Multiphysics Modeling of CO_2 Gas Flowing in High-Pressure Pipelines

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MOTIVATION

- **Limitations of Traditional Models:** The Battelle Two-Curve Model (BTCM), widely used for fracture control, gives non-conservative predictions for modern steels and CO_2 mixtures as it neglects fracture propagation, multiphase decompression, and soil–pipe interactions.
- **Need for Advanced FSI Approaches:** FSI models provide a more realistic view of ductile fracture, capturing pipe deformation, fluid decompression, and backfill effects—crucial for safe and reliable CO_2 pipeline design.

THEORETICAL BACKGROUND

- Yield function

$$f(\sigma,k) = (\bar{\sigma} - k) = \sqrt{(P\sigma) * \sigma} - k = 0$$

- Deformation resistance (k)

$$k(\bar{\epsilon}_p, \dot{\bar{\epsilon}}_p, T) = k(\bar{\epsilon}_p) f(\dot{\bar{\epsilon}}_p) f(T)$$

- Critical equivalent plastic strain to fracture initiation

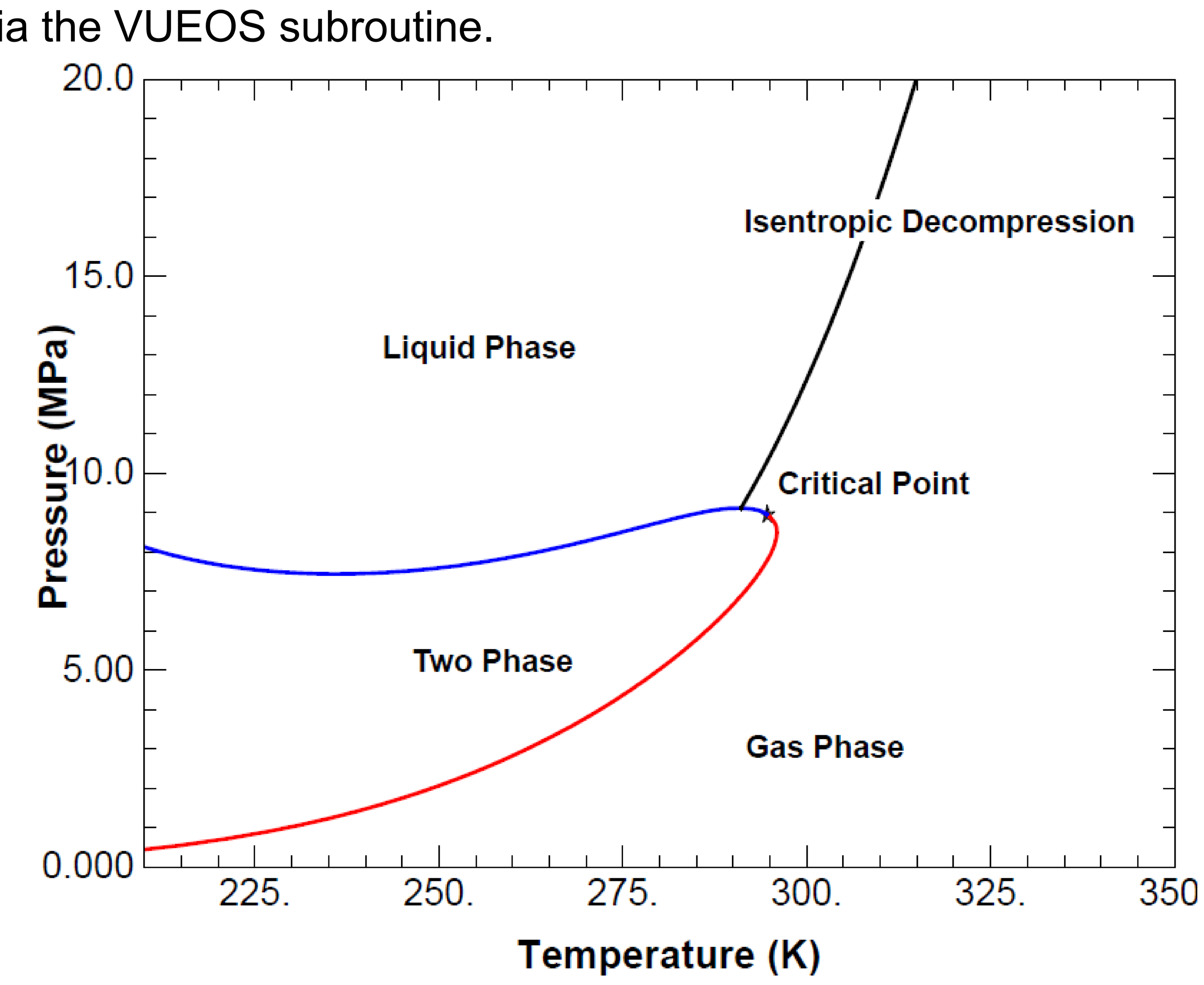
$$\hat{\epsilon}(\eta,\bar{\theta}) = \{\frac{A}{c_2}[c_3 + f_I(\bar{\theta})][c_1 + f_{II}(\eta,\bar{\theta})]\}^{-\frac{1}{n}}$$

