Porous Media Approach for Modeling Closed Cell Foam

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In order to minimize boil off of the liquid oxygen and liquid hydrogen and to prevent the formation of ice on its exterior surface, the Space Shuttle External Tank (ET) is insulated using various low-density, closed-cell polymeric foams. Improved analysis methods for these foam materials are needed to predict the foam structural response and to help identify the foam fracture behavior in order to help minimize foam shedding occurrences. This presentation describes a continuum based approach to modeling the foam thermo-mechanical behavior that accounts for the cellular nature of the material and explicitly addresses the effect of the internal cell gas pressure.

A porous media approach is implemented in a finite element frame work to model the mechanical behavior of the closed cell foam. The ABAQUS general purpose finite element program is used to simulate the continuum behavior of the foam. The soil mechanics element is implemented to account for the cell internal pressure and its effect on the stress and strain fields. The pressure variation inside the closed cells is calculated using the ideal gas laws. The soil mechanics element is compatible with an orthotropic materials model to capture the different behavior between the rise and in-plane directions of the foam.

The porous media approach is applied to model the foam thermal strain and calculate the foam effective coefficient of thermal expansion. The calculated foam coefficients of thermal expansion were able to simulate the measured thermal strain during heat up from cryogenic temperature to room temperature in vacuum. The porous media approach was applied to an insulated substrate with one inch foam and compared to a simple elastic solution without pore pressure. The porous media approach is also applied to model the foam mechanical behavior during subscale laboratory experiments. In this test, a foam layer sprayed on a metal substrate is subjected to a temperature variation while the metal substrate is stretched to simulate the structural response of the tank during operation. The thermal expansion mismatch between the foam and the metal substrate and the thermal gradient in the foam layer causes high tensile stresses near the metal/foam interface that can lead to delamination.

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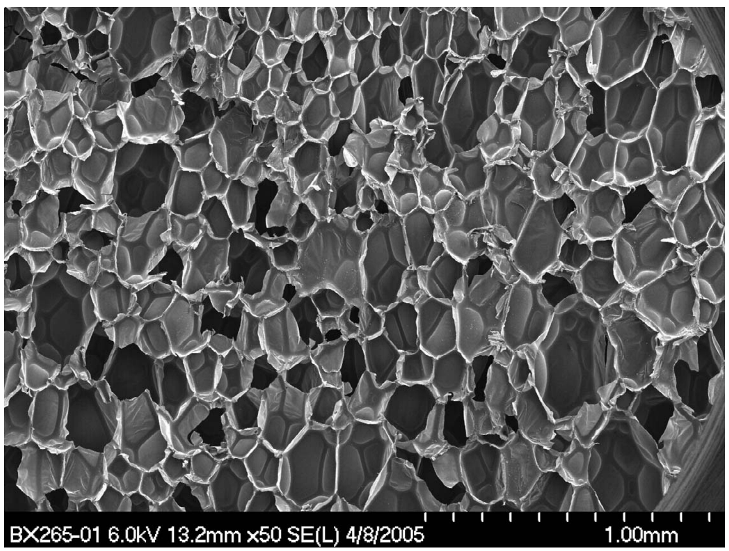
SOFI Closed Cell Foam

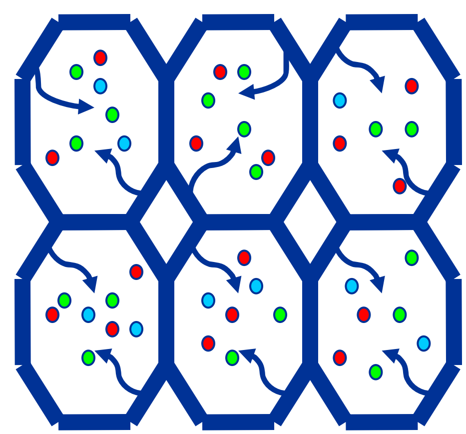
Rise

BX-265



In-plane

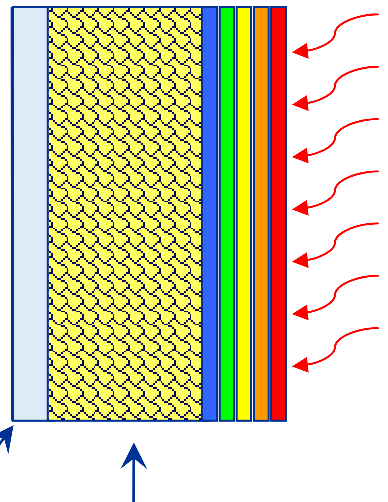
- 97% void filled with entrapped gases
- Polymeric cell walls
- Anisotropic properties
- Polymer out-gas upon heating:
  - weakens cell walls
  - creates additional internal pressures
  - results in a unique thermal expansion behavior

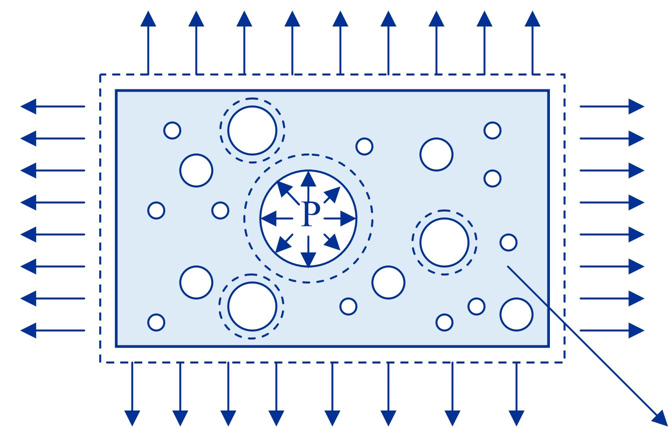


Space Shuttle External Tank Foams

- BX265
- NCFI
- PDL

Application of Porous Media Principles to Foam Thermo-mechanics





Generalized 3-D Constitutive Relations for Porous Media

$$\sigma_{ij} = C_{ijkl}\left(e_{kl} - \alpha_{kk}^{T}\Delta T\right) - \alpha_{ij}^{P} P$$

C_{ijkl}	Elastic stiffness tensor	P	Cell internal pressure
α_{ij}^{P}	Stress-Pressure coupling tensor	$\Delta T = \left(T - T_{ref}\right)$	Change in temperature
α_{kk}^{T}	Coefficient of thermal expansions		

SOFI Mechanical Properties from FEA Unit Cell Model

BX-265

Temp (C)	E11 (MPa)	E22 (MPa)	E33 (MPa)	nu12	nu13	nu32
-251	10.97	10.97	39.89	0.488	0.143	0.520
-196	10.97	10.97	39.89	0.488	0.143	0.520
24	4.99	4.99	18.13	0.488	0.143	0.520

NCFI

Temp (C)	E11 (MPa)	E22 (MPa)	E33 (MPa)	nu12	nu13	nu32
-251	9.96	9.96	45.75	0.528	0.114	0.524
-196	9.96	9.96	45.75	0.528	0.114	0.524
24	4.53	4.53	20.80	0.528	0.114	0.524

PDL

Temp (C)	E11 (MPa)	E22 (MPa)	E33 (MPa)	nu12	nu13	nu32
-253	31.85	31.85	49.96	0.362	0.249	0.391
-196	25.03	25.03	39.26	0.362	0.249	0.391
24	12.74	12.74	19.99	0.362	0.249	0.391

with $G_{12} = \frac{E_{11}}{2(1+\nu_{12})}$ $(in-plane \quad isotropic)$ $\quad G^{*}_{31} = \frac{2\,G_{12}}{(1+R)}$ $(Rise)$

* Ref. Gibson Ashby

Calibration of Thermal Expansion Coefficients

$$e_{ij} = P\, S_{ijkl}\, \alpha^{P}_{kl} + \alpha^{T}_{ii}\, \Delta T$$

Assuming $\alpha^{P}_{ij} = [I]$

$$\varepsilon_{11} = (p_{cell} - p_{ext})\frac{1-\upsilon_{12}-\upsilon_{13}}{E_{11}} + \alpha^{T}_{11}(T - T_{ref})$$

$$\varepsilon_{22} = (p_{cell} - p_{ext})\frac{1-\upsilon_{21}-\upsilon_{23}}{E_{22}} + \alpha^{T}_{22}(T - T_{ref})$$

$$\varepsilon_{33} = (p_{cell} - p_{ext})\frac{1-\upsilon_{31}-\upsilon_{32}}{E_{33}} + \alpha^{T}_{33}(T - T_{ref})$$

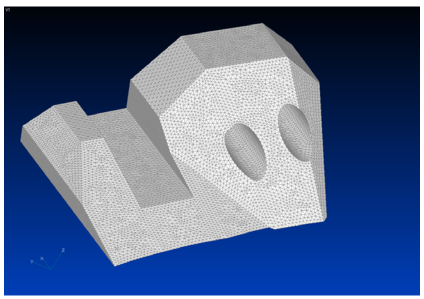
Solving for α^{T}_{kk} yields:

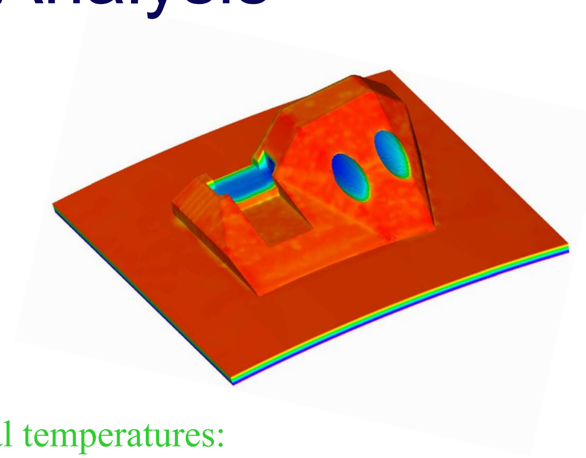
$$\alpha^{T}_{11} = \frac{\varepsilon_{11}}{T - T_{ref}} - \frac{p_{cell} - p_{ext}}{T - T_{ref}} \cdot \frac{1-\upsilon_{12}-\upsilon_{13}}{E_{11}}$$

$$\alpha^{T}_{22} = \frac{\varepsilon_{22}}{T - T_{ref}} - \frac{p_{cell} - p_{ext}}{T - T_{ref}} \cdot \frac{1-\upsilon_{21}-\upsilon_{23}}{E_{22}}$$

$$\alpha^{T}_{33} = \frac{\varepsilon_{33}}{T - T_{ref}} - \frac{p_{cell} - p_{ext}}{T - T_{ref}} \cdot \frac{1-\upsilon_{31}-\upsilon_{32}}{E_{33}}$$

