

# Thermal Expansion of Polyurethane Foam

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Closed cell foams are often used for thermal insulation. In the case of the Space Shuttle, the External Tank uses several thermal protection systems to maintain the temperature of the cryogenic fuels. A few of these systems are polyurethane, closed cell foams. In an attempt to better understand the foam behavior on the tank, we are in the process of developing and improving thermal-mechanical models for the foams. These models will start at the microstructural level and progress to the overall structural behavior of the foams on the tank.

One of the key properties for model characterization and verification is thermal expansion. Since the foam is not a material, but a structure, the modeling of the expansion is complex. It is also exacerbated by the anisotropy of the material. During the spraying and foaming process, the cells become elongated in the rise direction and this imparts different properties in the rise direction than in the transverse directions. Our approach is to treat the foam as a two part structure consisting of the polymeric cell structure and the gas inside the cells. The polymeric skeleton has a thermal expansion of its own which is derived from the basic polymer chemistry. However, a major contributor to the thermal expansion is the volume change associated with the gas inside of the closed cells. As this gas expands it exerts pressure on the cell walls and changes the shape and size of the cells. The amount that this occurs depends on the elastic and viscoplastic properties of the polymer skeleton. The more compliant the polymeric skeleton, the more influence the gas pressure has on the expansion. An additional influence on the expansion process is that the polymeric skeleton begins to breakdown at elevated temperatures and releases additional gas species into the cell interiors, adding to the gas pressure. The fact that this is such a complex process makes thermal expansion ideal for testing the models.

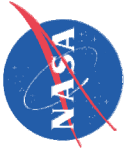
This report focuses on the thermal expansion tests and the response of the microstructure. A novel optical method is described which is appropriate for measuring thermal expansion at high temperatures without influencing the thermal expansion measurement. Detailed microstructural investigations will also be described which show cell expansion as a function of temperature. Finally, a phenomenological model on thermal expansion will be described.

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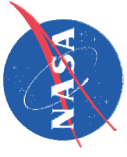


# Thermal Expansion of Polyurethane Foam

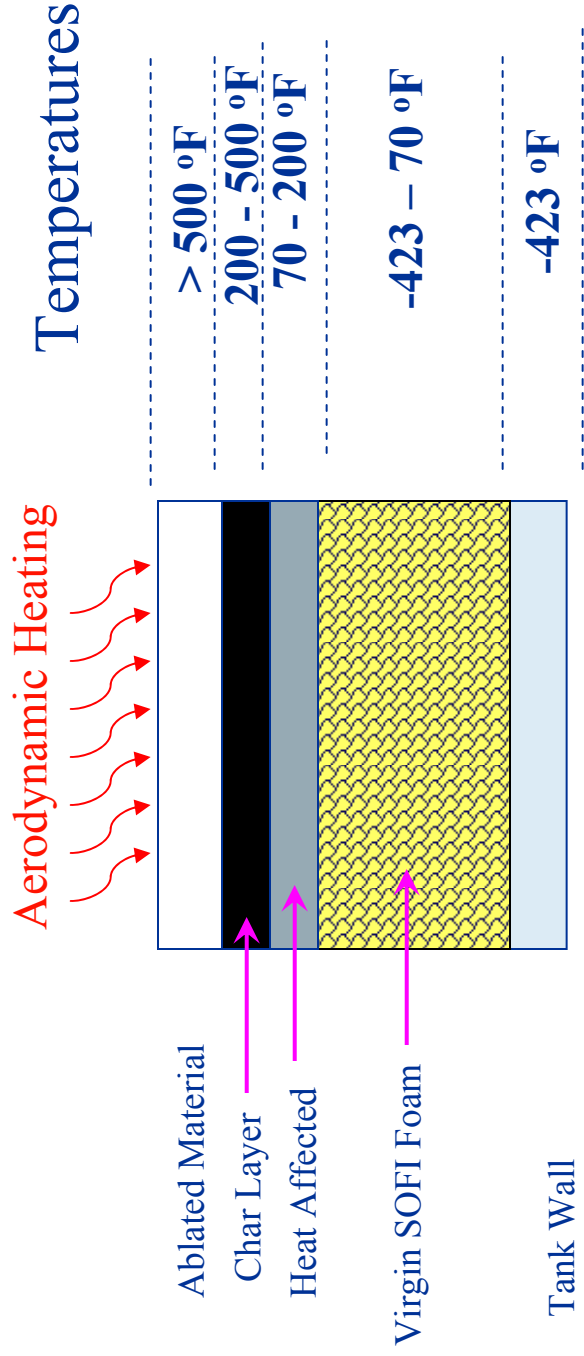
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*NASA Glenn Research Center*

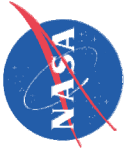
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The Pennsylvania State University  
University Park, PA

August 14, 2006



# Expected Foam Temperature Profile





## Importance of CTE

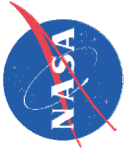
- Al-substrate has a CTE of  $2 \times 10^{-5}/^{\circ}\text{C}$
- Polymer foams have an approximate CTE of  $1 \times 10^{-4}/^{\circ}\text{C}$
- Thermal strain ( $\varepsilon$ ) equals:

$$\varepsilon = \Delta\alpha\Delta\mathbf{T} = 0.045$$

where  $\Delta\mathbf{T} = 580\text{ }^{\circ}\text{C}$

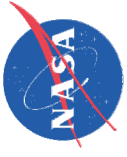
  $\sigma_{\text{foam}} \sim \text{UTS}_{\text{foam}}$

