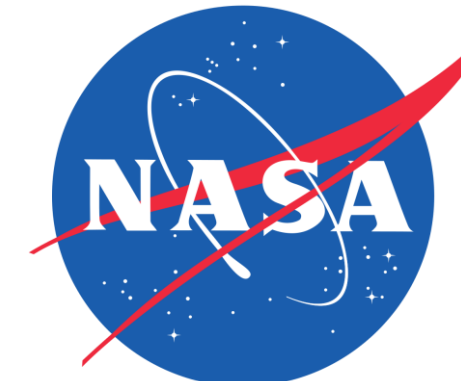


Updates to PATO's Thermo-Mechanical Model

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Stress Contributors in TPS Materials

During atmospheric entry, in addition to modeling the thermal response of Thermal Protection Systems (TPS), it's crucial to estimate the mechanical response to account for additional surface recession due to mechanical erosion and potential failure modes of the TPS materials. Several mechanisms contributing to stress in ablative heat-shields have been identified in literature over the past decades [1–3]:

- Shear forces and pressure from the flow field.
- Thermal expansion induced by the material's temperature field.
- Pyrolysis shrinkage of the material during decomposition.
- Internal pressure from pyrolysis gas trapped in the material.

How much each of these mechanisms contribute to the overall stress depends on the aerothermal environment and the TPS material used.

