

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.

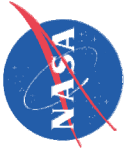
One of the key properties for model characterization and verification is thermal expansion. Since the foam is not a material, but a structure, the modeling of the expansion is complex. It is also exacerbated by the anisotropy of the material. During the spraying and foaming process, the cells become 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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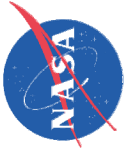


Thermal Expansion of Polyurethane Foam

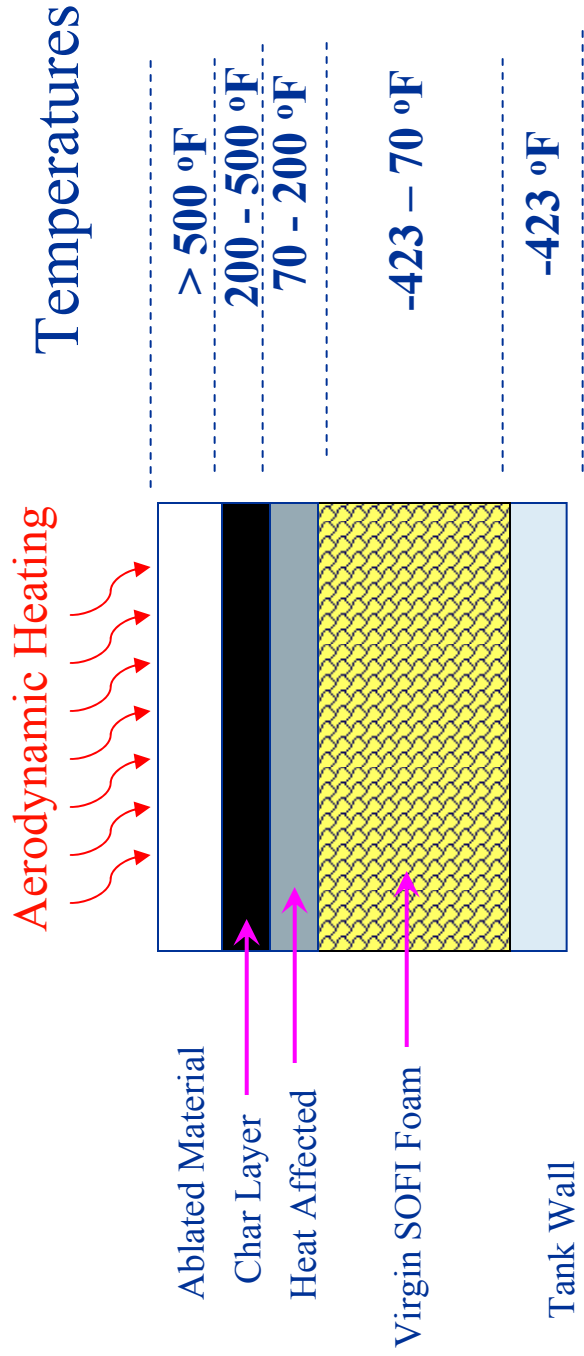
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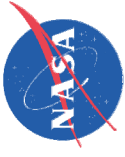
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43rd Annual Technical Meeting of the Society of Engineering Science
The Pennsylvania State University
University Park, PA

August 14, 2006



Expected Foam Temperature Profile





Importance of CTE

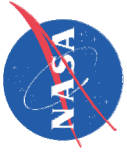
- Al-substrate has a CTE of $2 \times 10^{-5}/^{\circ}\text{C}$
- Polymer foams have an approximate CTE of $1 \times 10^{-4}/^{\circ}\text{C}$
- Thermal strain (ε) equals:

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

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

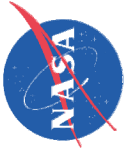
 $\sigma_{\text{foam}} \sim \text{UTS}_{\text{foam}}$