- **Thermal strains are significant and can cause cracking**



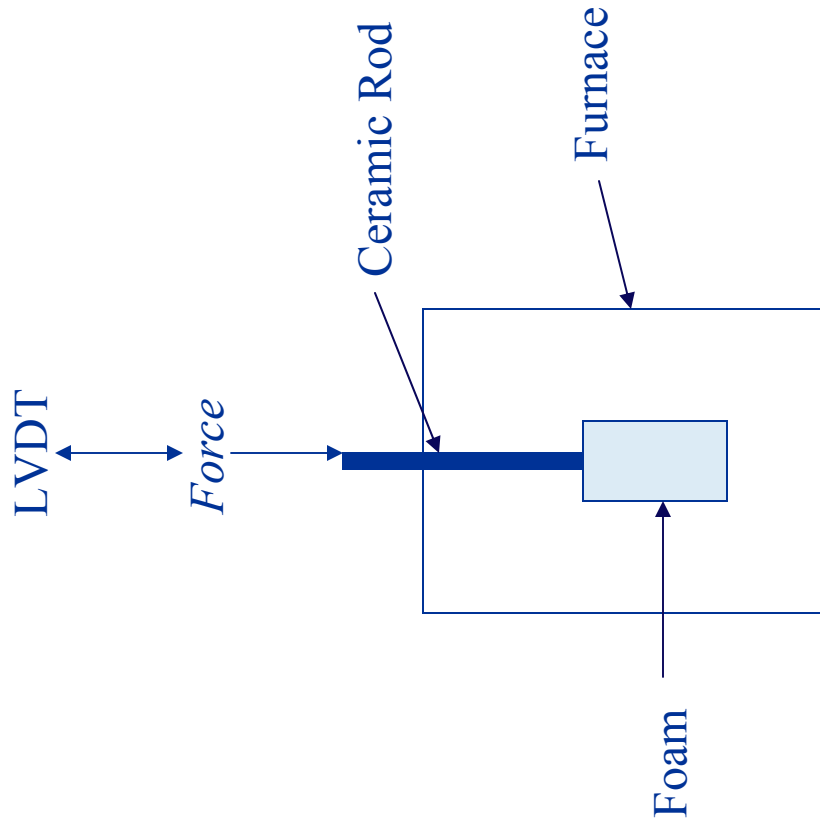
## Goal

The purpose of this study is to investigate the mechanisms of foam thermal expansion to guide model development

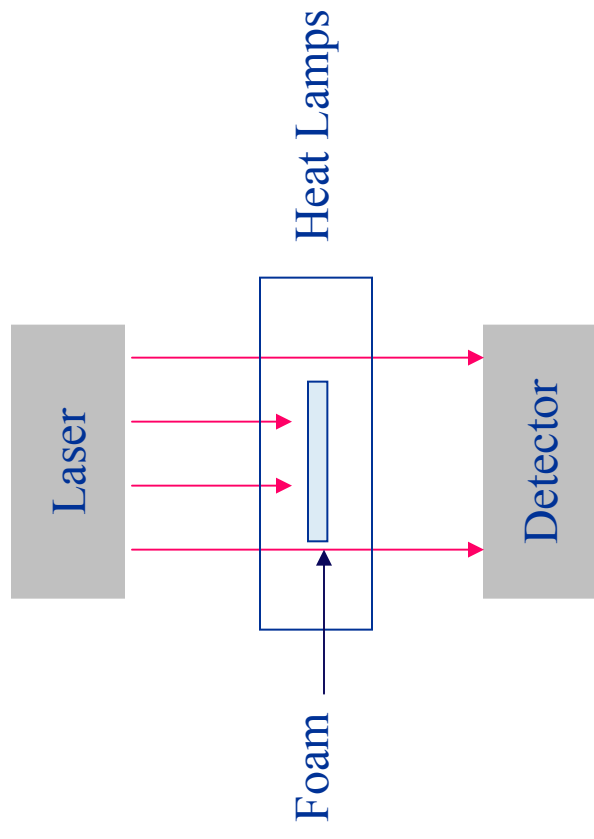


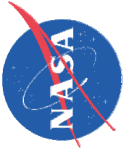
# Measurement of Thermal Expansion

## Conventional CTE Rig

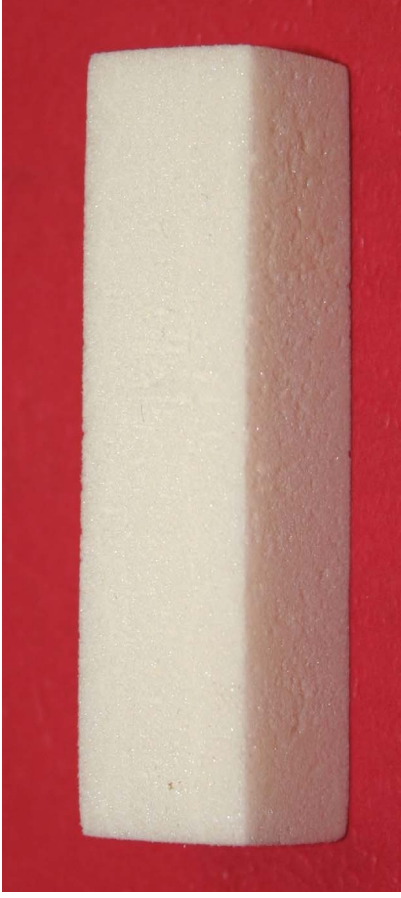


## Non-Contacting CTE Rig





## Distortion of Foam Due to Temperature Changes



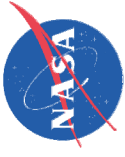
As-cut



Heated to  
170 C



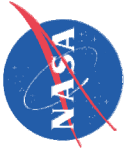
Heated to  
300 C



## Problems Associated With Thermal Measurements

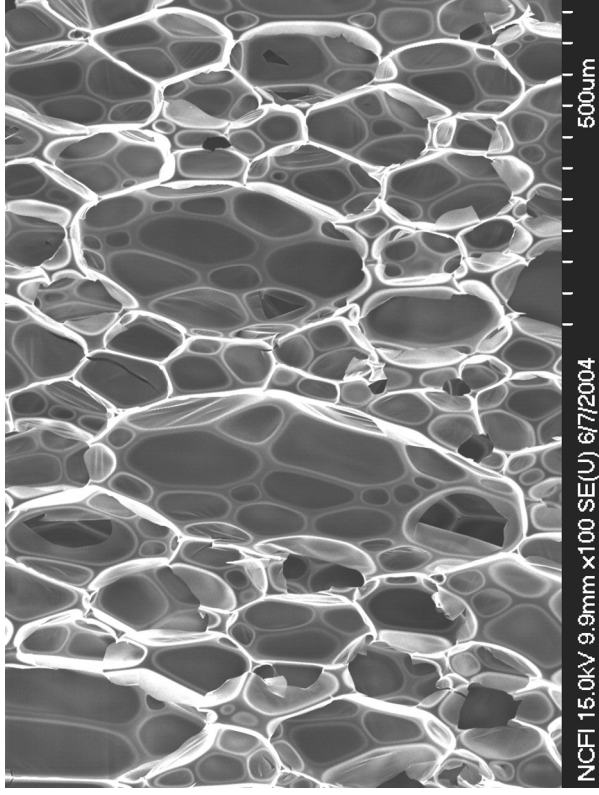
- Temperature measurements and thermal gradients
  - Foam is a thermal insulator
- Anisotropy of foam microstructure
  - Elongated cellular structure
  - Knit Lines
  - Large cells and voids
- Twisting, warping, and distortion of foam samples





## Foam Microstructure

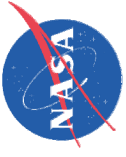
- 97% air; density = 0.03 g/cc
- Polymeric cell walls
- Due to its microstructure, material is anisotropic (possess different material properties in different directions)



