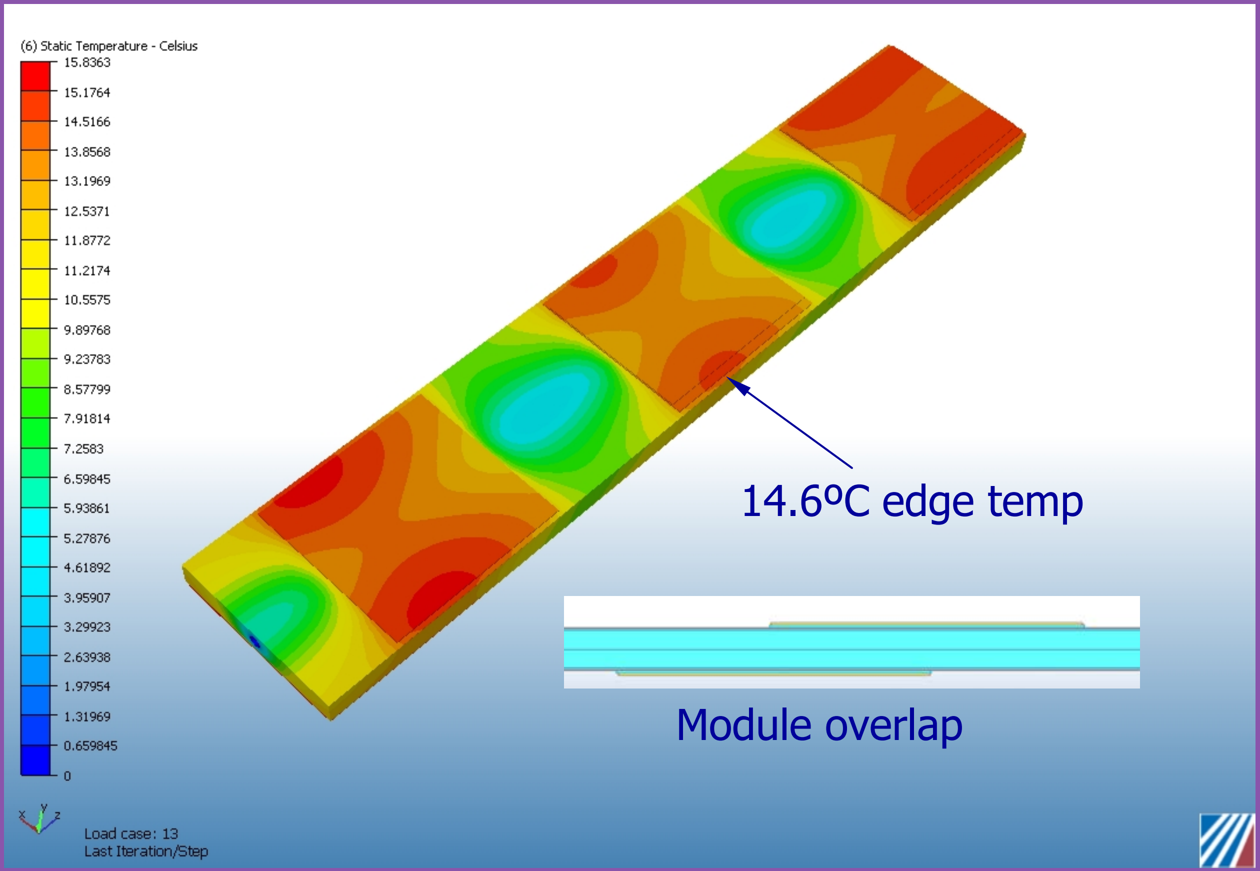
Solution Summary

Item (Chip Power 0.5W/cm^2)	t (mm)	K (X/Y/Z W/mK)	A	A*	B	B*	C	D	D*	D**	F
ΔT (°C)			8.6	6.5	13.6	11.4	12.5	11.8	9.8	8.2	10.4
Cooling Tube		186									
U-tube 2.8mm OD (0.3048mm wall)			x	x							
Single tube 2.8mm OD					x	x	x	x	x	x	x
Facing (K13D2U-55% fiber fraction)	0.21	294/148/1.3	x	x	x	x				x	
Facing CC	0.21	314/183/25					x	x	x		x
Cable	0.174	79/79/0.28	/0.28	/1	/0.28	/1	/0.28	/0.28	/0.28	/0.28	/1
Sensor	0.300	148	x	x	x	x	x	x	x	x	x
Chips	0.325	148	x	x	x	x	x			x	x
50microns Si/275microns diamond	0.325	1460/1460/650						x	x		
Carbon Foam for Sandwich	4.8	W/mK	10	10	10	10	10	10	20	100	10
Carbon Foam to Tube	0.10	1	x	x	x	x	x	x	x	x	x
Carbon Foam to Facing	0.075	1	x	x	x	x	x	x	x	x	x
Facing to Cable	0.050	0.8	x	x	x	x	x	x	x	x	x
Cable to Chips	0.1	0.8	x	x	x	x	x	x	x	x	x

Thermal FEA for Single Tube Stave

- **Preliminary, 1st cut model, 3 modules front and back**
  - Use in-board module for indicator of peak steady state temp (14.6ºC)
  - Compare against 13.6ºC from earlier model



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Observations

- **U-Tube versus Single Cooling Tube**
  - Minimizing thermal gradient favors U-Tube
    - On direct comparison, U-Tube has a 5ºC advantage (8.6 versus 13.6)
    - Advantage can be reduced through substitution of materials
      - With CC facing and CVD chip differential reduces by 1.8ºC (B vs D)
- **Cable thermal conductivity (thickness 0.28W/mK) has impact, nearly same for single tube and U-Tube**
    - U-Tube with cable K=1W/mK, drops by 2.1ºC
    - Single tube with cable K=1W/mK, drops by 2.2ºC
    - Percentage wise the cable drop is a larger fraction in the U-Tube, 2.1ºC out of 8.6ºC versus 2.2ºC out of 13.6ºC
- **Doubling carbon foam conductivity (20 versus 10W/mK) drops the gradient in the *single tube design* by 2.2ºC for the K13D2U facings and cable K of 0.28W/mK**

Observations (continued)

- **To Realize a Competitive Single Tube Design, Suggest Using:**
  - CC facings
  - Standard Chip
  - Producing all foam core at least 15W/mK
  - Cable (0.28W/mK)
  - *Thermal estimate is 11.04ºC*
    - Adding POCO foam around cooling tube produces a slight benefit, becoming 10.54ºC, with foam at 15W/mK
- **For comparison: U-tube with basic materials: 8.6ºC (foam at 10W/mK)**
- **Recommend measuring cable thermal conductivity**

Foams for Detector Applications

- **Foam Types**
  - Thermally Enhanced Carbon Foam (Allcomp)
  - Graphitic Foam (POCO, Kopper)
- **Topics (if time permits)**
  - Material Properties
    - E, G, stress-strain, non-linearity
  - Differential Contraction of Dissimilar materials
    - Is FEA model length important?
  - Adhesive bond stresses
    - Joining POCO foam to Al tube (Steel also, but not covered here)
  - Recent Thermal conductivity measurements