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



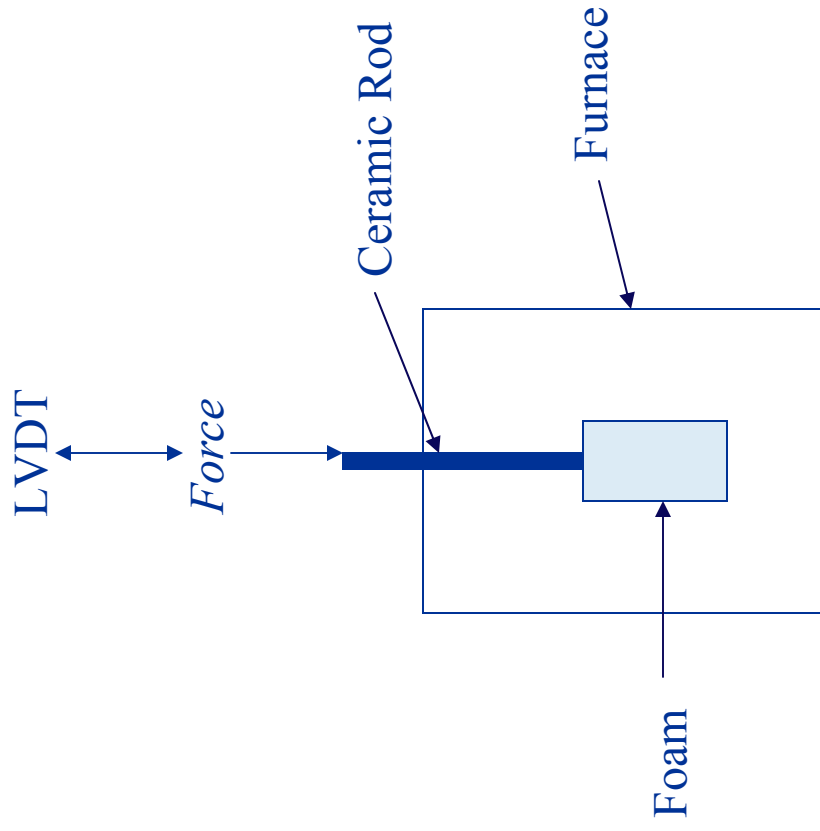
Goal

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

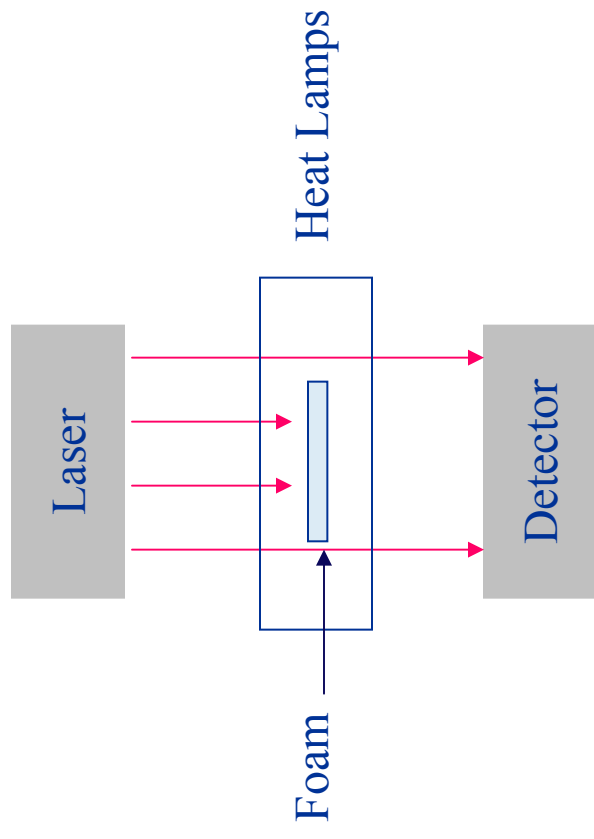


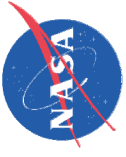
Measurement of Thermal Expansion

Conventional CTE Rig

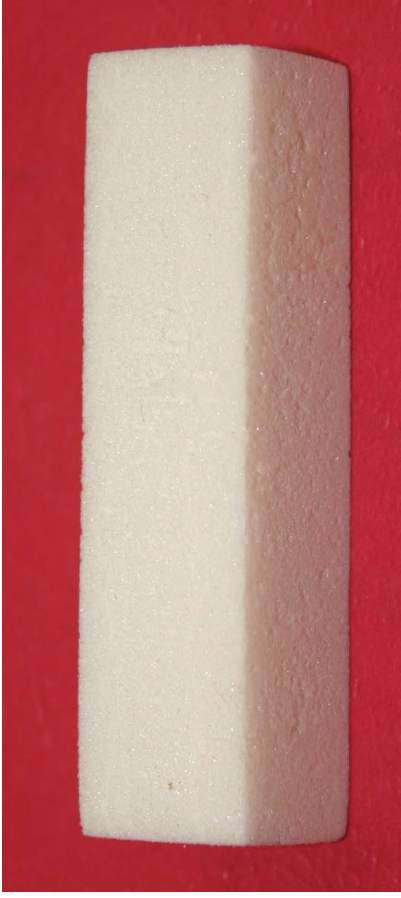


Non-Contacting CTE Rig





Distortion of Foam Due to Temperature Changes



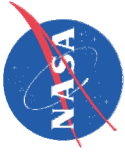
As-cut



Heated to
170 C

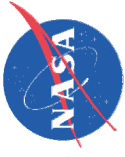


Heated to
300 C



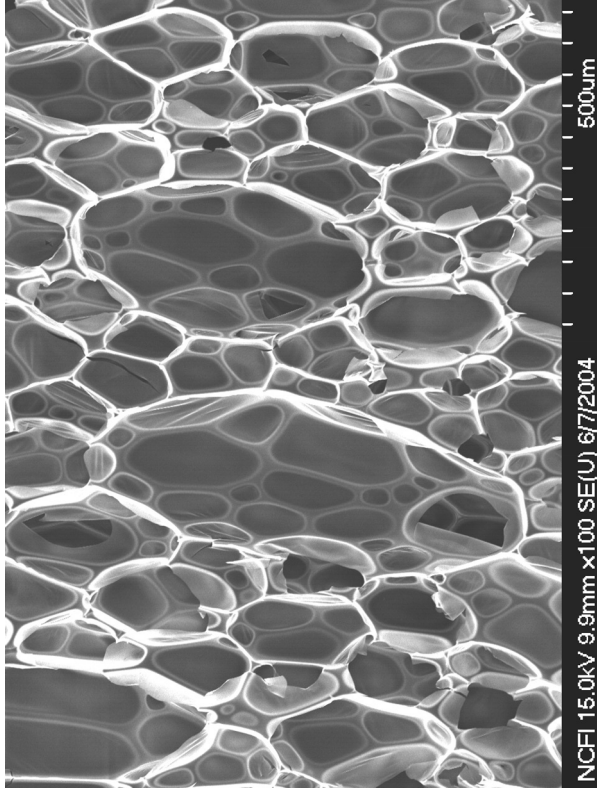
Problems Associated With Thermal Measurements