Flow Chart for Pore Pressure Analysis Approach





Finite Element Mesh of Foam Application

ABAQUS FE Thermal Analysis Solution

Nodal temperatures:
Temperature Distributions in the Foam

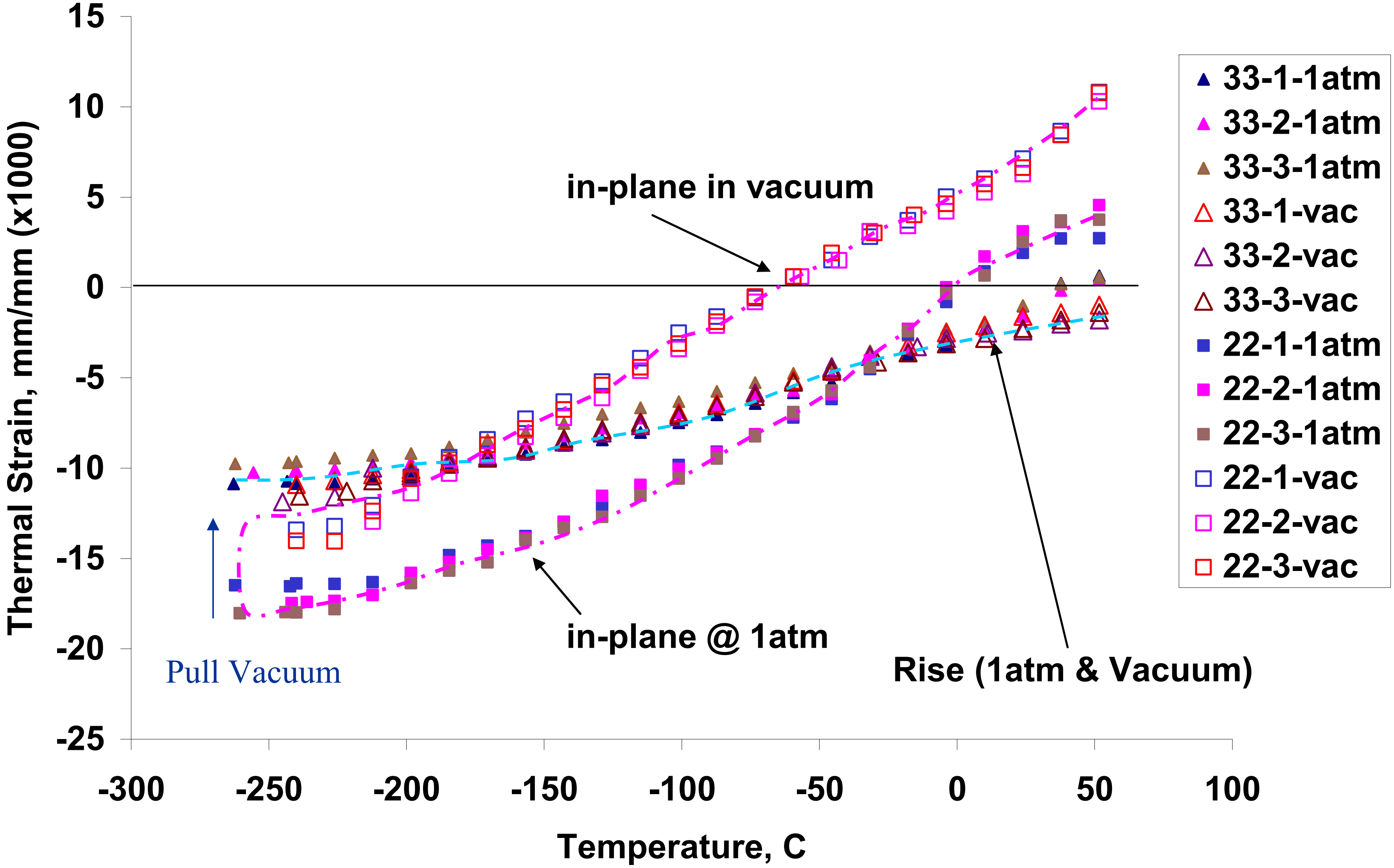
Pore Pressure Subroutine

Nodal internal cell gas pressures:
Pressure Distributions in the Foam

ABAQUS FE Porous Media Analysis Solution

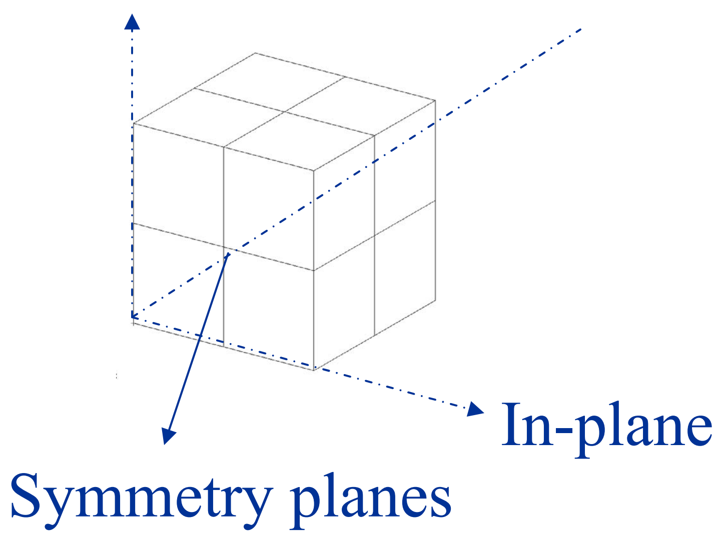
Solid Skeleton Stress Distribution

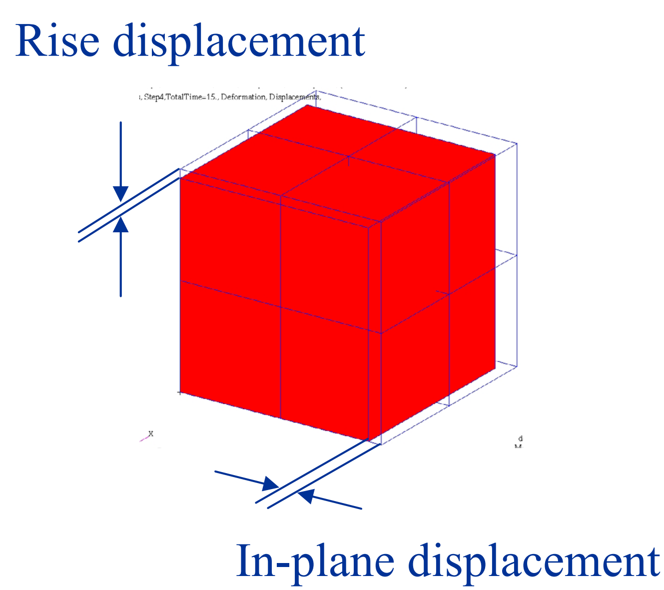
NCFI-24-124



Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

Porous-Media applied to thermal-strain experiment





Note

- Use the 1-atm thermal strain for calibrating the Porous-Media CTE
- Verify the CTE and pore pressure using the vacuum data

Calibrated SOFI CTE

BX-265

Temp (C)	$\alpha^T 11$ (1/C)	$\alpha^T 22$ (1/C)	$\alpha^T 33$ (1/C)
-253	5.90E-05	5.90E-05	3.68E-05
-196	6.90E-05	6.90E-05	4.23E-05
-73	8.94E-05	8.94E-05	5.32E-05
24	**1.65E-04**	**1.65E-04**	**9.96E-05**
93	2.40E-04	2.40E-04	1.46E-04

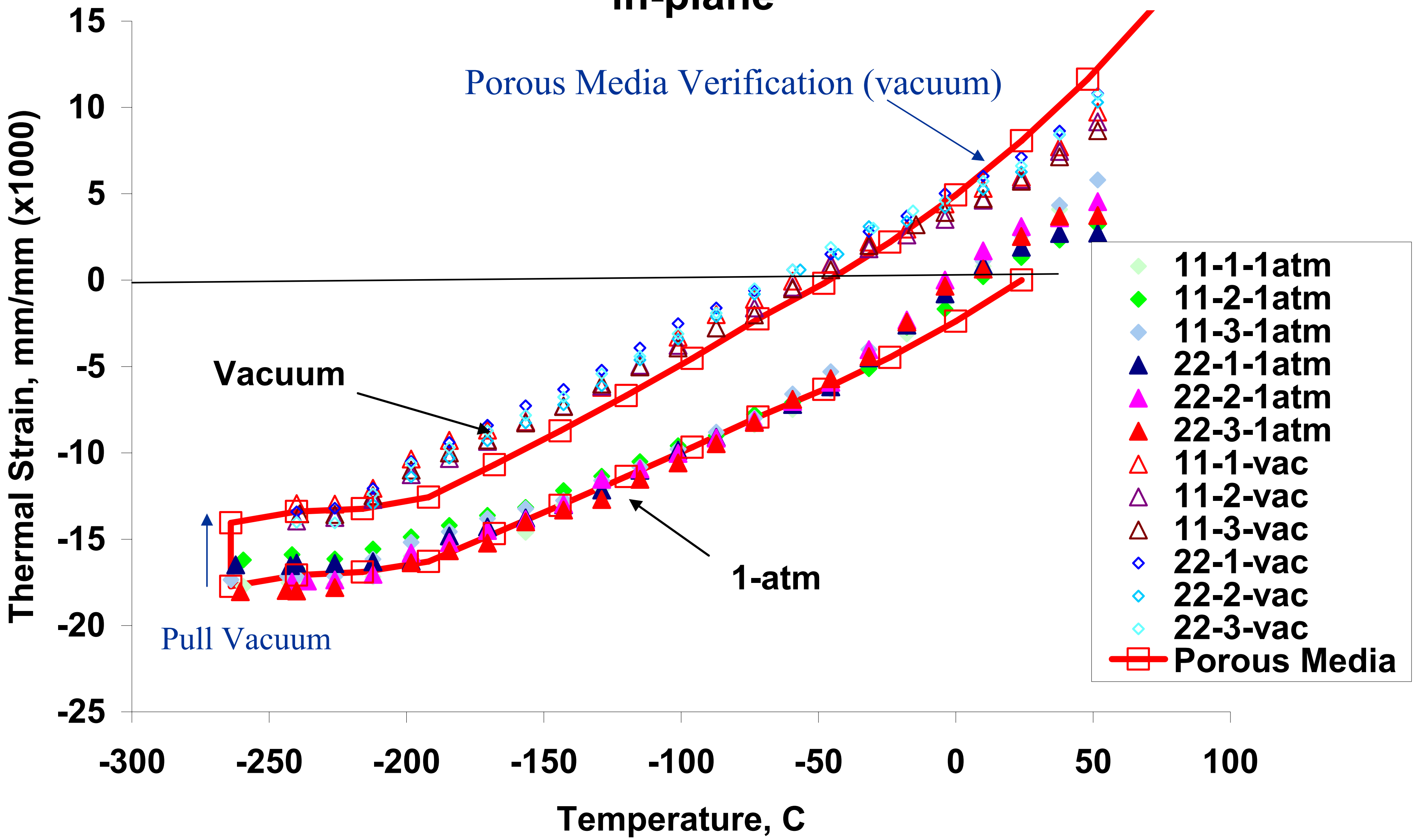
NCFI 24-124

Temp (C)	$\alpha^T 11$ (1/C)	$\alpha^T 22$ (1/C)	$\alpha^T 33$ (1/C)
-253	4.92E-05	4.92E-05	3.72E-05
-196	6.29E-05	6.29E-05	4.59E-05
-73	6.34E-05	6.34E-05	6.23E-05
24	7.80E-05	7.80E-05	8.21E-05
93	9.26E-05	9.26E-05	1.02E-04
149	2.03E-04	2.03E-04	1.93E-04

PDL-1034

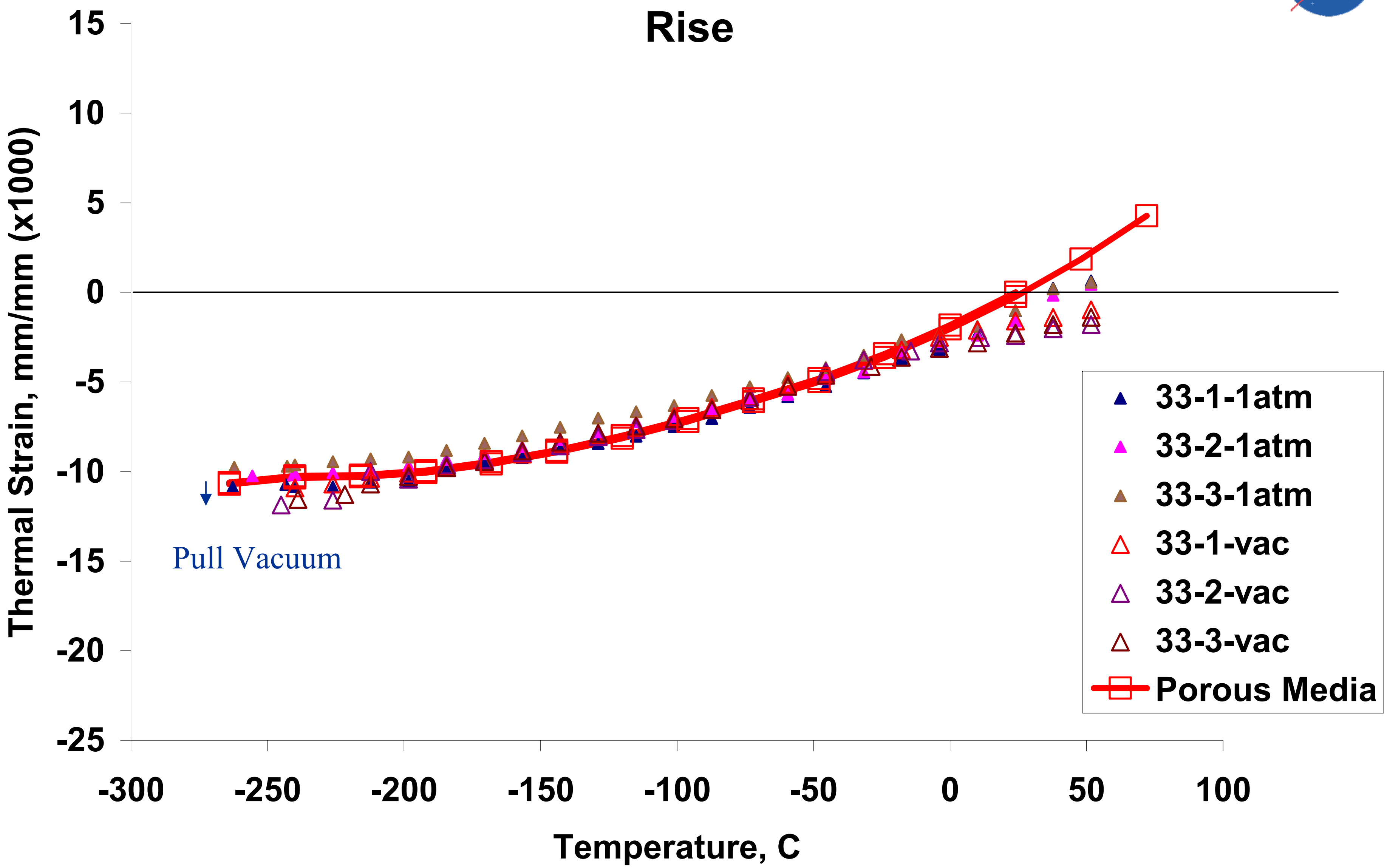
Temp (C)	$\alpha^T 11$ (1/C)	$\alpha^T 22$ (1/C)	$\alpha^T 33$ (1/C)
-253	4.61E-05	4.61E-05	4.12E-05
-196	5.67E-05	5.67E-05	5.14E-05
-73	7.02E-05	7.02E-05	6.40E-05
24	1.35E-04	1.35E-04	1.40E-04
93	1.99E-04	1.99E-04	2.16E-04
149	4.76E-04	4.76E-04	5.63E-04