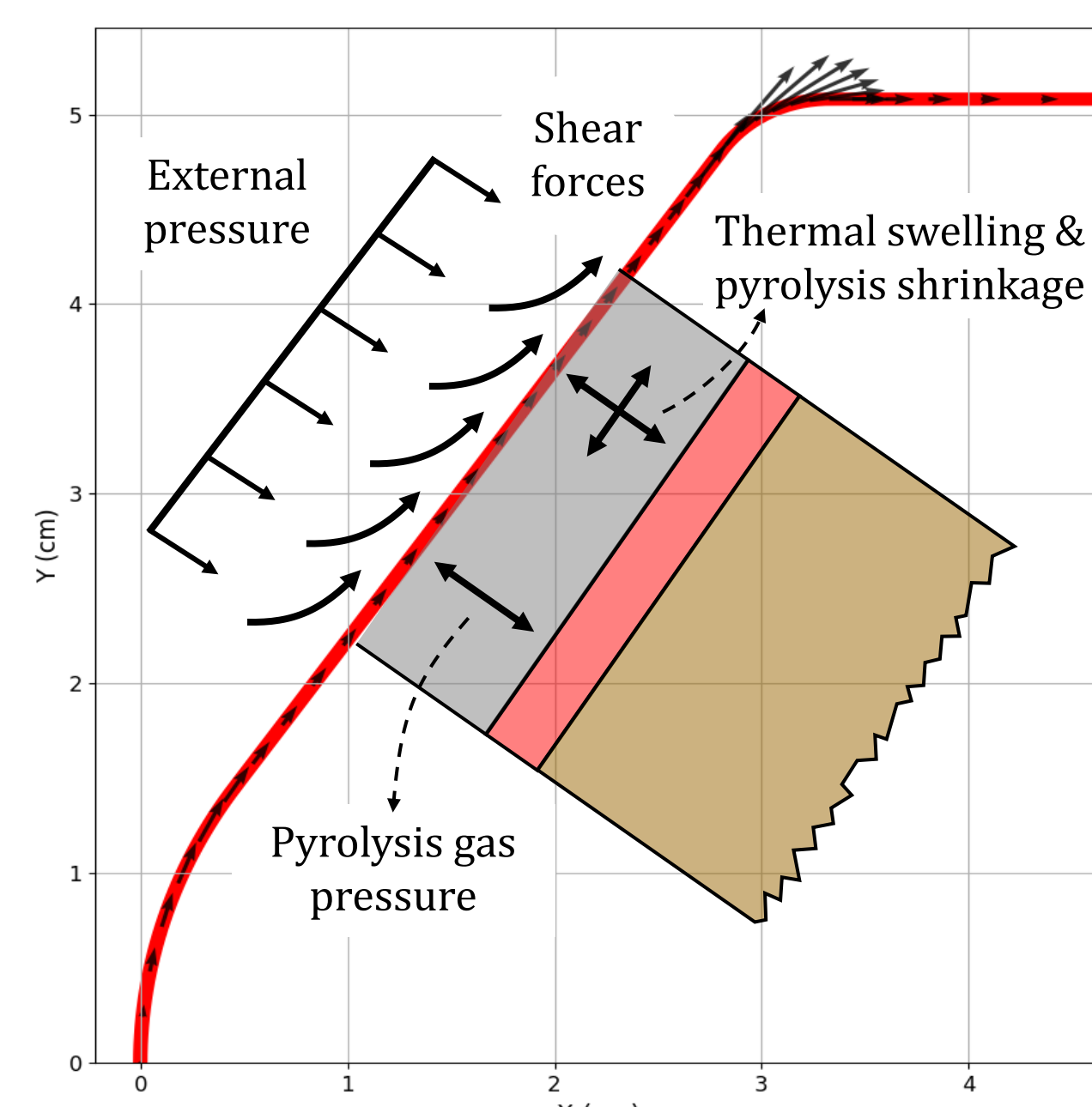


Fig. 1 Stress contributing mechanisms.

Solid Mechanics Model Updates

This poster presents the updates to the Porous material Analysis Toolbox based on OpenFOAM (PATO) [4] to account for all stress contributors and explains the modeling workflow utilizing experimental data to extract the material properties needed to model the thermo-mechanical behavior of the “AblationTestCase_2.x”, an ablative test case using equilibrium surface balance with the theoretical TACOT material [5].

The stress from pyrolysis gas is modeled by incorporating the internal pressure gradient into PATO's conservation of linear momentum equation. The internal pressure field is derived from PATO's Darcy's law solver.

The material's permeability and pyrolysis shrinkage can now be modeled as functions of Beta (degree of pyrolysis) using a tabular input, instead of linearly interpolating from virgin to char.

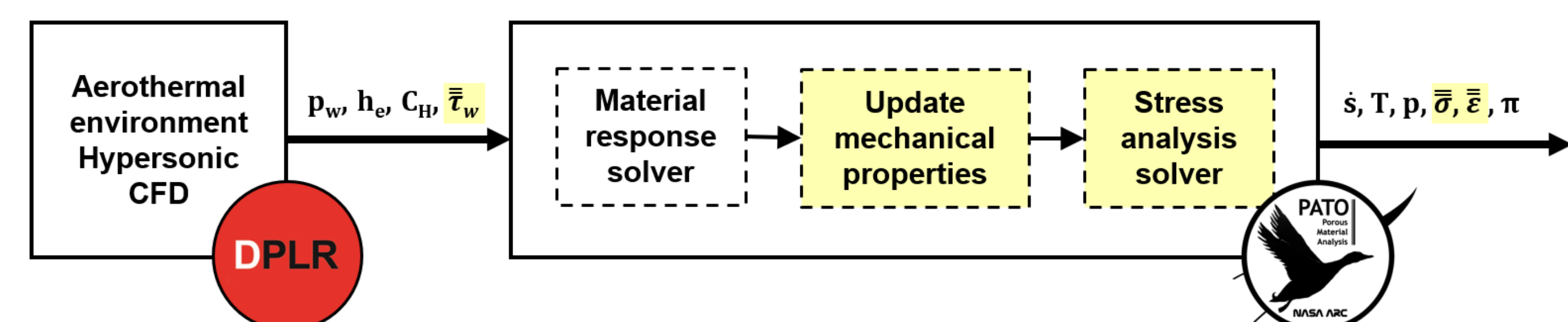


Fig. 2 Flow diagram of PATO's thermo-mechanical coupling.

Expansion and Shrinkage Modeling

TPS swelling and shrinkage behaviors are driven by the following phenomena:

- Thermal expansion which is intrinsic to any material – $F(T)$
- Pyrolysis shrinkage due to material decomposition – $F(Beta)$
- Material swelling due to pyrolysis gas trapped in the material – $F(\nabla p)$

These mechanisms are independently modeled in PATO.



Fig. 3 RTV-560 cylindrical sample heated to ~773K.