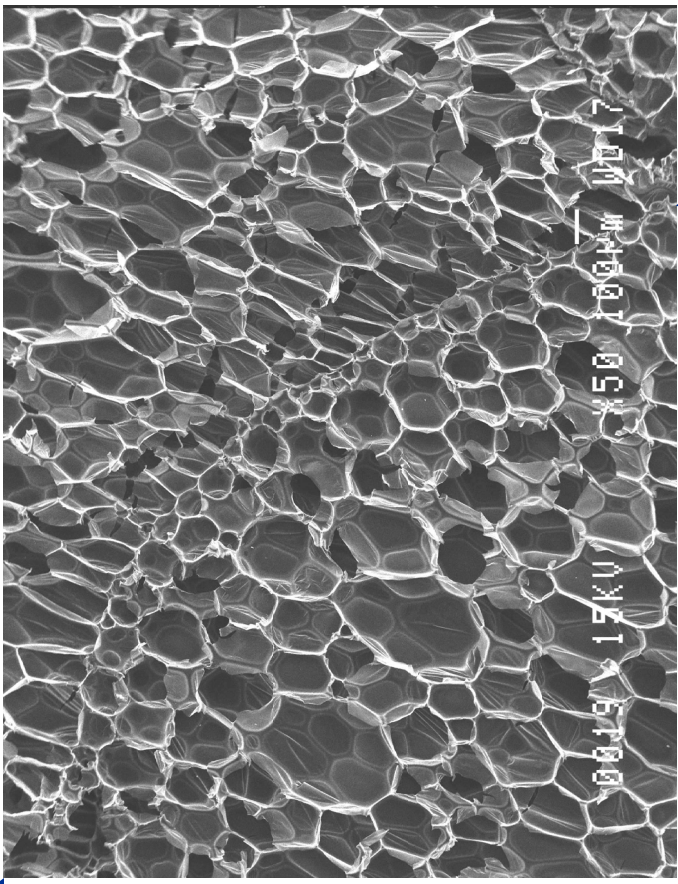
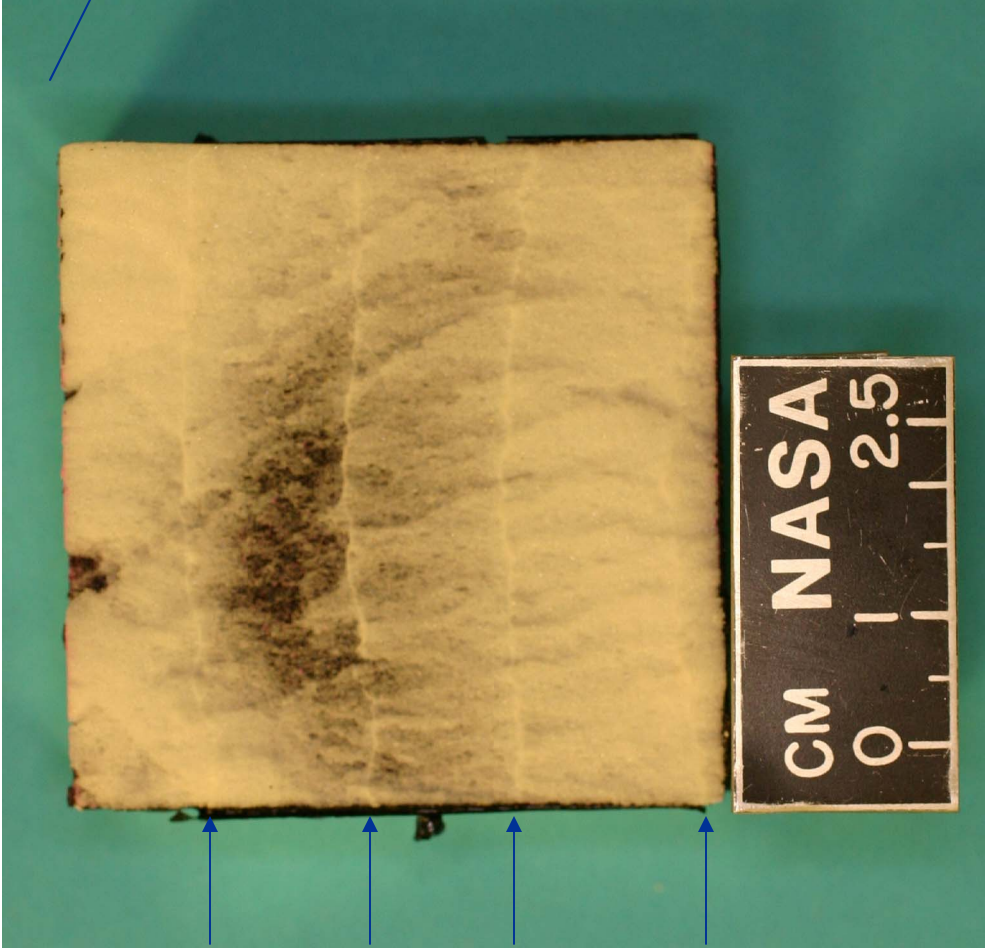
Parallel-to-rise  
direction