- 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



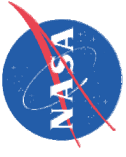
Foam Microstructure

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

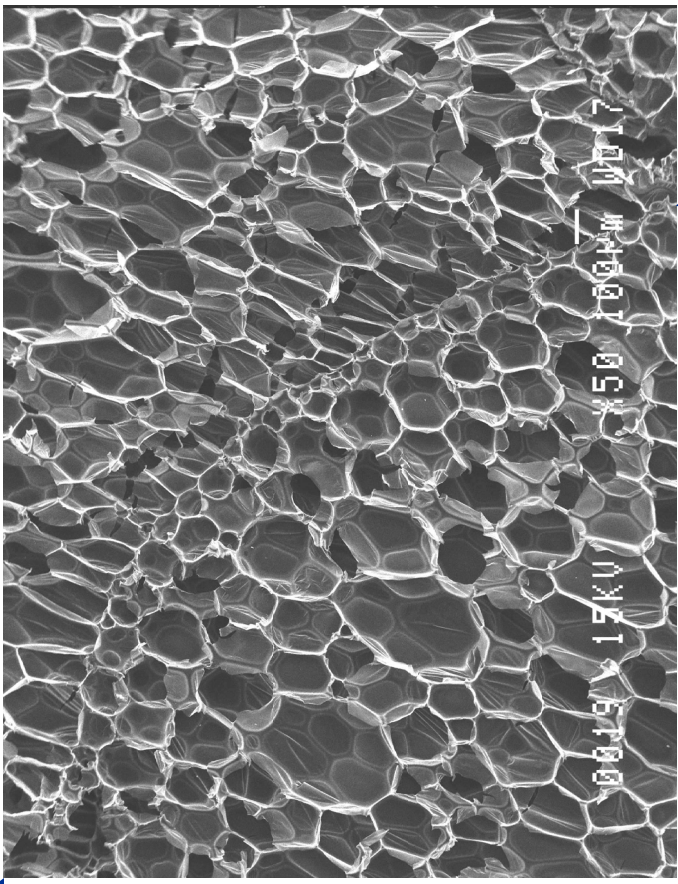
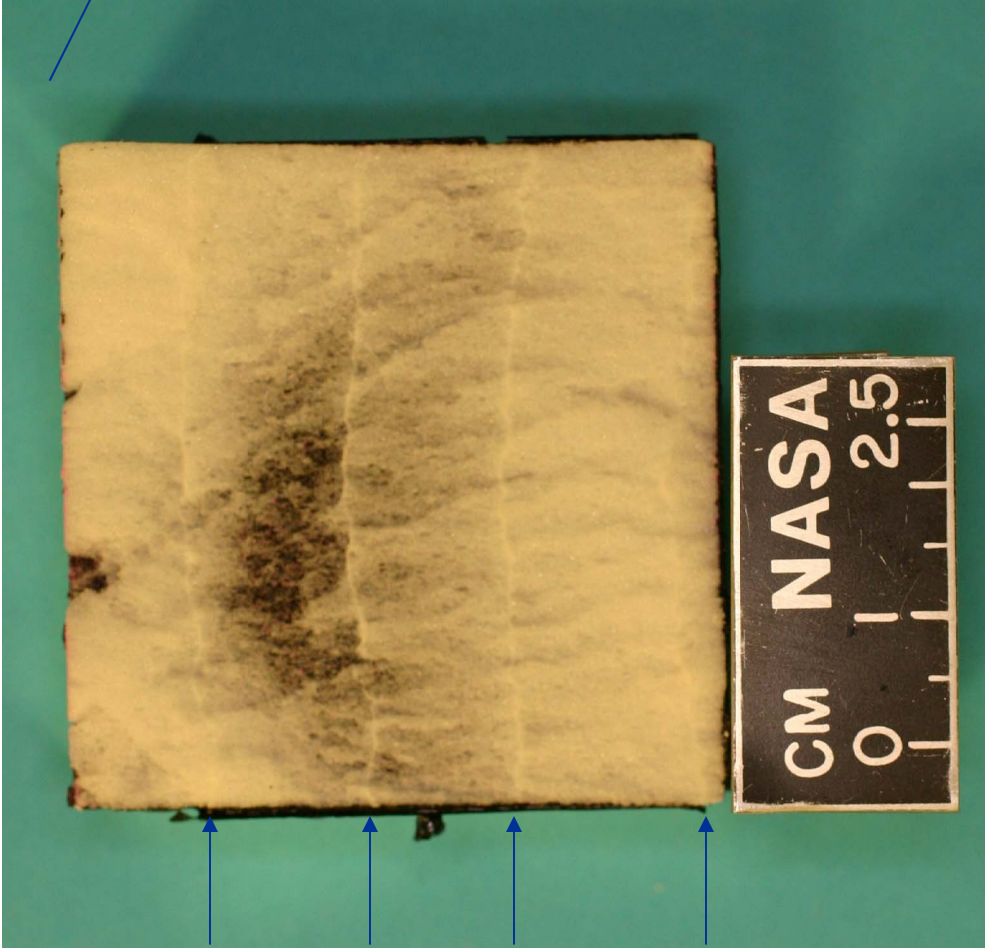