NCFI-24-124 in-plane



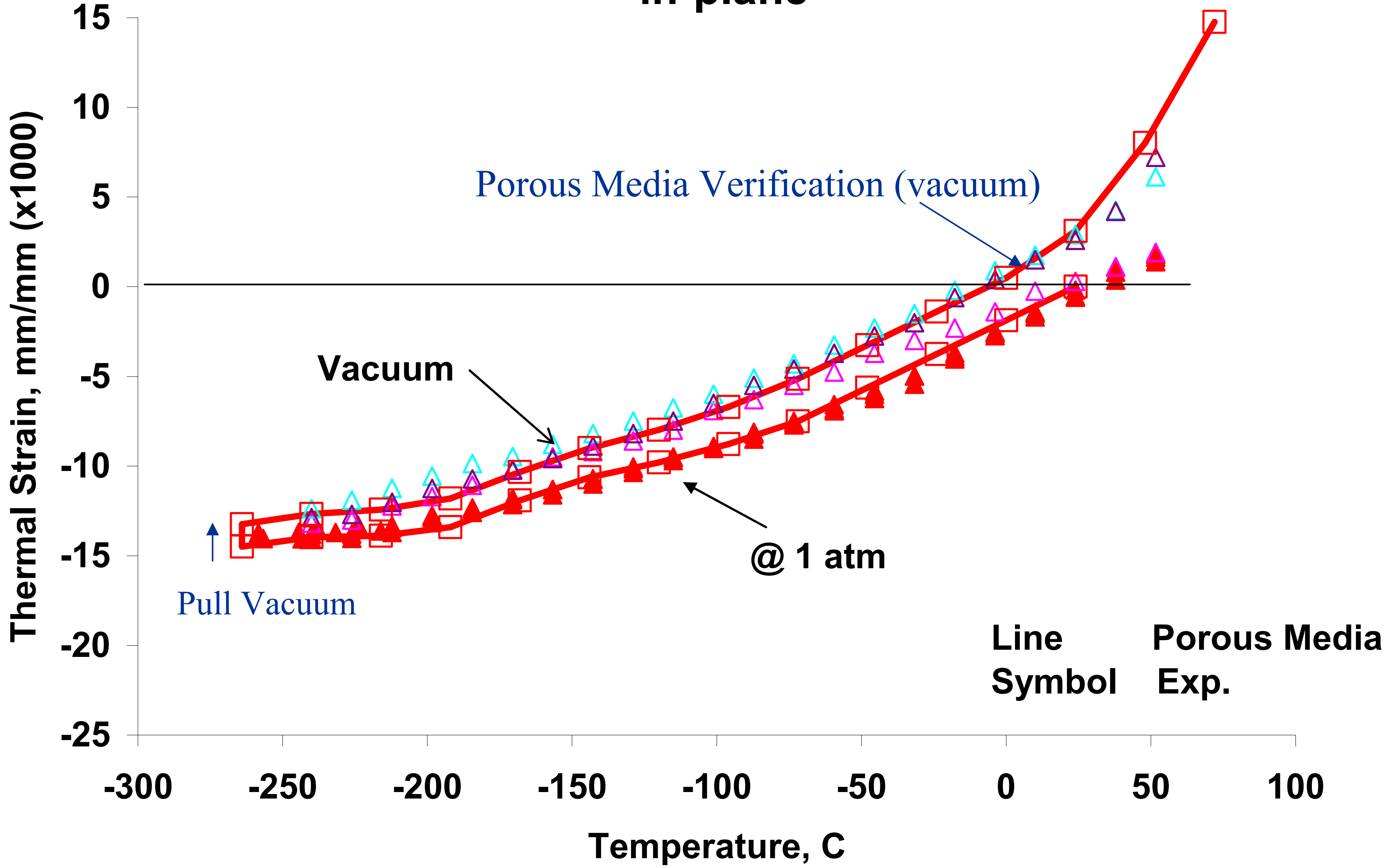
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

NCFI-24-124 Rise



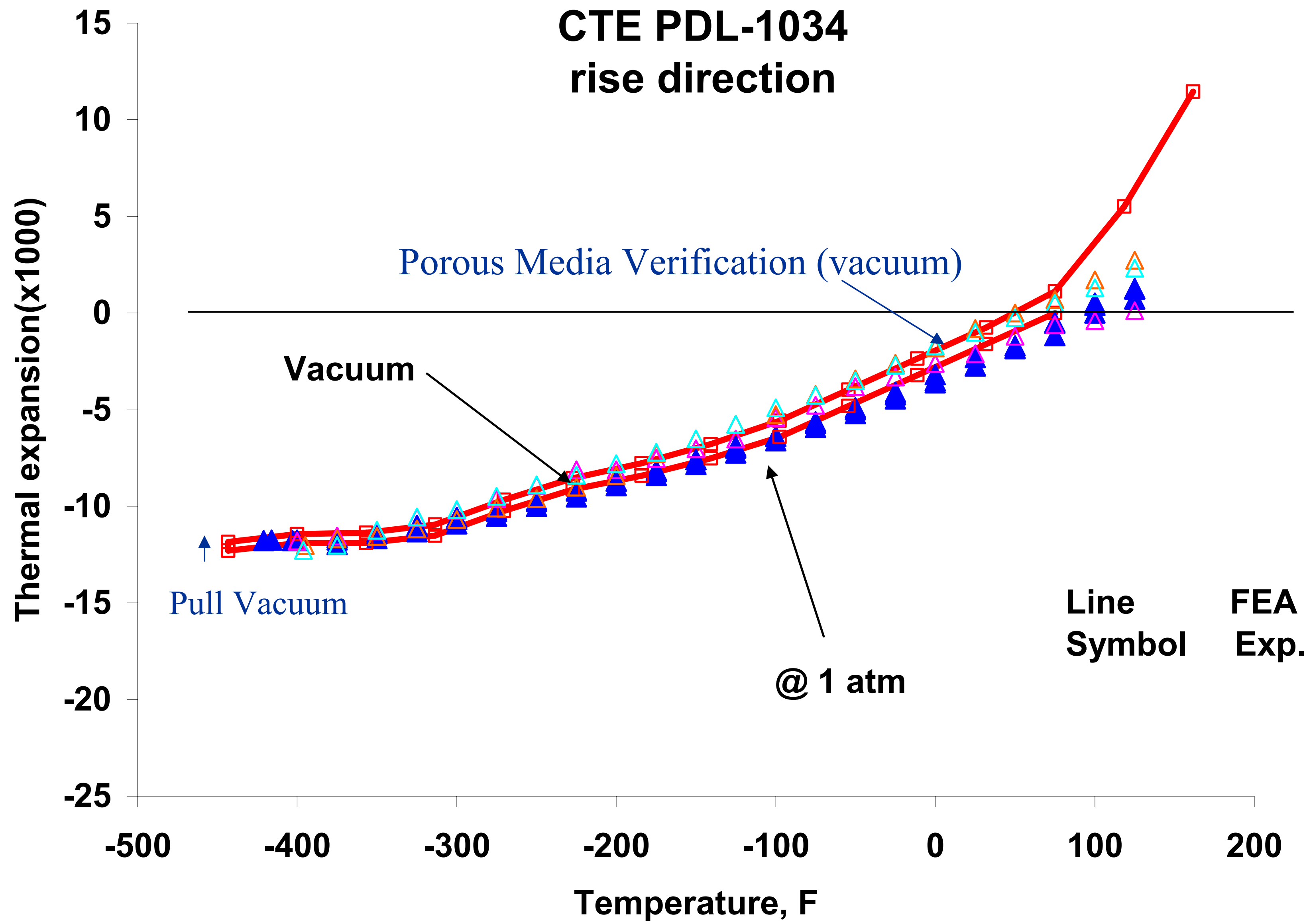
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

CTE, PDL-1034 in-plane



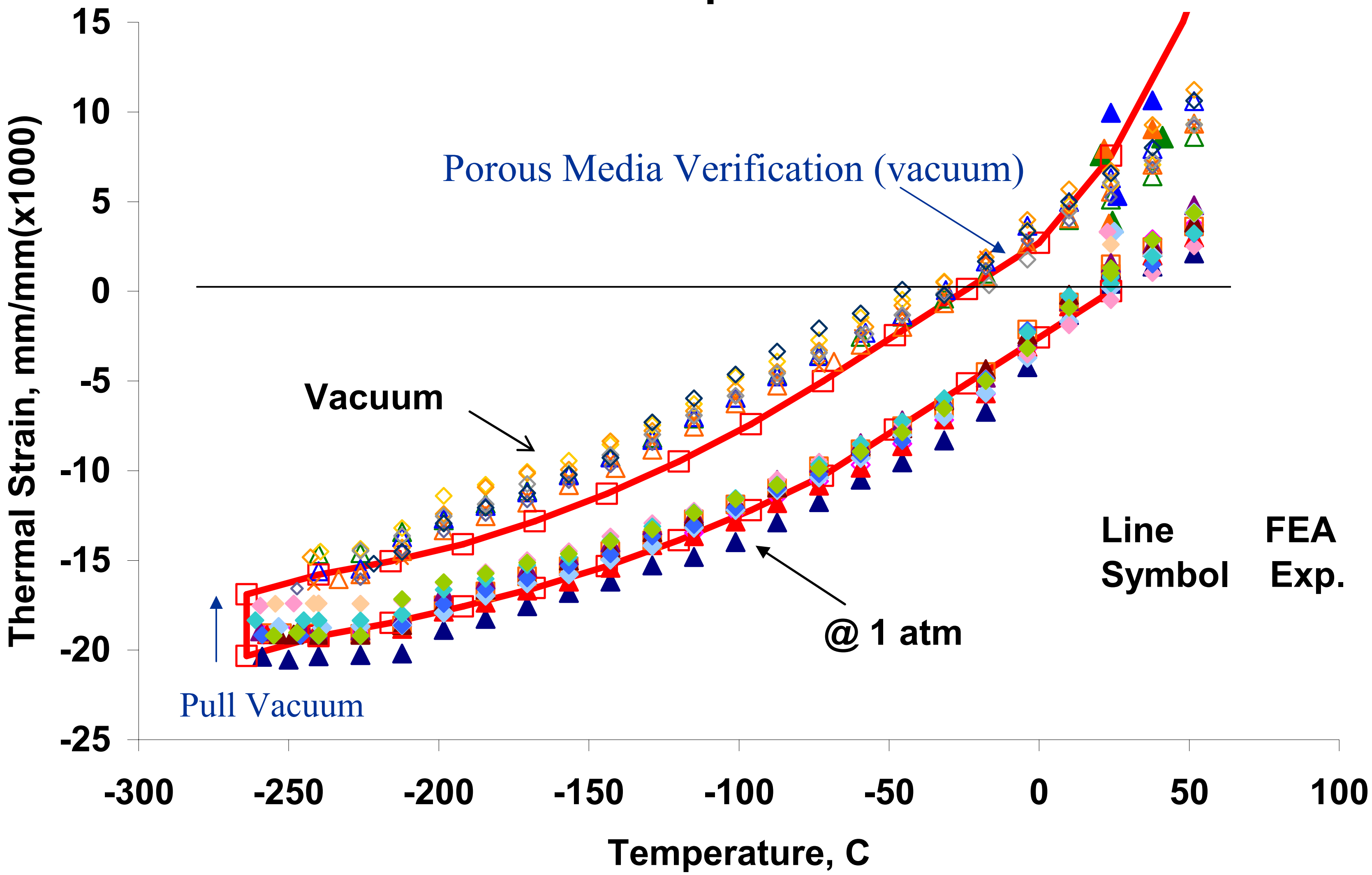
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

