SAND2021-8246PE

SAND2021-X PE

Hydrogen-assisted fatigue and fracture of pressure vessels and line pipe steels

Chris San Marchi, Joe Ronevich
Sandia National Laboratories, Livermore CA

Materials Challenges in Assessment of Fitness for Service

EPRI Virtual Workshop in collaboration with
ASME 2021 PVP Conference

16 July 2021

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Motivation

With growing interest in decarbonization, hydrogen is being considered as a means to reduce carbon in energy infrastructure

Challenge

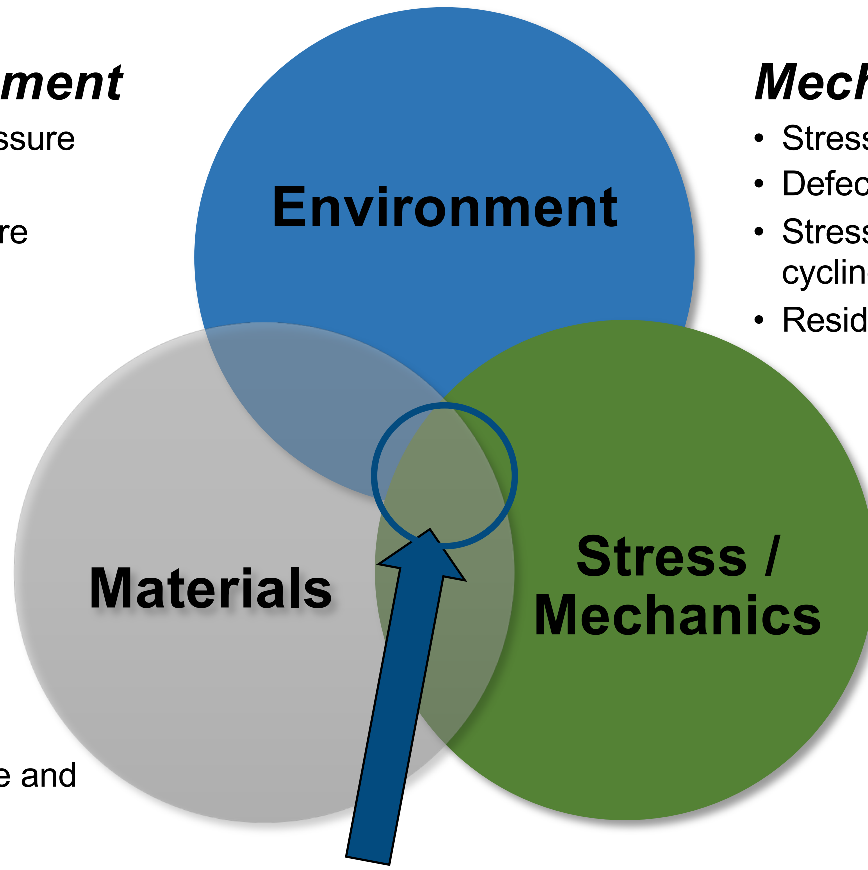
Hydrogen degrades fatigue and fracture resistance of steels, and the effects on pressure vessel and line pipe steels are significant

Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses

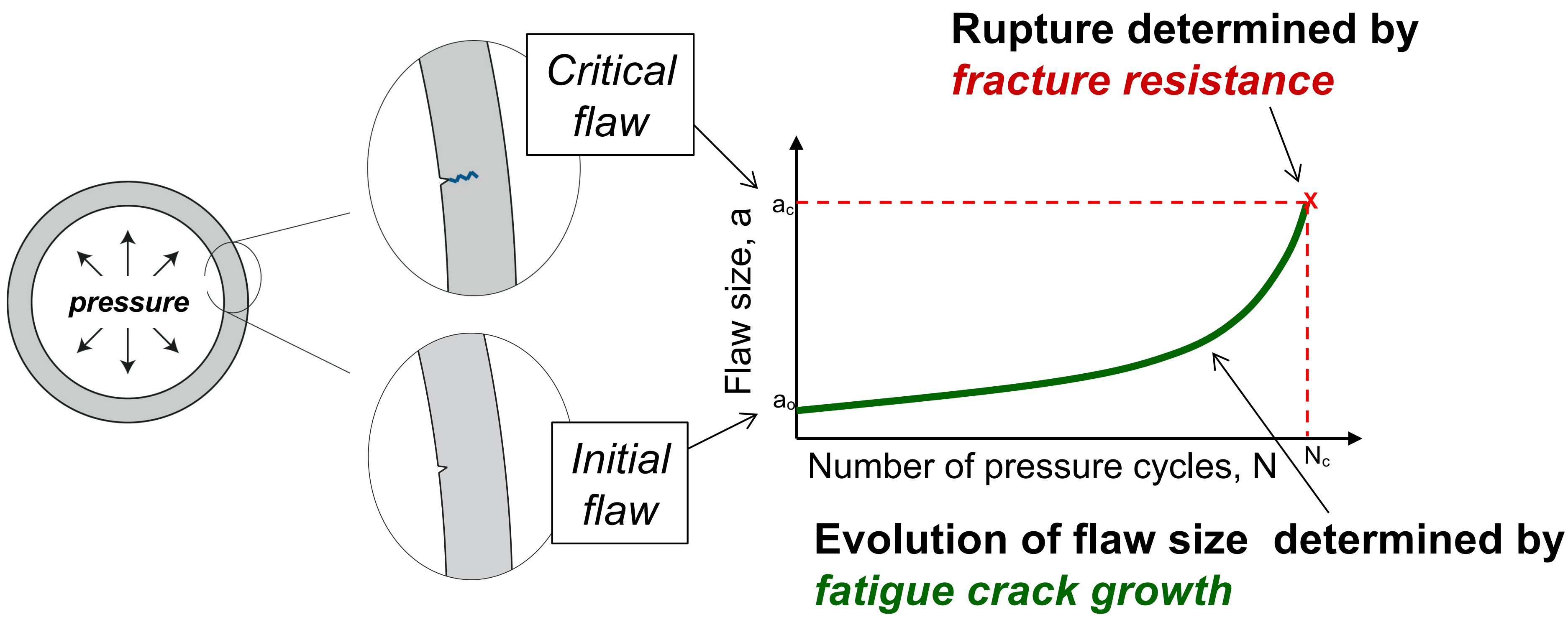


Materials

- Strength
- Microstructure and homogeneity

*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

Structural integrity assessment includes fracture mechanics-based analysis



ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

The effects of high-pressure hydrogen on fatigue crack growth in pressure vessels steels are characterized by the ASME CC2938 design curve

The pressure compensation term is not in CC2938

f is the thermodynamic pressure or fugacity

f_o is a reference fugacity

Ref: San Marchi et al, PVP2019-93803

$$\frac{da}{dN} = C_1 \left[\frac{1 + C_2 R}{1 - R}\right] \Delta K^{m_1} \left(\frac{f}{f_0}\right)^{1/2}$$