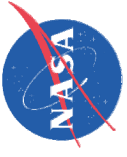
↑ Parallel-to-rise
direction

→ Perpendicular-to-rise
direction

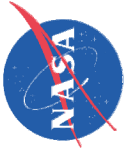


Knitlines

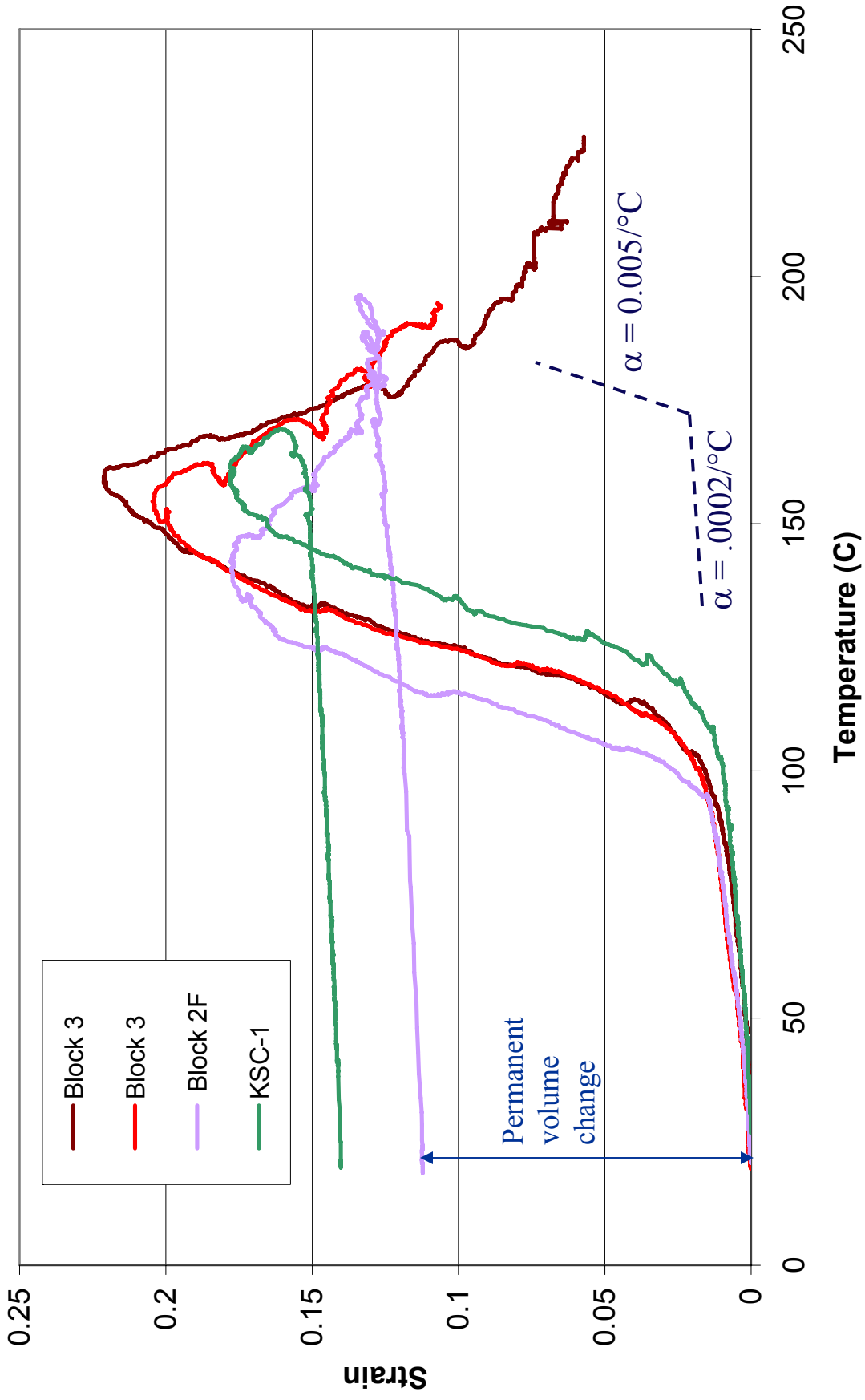


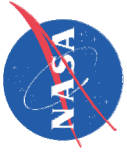


Results

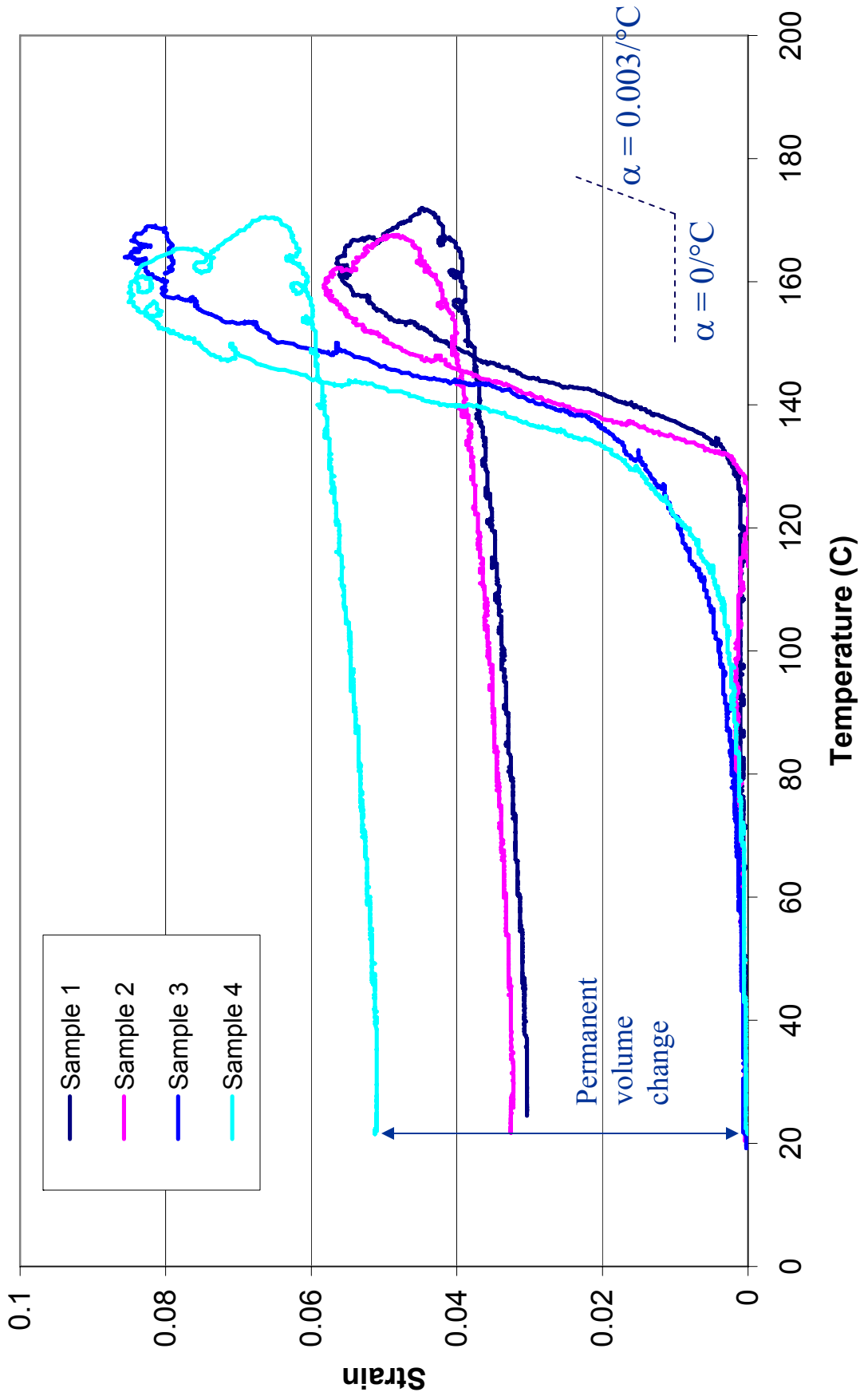


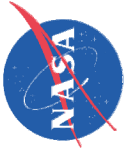
Thermal Expansion Perpendicular to Rise Direction