Foams for Detector Application

- **Technical Areas of Interest**
  - Allcomp Processed RVC carbon foam, 0.1 to 0.2g/cc
    - Thermal and structural adequacy in very lightweight form
  - Graphitic high conductivity foam (POCO, Kopper)
    - Most common use at 0.5g/cc to 0.9g/cc
      - Can be used sparely used in high heat flux regions without serious impact on radiation length
      - Recent interest, what happens to structural and thermal properties at very low density
- **Generic interest to all foams**
  - Over what domain is stress strain curve linear?
  - What happens as limits in tension and compression are reached?
    - Tests show that POCO foam under compression exhibits plasticity over fairly high strains before crushing

Carbon Foam Properties

- **Objectives of Allcomp Carbon Foam Program**
  - Produce low density carbon foam suitable to thermal applications with established structural properties
  - To effectively apply lightweight carbon foam in a detector application we must:
    - Characterize both linear and non-linear structural behavior
    - Basic question being addressed now is how foam density affects:
      - Thermal and structural, will vary with foam density and foam processing
    - Work by Ashby (others) point to a focus on E and G as function of density
      - Ashby related E and G to the solid property by the square of the density ratio, multiplied by a constant C, which varies according to the type of foam, open cell, closed cell, etc.
    - With regard to strength, must quantify tensile fracture, compressive plasticity (cell buckling), and shear strength to adequately interpret FEA modeling---*this goes beyond Ashby*
      - Must assess sandwich core shear stiffness, i.e. tube and foam combined

Ashby Relationships for Cellular Materials

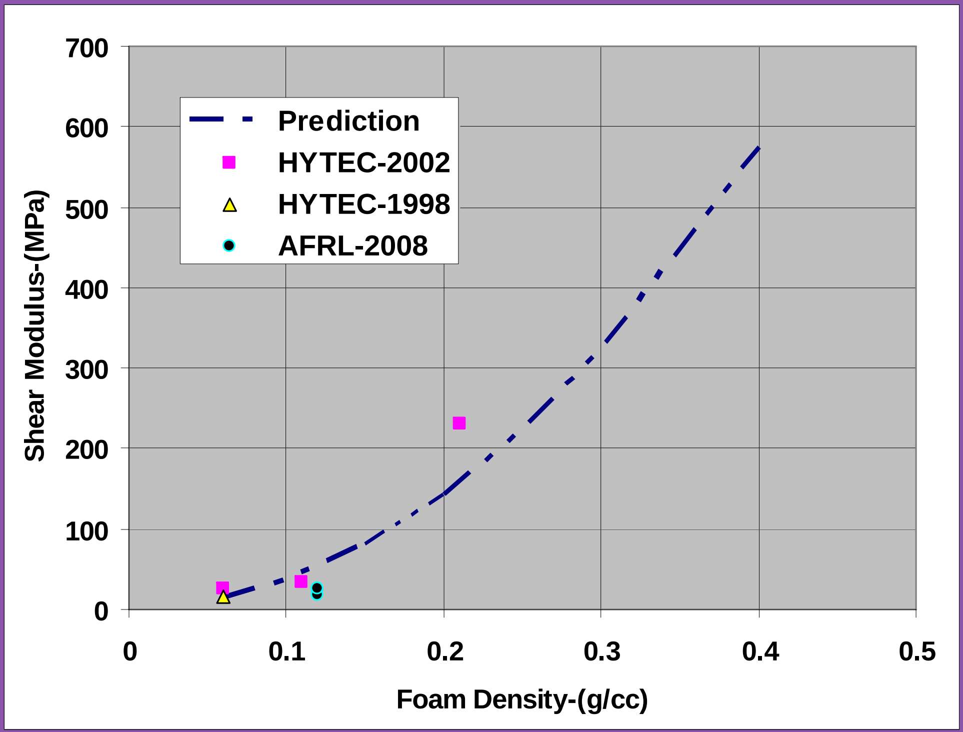
$$\frac{E_f}{E_s} = C \times (\frac{\rho_f}{\rho_s})^2 \qquad \frac{G_f}{E_s} = 0.385 \times (\frac{\rho_f}{\rho_s})^2 \qquad \frac{\sigma_y}{E_s} = 0.3 \times (\frac{\rho_f}{\rho_s})^{3/2}$$

C taken equal to 1 for open cell foams

- **As we progress in our testing we will test correlation using Ashby's relationships**
  - Literature covers open and closed cells, mostly polymeric, with limited data on aluminum foams
  - Argument advanced is regardless of material these relationships are useful for normalizing the data
  - We are looking into the utility for graphitic and RVC foams

Old and New Data on CVD Foam (100ppi)

- **Data in figure obtained by sandwich bend tests and dynamic vibration testing of Allcomp processed RVC foam**
  - RVC carbon foam responds to CVD densification as square of density change
  - Question is what happens to enhanced structural property after heat treatment



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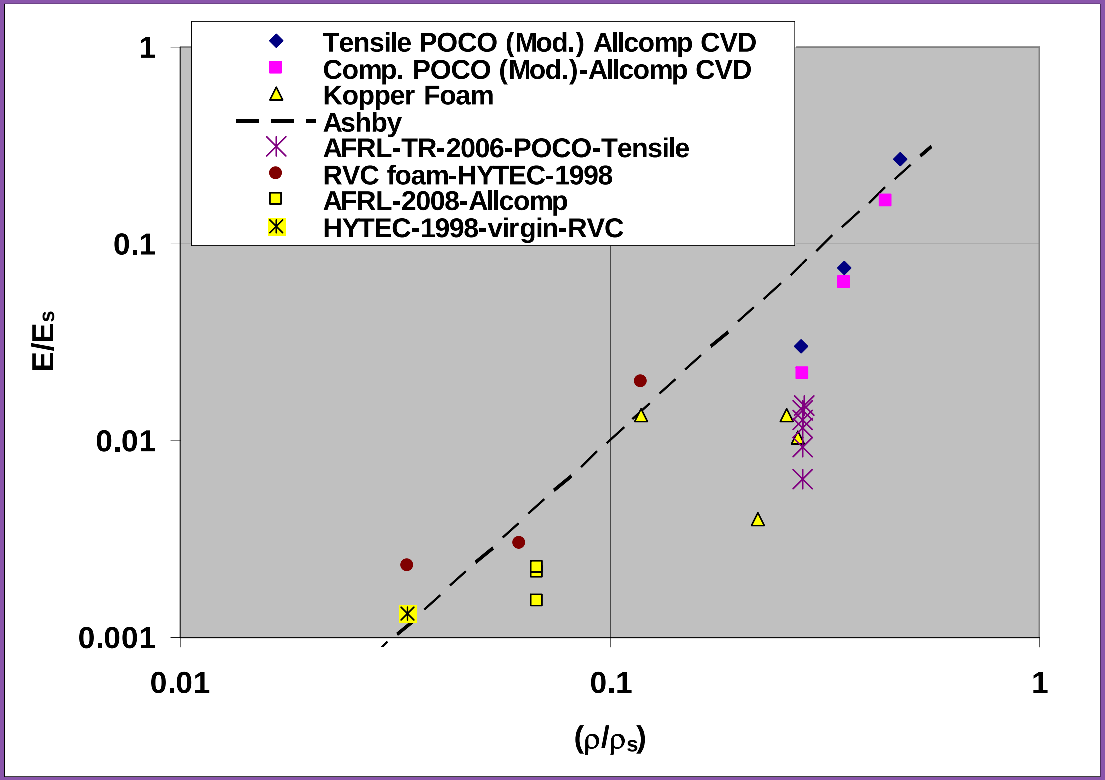
Relative Young's Modulus vs Relative Density

