Metallurgy and Material Considerations for Hydrogen Blending

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Agenda

- Overview of Hydrogen Blending
- Hydrogen Embrittlement
- Fatigue Crack Growth
- Fracture Resistance
- Considerations for Plastic Pipe
- Machine Learning
- Conclusion

Overview of Hydrogen Blending

- 2-20% hydrogen blend
- More economic and produces less greenhouse gas than transporting via truck
- Avoid capital cost of building new pipelines for hydrogen
- Concerns:
    - Compatibility of pipe materials
    - Processing and pipeline operation
    - Leakage and pipeline integrity
    - Safety and impact to end users

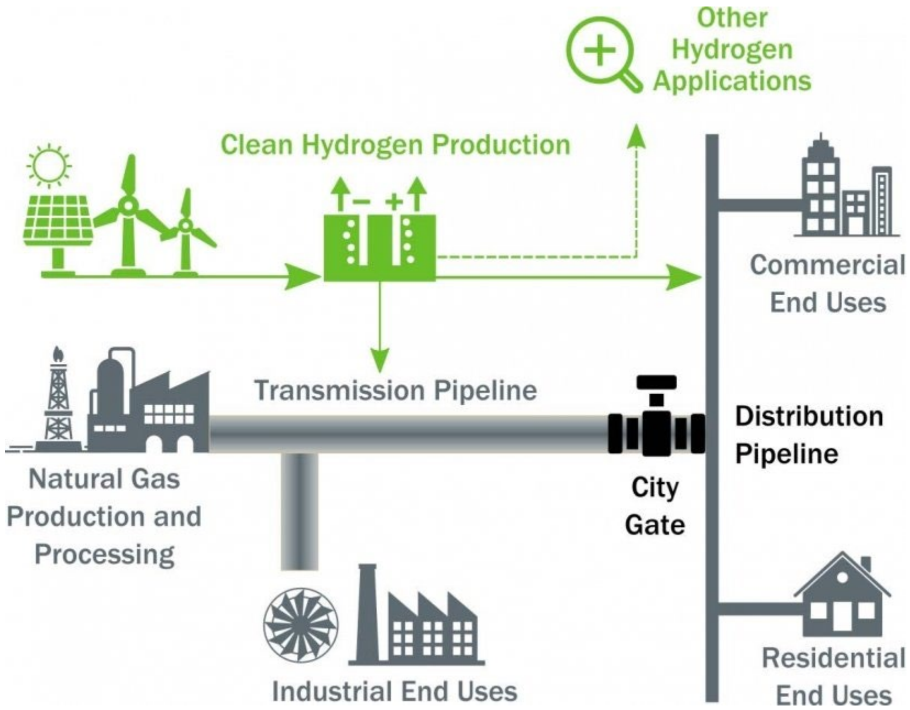

Fig 1. United States Department of Energy opportunities for hydrogen blending [2]

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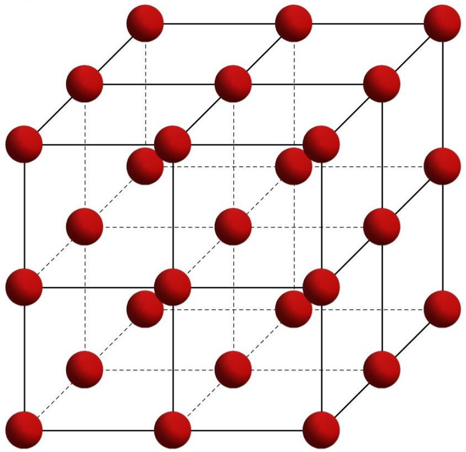
[2] Department of Energy, 2020c. Road Map to US Hydrogen Economy. Washington DC, US

[3] Cheng, W., & Cheng, Y. F. (2023). A techno-economic study of the strategy for hydrogen transport by pipelines in Canada. Journal of Pipeline Science and Engineering, 3(3), 100112. https://doi.org/10.1016/j.jpse.-2023.100112

Hydrogen Embrittlement

- Phenomenon in metal pipe in which hydrogen atoms enter the metal lattice and induce cracking
  - Environmental hydrogen embrittlement
  - ★ Internal hydrogen embrittlement
- Hydrogen embrittlement contributes to:
  - Fatigue crack growth
  - Fracture resistance