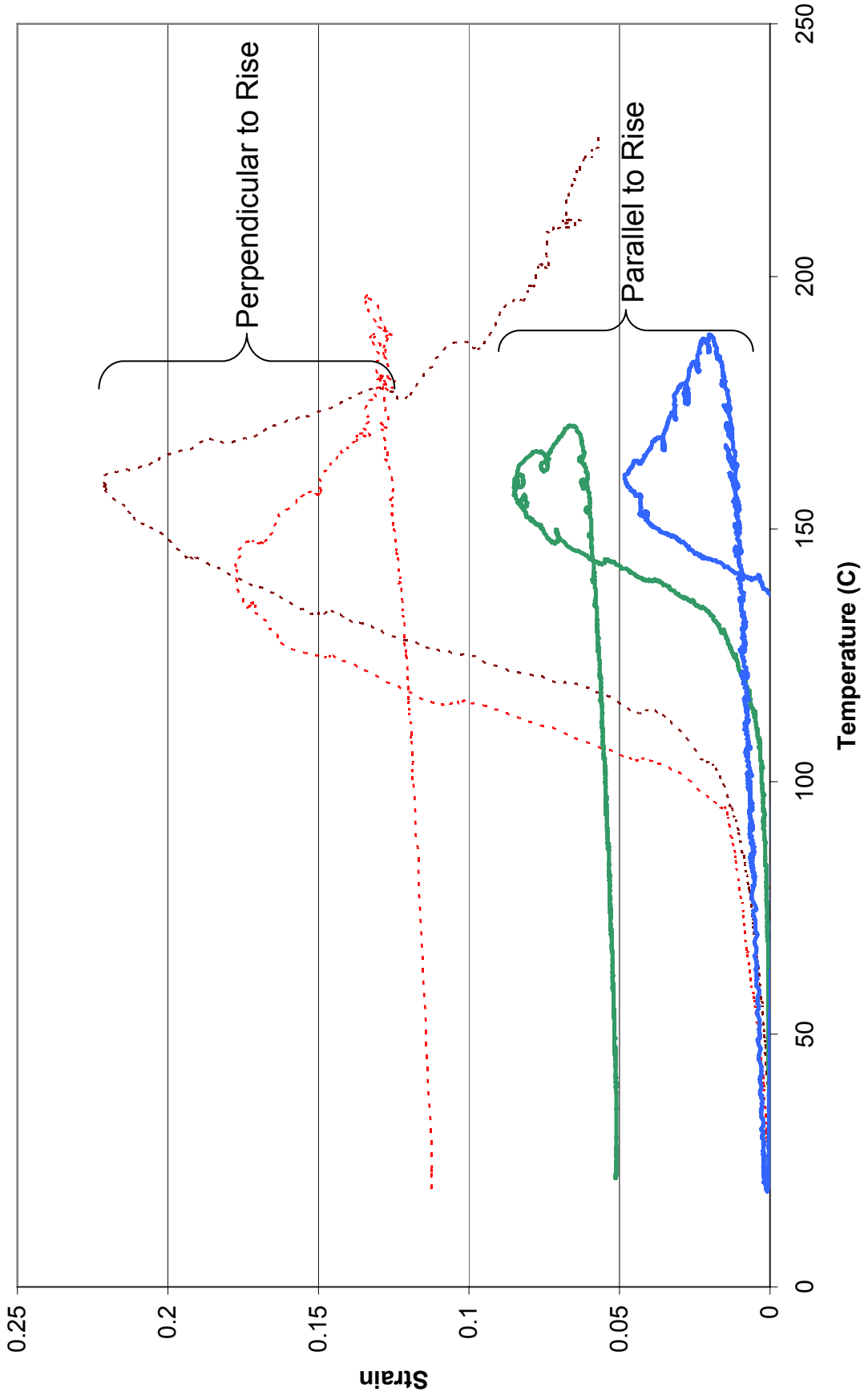


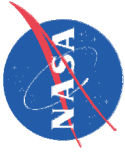
Thermal Expansion Parallel to Rise Direction





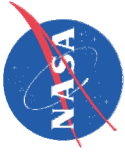
Thermal Expansion in Both Directions





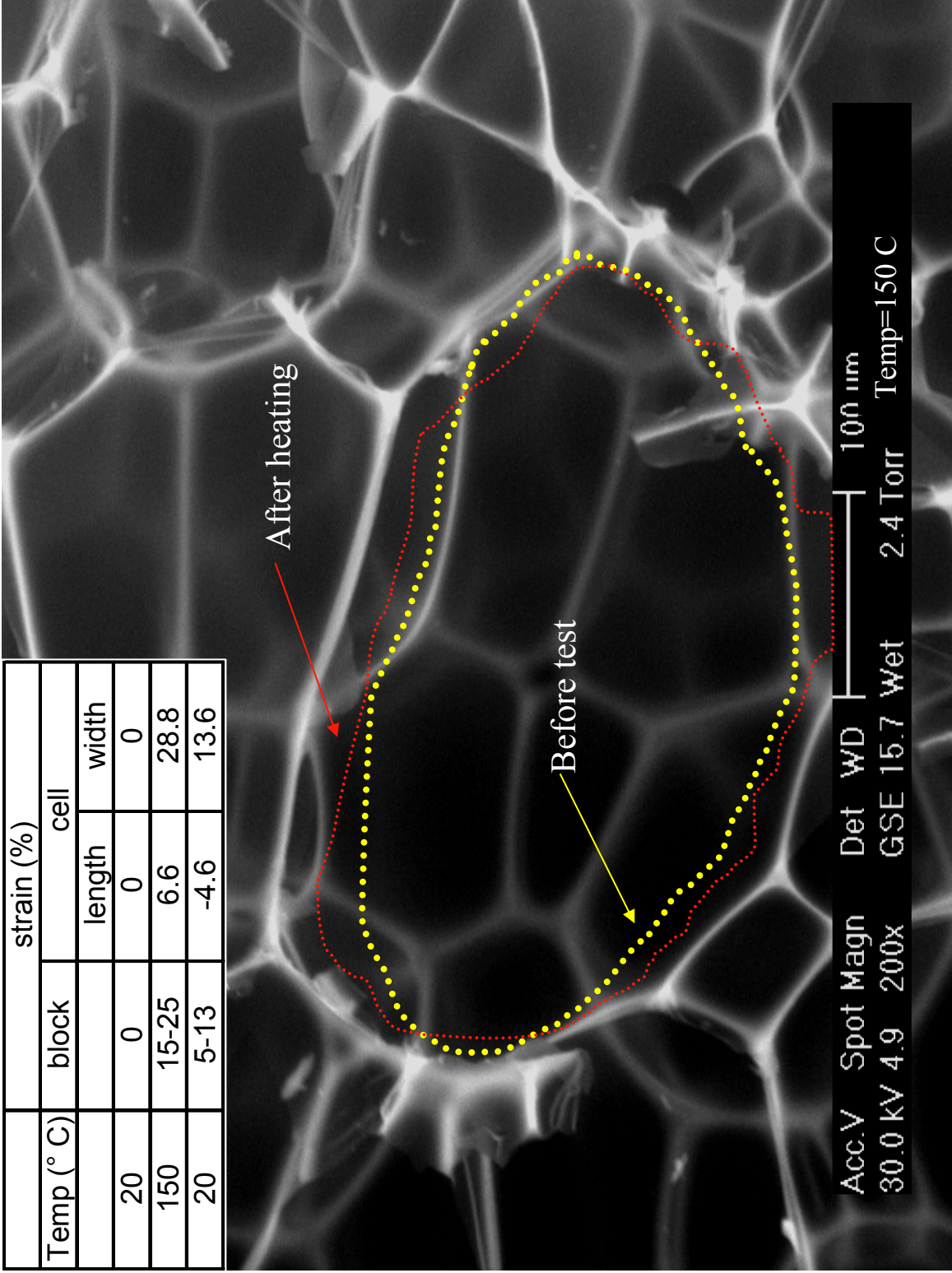
Mechanism of Foam Expansion

- 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

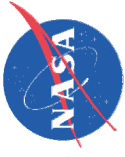
| Temp (°C) | block | strain (%) | |
|-----------|-------|------------|-------|
| | | length | width |
| 20 | 0 | 0 | 0 |
| 150 | 15-25 | 6.6 | 28.8 |
| 20 | 5-13 | -4.6 | 13.6 |