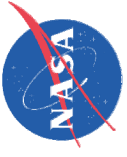


Perpendicular-to-rise  
direction

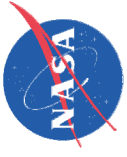


# Knitlines

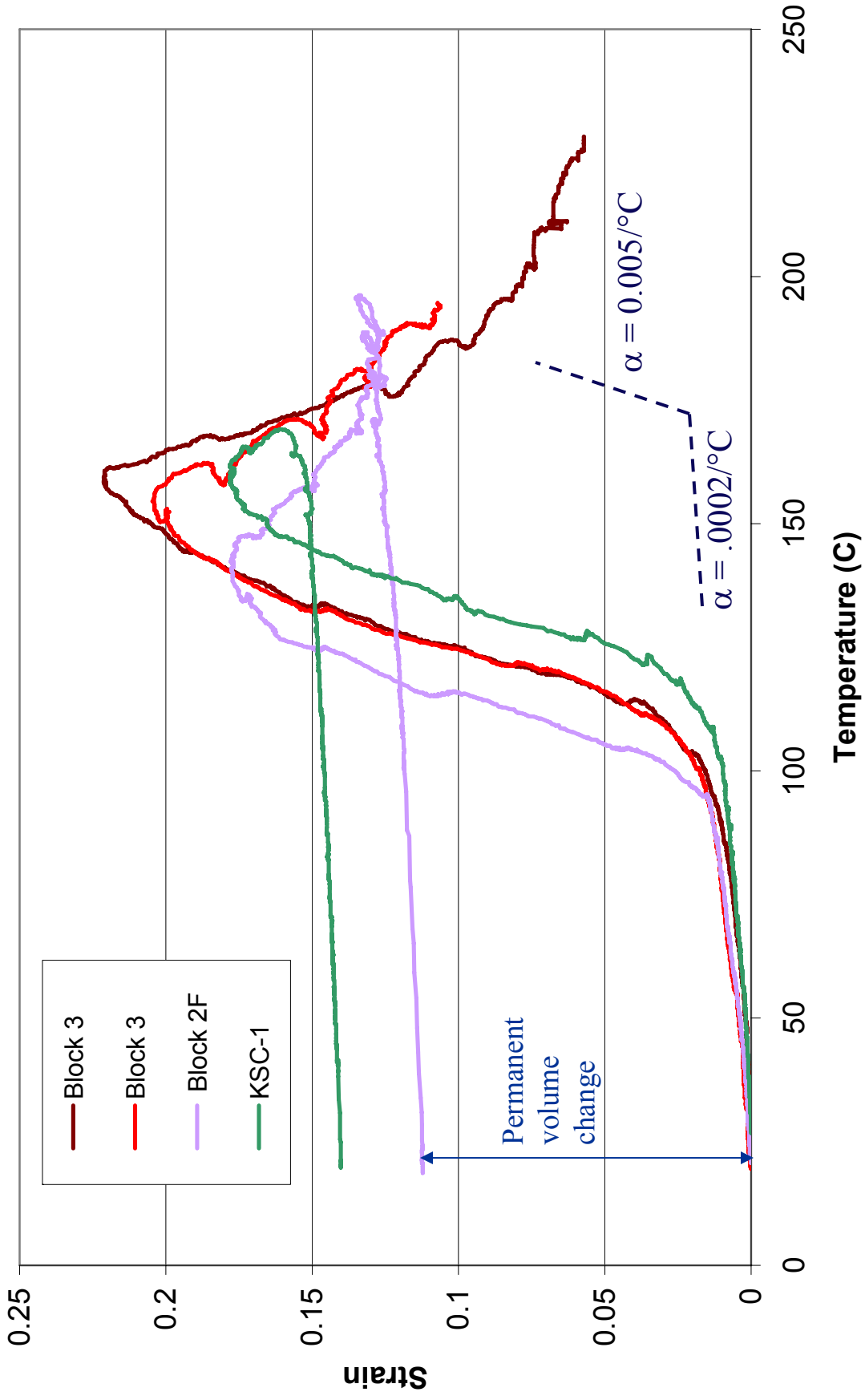


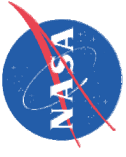


# Results

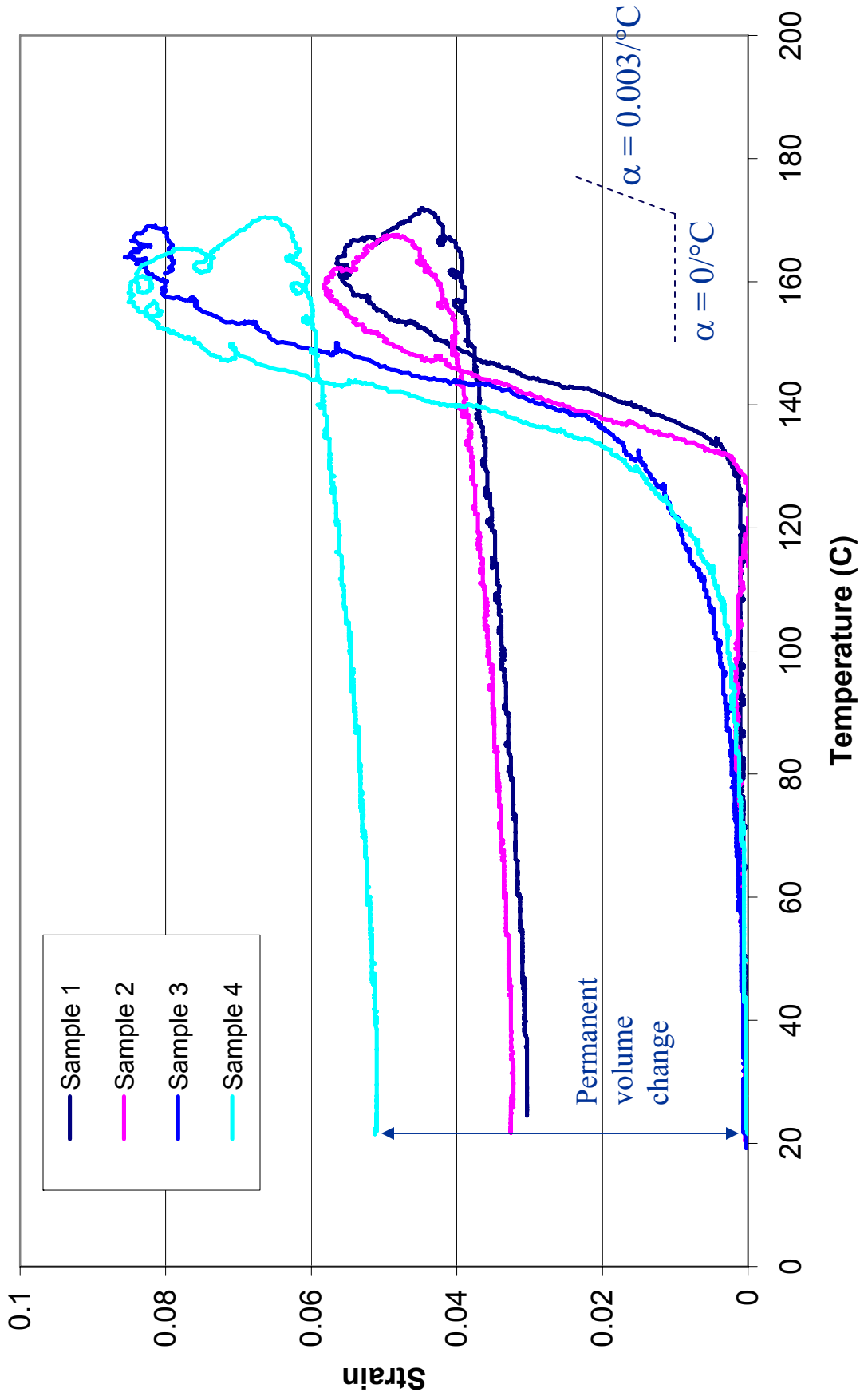


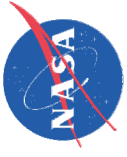
# Thermal Expansion Perpendicular to Rise Direction