CTE PDL-1034 rise direction



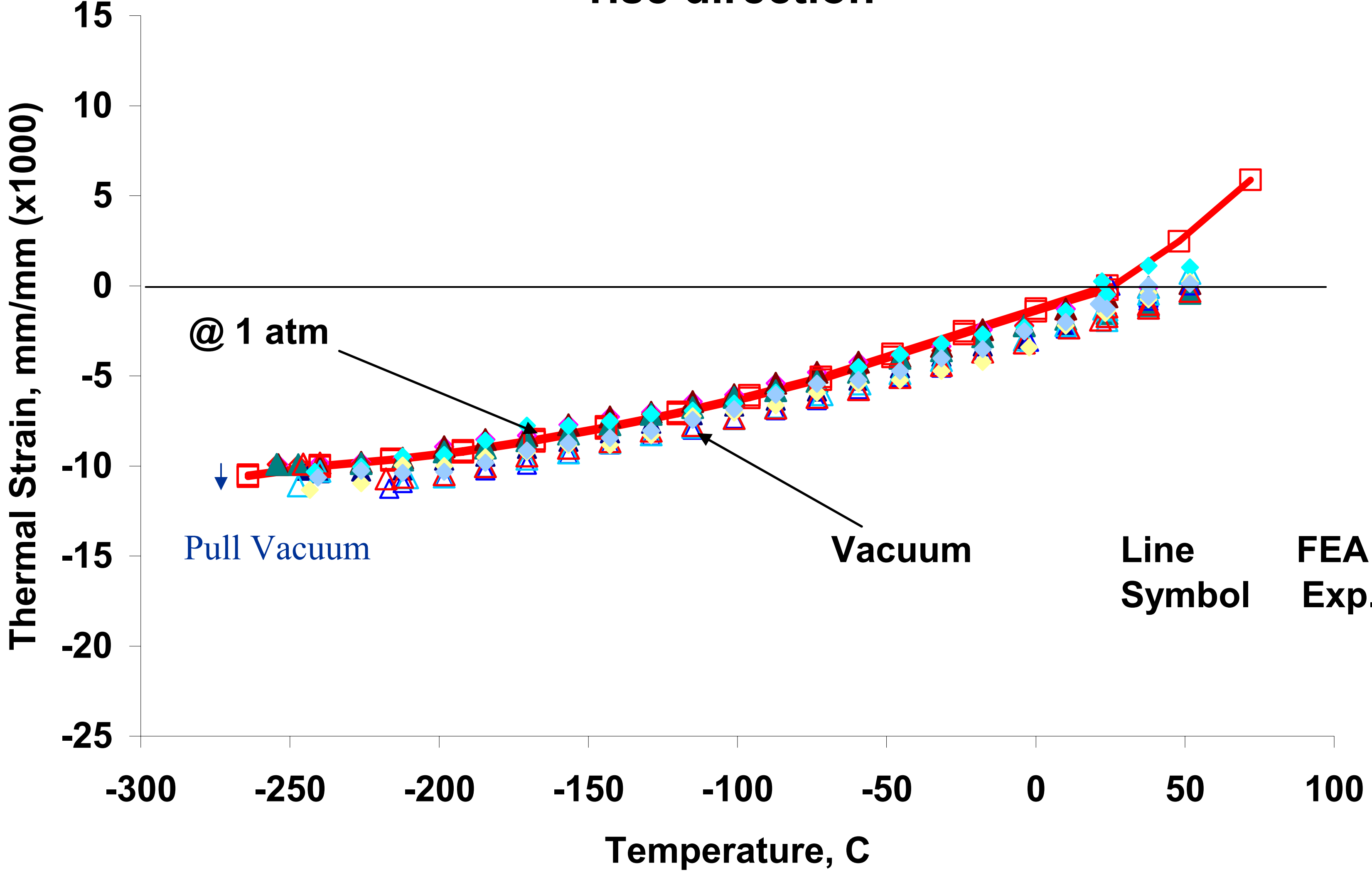
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

CTE, BX-265 in-plane



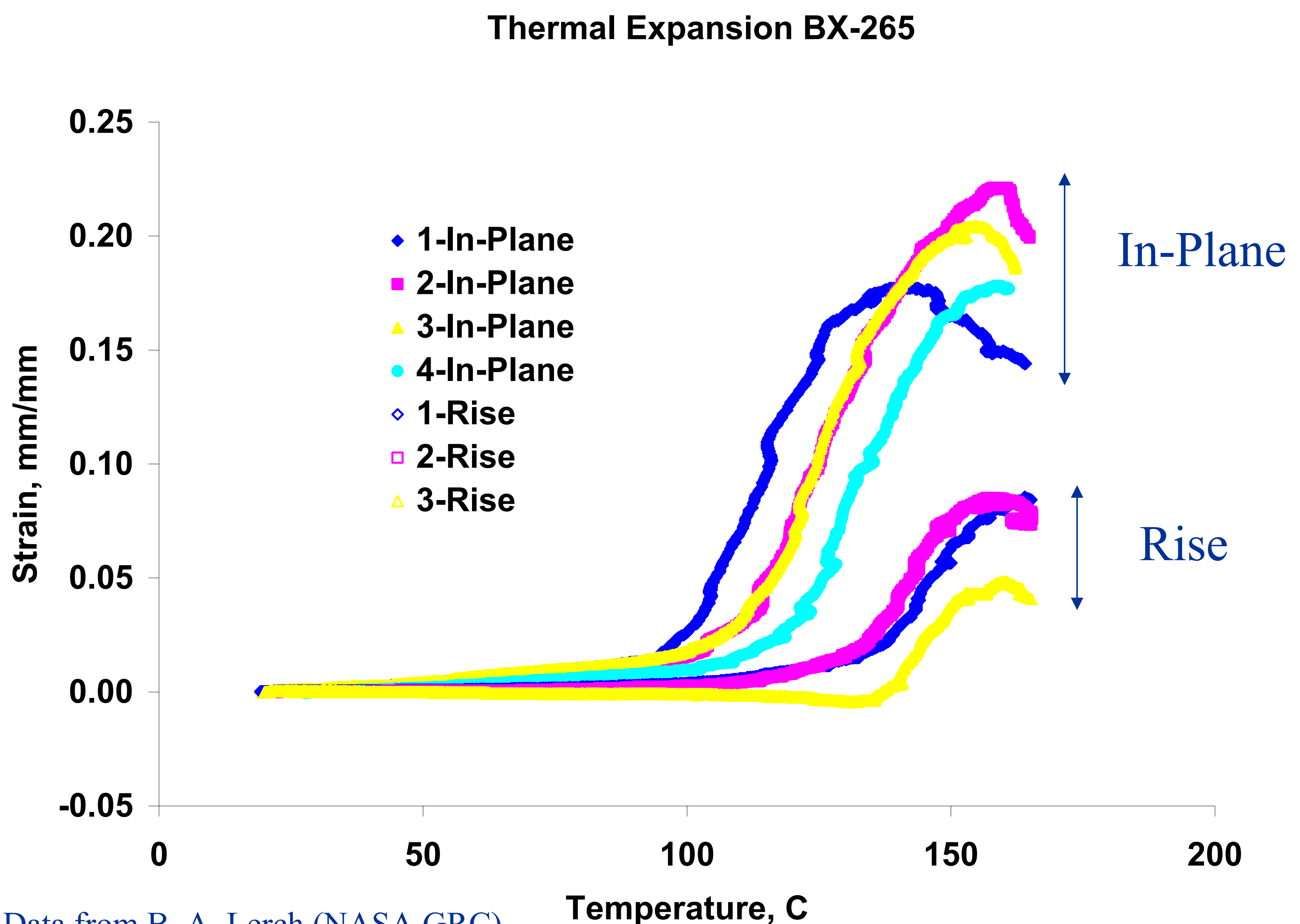
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

CTE BX265
rise direction



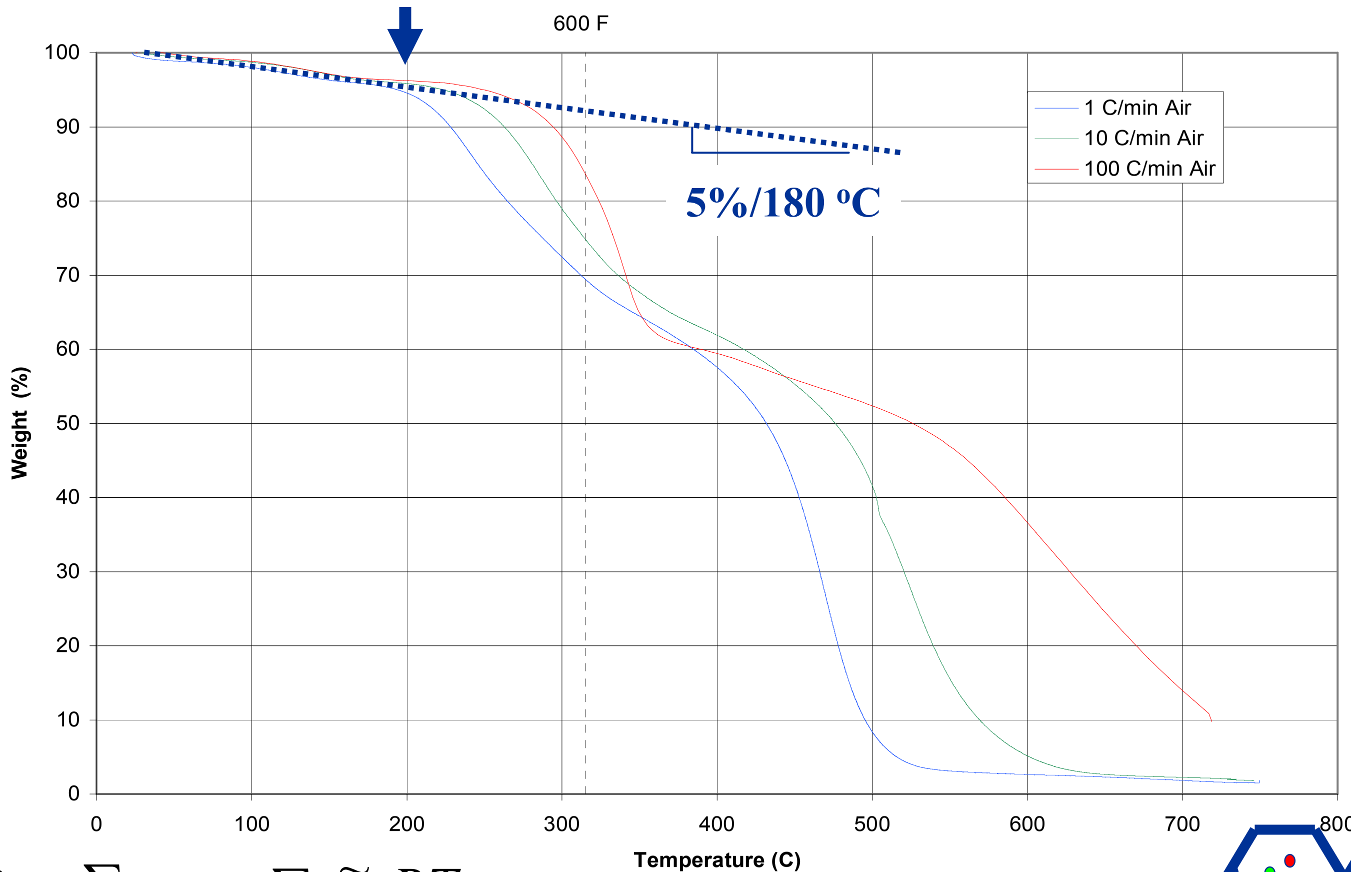
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613

High Temperature Thermal Strain



Data from B. A. Lerch (NASA GRC)

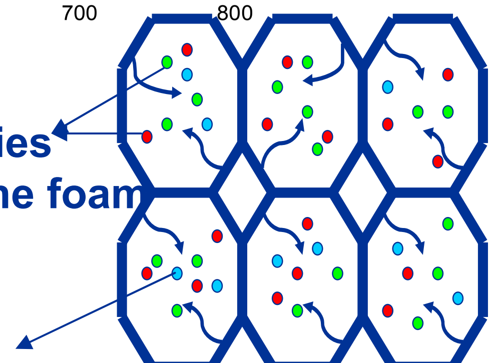
Thermogravimetric Analysis of Pulverized BX-265