[4] Jia, G., Lei, M., Li, M., Xu, W., Li, R., Lu, Y., & Cai, M. (2023). Hydrogen embrittlement in hydrogen-blended natural gas transportation systems: A Review. International Journal of Hydrogen Energy, 48(82), 32137–32157. https://doi.org/10.1016/j.ijhydene.-2023.04.266

Fatigue Crack Growth Rate

- Stress Intensity Factor (K) – describes the stress state at the tip of the crack
    - Function of crack size, part geometry, and applied stress

K_C = critical stress intensity factor
K_I = mode I stress intensity factor
K_{IC} = plane strain fracture toughness
K_{JIC} = fracture toughness with inclusion of plastic fracture

$$K_{IC} \leq K_I = Y\sigma\sqrt{\pi a}$$

Experimental
Fatigue crack growth at 3% hydrogen blend in API X52 pipe at 0.1MPa (14.5psi)

Computational
Fatigue crack growth rate model that depicts hydrogen effects on initial crack size growth rate using textbook SIF calculation

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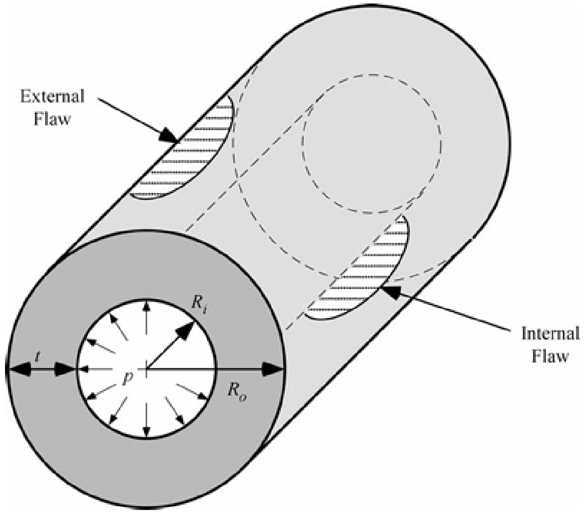
[1] Amaro, R. L., Drexler, E. S., & Slifka, A. J. (2014). Fatigue crack growth modeling of pipeline steels in high pressure gaseous hydrogen. International Journal of Fatigue, 62, 249–257. https://doi.org/10.1016/j.ijfatigue.2013.10.013

[8] Ronevich, J., & San Marchi, C. (2021). Materials compatibility concerns for hydrogen blended into natural gas (PVP2021-62045). Proposed for Presentation at the ASME Pressure Vessels and Piping Division Conference (PVP2021) In ,. https://doi.org/10.2172/1884064

Anderson Solution



Internal Flaw:

$$K_I = \frac{pR_o^2}{R_o^2 - R_i^2}\left[2G_0 - 2\left(\frac{a}{R_i}\right)G_1 + 3\left(\frac{a}{R_i}\right)^2 G_2 - 4\left(\frac{a}{R_i}\right)^3 G_3 + 5\left(\frac{a}{R_i}\right)^4 G_4\right]\sqrt{\frac{\pi a}{Q}}$$

External Flaw:

$$K_I = \frac{pR_i^2}{R_o^2 - R_i^2}\left[2G_0 + 2\left(\frac{a}{R_o}\right)G_1 + 3\left(\frac{a}{R_o}\right)^2 G_2 + 4\left(\frac{a}{R_o}\right)^3 G_3 + 5\left(\frac{a}{R_o}\right)^4 G_4\right]\sqrt{\frac{\pi a}{Q}}$$

Increasingly inaccurate for low crack depth/length ratios (long, shallow cracks)

Fracture Resistance

- Fracture toughness – resistance of a pipeline material to crack propagation
  - Function of steel composition, microstructure, and temperature
  - Decreases in the presence of hydrogen