- **Sparse data-- prone to scatter**
  - Lack independent measurements of E (tensile) and G (shear) on same specimen
    - E (tensile) more common measurement, on occasion E (compressive)
    - G (shear) infrequently measured, estimated based isotropy and v=0.3

Solid properties for normalizing data based on pyrolytic graphite

E_s=29.6GPa
ρ_s=1.78g/cc
σ_s=68.9MPa
v=0.3



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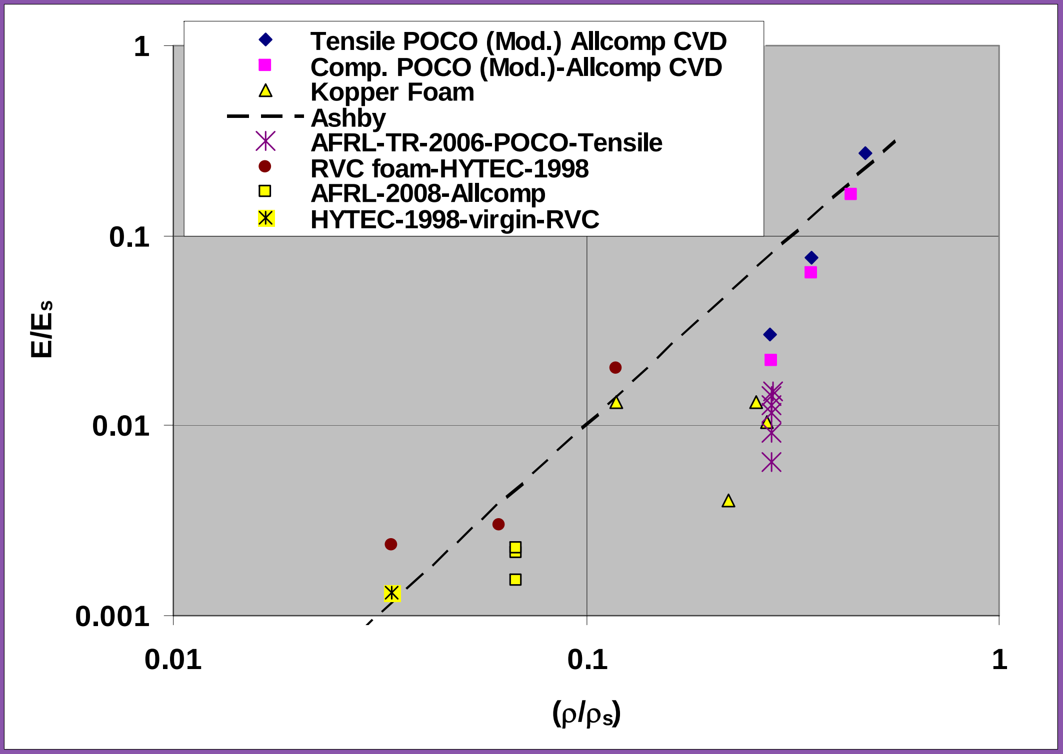
Relative Shear Modulus vs Relative Density

- **HYTEC 2002, HYTEC 1998, and AFRL-2008-Allcomp, actual shear measurements**
  - Balance of data using Young's modulus and $G = \frac{E}{2(1+\upsilon)}$



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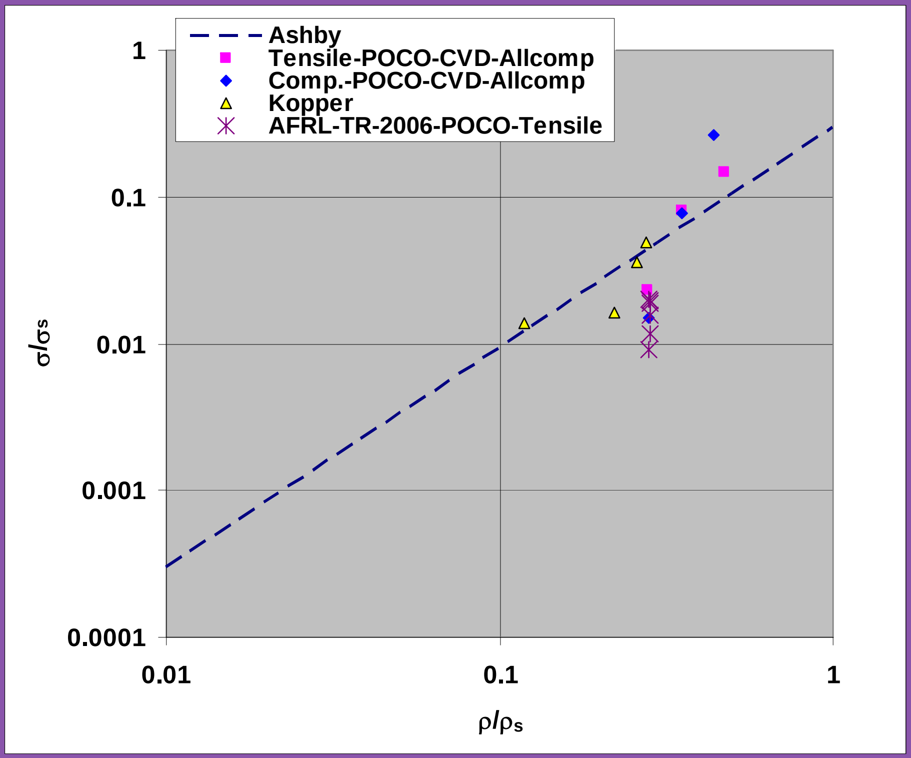
Relative Yield Strength vs Relative Density

- **Graphitic foam, POCO (Allcomp modified) and Kopper stress measurements**
  - Intend to expand on lower relative density region on RVC enhanced foam