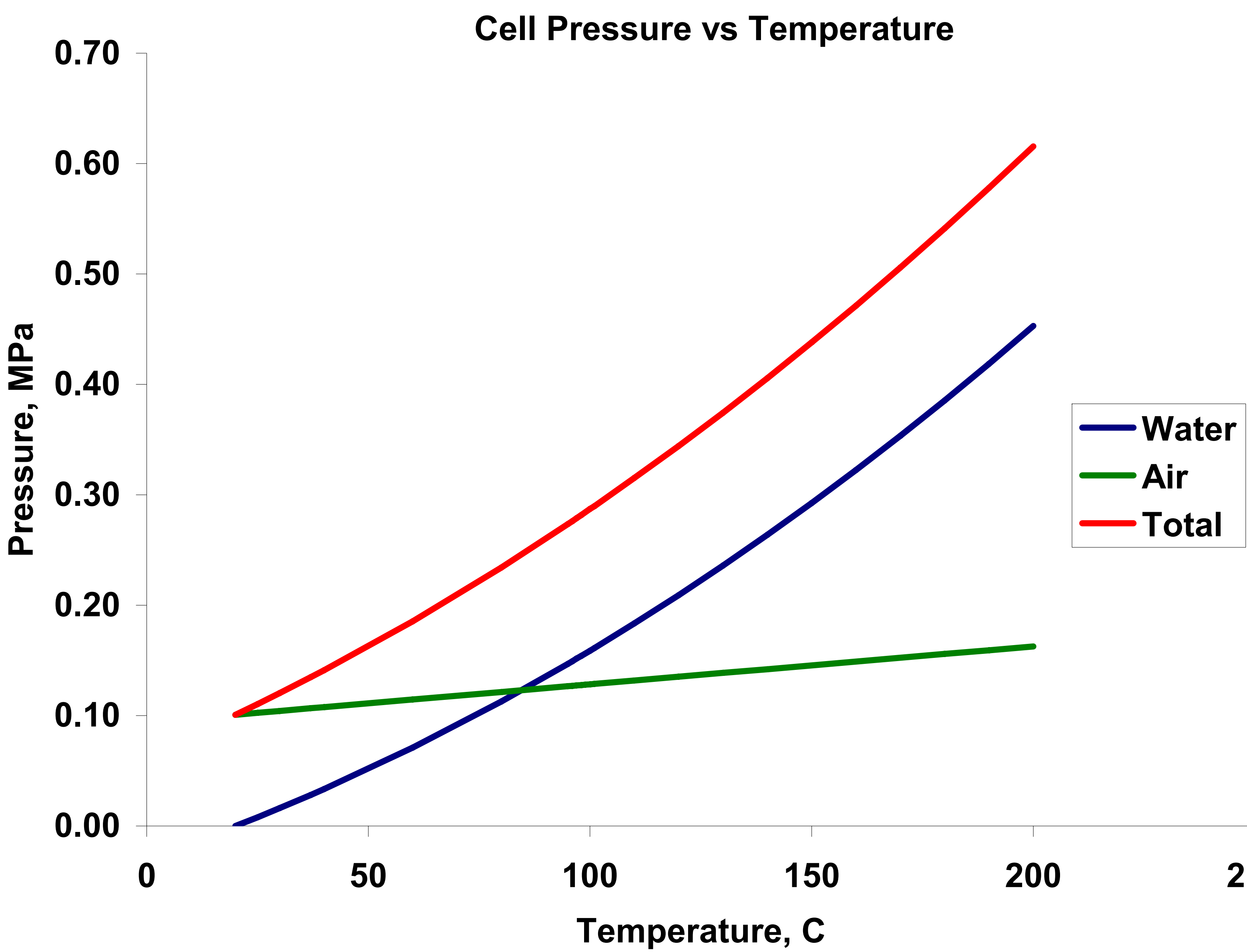


$$P = \sum p_i = \sum \tilde{\rho}_i RT$$

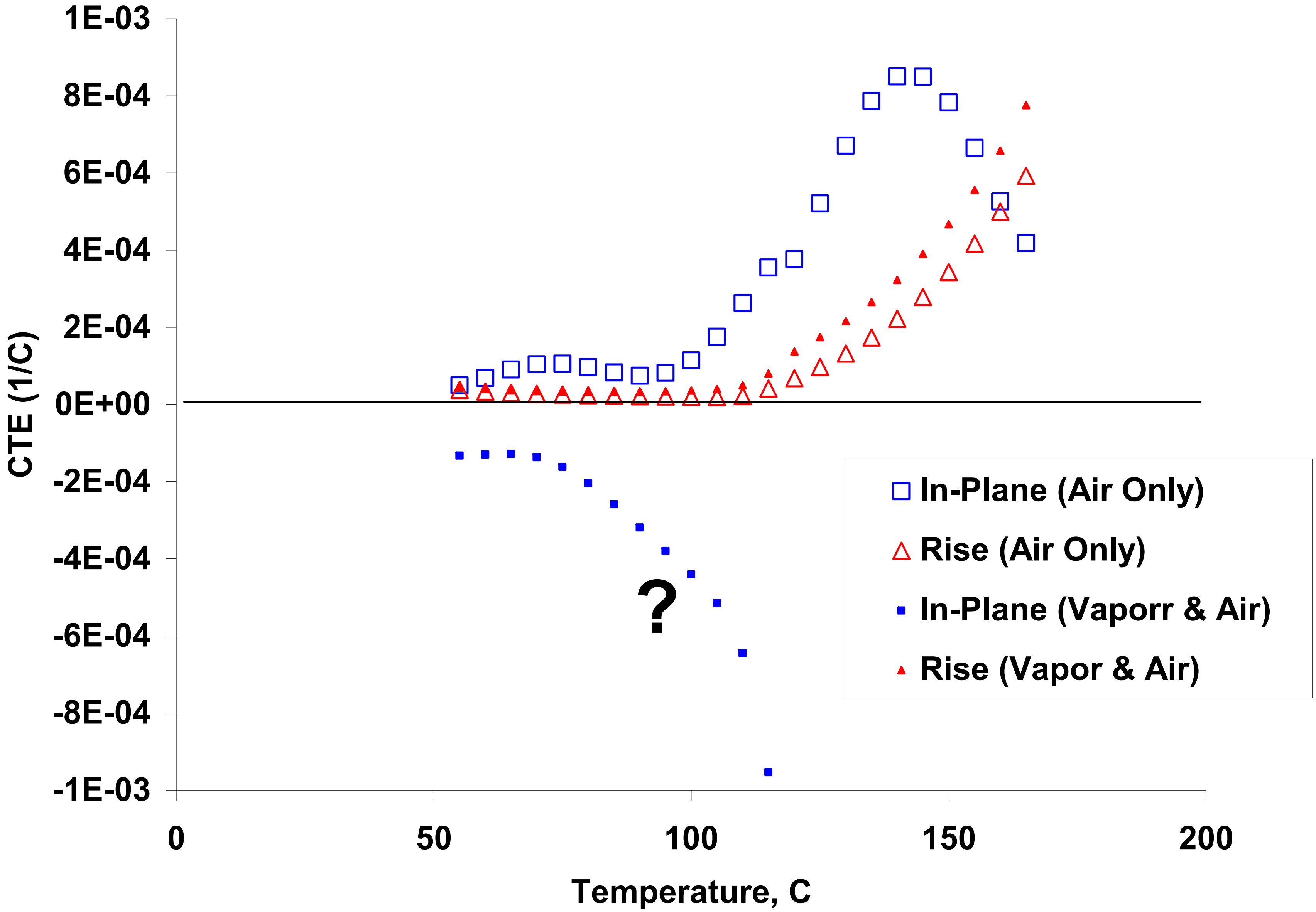
$\tilde{\rho}_i$, the molar density of the ith gas in the cells, given by

$$\tilde{\rho}_i = \tilde{\rho}_i^o + \int_t \frac{d\rho_{i,s}}{dt} dt$$

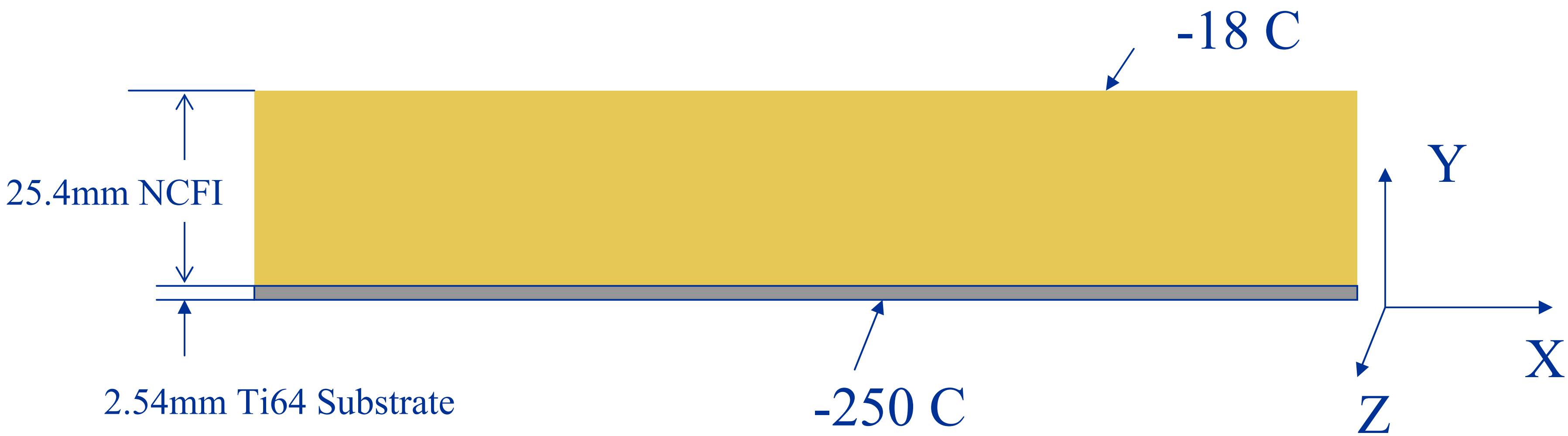


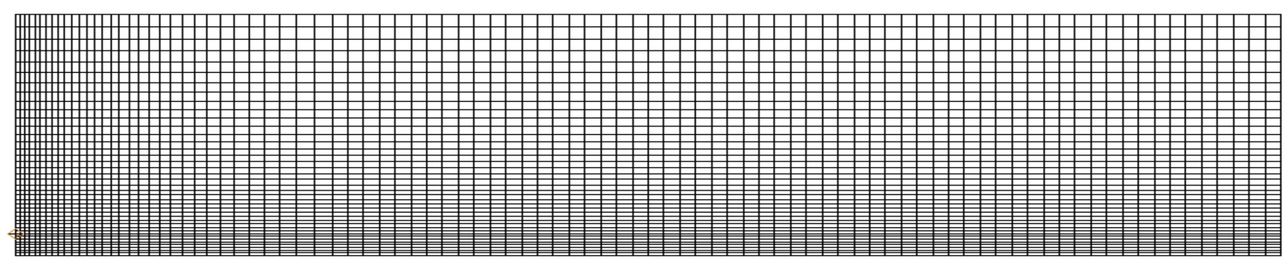

Cell Pressure vs Temperature
Pressure, MPa
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
50
100
150
200
250
Temperature, C
Water
Air
Total