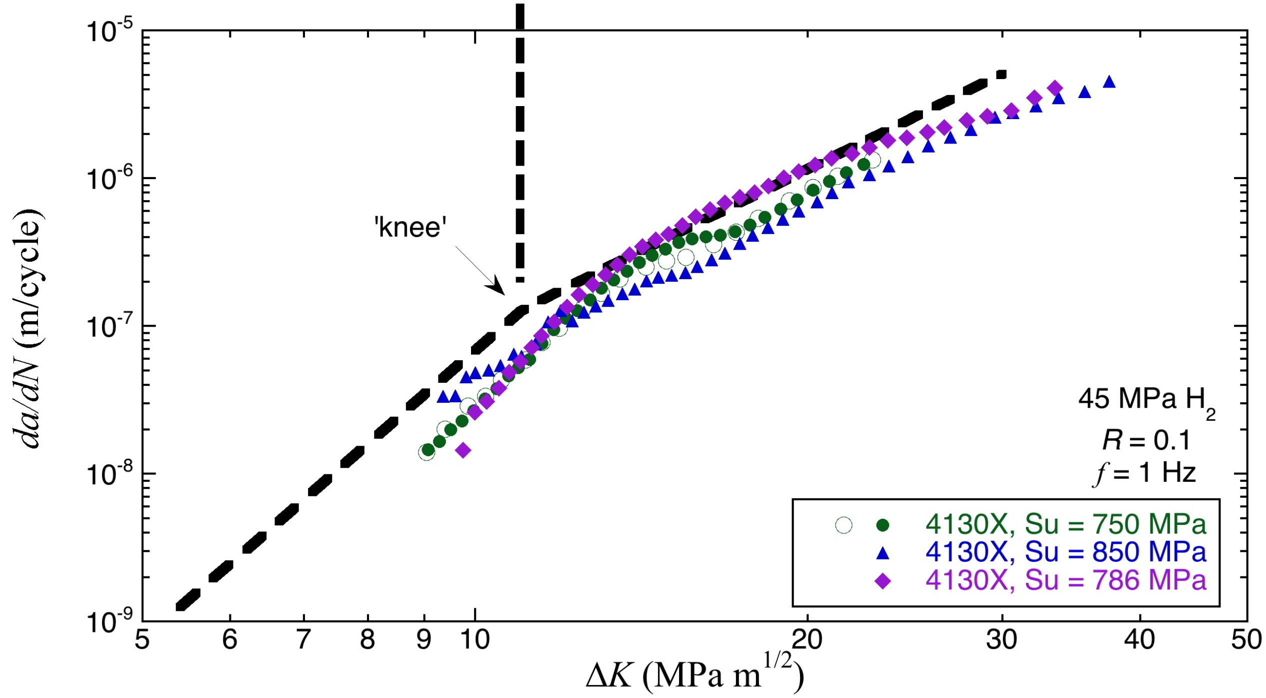
Pressure dependent

Intermediate ΔK

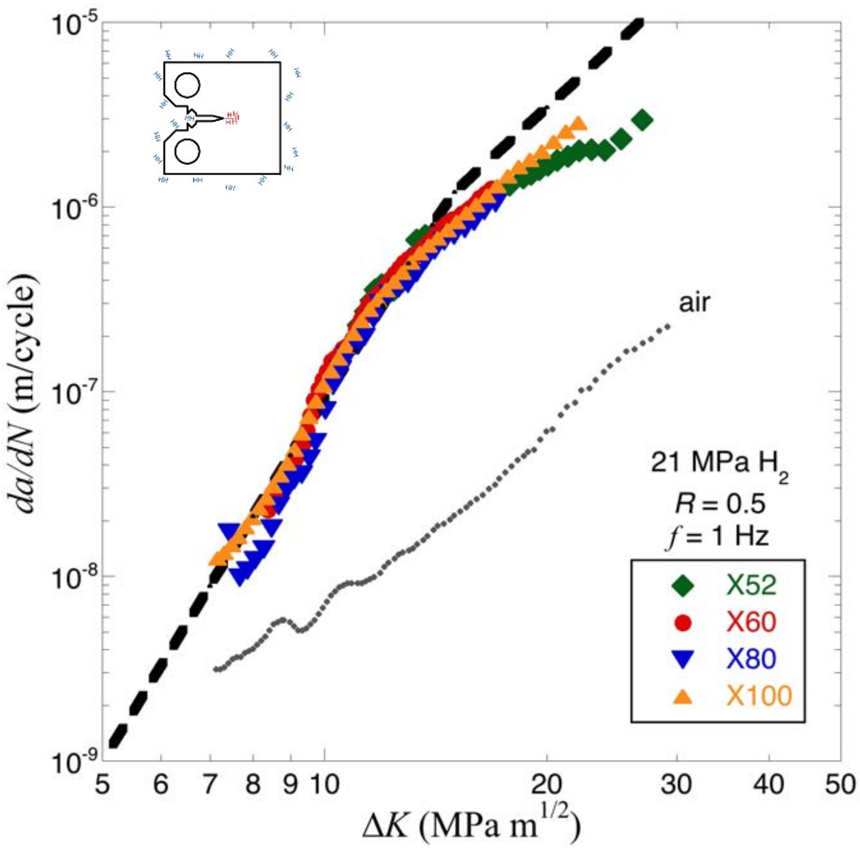
$$\frac{da}{dN} = C_3 \left[\frac{1 + C_4 R}{1 - R}\right] \Delta K^{m_2}$$