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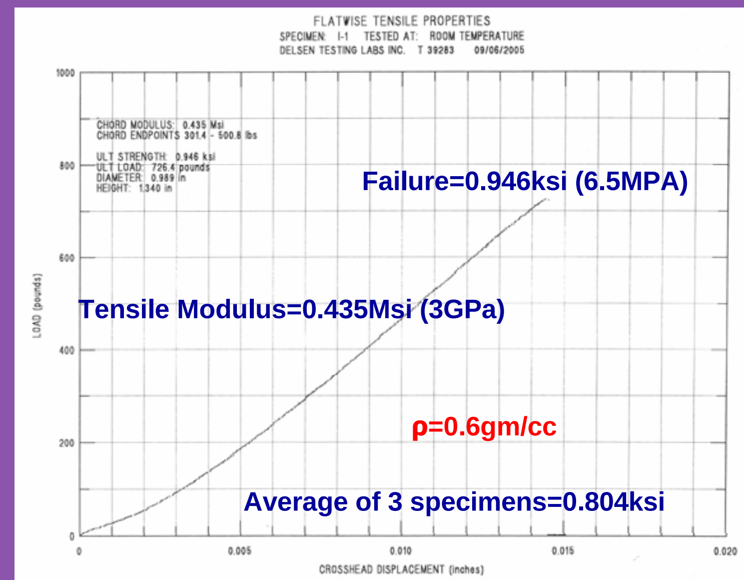
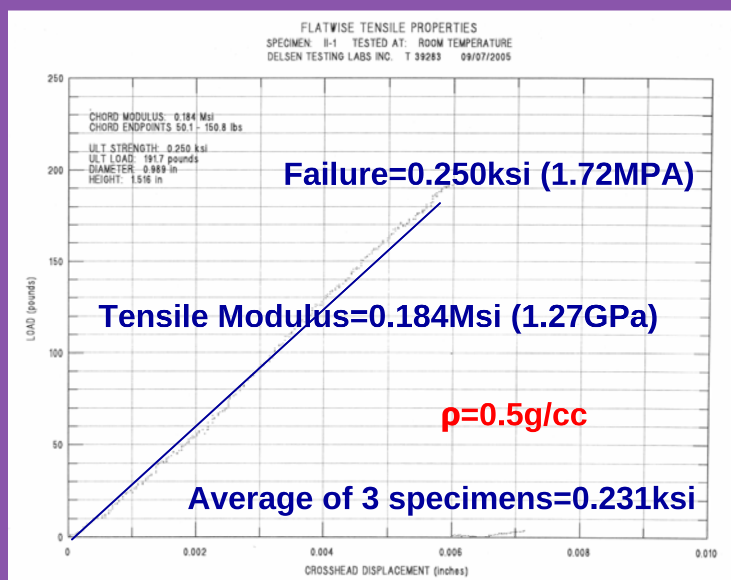
Allcomp Processed POCO Foam

Objective to increase tensile strength of POCO for NASA project



Densified POCO



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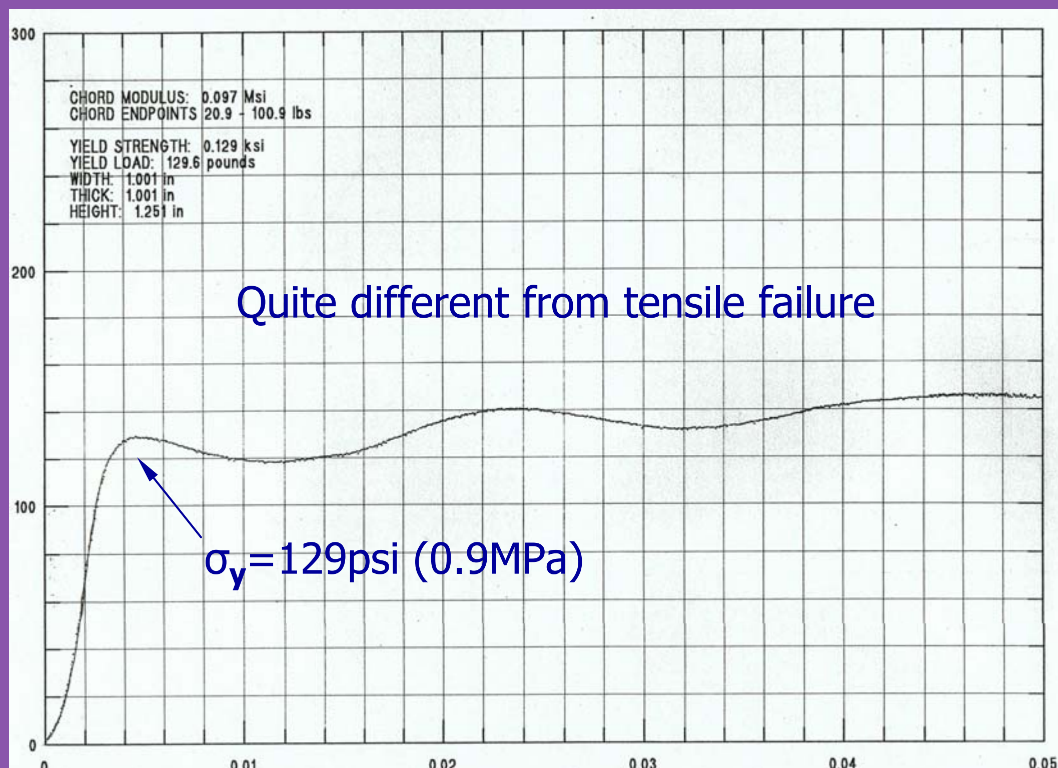
POCO Foam Compressibility-Non Linear

- **Exhibits plastic behavior out to strain of 0.05**
  - Understanding plasticity of foams in any of its structural properties is key to interpreting results of FEA



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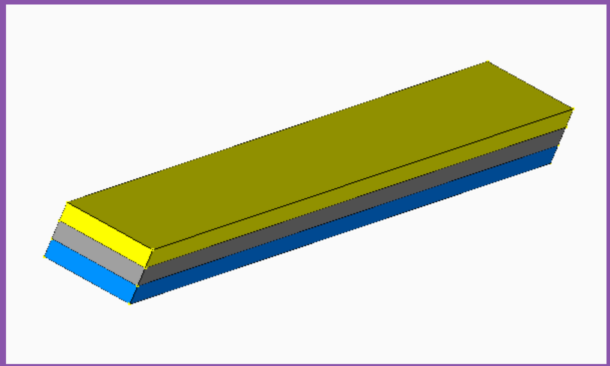
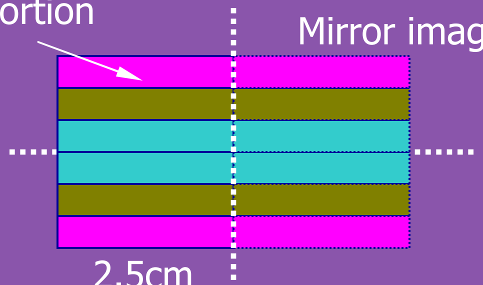
Interfacial Foam Stress Analysis