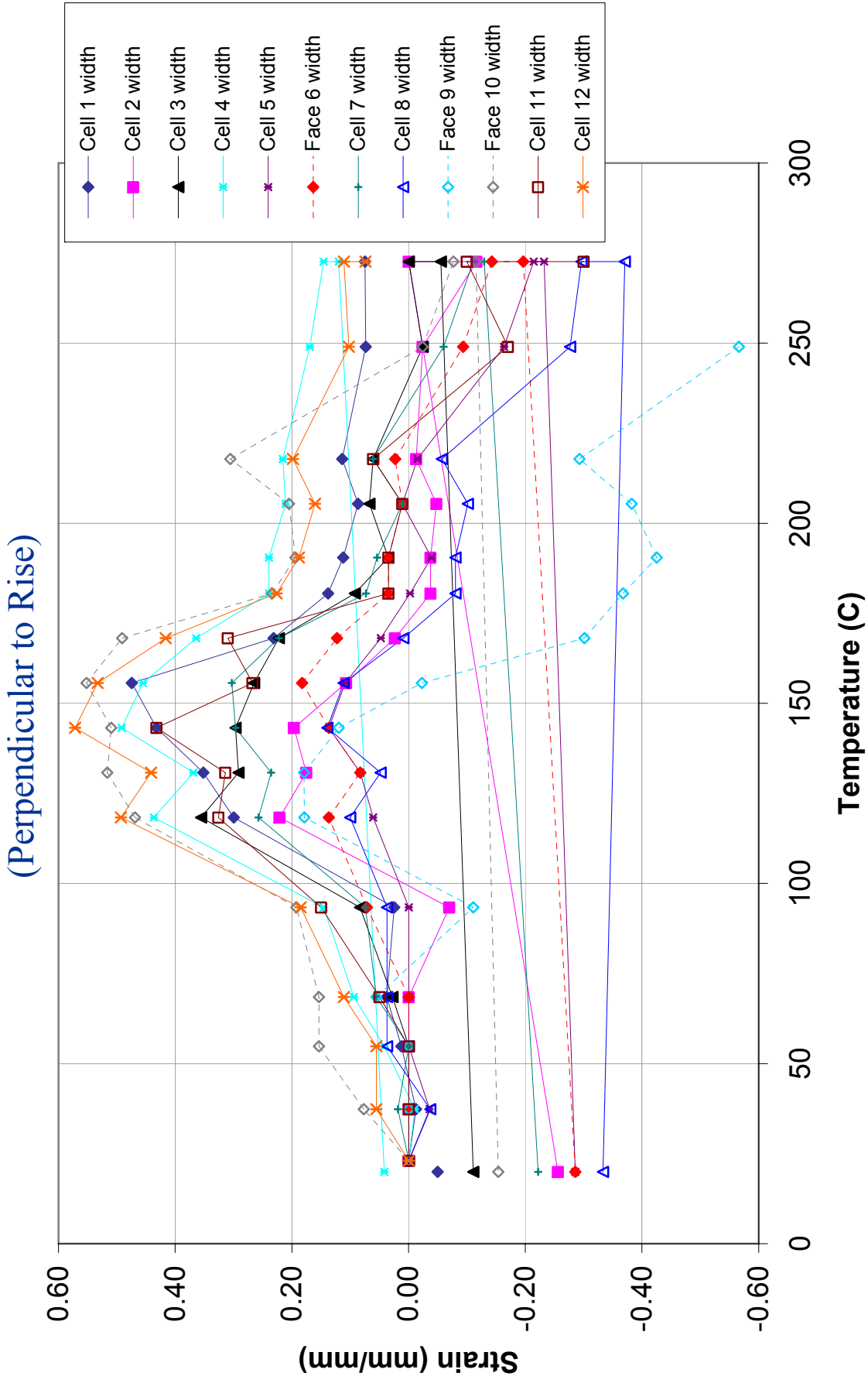
Cell expansion due to thermal exposure

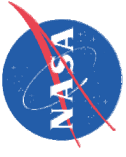
Cell expands mostly in the width direction (perpendicular to rise)