NOT pressure dependent

Large ΔK



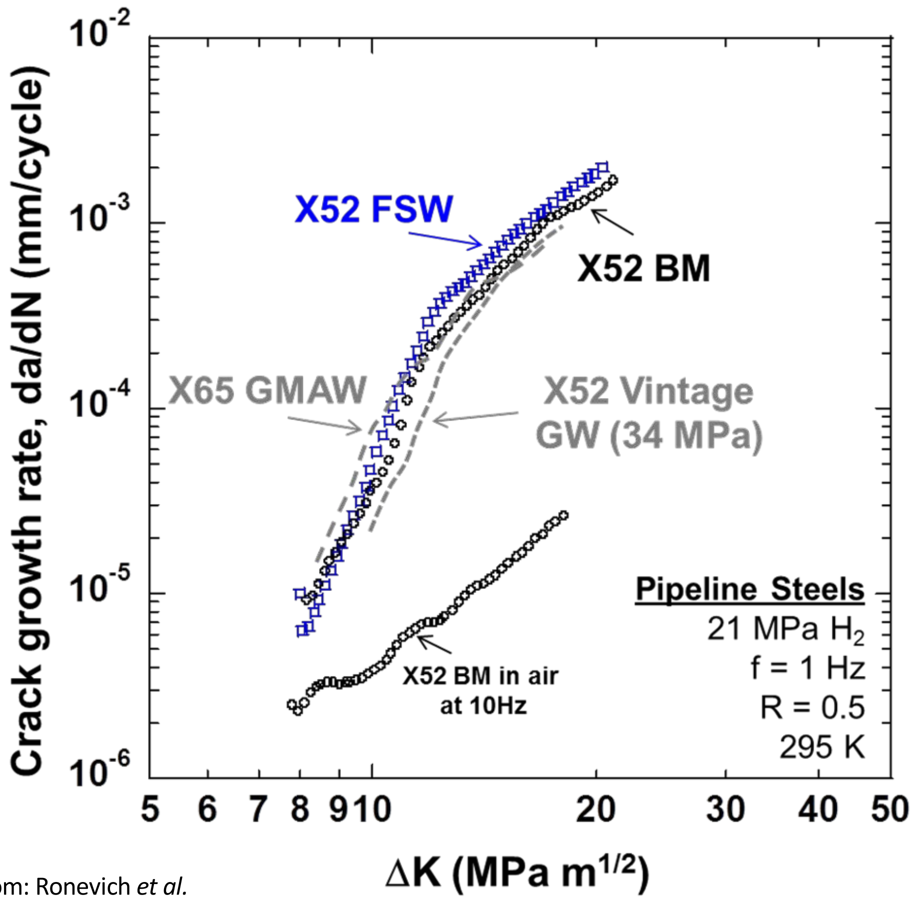
The effects of hydrogen on pipeline steels are captured by CC2938 design curve for pressure vessels



Similar fatigue crack growth behavior is observed in pipeline steels for:
- **Wide range of strength**
- **Wide range of microstructure**