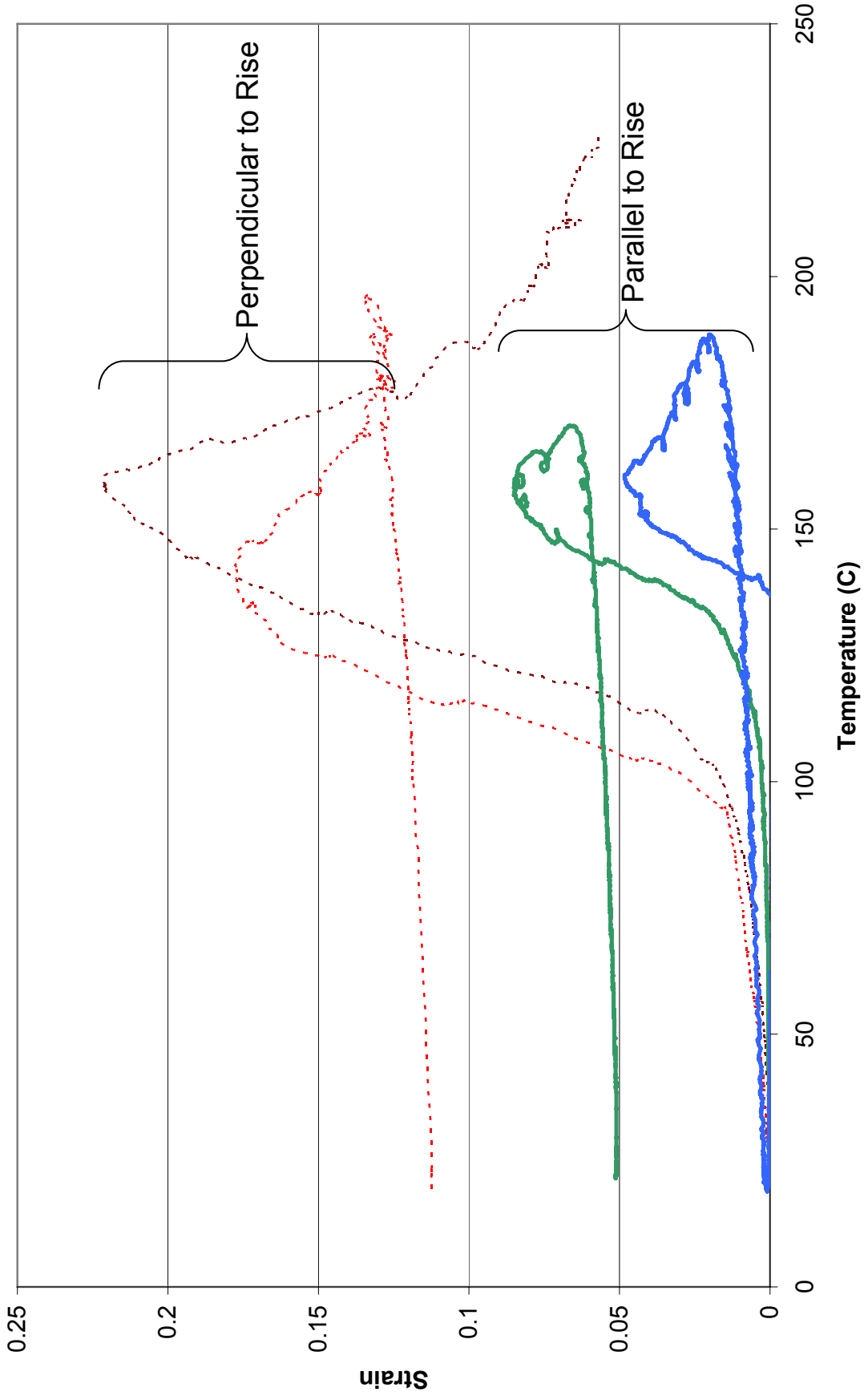


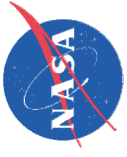
# Thermal Expansion Parallel to Rise Direction