- Damage model (linear damage accumulation law and softening variable)

$$D = \int_0^{\bar{\epsilon}_p{}^f} \frac{d\bar{\epsilon}_p}{\bar{\epsilon}_p{}^f(\eta,\bar{\theta})}, \qquad \omega = \left(\frac{D_c - D}{D_c - D_0}\right)^h$$

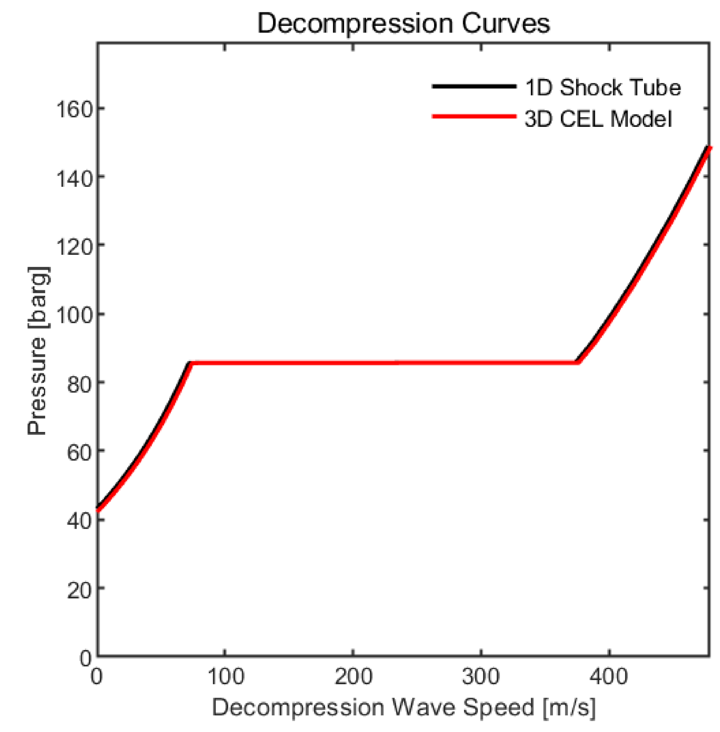
CO_2 Modeling

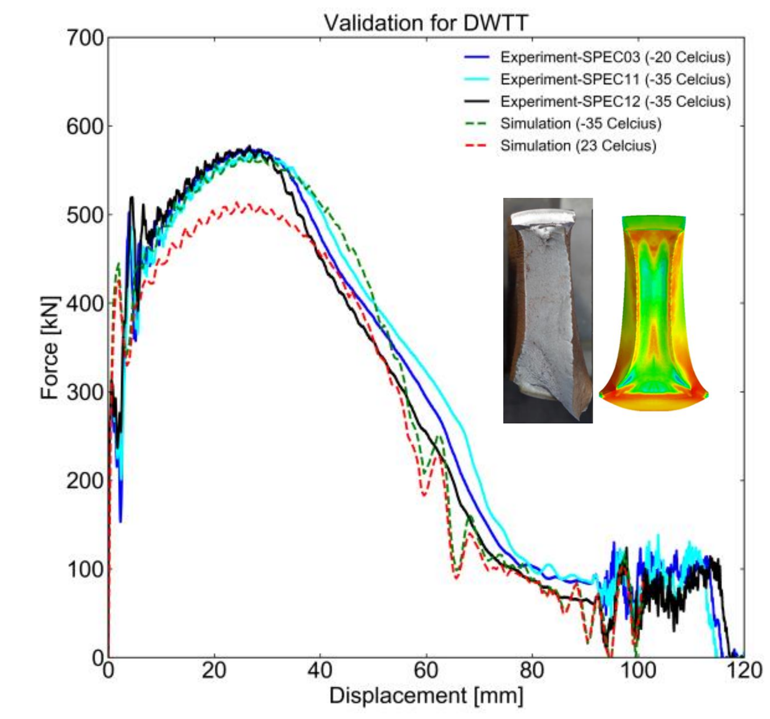
- The GERG-2008 EOS was implemented for CO_2 mixture modeling via the VUEOS subroutine.



CALIBRATION / VALIDATION