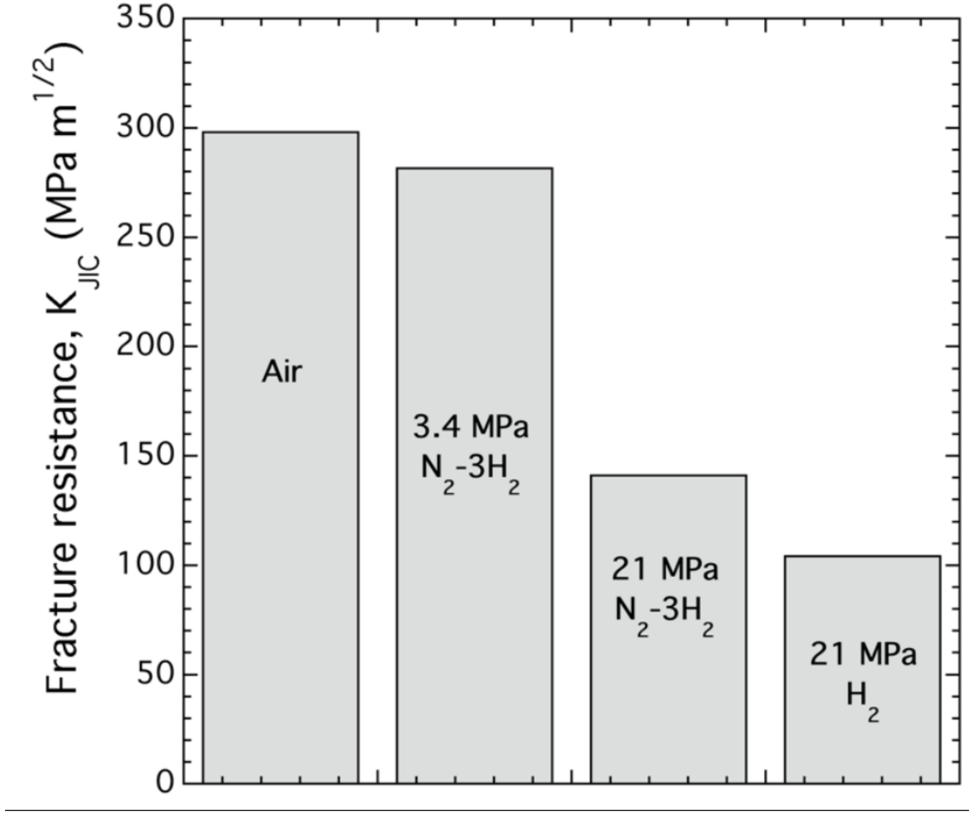


Fig 2. Fracture resistance of X52 pipeline steel in gaseous hydrogen environments [8]

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[8] Ronevich, J., & San Marchi, C. (2021). Materials compatibility concerns for hydrogen blended into natural gas (PVP2021-62045). Proposed for Presentation at the ASME Pressure Vessels and Piping Division Conference (PVP2021) In ,. https://doi.org/10.2172/1884064

Crack Propagation

- Flaw #1 –smallest defect that has 90% probability of detection with ILI-EMAT device
  - Fails by plastic collapse at same pressure in hydrogen as natural gas
- Flaw #5 –through-crack of pipe wall thickness
  - Fails by elastoplastic fracture at a lower pressure in hydrogen than natural gas
- Fracture probability is dependent on crack size