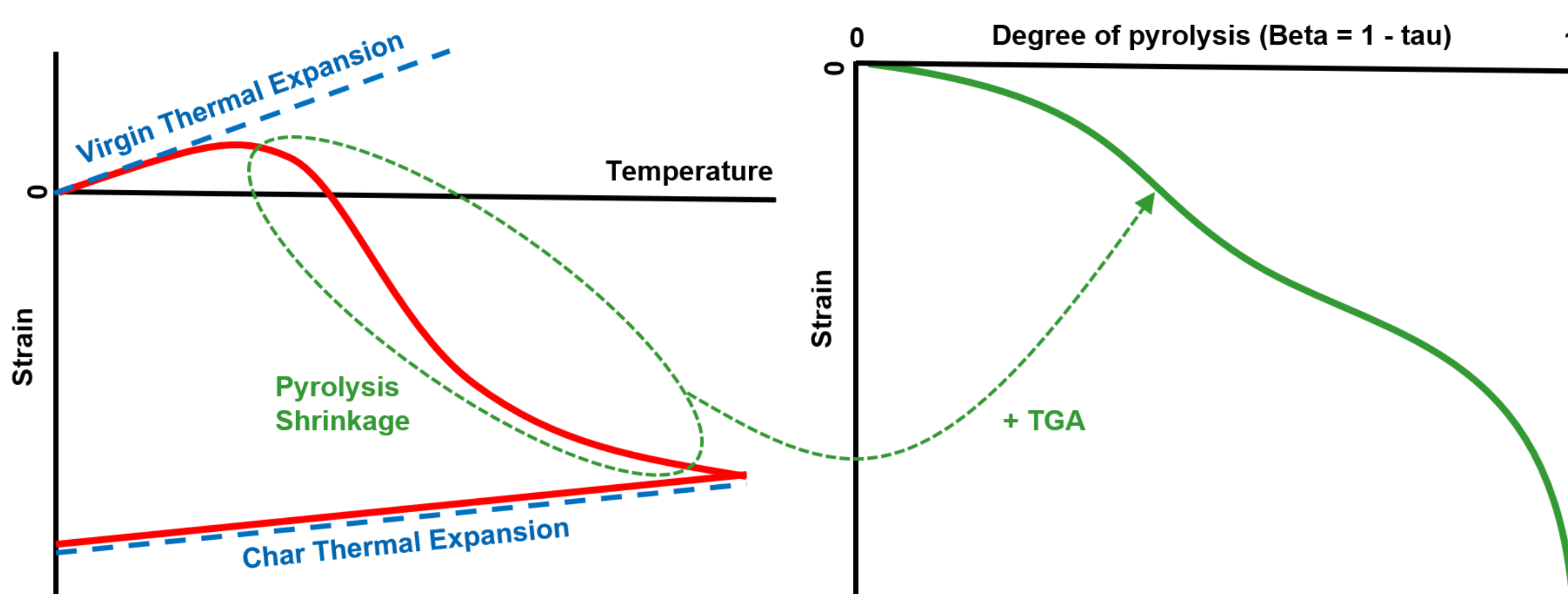


Fig. 4 Typical TPS dilatometry data used to extract the thermal expansion coefficients (left) and pyrolysis shrinkage as function of Beta obtained by combining dilatometry with material's TGA data (right).

Mechanical Properties and Permeability Model

Considering that TACOT is a theoretical material inspired by low density carbon/phenolic ablators, a Young modulus of 150 MPa [6] that decreases at high temperatures, and a constant Poisson's ratio of 0.3 were used as mechanical properties.

In addition, to assess the relevance of the stress contribution from the internal pressure, a study was conducted using four material models with different permeabilities as function of Beta. The results of this study are shown in the final section of this poster.