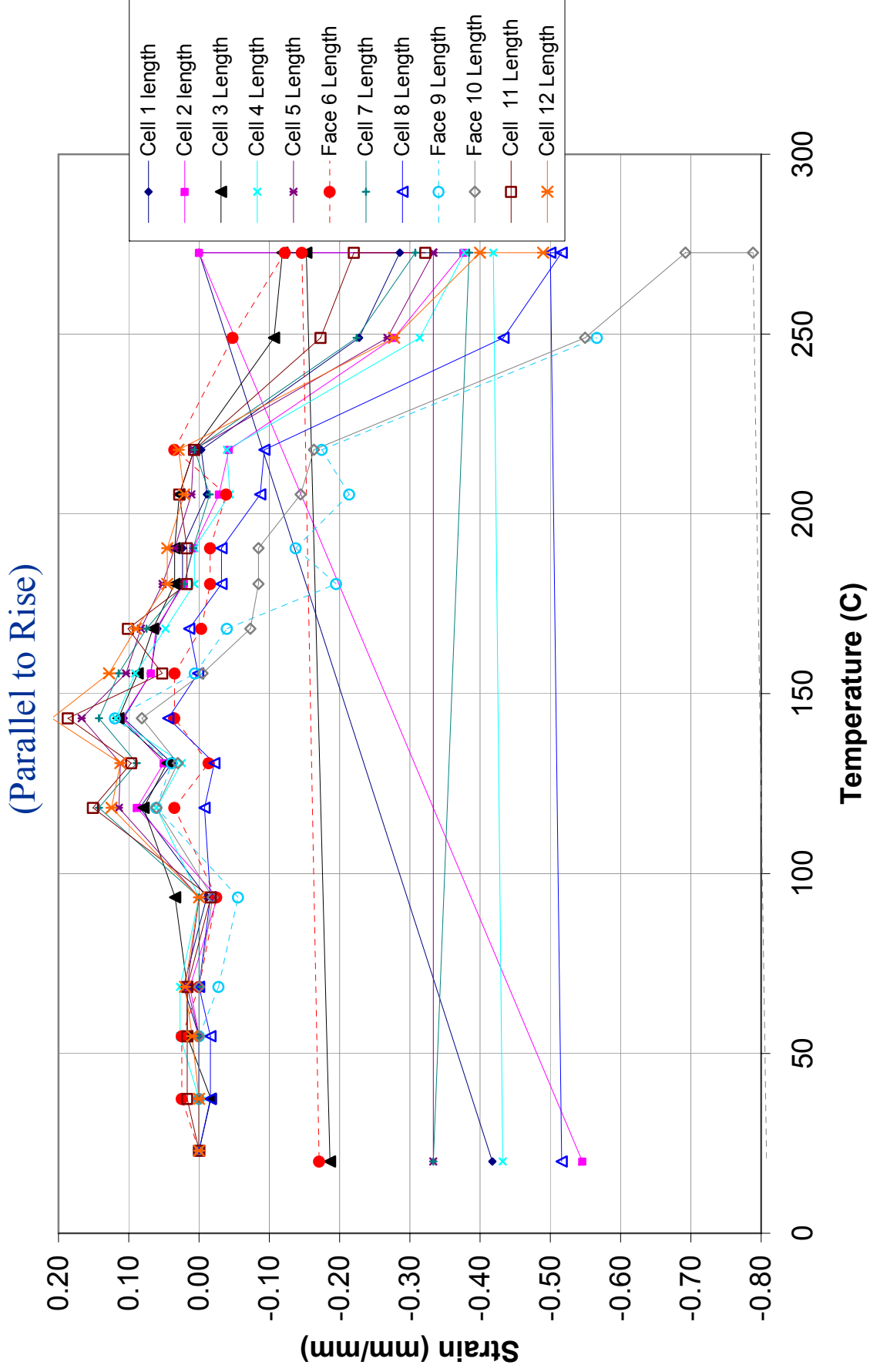


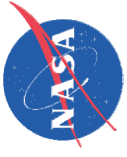
Cell Width Thermal Expansion



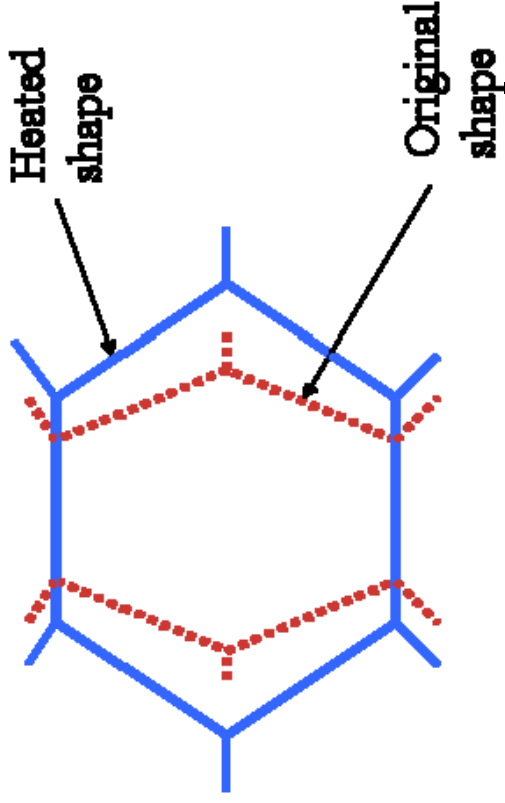
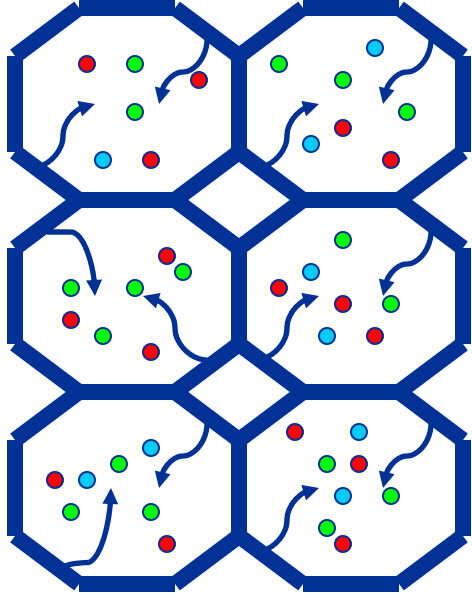