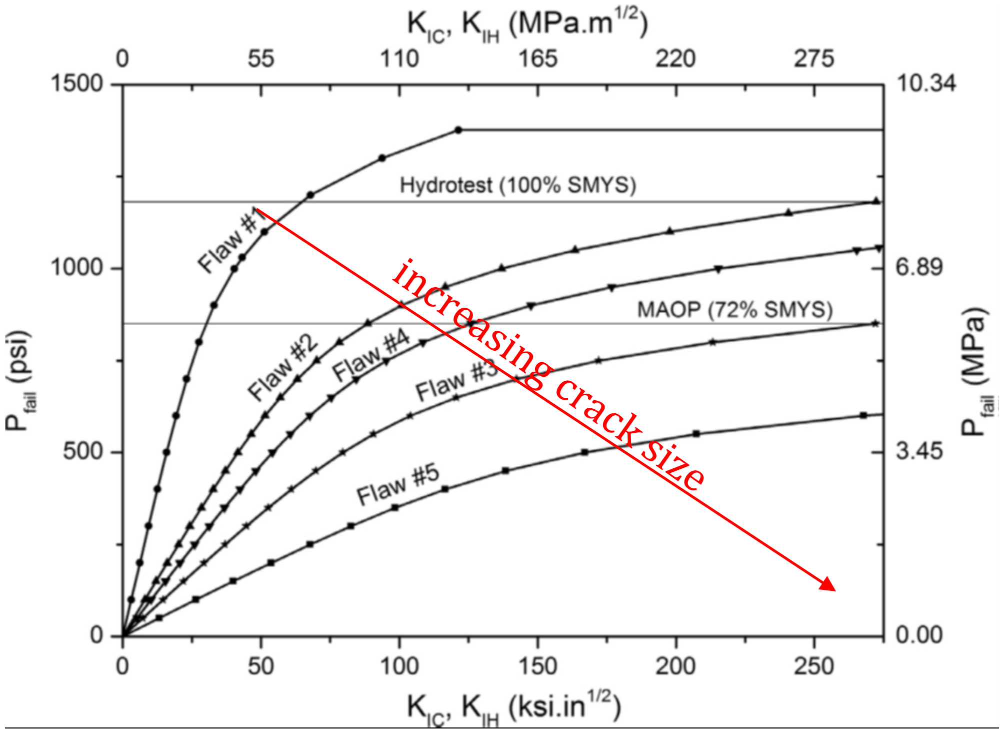


Fig 3. Failure pressure of a pipeline with varying flaw sizes vs. fracture toughness [5]

[5] Kappes, M. A., & Perez, T. E. (2023). Blending hydrogen in existing natural gas pipelines: Integrity consequences from a fitness for service perspective. Journal of Pipeline Science and Engineering. https://doi.org/10.2139/ssrn.4424788

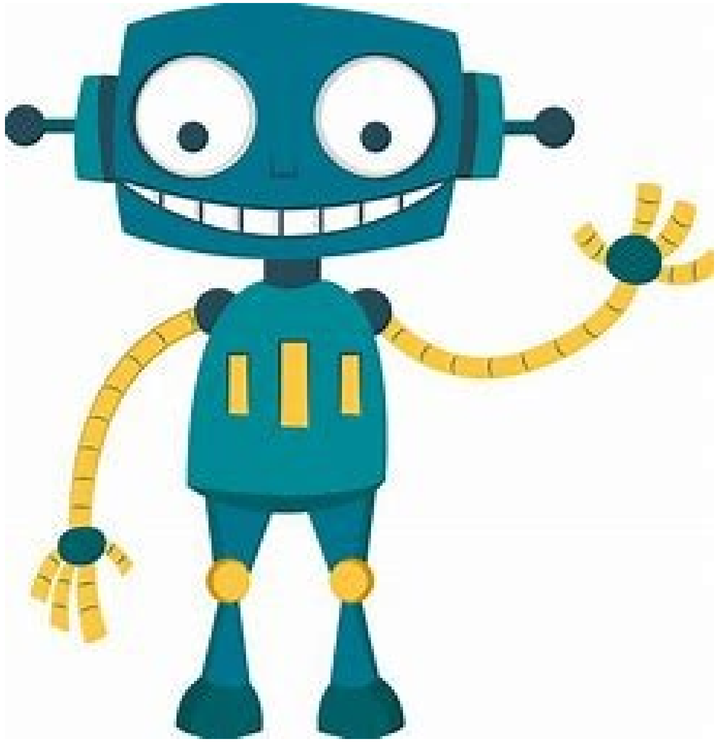
Considerations for Plastic Pipe

- Hydrogen leakage through pipe walls
  - Low density
  - High diffusivity

- PE 2306 (Aldyl-A)
  - Increased susceptibility to brittle fracture

[10] Topolski, K., Reznicek, E., Erdener, B., San Marchi, C., Ronevich, J., Fring, L., Simmons, K., Fernandez, O., Hodge, B.-M., & Chung, M. (2022). Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology. https://doi.org/10.2172/1893355

Machine Learning Overview



Analyze and interpret patterns and structures of data

Create interpretable models that accurately describe data

Build upon linear algebra, statistics and probability, optimization, and differential equations

Machine Learning Models

Experimental/Computational Data

Training Data (70%)

- Find model parameters
- Calculate training error

Validation Data (20%)

- Tune hyperparameters
- Calculate validation error

Test Data (10%)

- Evaluate final error

- Adjust hyperparameters until sufficient training and validation errors are reached
- Calculate final error to assess model accuracy

Repeat process with different training/validation/test data divisions to obtain the best model (cross-validation)

Machine Learning Models

Surrogate Models to Predict SIF in Offshore Piping

- Multiple linear regression
- Polynomial regression
- Gaussian process regression
- Neural network
- Support vector regression
- Relevance vector regression

[6] Keprate, A., Chandima Ratnayake, R. M., & Sankararaman, S. (2017). Comparison of various surrogate models to predict stress intensity factor of a crack propagating in offshore piping. Journal of Offshore Mechanics and Arctic Engineering, 139(6). https://doi.org/10.1115/1.4037290