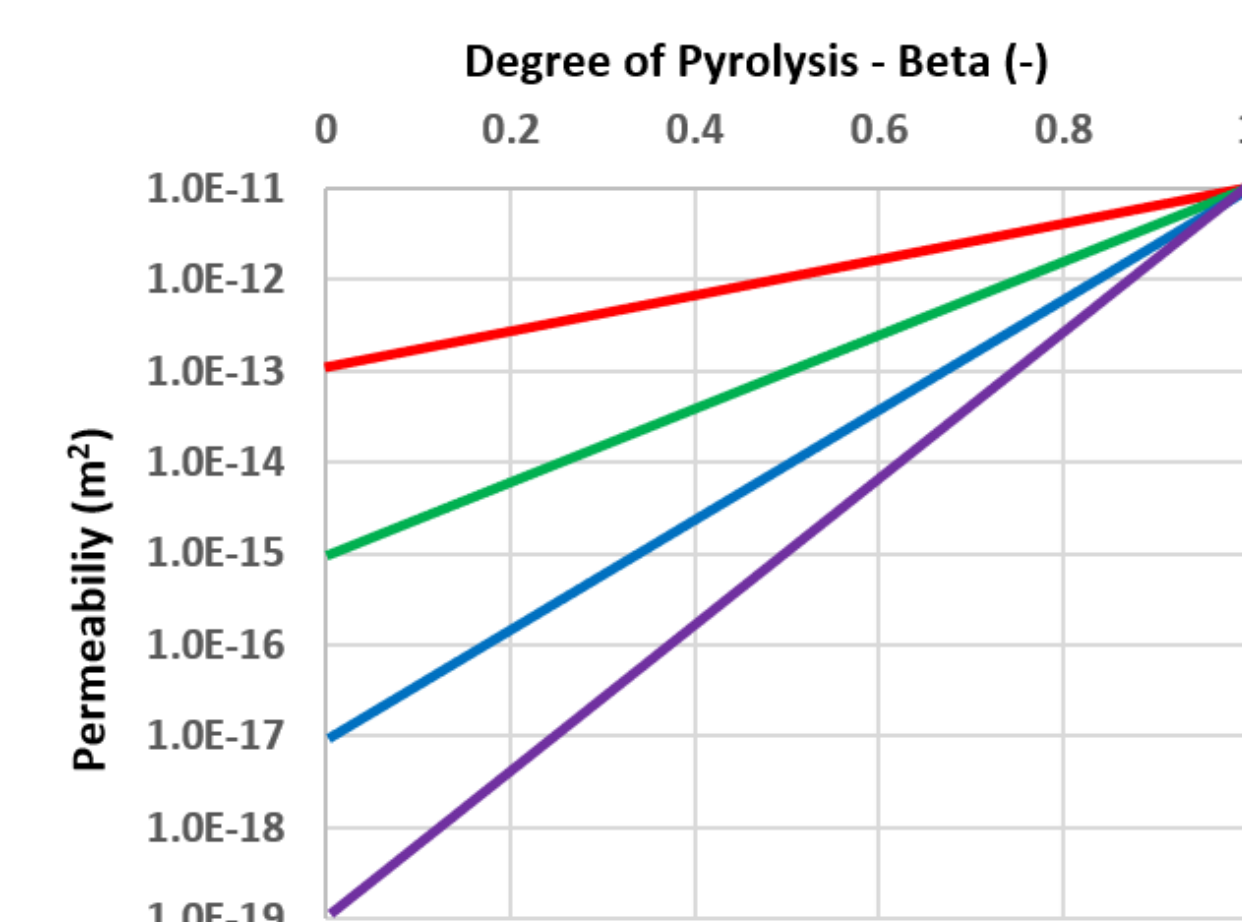


Fig. 5 Permeability cases studied.

Thermo-Mechanical Results

PATO's tutorial case “AblationTestCase_2.x” was run for the virgin permeability case $K=10^{-15}$ with the different stress contributing physics turned ON and OFF to assess their impact in the material's stress field. The results displayed below correspond to the timestep 40 seconds.