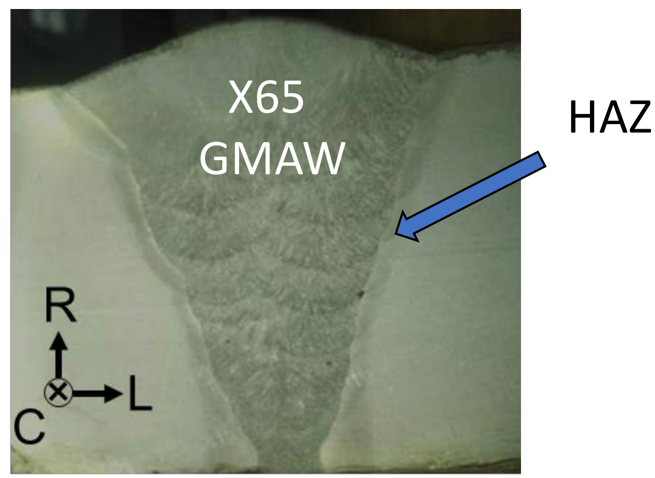
- **What about welds?**
- **Does this design curve capture fatigue behavior of relevant piping and pipeline steels at low pressure?**
- **What is the effect of pressure on fracture?**

Welds and base materials behave similarly



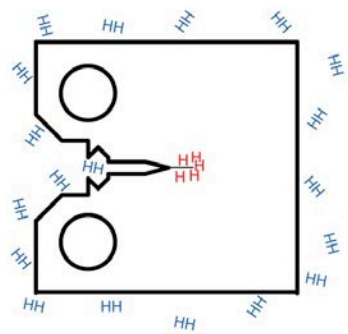
From: Ronevich *et al.* *IJHE* 42 (2017)

- **To first order, welds show similar fatigue and fracture behavior in gaseous hydrogen as the base metals**
- **Similar trends have been observed for a variety of weld processes**



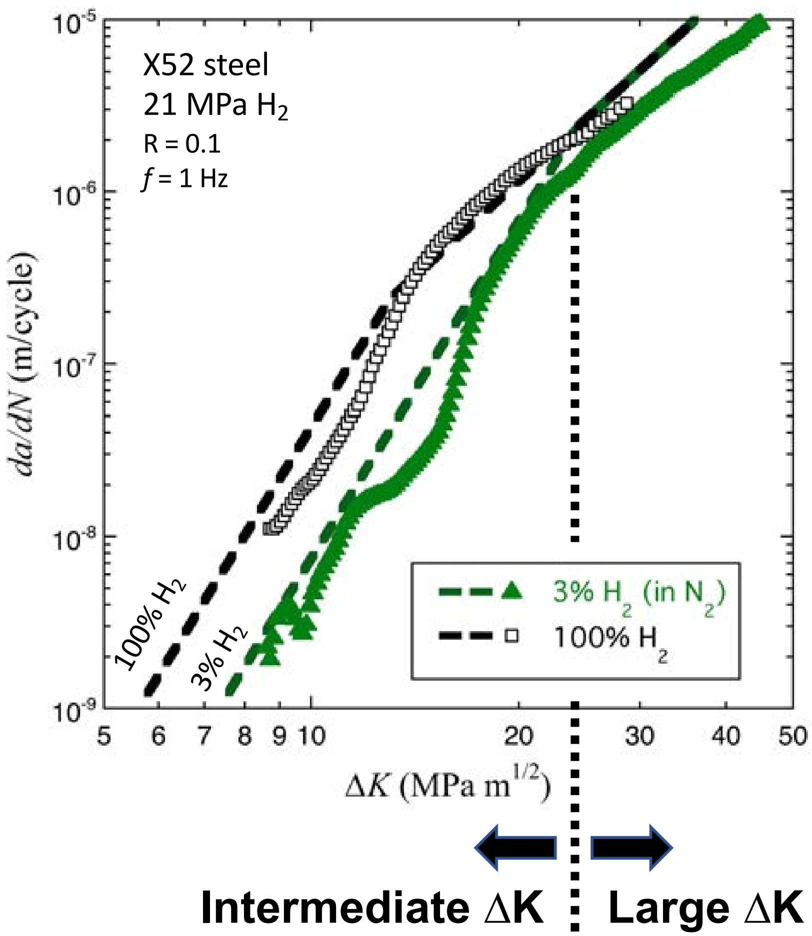
Fatigue crack growth and fracture resistance were measured in low partial pressure hydrogen