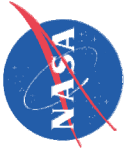
# Thermal Expansion in Both Directions





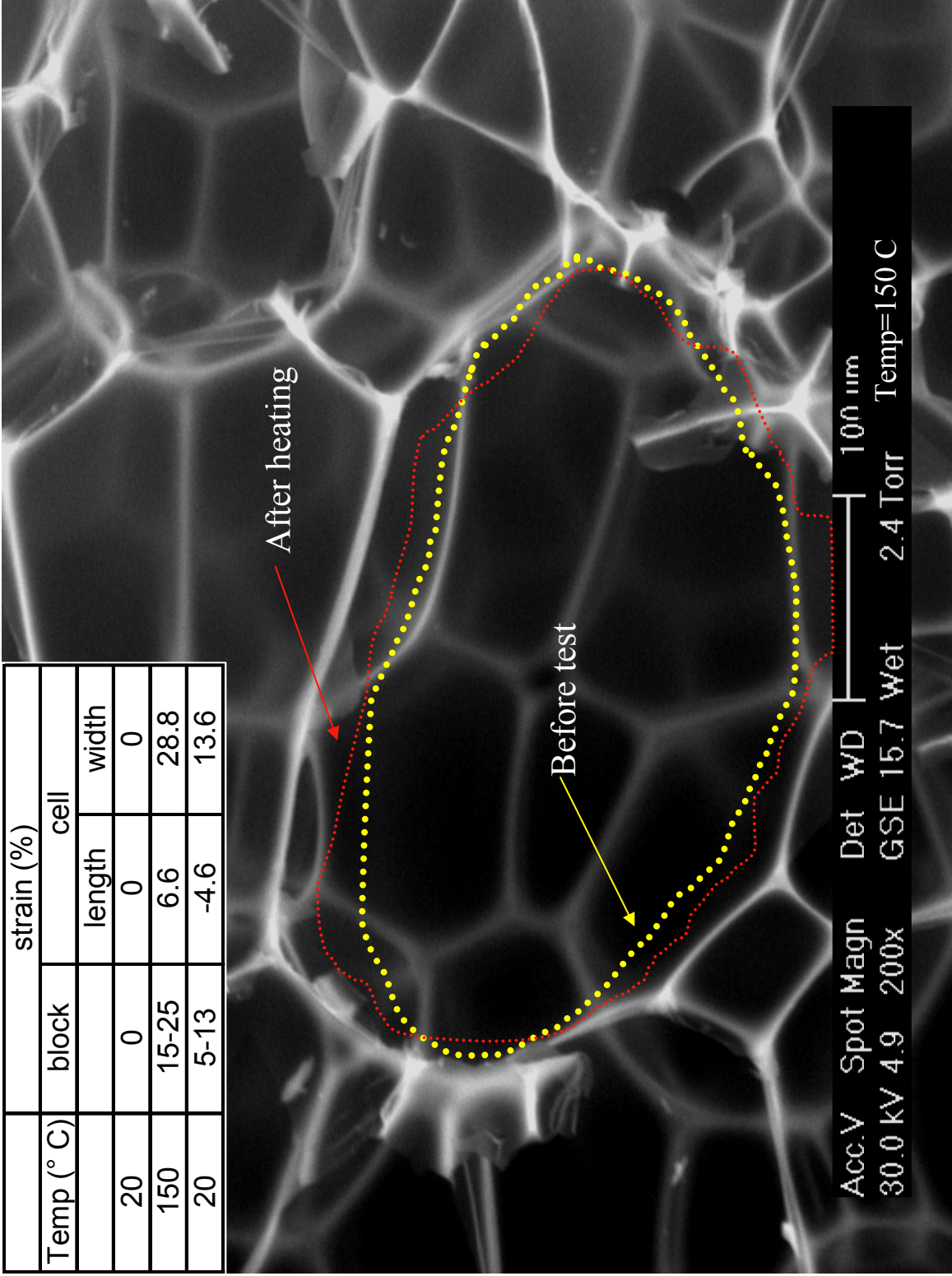
## Mechanism of Foam Expansion

- Hot stage experiments conducted on foam samples
- Individual foam cells examined in SEM during heating and cooling
- Expansion and contraction of cells observed as a function of temperature
- Both whole cells and faces were examined



# Hot Stage Experiments

Temp (°C)	block	strain (%)	
		length	width
20	0	0	0
150	15-25	6.6	28.8
20	5-13	-4.6	13.6

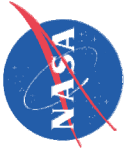


Cell expansion due to thermal exposure

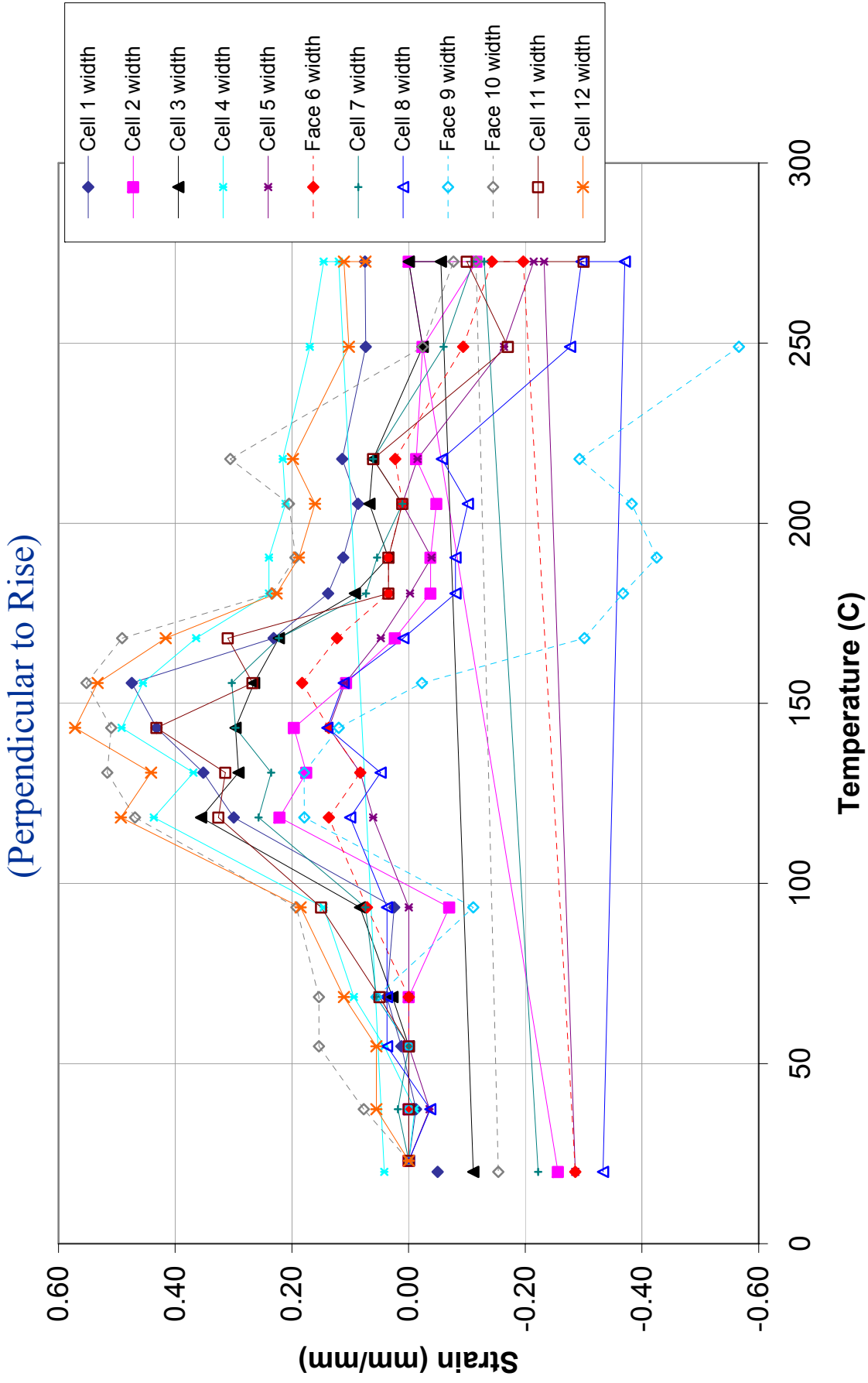
Cell expands mostly in the width direction (perpendicular to rise)