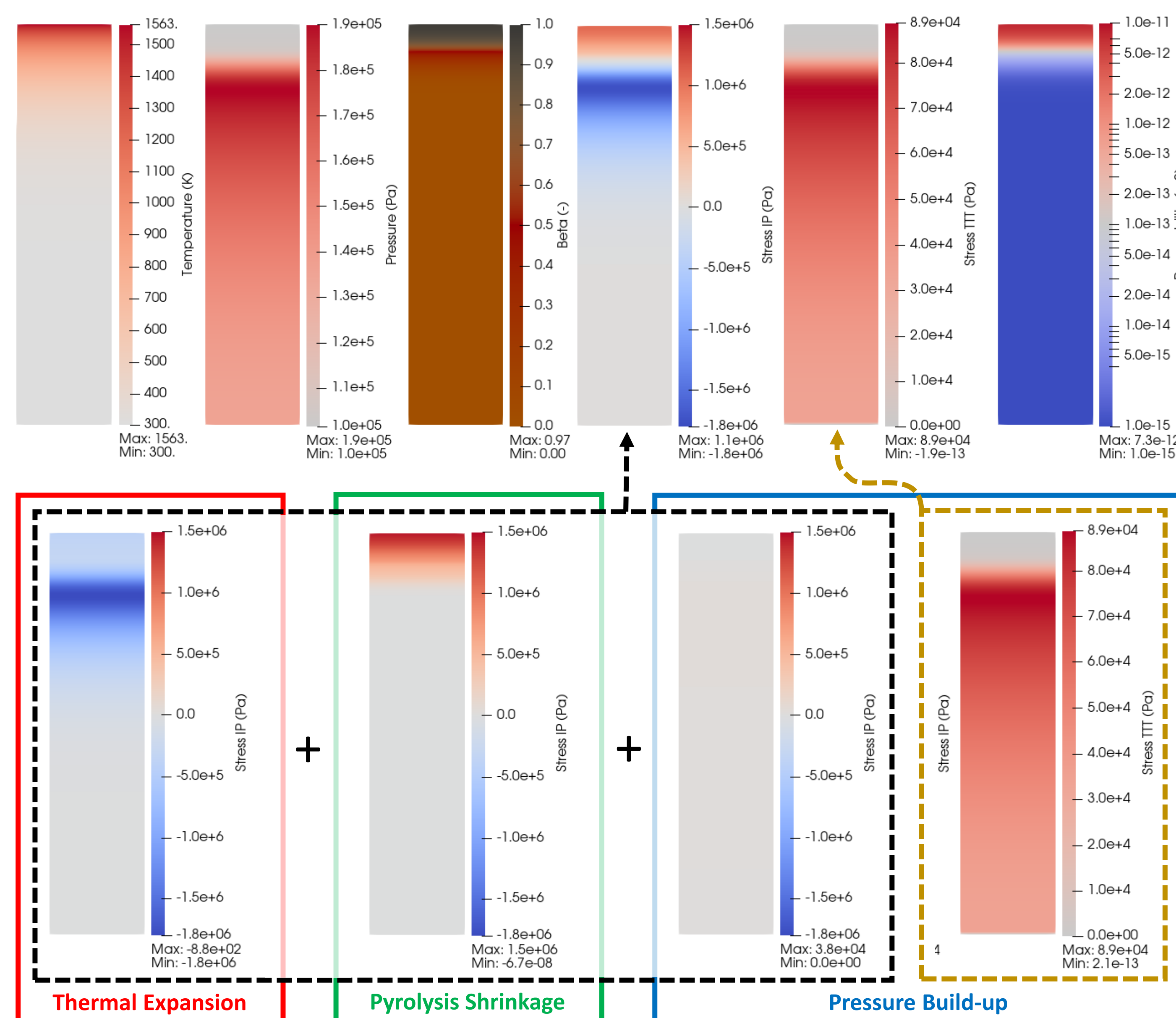


Fig. 6 Temperature, pressure, Beta, stress in-plane/through-the-thickness (IP/TTT) and permeability fields from “AblationTestCase_2.x” accounting for all stress contributing mechanisms (top) and from each mechanism independently (bottom).

Effect of Permeability on TTT Stress

Permeability have a significant impact on the mechanical behavior of TPS materials during atmospheric entry. If the permeability is too low, the material will be unable to outgas pyrolysis decomposition products, leading to increased localized internal pressures that result in additional stress. This tensile stress would primarily be in the TTT direction but would also introduce in-plane shrinkage through the Poisson's ratio.