Calibrated High temperature BX-265 CTE

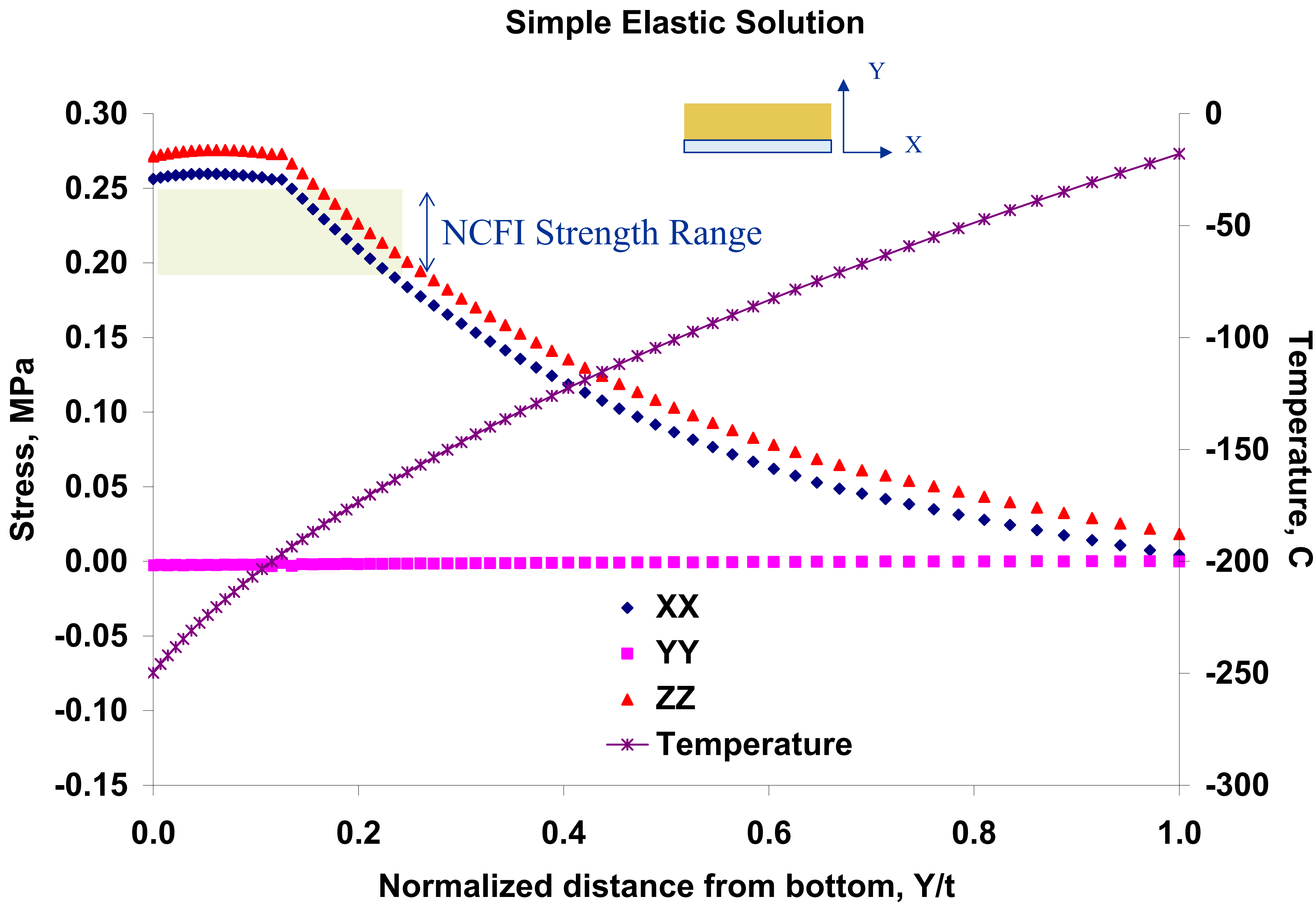


Simple Example to Determine the Advantage of the Porous Media Formulation



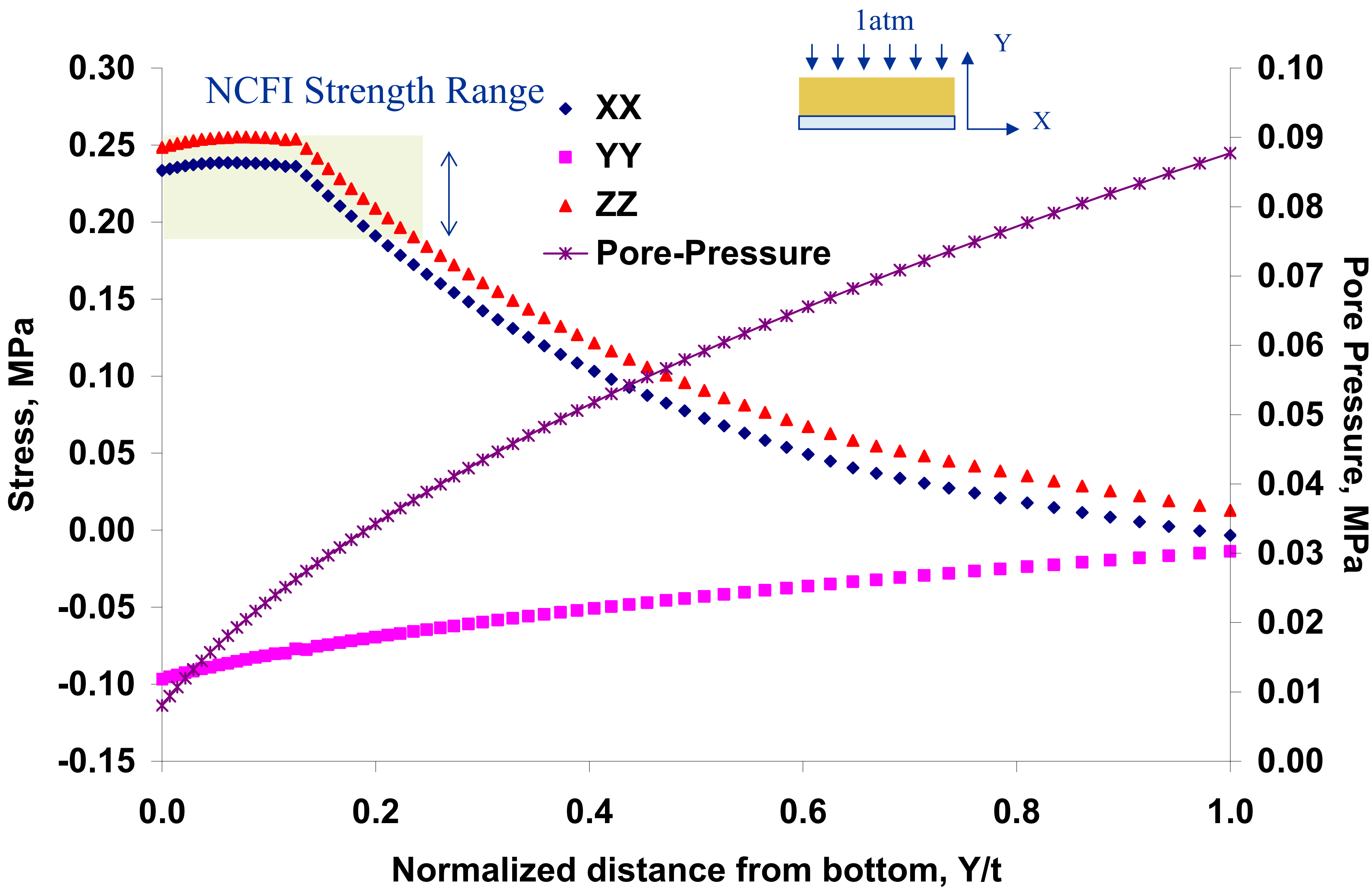


Foam through thickness stress profiles

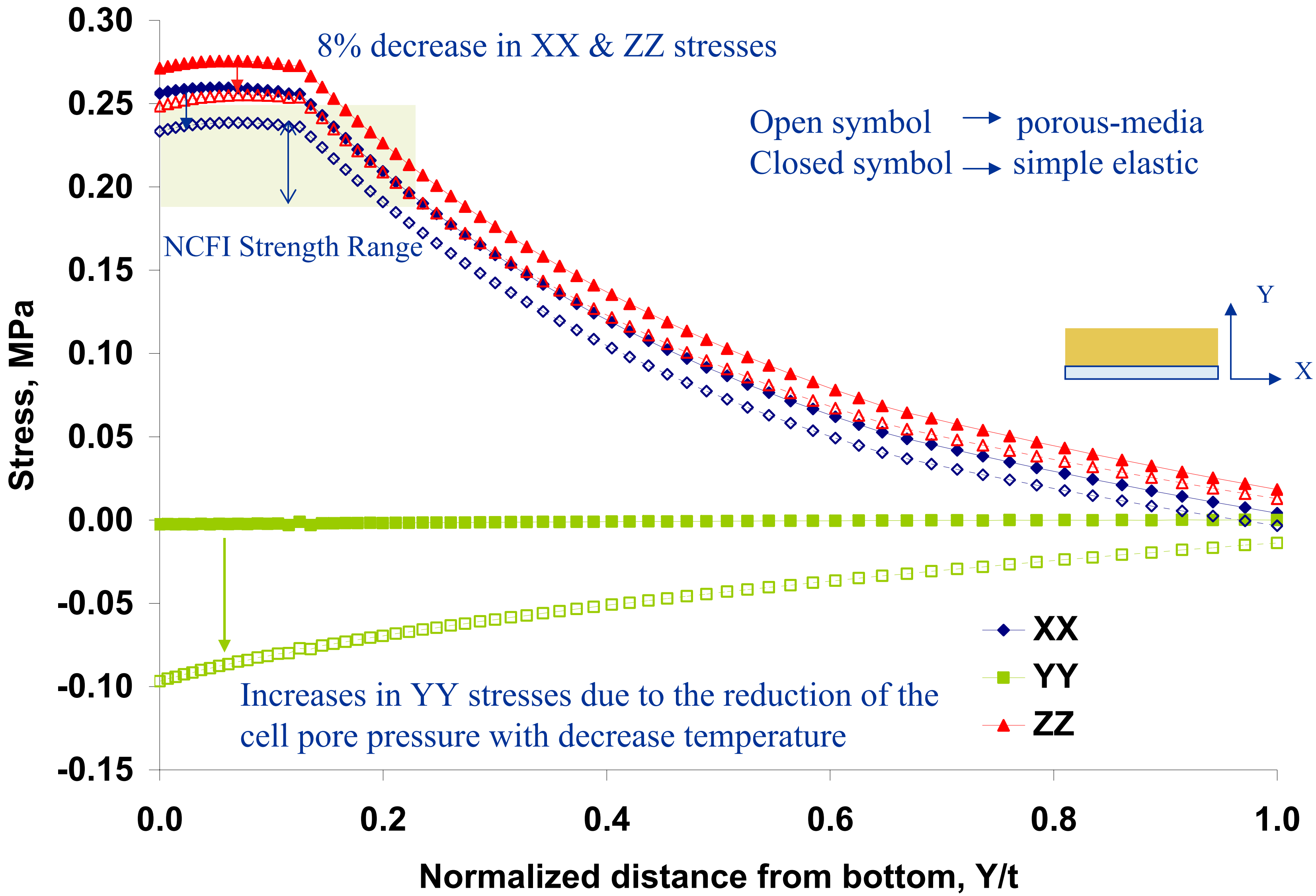


Foam through thickness stress profiles

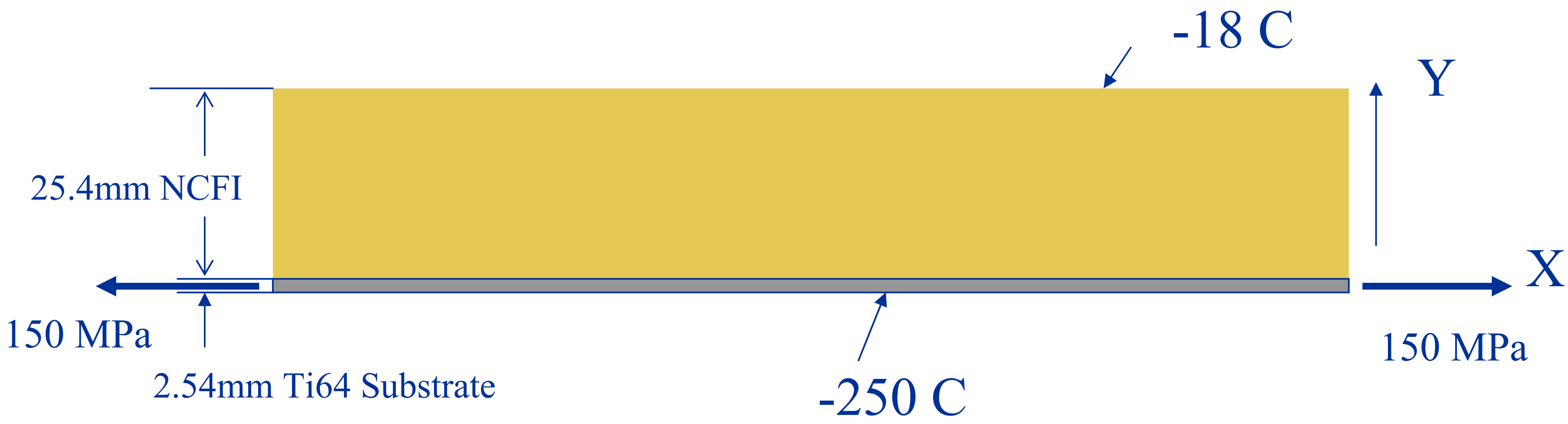
Porous Media Solution



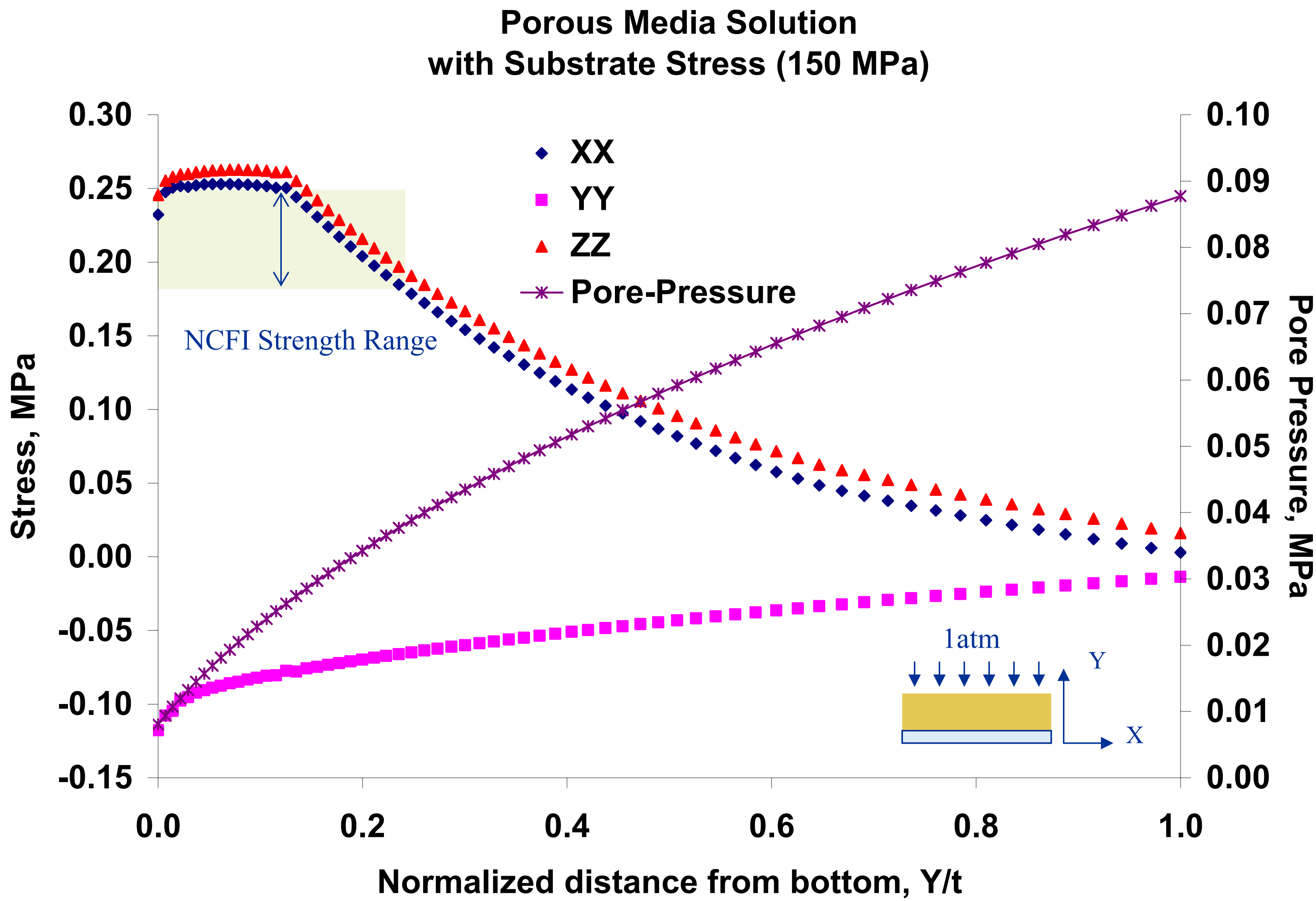