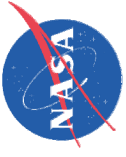




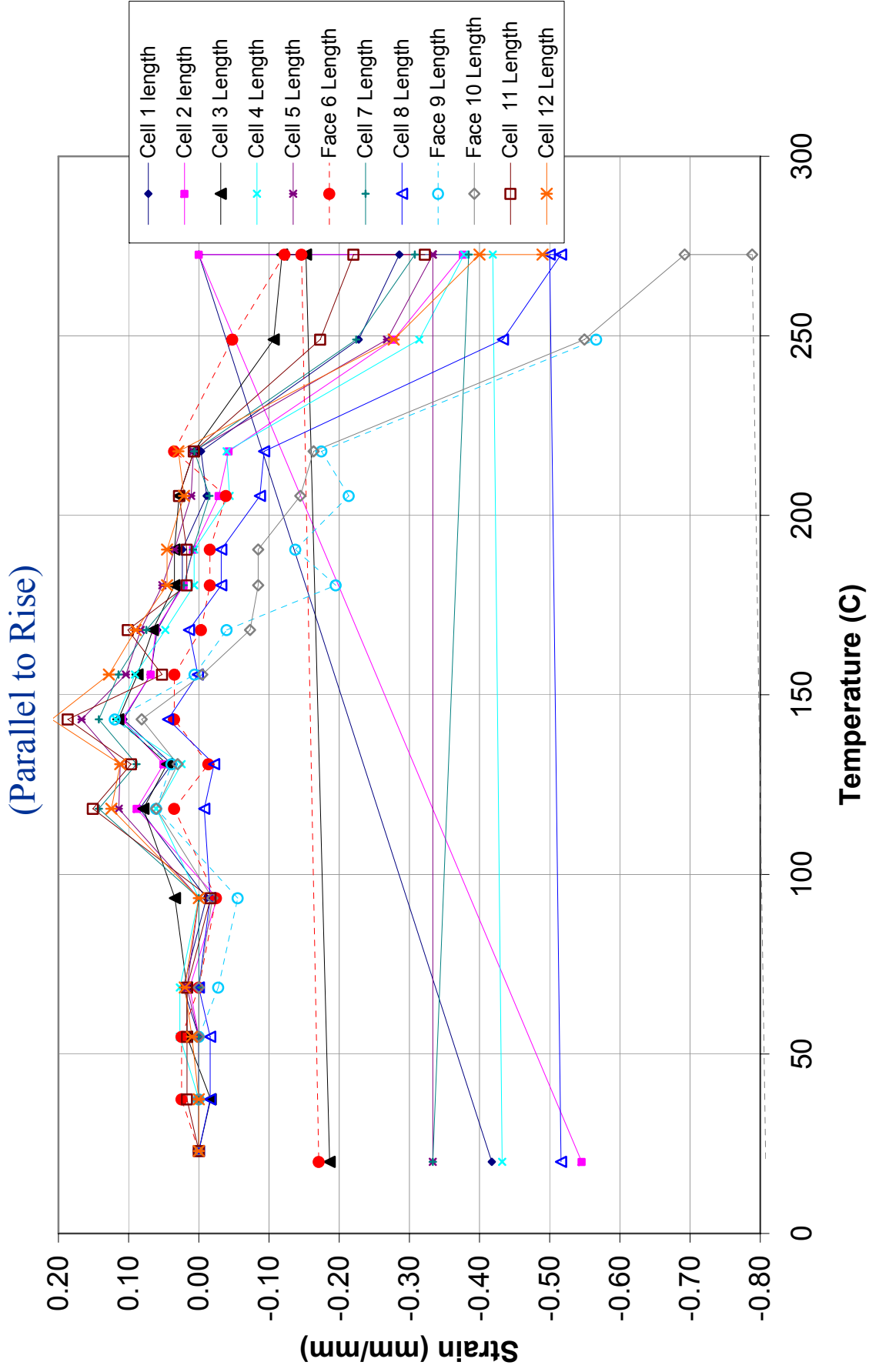


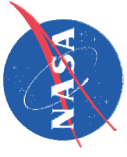
# Cell Width Thermal Expansion



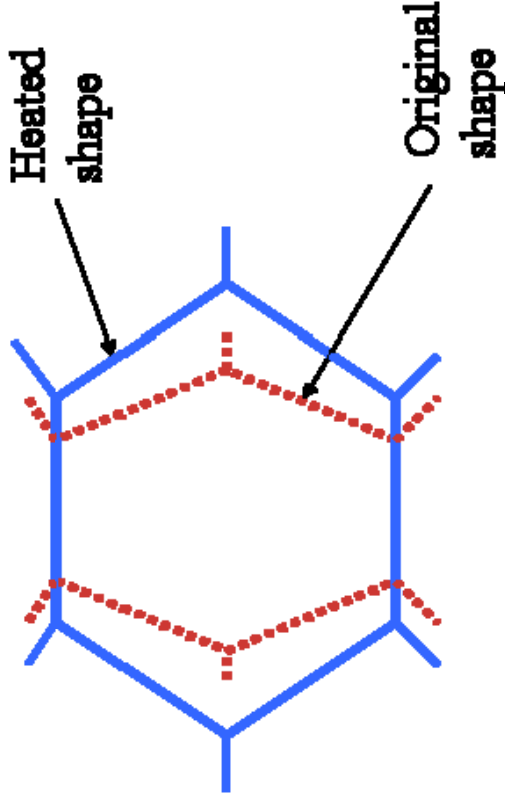
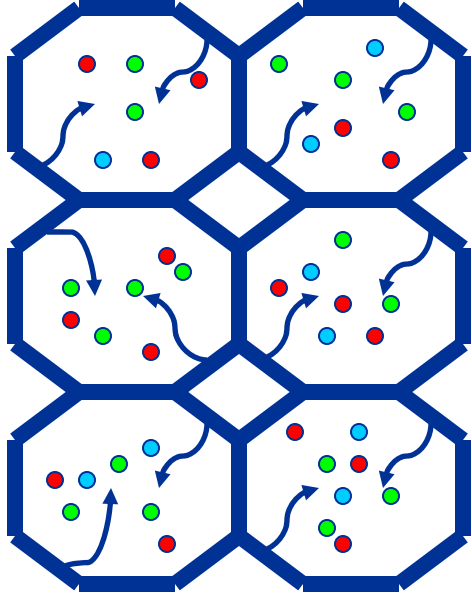