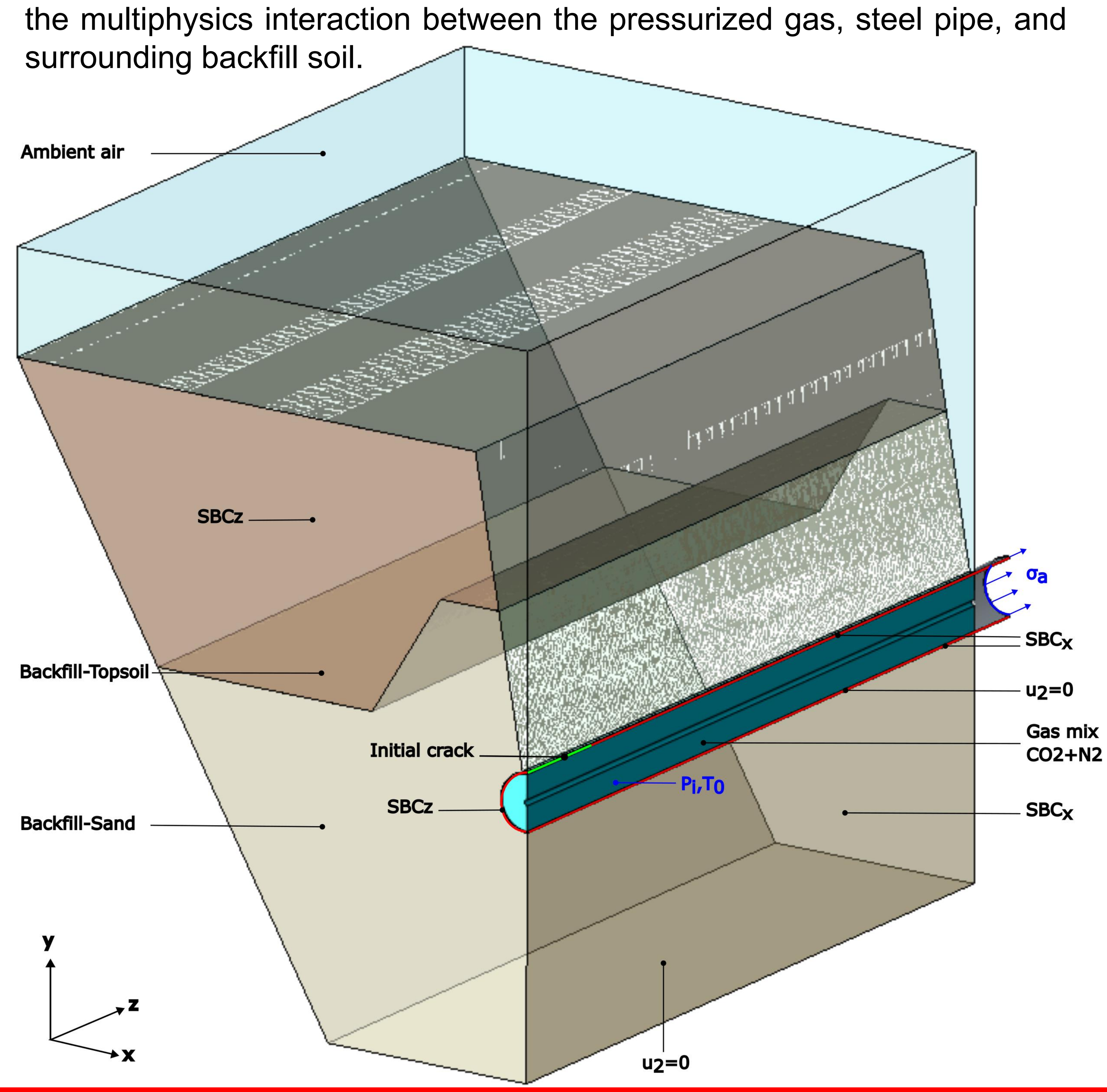
- Model parameters were calibrated using custom-made geometry samples subjected to various loading modes (tension, compression, and shear) in conjunction with finite element simulations. Validation was conducted against experimental Drop Weight Tear Test (DWTT) and Charpy impact (CV) test results , and decompression wave speeds were validated against shock tube measurements assuming w.