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Machine Learning Models

Polynomial Regression

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \epsilon$$

goal is to find the coefficients:

$$\beta_0, \beta_1, \beta_2 \ldots \beta_n$$

where n is the degree of the polynomial and Є is the error term

Gaussian Process Regression

$$p(y_p | x_p, x_T, y_T, \theta) \sim N(m \cdot s)$$

where θ is the hyperparameters, m is the mean, and s is the covariance matrix

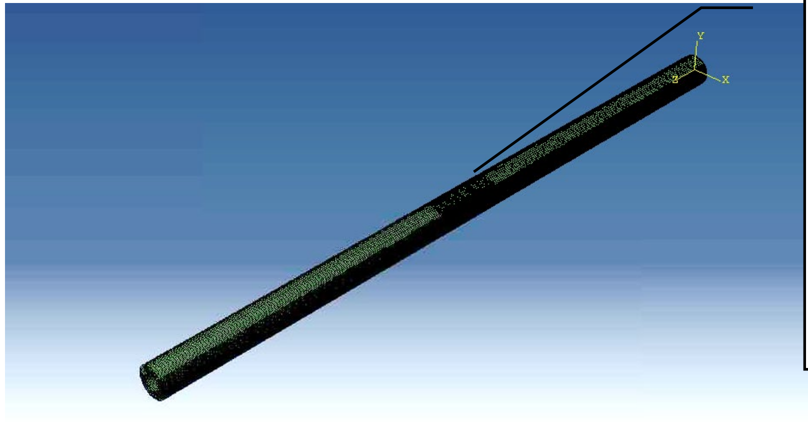
Adaptive Gaussian Process Regression Model

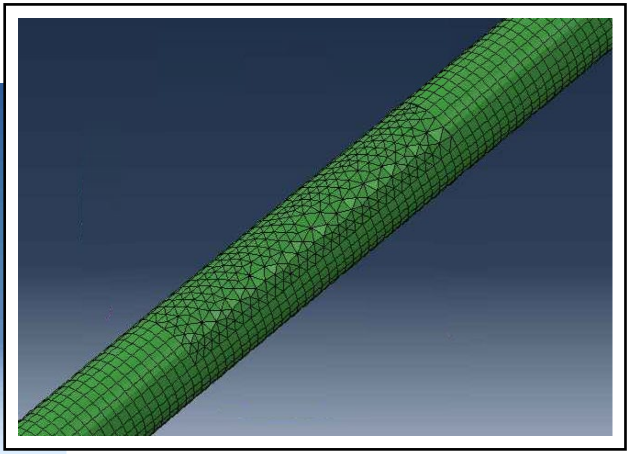
- Adaptive training based on selected data points with largest variance
  - Produces more accurate model

[7] Keprate, A., Chandima Ratnayake, R. M., & Sankararaman, S. (2018). Experimental validation of the adaptive gaussian process regression model used for prediction of stress intensity factor as an alternative to finite element method. Journal of Offshore Mechanics and Arctic Engineering, 141(2). https://doi.org/10.1115/1.4041457

Machine Learning Models

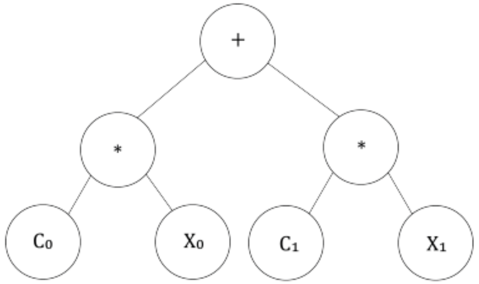
Generate training data from 1000 pipe models with varying wall thickness and crack sizes





Genetic Programming Based Symbolic Regression (GPSR)

- Learn mathematical expressions for K calculation



AGraph

Learn a more accurate alternative to the Anderson solution for K calculation that can be utilized for a variety of applications

Conclusion and Further Work

Hydrogen Blending

- Low-cost and efficient way to transport hydrogen
- 2-20% hydrogen blend
- Hydrogen embrittlement
    - Increase fatigue crack growth rate
    - Decrease fracture toughness
- Minimal concerns for polyethylene pipe
    - More research is needed to determine the lasting effects of hydrogen on polyethylene pipe

Machine Learning

- Tool to assess cracking in natural gas pipelines using a hydrogen blend
    - K calculation
- Many different algorithms with varying accuracy
- Further research needed to assess machine learning algorithms for this specific application and alternative K calculations

Questions