- **Preliminary stress analysis**
  – Estimate stress from dissimilar CTE effects
    - Room temp to -35C
    - Shear stress and Von Mises stress in foam
      – Foam transfers shear from composite facing to tube
        - Composite expands and tube contracts during cool-down, foam contracts also
  – Question arises as how the stress solution varies with model length
    - Does the shear stress become a problem in long bonded sections?
      – POCO, if used, can result in bonded lengths of ~0.3048m (12in)
  – How does the foam material properties affect the solution
    - Linear stress-strain versus non-linear

Simple Plate Model/ Linear Foam Properties

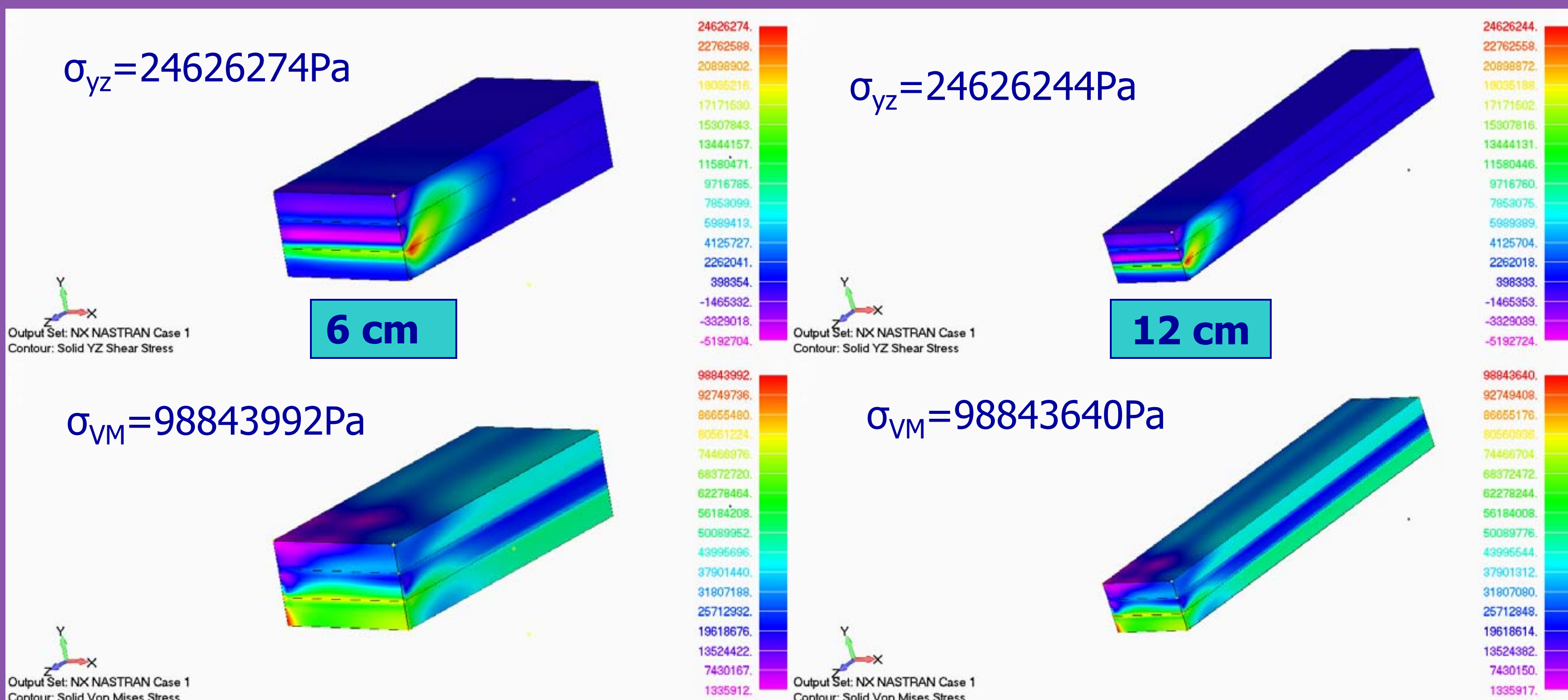
- **Three layer plate**
  - Each plate 5mm thick
  - Bottom plate is Al, mid plate POCO foam, top plate steel
  - Symmetry boundary conditions in X, Y and Z
    - Model length (Z) varies from .06m to 0.48m
    - Width constant (X) .025cm
    - Stack simulates 10mm thick middle plate with two outer steel plates
- **For both plates being Al, the Von Mises stress does not change with increased model length**
  - Very compliant 5mm foam middle





CTE Effects as Function of Length

- **3 Materials (see previous model)-Al, Be, Steel**
  - Two lengths 6cm and 12cm, 60ºC ΔT
  - *<u>Same shear stress and same Von Mises stress</u>*



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Simple Plate Solution with Foam in Middle

- **Foam Model- Non Linear (100psi stress limit)**
  - *POCO Foam E=0.5GPa, G=0.192GPa, plastic at 0.7MPa (100psi)*
- **Use 6cm and 12 cm model as previously discussed (Al to steel with 5mm of POCO foam)**

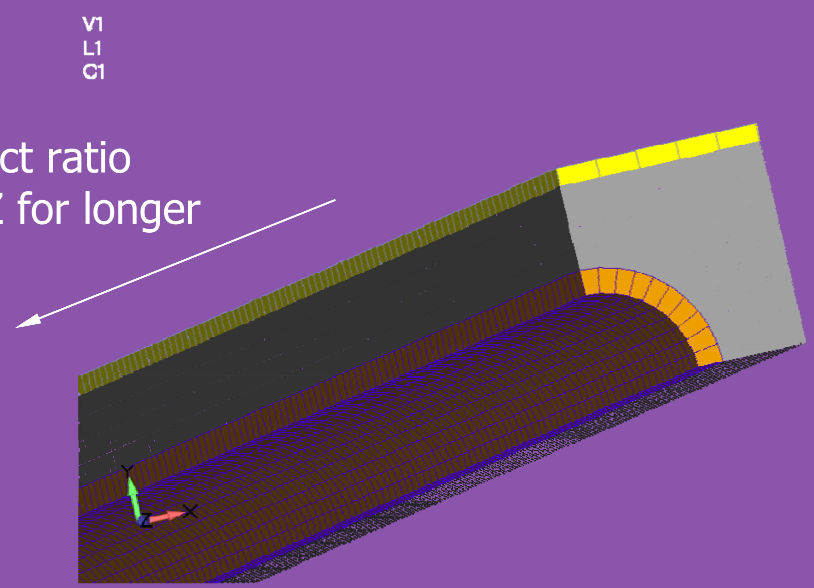
Model Length	Von Mises (MPa	Shear stress (MPa)
0.06m	614799	303817
0.12m	641344	291322
	4.3%	4.1%

Mesh density is same in both models, thus model length should not be an issue in assessing foam stress except in cases with significant changes in mesh density or aspect ratio

Foam/Tube Thermal Stress

- **NASTRAN Model**
  - 2.8mm OD Al tube, encased with POCO foam
  - K13D2U composite facing
  - 1/8th symmetry used to control model size
  - Solutions covered both linear and non-linear foam properties
  - Thermal induced strain from 60C temperature change
  - Two model lengths used to assess dependence of foam shear stress on length