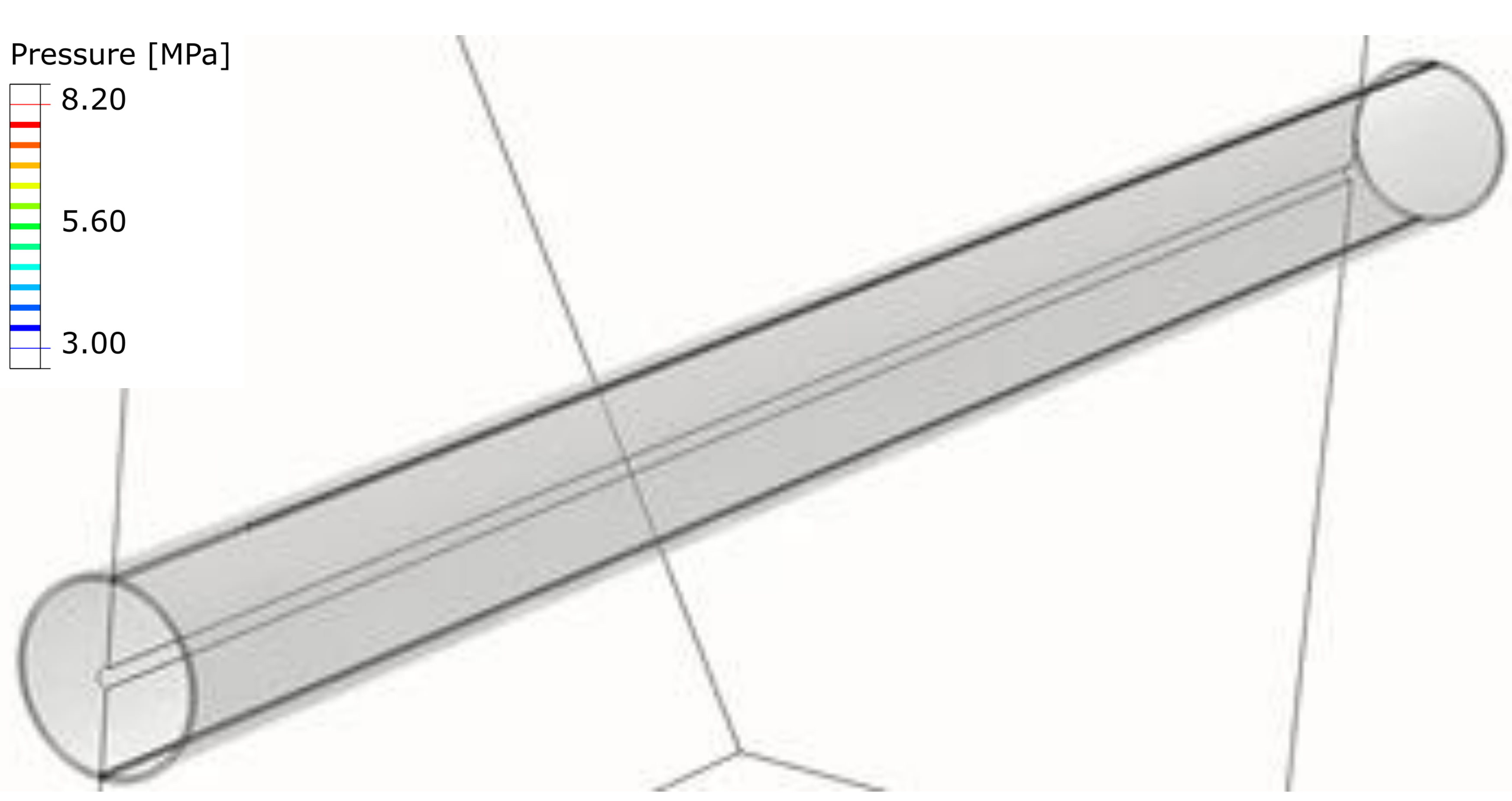


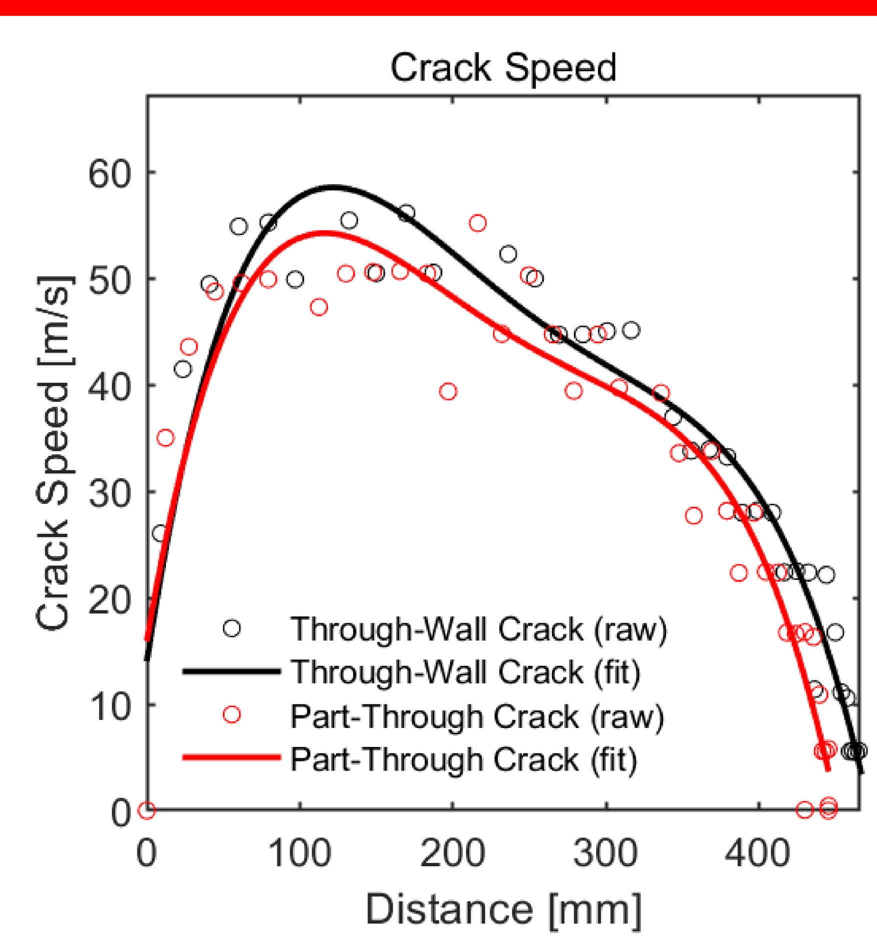
Model Set-up

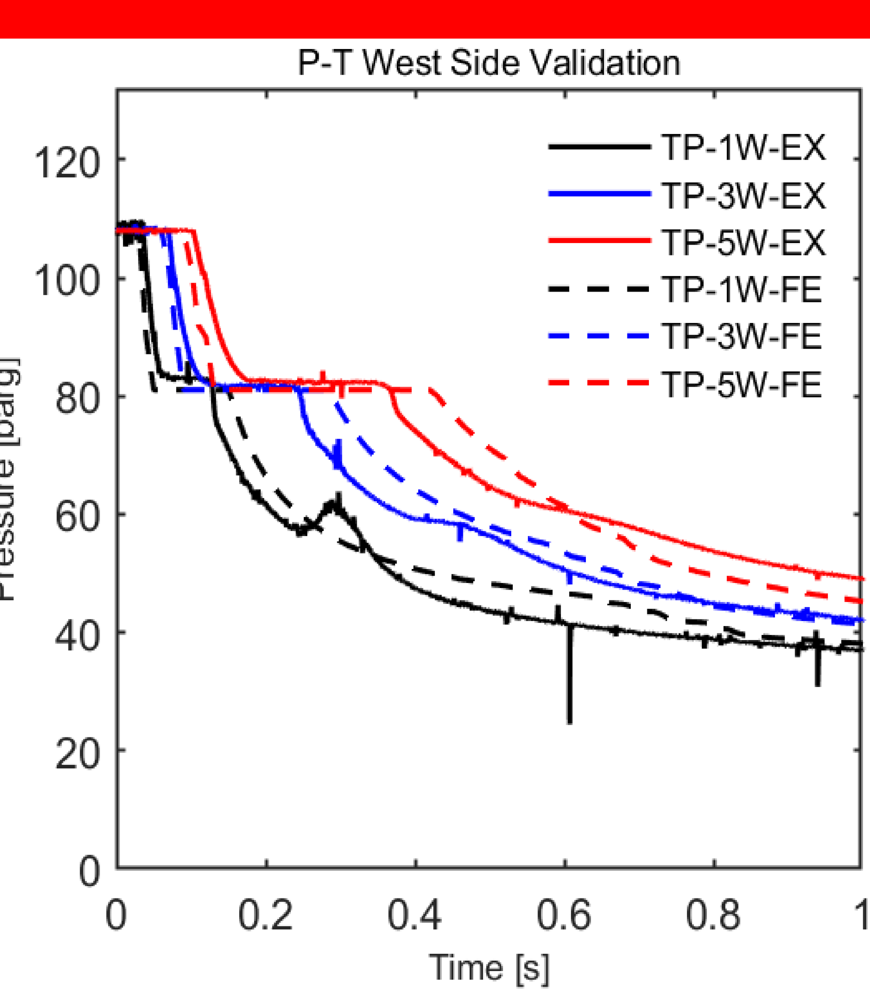
- A Coupled Eulerian–Lagrangian (CEL) model was developed to capture the multiphysics interaction between the pressurized gas, steel pipe, and surrounding backfill soil.



Results







Computational Resources

- The phenomenological material model was implemented in **Abaqus** through VUMAT subroutine.
- The simulation was executed on the **HPRC Grace cluster**, utilizing **one node** with **48 CPU cores** and **360 GB of memory**, processing **approximately 1.17 million elements** over a **7-day runtime**.

Conclusion

- The developed CEL approach accurately captured crack arrest behavior with excellent agreement to full-scale burst test (FSBT) observations, demonstrating high predictive fidelity.
- The multiphysics coupling between gas, steel pipe, and backfill soil was effectively resolved, accurately capturing the fluid–structure interaction between ductile crack propagation and decompression behavior.
- The integrated multiphysics framework provides a robust foundation for future parametric studies and optimization of pipeline integrity under varying soil and gas conditions.