Comparison of the stress distribution between the two methods



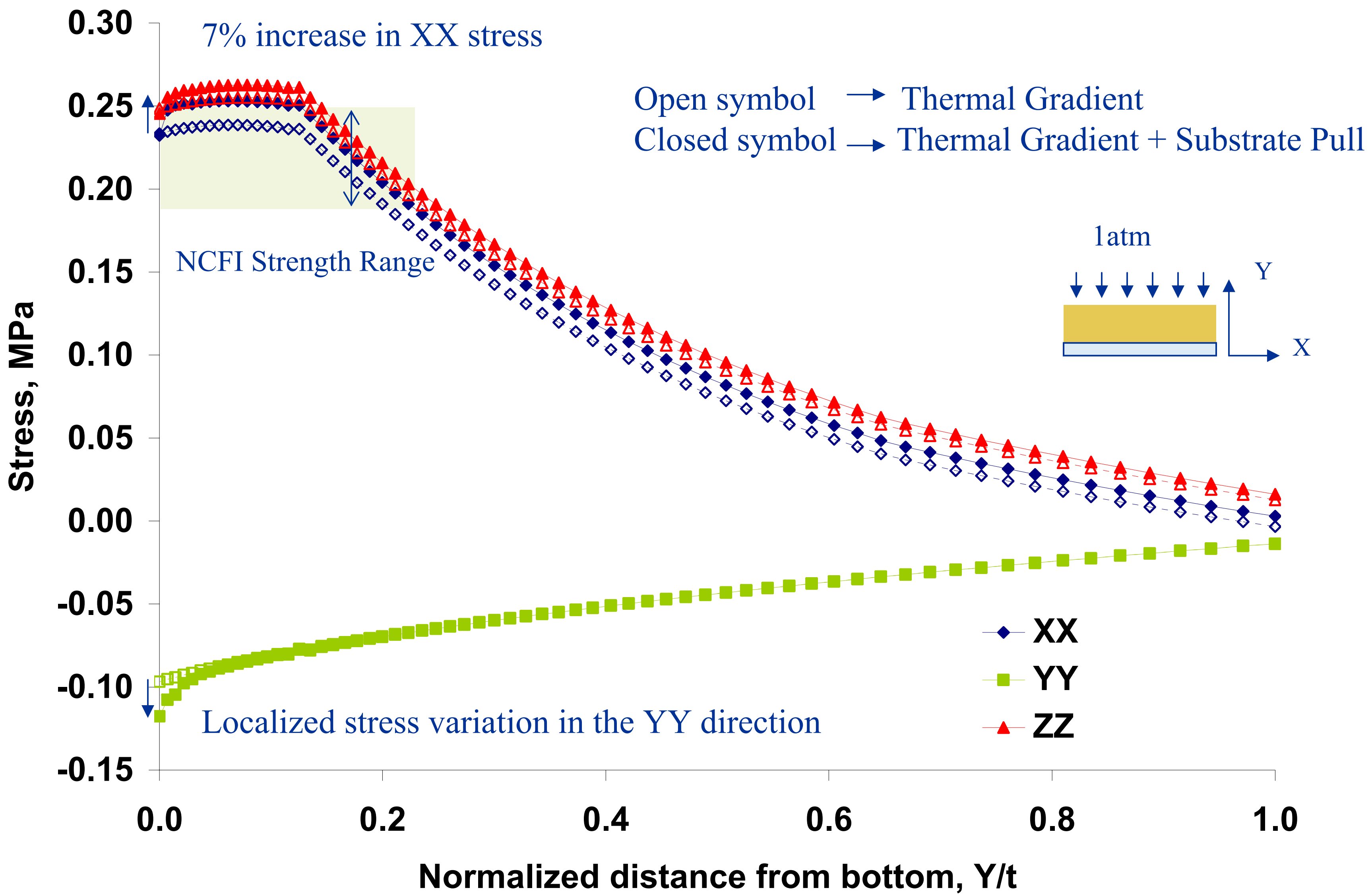
Thermal Gradient with Substrate Stress



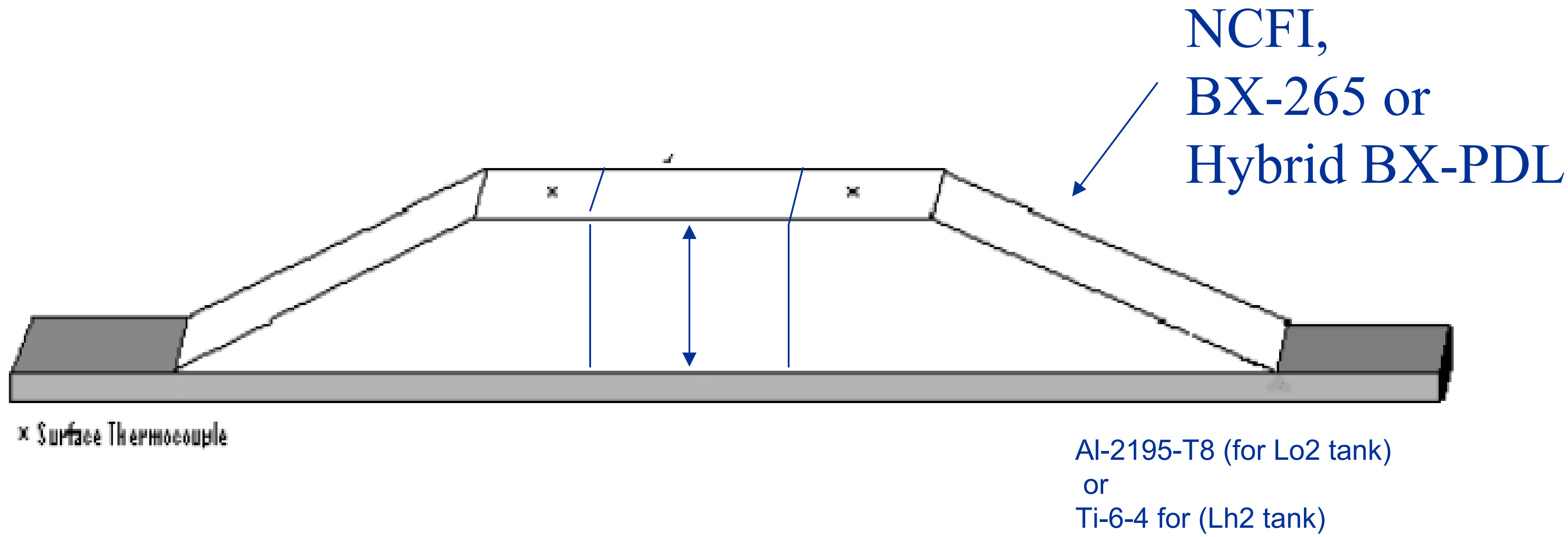
Foam through thickness stress profiles



Foam through thickness stress profiles



Modeling the Cryoflex specimen

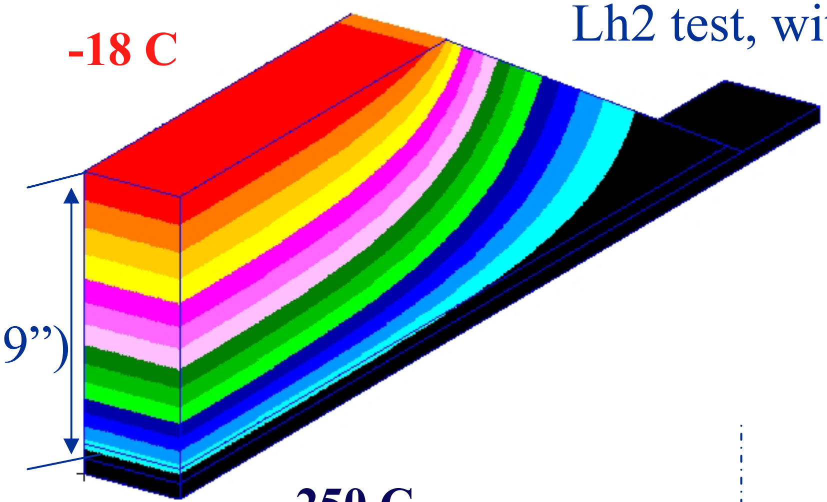


Temperature Profile for Gradient Test

Lh2 test, with Ti substrate

-18 C

5 cm (1.99")