Element aspect ratio increases in Z for longer model



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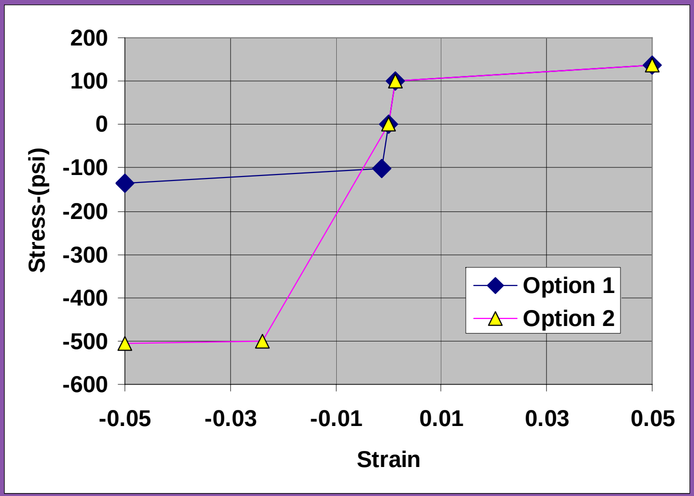
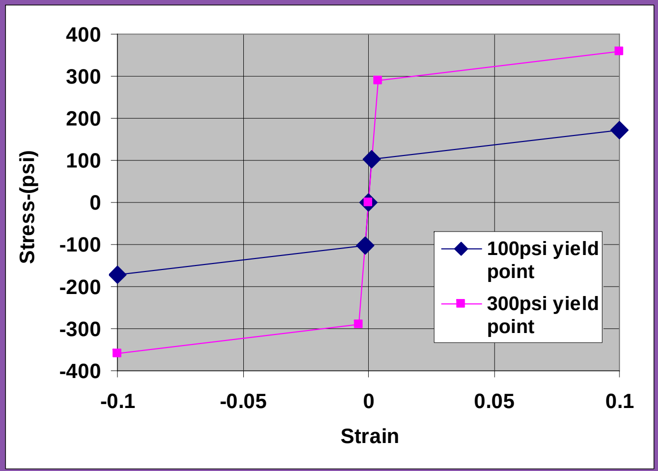
POCO Foam Properties

- **Data somewhat sparse and incomplete**
  - In some cases E measured but not G or vice versa
    - Tensile and compressive from same batch not generally available
  - E (tensile and compression) and G as function of density is what is needed

There is evidence that compressive strain behavior widely different from tensile



Implies high compressive strength



For now used this

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Stave Tube/Non-Linear Foam Model

Test for model length with non-linear foam material-no adhesives

Model	Peak Foam Stress				Foam CTE	Comments
Length/element	Shear (σ_{yz} Pa)	Normal (σ_z Pa)	Element strain	Von Mises (Pa)	ppm/C	
4cm/25440	354,596	255,143	0.0379	775,641	4	8 node brick
60cm/72092	463,521	197,114	0.030	831,961	4	8 node brick
4cm/25440	325,297	214,415	0.0221	699,655	4	21 node brick
4cm/25440	362,070	253,698	0.038	780,440	2	8 node brick

Factor of 15 change in length for 31% change in shear stress and 7.3% in Von Mises stress is <u>due to mesh density change between models</u>

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Stave Tube/Non-Linear Foam Model (2 mil Thick Adhesives)

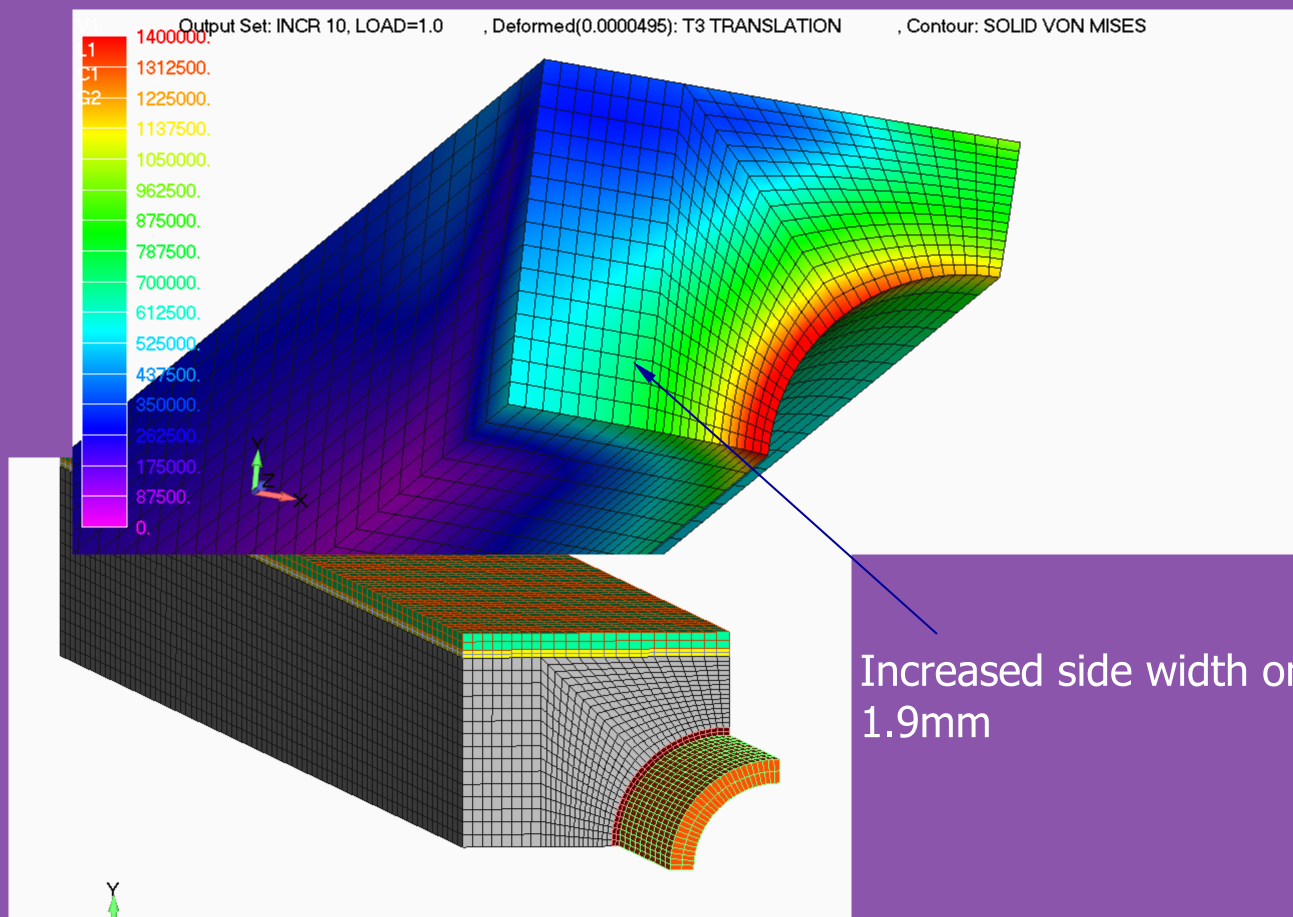
Semi-rigid → (Aluminum Tube/EG7658 Adhesive/Foam E=0.5GPa σy=0.7MPa)