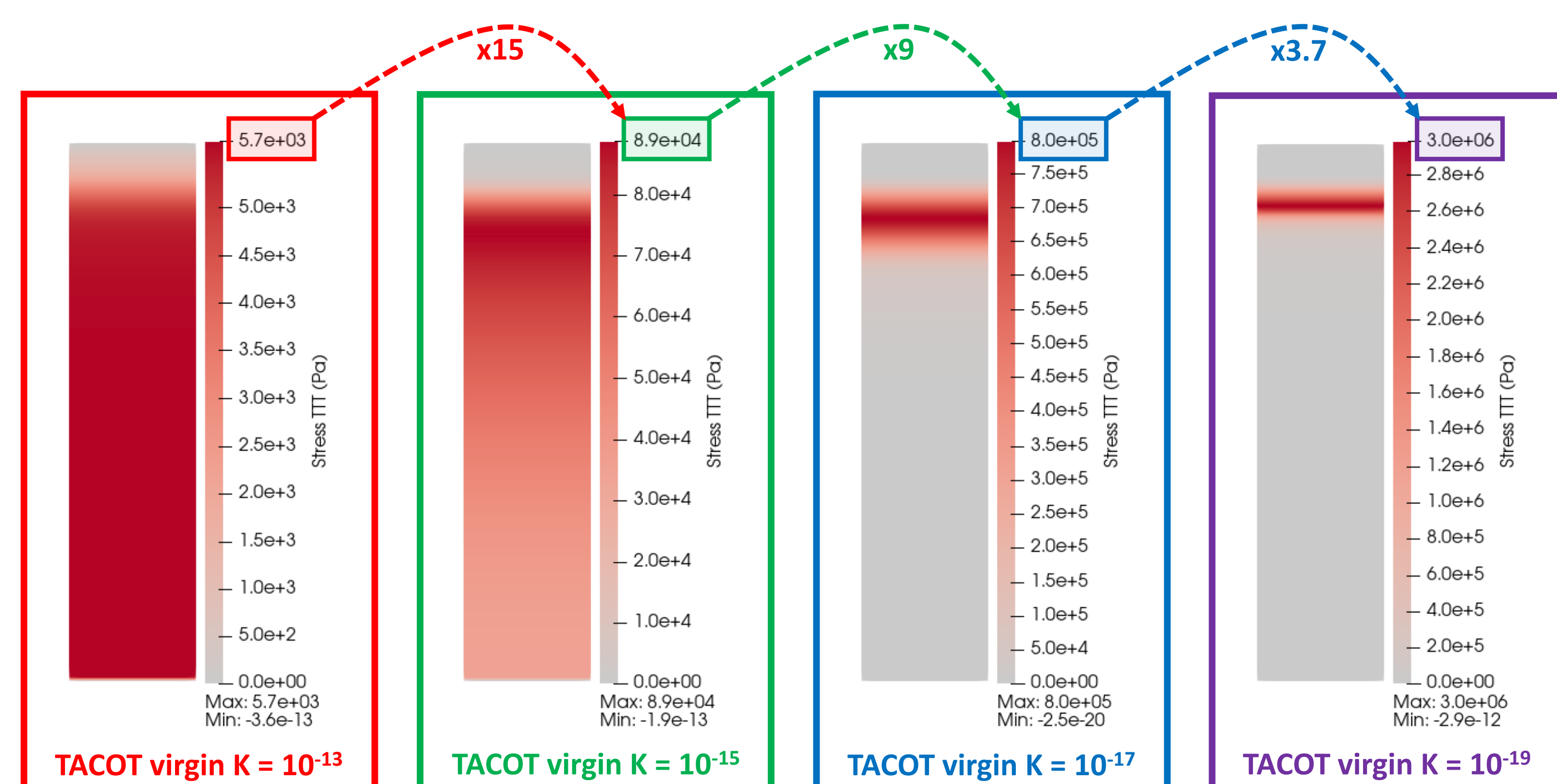


Fig. 7 Through-the-thickness stress for the four TACOT material models analyzed with different permeability (K) values using “AblationTestCase_2.x” tutorial case.

References

- [1] P. J. Schneider *et al.* (1968), *AIAA Journal*.
- [2] J. Sullivan *et al.* (1987), *22nd Thermophysics Conference*.
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- [5] J. Lachaud *et al.* (2012), *5th Ablation Workshop*.
- [6] P. Agrawal *et al.* (2011), *AIAA Thermophysics Conference*.