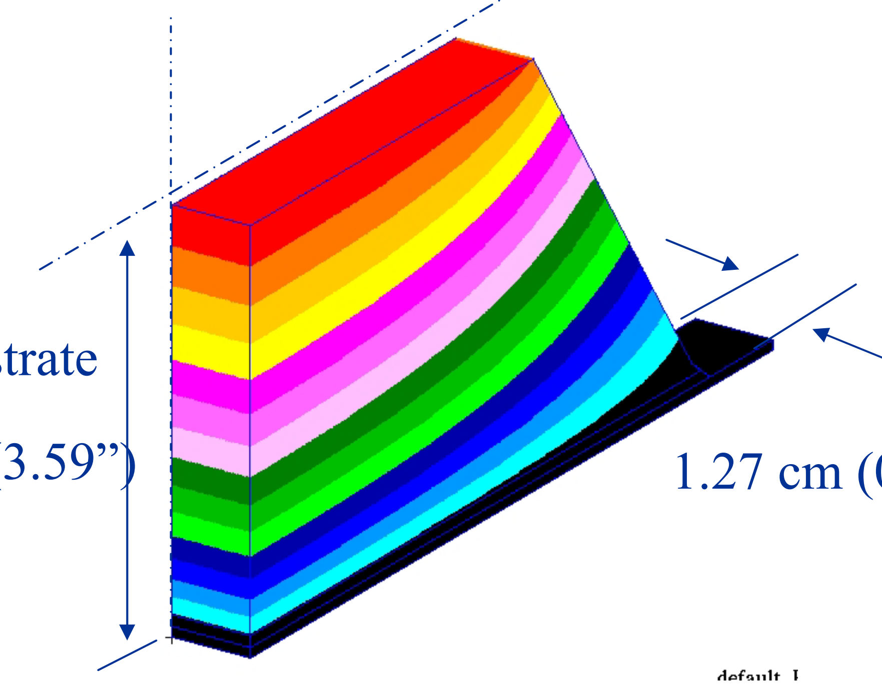


-250 C

Symmetry

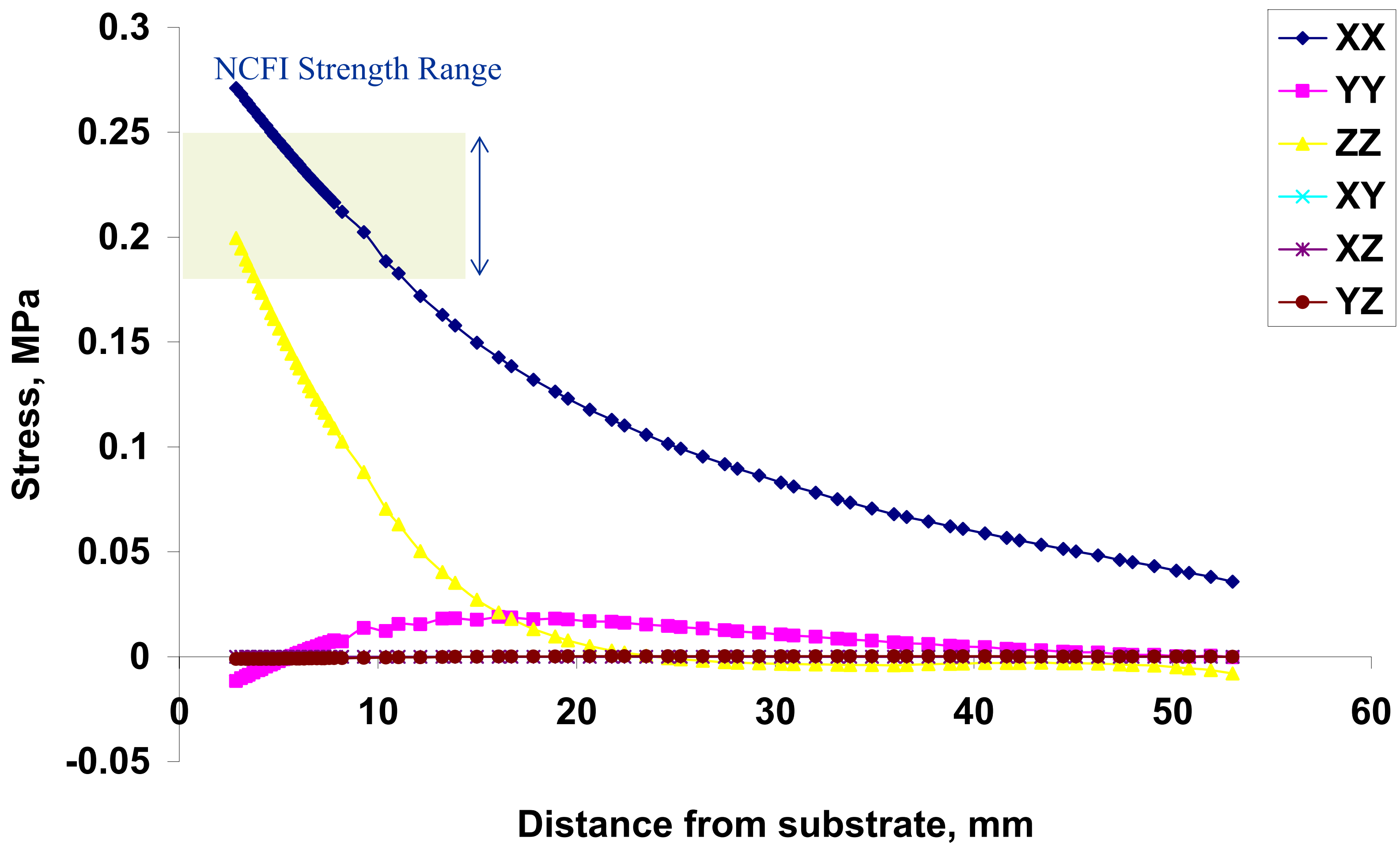
Lo2 test, with Al-2195-T substrate

9.2 cm (3.59")

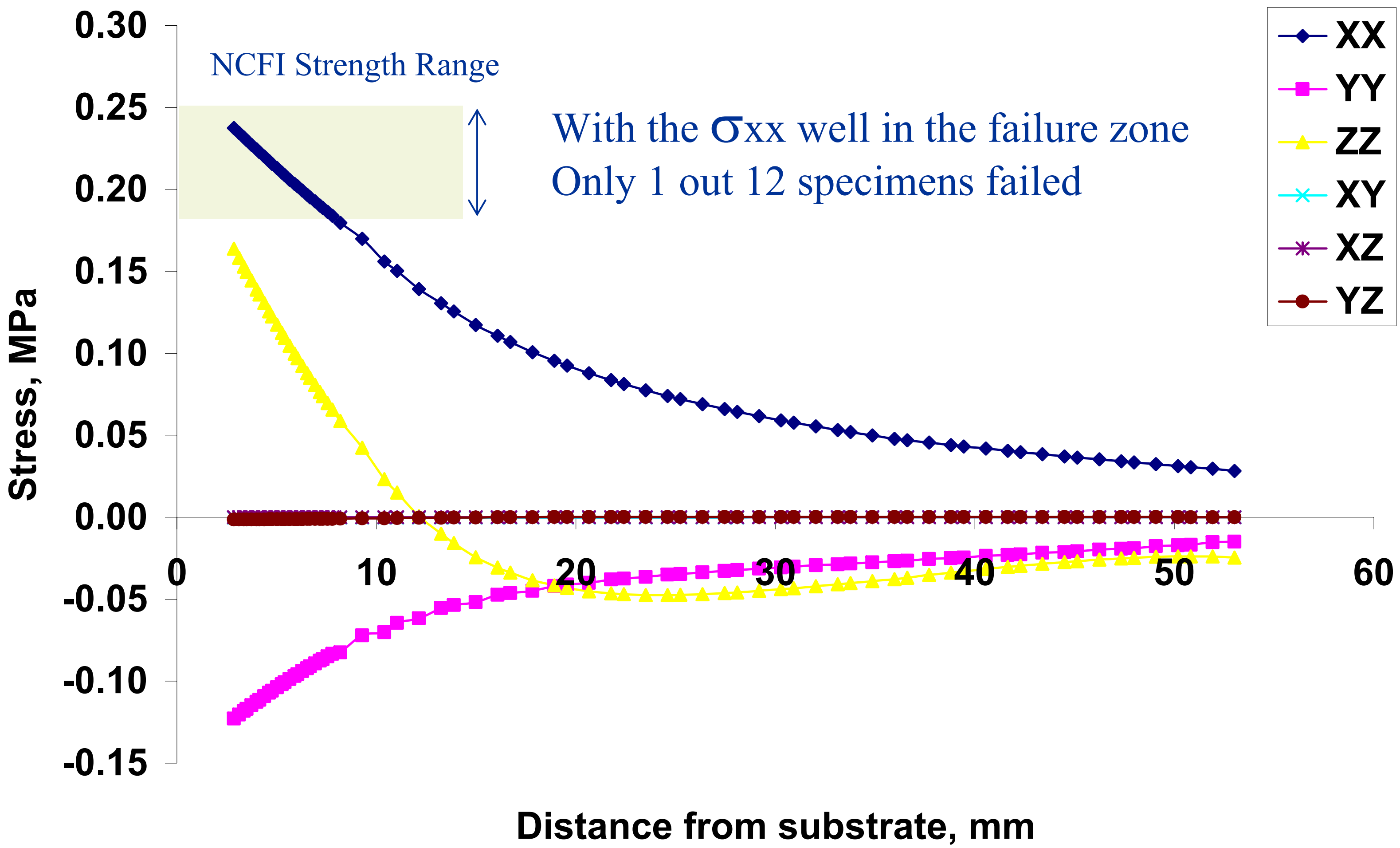


1.27 cm (0.5")

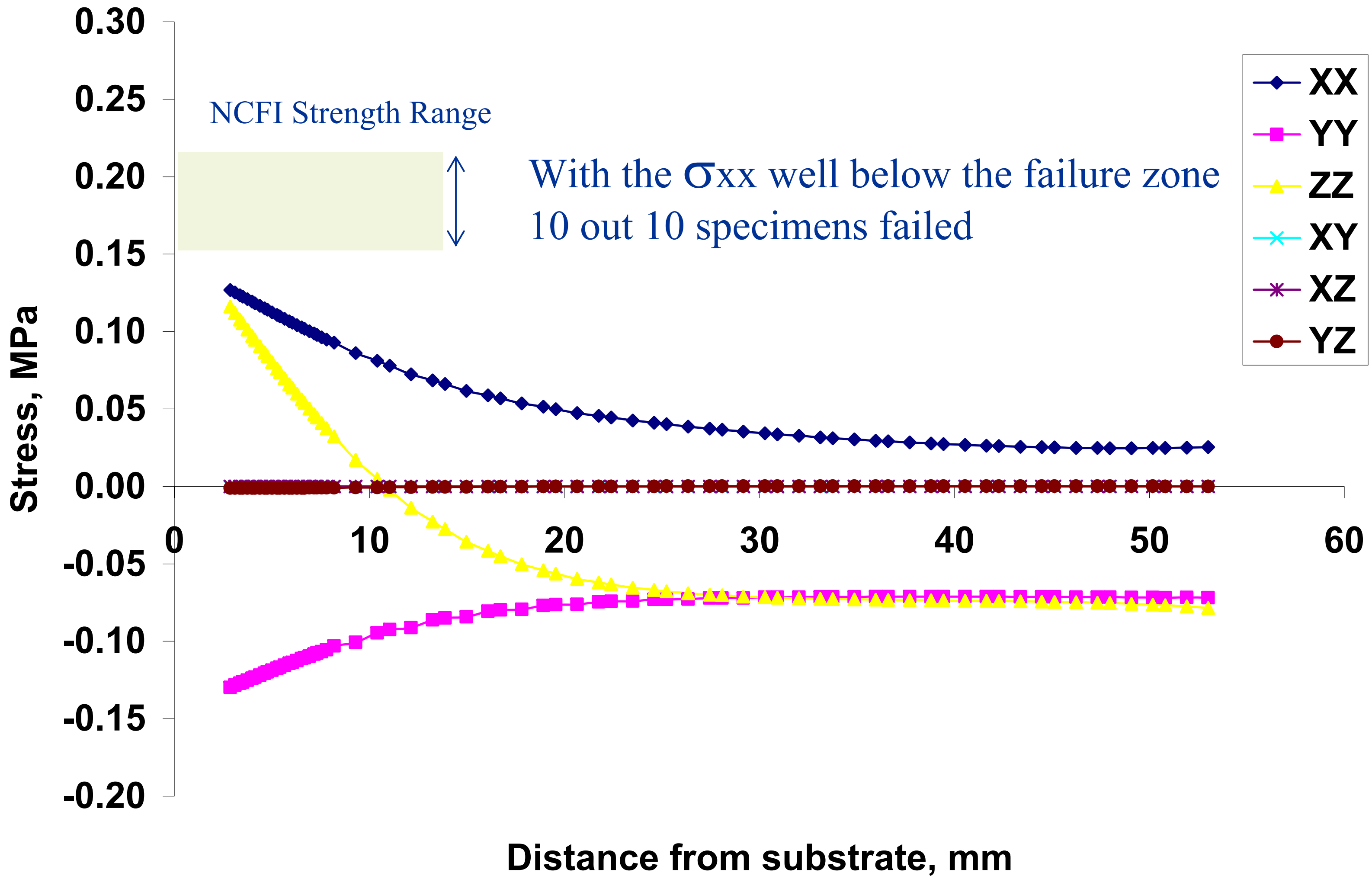
LH2 Gradient (@-17.8C to -245C, 950MPa)
No Slit, No Pore Pressure



LH2 Gradient (@-17.8C to -245C, 950MPa) No Slit, With Pore Pressure



LH2 Immersion (@-185C, 122MPa)
No Slit, With Pore Pressure



Transversely isotropic material, Hyper-elliptic failure function

$$a_1\left(\sigma_{11}^2+\sigma_{22}^2\right)+a_3\left(\sigma_{33}^2\right)+a_4(\sigma_{11}\cdot\sigma_{22})+a_5(\sigma_{11}\sigma_{33}+\sigma_{22}\sigma_{33})+a_7(\sigma_{11}+\sigma_{22})+a_9\sigma_{33}$$
$$+(2a_1-a_4)\sigma_{12}^2+a_{11}(\sigma_{13}^2+\sigma_{23}^2)=1$$

Summary

- The porous media approach was applied to three ET SOFI materials.
- The Anisotropic CTE tensors were derived to provide with good results for the strain variation as a function of temperature in vacuum.
- A high temperature CTE was derived based on TGA data showing an in-plane negative CTE.
- The implementation of the porous media into ABAQUS was outlined.
- The stress distribution of the cryoflex specimens were determined for the immersion and gradient tests.
- The maximum stress calculated was inconsistent with the experimentally observed failures.

Future Work

- Investigate the soundness of a negative in-plane CTE for BX-265
- Develop a failure criteria for the cryoflex specimen based on the experimental observation and FEA results