Compliant → (Aluminum Tube/SE4445 Adhesive/Foam E=0.5GPa σy=0.7MPa)

Model	Peak Stresses				Foam CTE	Comments
Length/element	Shear (σ_{yz} MPa)	Normal (σ_z MPa)	Element strain	Von Mises (MPa)	ppm/C	
Aluminum Tube/EG7658 Adhesive/Foam E=0.5GPa σy=0.7MPa						
4cm/37929 POCO Foam	0.421	0.208	0.032	0.801	4	8 node brick
4cm/38740 Tube EG7658 Adhesive	0.736	1.882 (273psi)	n/a	3.410 (495psi)	4	8 node brick (2mil thick)
4cm/41061 Facing Adhesive	1.929 (280psi)	1.440 (209psi)	n/a	15.336 (2225psi)	4	8 node brick (2 mils thick)
Aluminum Tube/SE4445 Adhesive/Foam E=0.5GPa σy=0.7MPa						
4cm/37929 POCO Foam	0.392	0.168	0.0027	0.713	4	8 node brick
4cm/38740 Tube SE4445 Adhesive	0.664	0.093	n/a	1.164	4	8 node brick (2mil thick)
4cm/41061 Facing Adhesive SE4445	1.68	15.08	n/a	15.66	4	8 node brick (2 mils thick)

Stave Tube/Non-Linear Foam Model (4 mil Thick Adhesives)

- **Revised Model**
  - Increased bond line thickness to 4mils and extended tube



Increased side width on POCO to 1.9mm

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Stave Tube/Non-Linear Foam Model (4 mil Thick Adhesives)

Higher strength POCO Foam but same stiffness

Aluminum Tube/Adhesive (4mils)/ E=0.5GPa, σy=1.75MPa New Model (POCO Foam minimum side thickness 1.9mm)						
Model Length 4cm	MPa Shear (σ_{yz})	MPa Normal (σ_z)	strain	MPa Von Mises (σ_{vm})	Foam CTE	Elements
POCO Foam increased width	0.257	0.61	0.0019/0.003	0.916/1.36 (197psi)	4	8 node brick
Tube Adhesive SE4445	0.34	0.0031	n/a	0.593 (86psi)	4	8 node brick (4 mils thick) 2layers
Facing Adhesive SE4445	0.191	0.5	n/a	0.331 (48psi)	4	8 node brick (4 mils thick) 2layers

4mil bond line reduces adhesive shear stress as expected, even for higher yield stress in foam

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Stave Tube/Non-Linear Foam Model (4 mil Thick Adhesives)

- EG7658 Semi-rigid adhesive (compared to rigid epoxy)

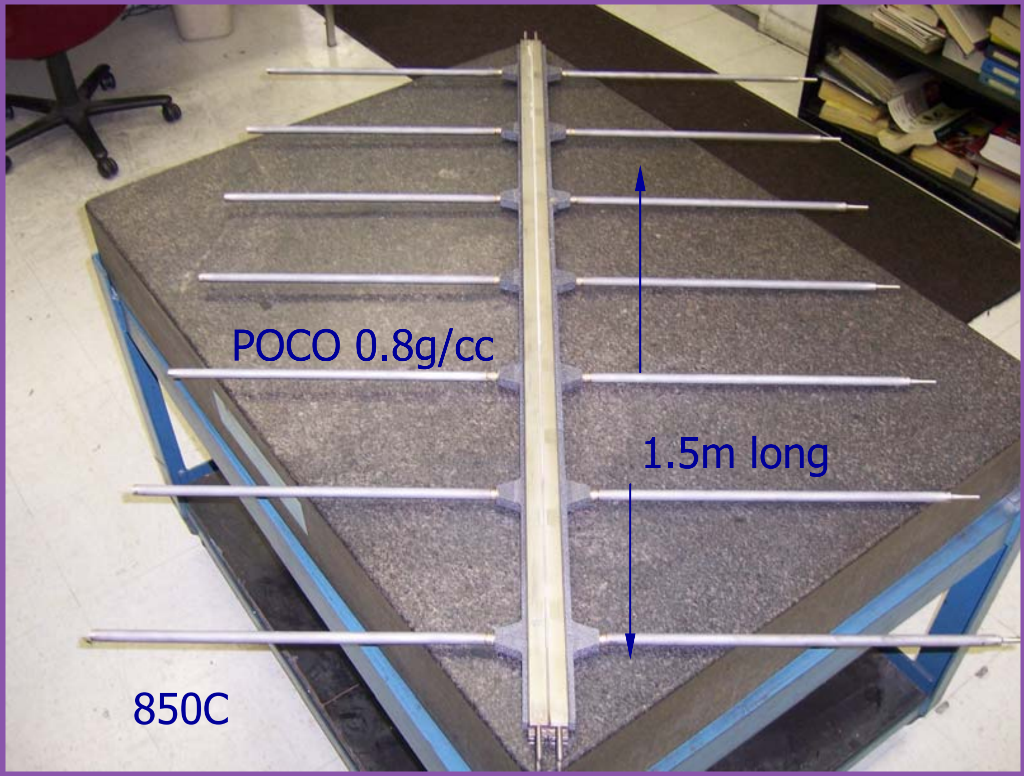
Aluminum Tube/Adhesive (4mils)/ E=0.5GPa, σy=1.75MPa New Model (POCO Foam minimum side thickness 1.9mm)						
Model Length 4cm	MPa Shear (σ_{yz})	MPa Normal (σ_z)	strain	MPa Von Mises (σ_{vm})	Foam CTE	Elements
POCO Foam increased width	0.372	0.303	0.0017/ 0.0034	0.855/1.59 (231psi)	4	8 node brick
Tube Adhesive SE4445	0.453	0.022	n/a	0.794 (115psi)	4	8 node brick (4 mils thick) 2layers
Facing Adhesive EG7658	0.284	2.44	n/a	2.44 (354psi)	4	8 node brick (4 mils thick) 2layers