Cell Length Thermal Expansion

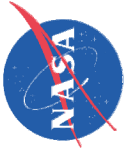




Basis for Model Development

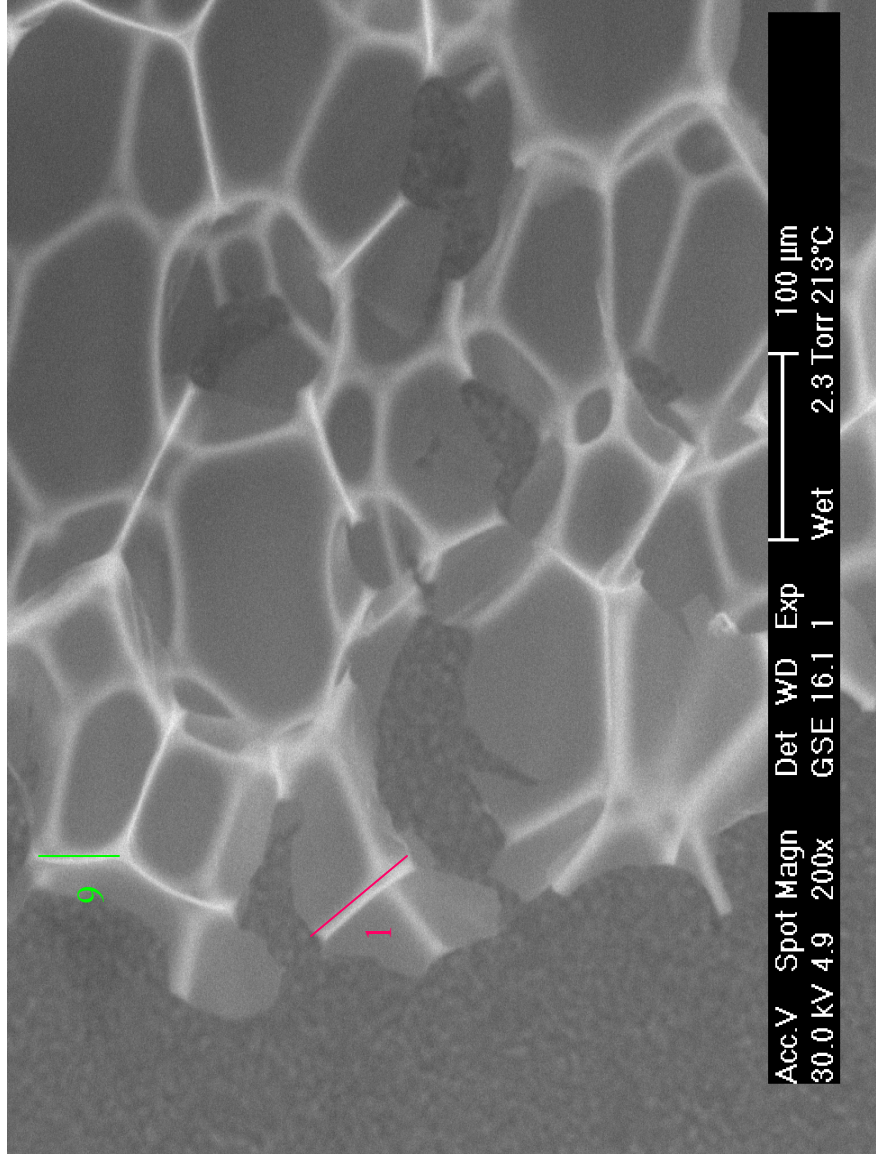


- Elongated cell structure
- Pore pressure increases with temperature
- Polymer softens with temperature

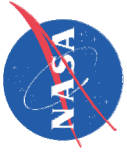


Thermal Behavior of Polymer Skeleton

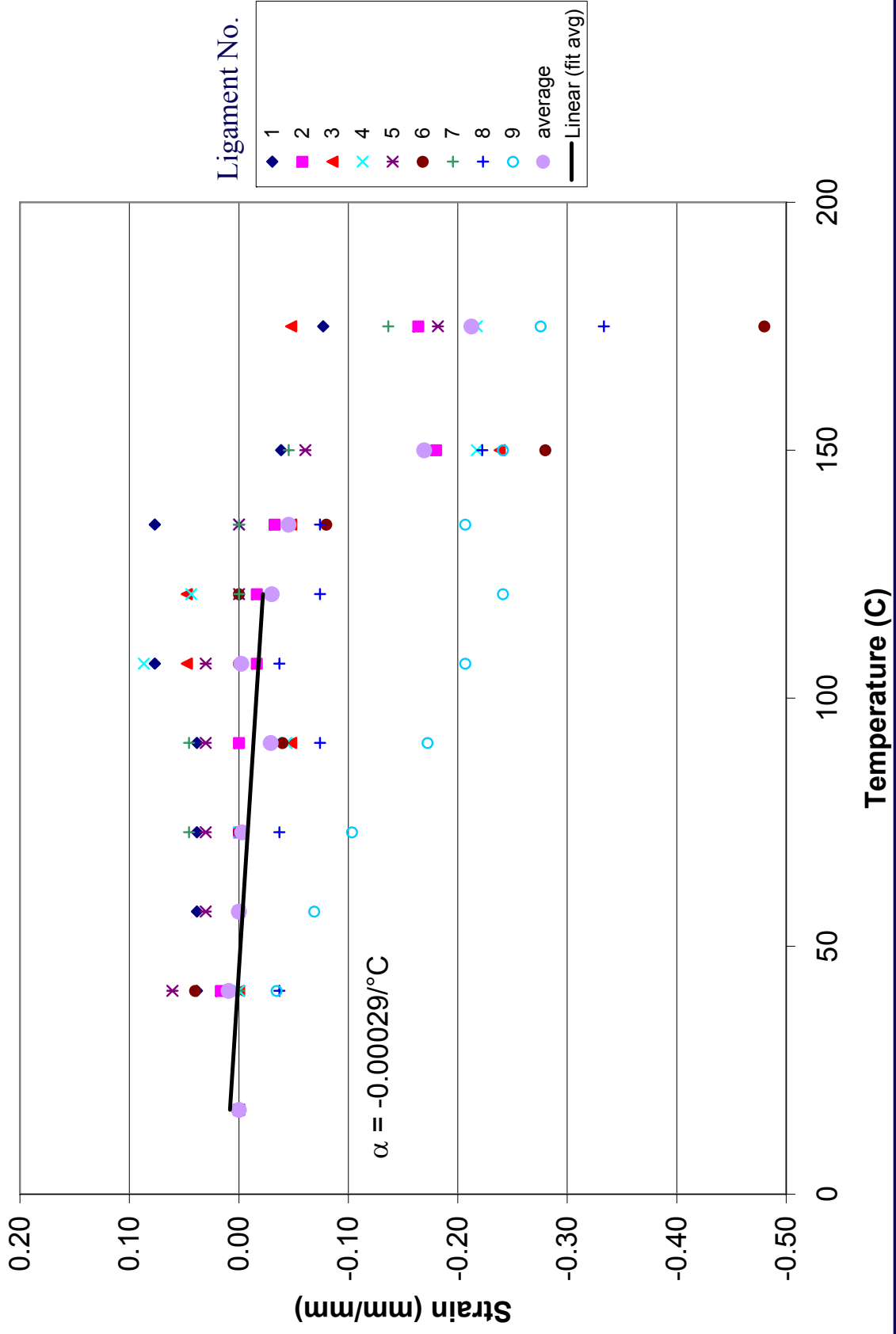
| Temp. (°C) | Ligament 1 | | Ligament 9 | |
|---------------|-----------------------------|---------------|-----------------------------|---------------|
| | length (μm) | strain (%) | length (μm) | strain (%) |
| 17 | 58 | 0 | 64 | 0 |
| 107 | 62 | 7.7 | 51 | -0.21 |
| 17 | 44 | -0.23 | 47 | -0.28 |

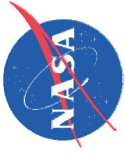


Portions of cells with
no influence
from pore pressure



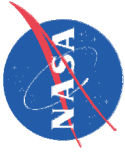
Thermal Behavior of Polymer Skeleton





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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