# Cell Length Thermal Expansion

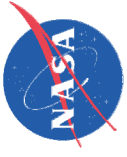




## Basis for Model Development

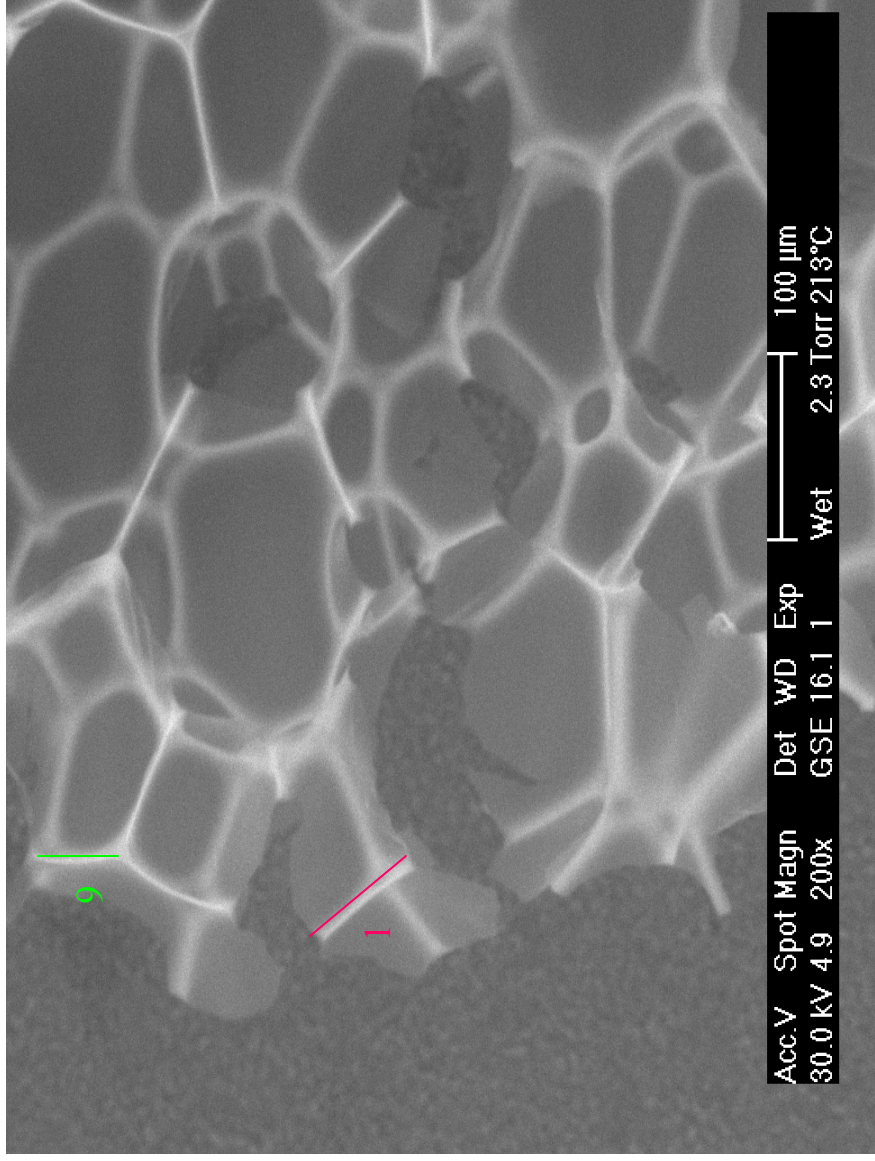


- Elongated cell structure
- Pore pressure increases with temperature
- Polymer softens with temperature

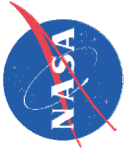


# Thermal Behavior of Polymer Skeleton

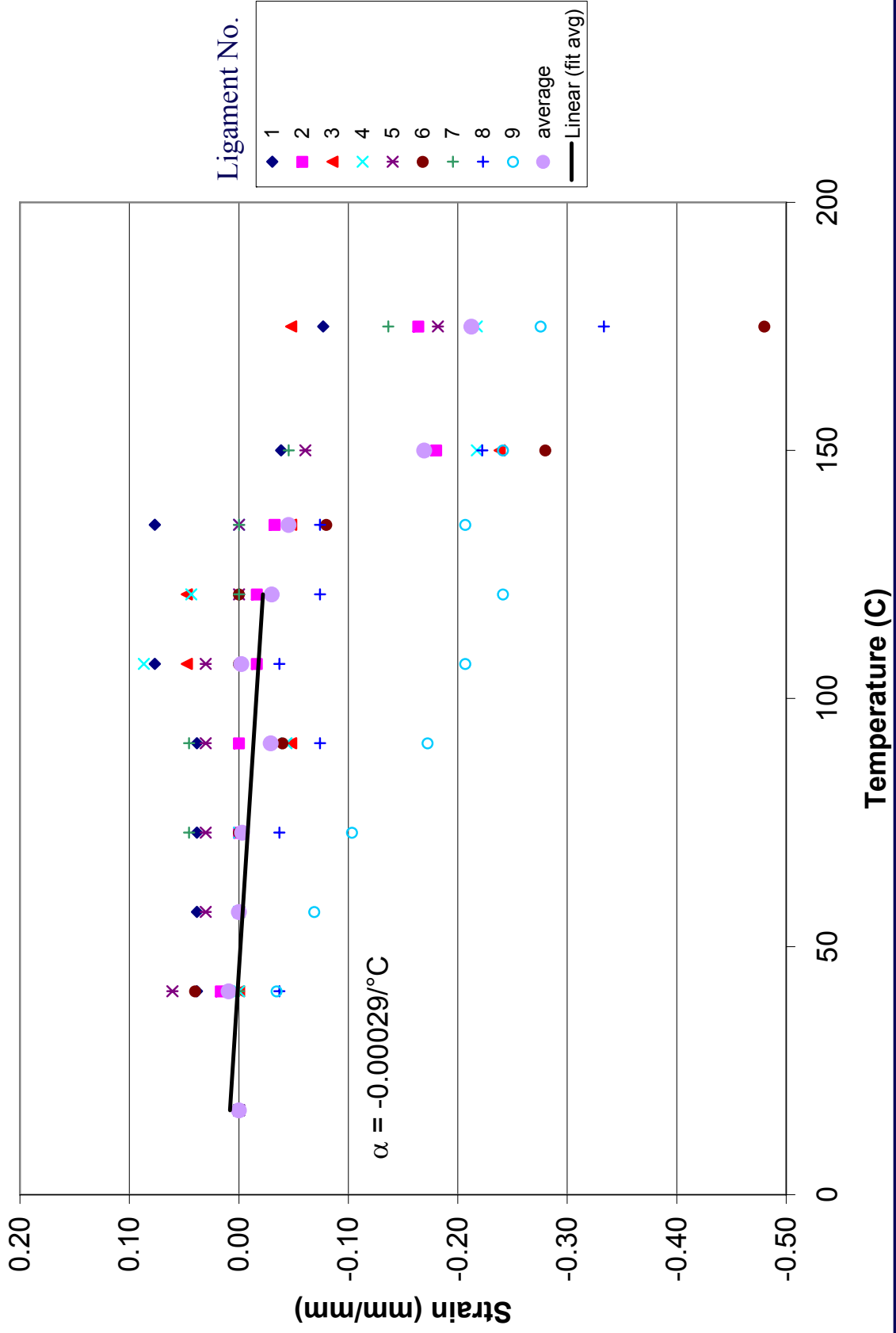
Temp. (°C)	Ligament 1		Ligament 9	
	length ( $\mu\text{m}$ )	strain (%)	length ( $\mu\text{m}$ )	strain (%)
17	58	0	64	0
107	62	7.7	51	-0.21
17	44	-0.23	47	-0.28

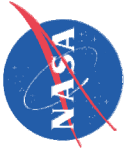


Portions of cells with  
no influence  
from pore pressure



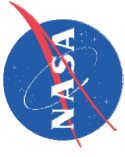
# Thermal Behavior of Polymer Skeleton





## Conclusions

- High temperature thermal behavior of the foam is a complex process driven by:
  - Cell anisotropy
  - Pore pressure
  - Polymer degradation
- Modeled using soils pore pressure approach and micromechanics



## Acknowledgements

- MSFC, KSC and MAF for supplying foam
- Center for Surface Analysis of Materials – CWRU for performing hot stage experiments
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- Pat Rogers, Brian Steeve and Scotty Sparks for their continued support and interest in the work