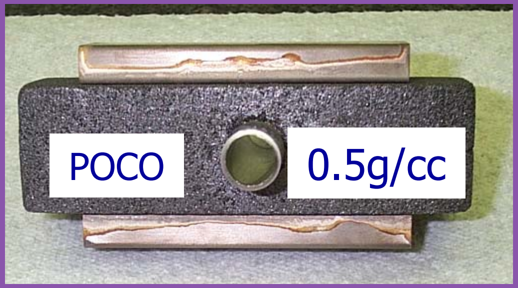
Adhesive/Foam Stress Analysis

- **Too numerous solutions to present**
  - No doubt more to come as material data becomes available
- **What can be said thus far**
  - High shear stresses in foam are at very end, diminishing toward center, becoming virtually zero
  - Non-linearity in foam (compression) is likely to reduce this stress at end of the stave
  - Addition of adhesive is treated as elastic media, does not account for the presence of foam ligaments in the adhesive material, thus:
    - Adhesive stress in very thin bond lines look like an area of concern, but may not be
    - Increasing adhesive bond line to 4mils from 2mils, reduces the adhesive stress to be within acceptable bounds, even without strengthening effect of foam ligaments
  - POCO foam/tube interfacial stresses have survived very high thermal induced strains from brazing without failure---as illustrated next

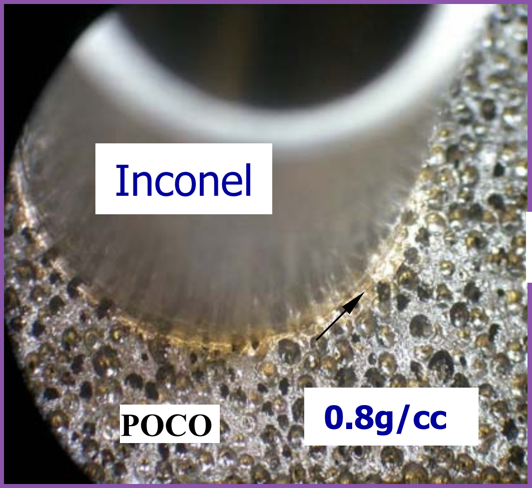
Joining POCO by Brazing-Thermal Stresses

- **Brazing titanium and Inconel to POCO at 850C and 1200C respectively. Foam accommodated large thermally induced strain**





850C



1250C

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Examples of POCO sustaining high cool-down stresses

Allcomp Carbon Foam Thermal Conductivity

- **Allcomp 2 K is ~8.2W/mK compared to 5.8W/mK for Allcomp 1**
  - Why is an area to be explored
- **Newly processed Allcomp foam in general is better, however there remains effects of processing that are not quite understood**

Recent Data

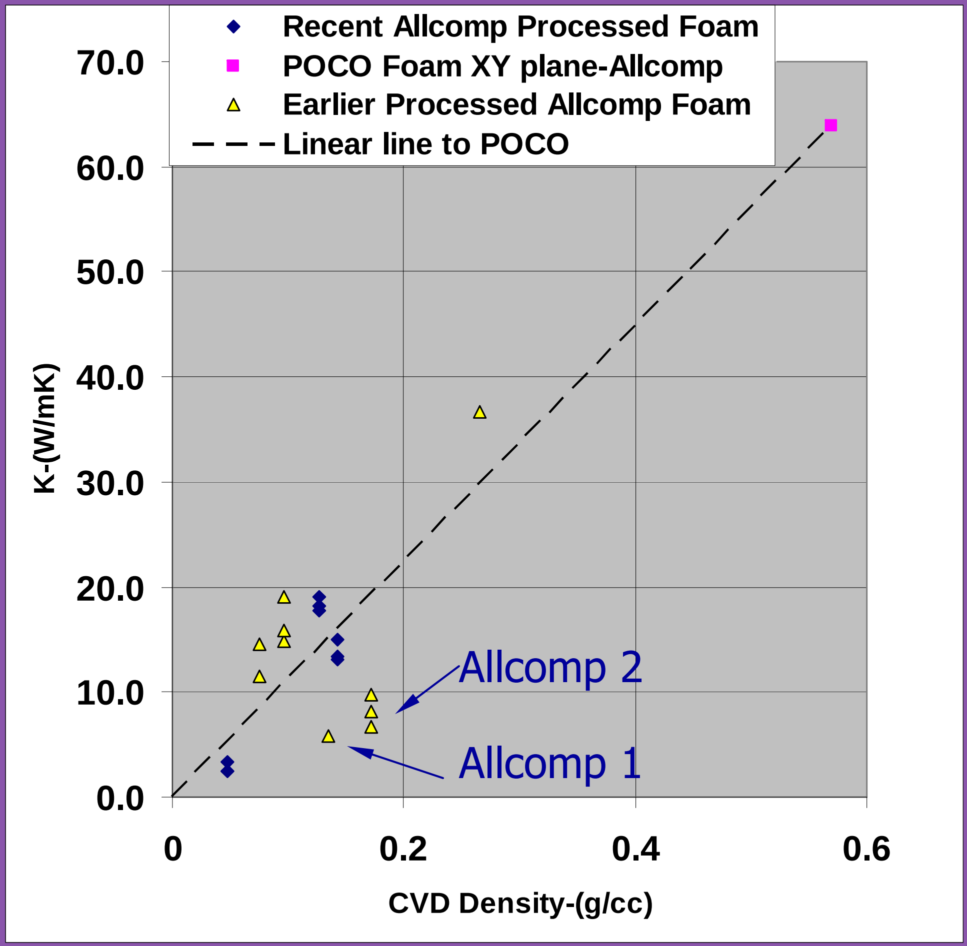
Foam	ID	Actual g/cc	K W/m.K	CVD material g/cc
100 ppi	k3	0.093	2.5	0.048
100 ppi	K3	0.093	3.3	0.048
100 ppi	k3	0.093	2.5	0.048
100 ppi	k4	0.188	13.0	0.143
100 ppi	k4	0.188	15.0	0.143
100 ppi	k4	0.188	13.4	0.143
100 ppi	k5	0.172	18.2	0.127
100 ppi	k5	0.172	19.0	0.127
100 ppi	k5	0.172	17.7	0.127

Earlier Data

	ID	Actual g/cc	K W/m.K		CVD Material g/cc
Poco	A	0.57	63.9		0.57
100 ppi	C	0.12	11.5		0.075
100 ppi	C	0.12	14.6		0.075
100 ppi	E	0.141	14.9		0.096
100 ppi	E	0.141	15.9		0.096
100 ppi	E	0.141	19.1		0.096
100 ppi	G	0.18	5.8	Allcomp 1	0.135
100 ppi	I	0.31	36.7		0.265
100 ppi	J	0.217	8.2	Allcomp 2	0.172
100 ppi	J	0.217	9.7	Allcomp 2	0.172
100 ppi	J	0.217	6.7	Allcomp 2	0.172

Foam K versus Amount of CVD

RVC Skelton=.045g/cc



W.O. Miller

Thermal K Test Summary

- **Allcomp 1 and 2**
  - Material used in LBNL thermal test
  - Allcomp 1: K was very low and inconsistent with all data
    - Do not have an explanation, but do have some unsubstantiated thoughts
  - Allcomp 2: Measurements of K by thermal diffusivity tends to agree with LBNL data
    - Still the processing did not reach expectations
  - More recent Allcomp foam processing is encouraging
    - If plotted on basis of CVD material converted to graphite the K comes in line with tests performed on POCO material by Allcomp
      - Comparison restricted to X-Y plane to be consistent