Material Evaluation: transmission pipe



- ***Material***: **API grade X52**
  - **Fe-0.87Mn-0.06C, polygonal ferrite with ~10% pearlite**
  - **YS = 429 MPa, TS = 493 MPa**
- ***Environment***:
  - **21 MPa total pressure: pure H_2**
  - **21 MPa total pressure: 3% H_2 (in inert) ~ 0.6 MPa hydrogen partial pressure**
- ***Stress***:
  - **Fatigue crack growth rate measured consistent with ASTM E647**
    - **fatigue typically terminated at a/W ~ 0.65**
  - **Elastic-plastic fracture resistance evaluated consistent with ASTM E1820 (rising load J_{IC} value)**
    - **Determined at the conclusion of the fatigue crack growth test**

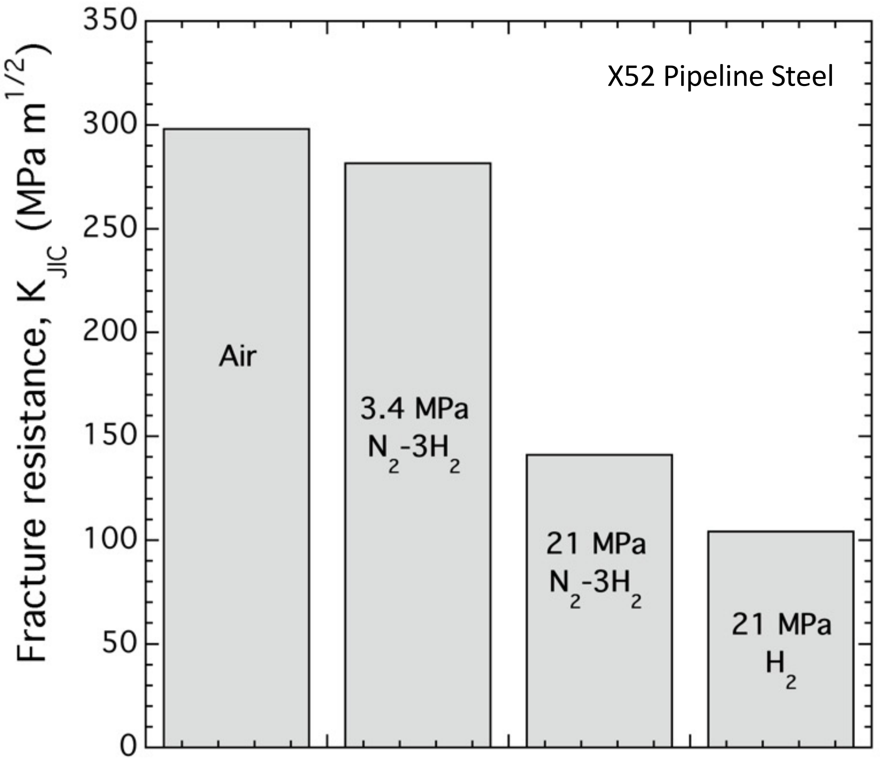
Fatigue crack growth of X52 is strongly affected by low partial-pressure hydrogen



- <u>Large ΔK</u>
  FCG remains independent of pressure
  - FCG in hydrogen at partial pressure of 0.6 and 21 MPa converge
- <u>Intermediate ΔK</u>
  FCG is dependent on hydrogen partial pressure
  - Dashed lines represent pressure-corrected predictions from ASME CC2938 for 100% and 3% H_2 at total pressure of 21 MPa
- <u>Small ΔK</u>
  FCG in hydrogen is insignificant in context of pressure applications ($<10^{-9}$ m/cycle)

Hydrogen-assisted fracture is apparent in low partial-pressure hydrogen

- Fracture resistance in pure hydrogen at pressure of 21 MPa is reduced by about 65%
  - In 3% H_2 (total pressure of 21 MPa), the reduction remains greater than 50%
- At lower partial pressure, the fracture resistance remained high
  - In contrast, literature results suggest a much larger reduction of fracture resistance in hydrogen at partial pressure of ~0.1 MPa (Briottet, Ez-Zaki, PVP2018-84658)
- Fracture resistance does not scale linearly with pressure†

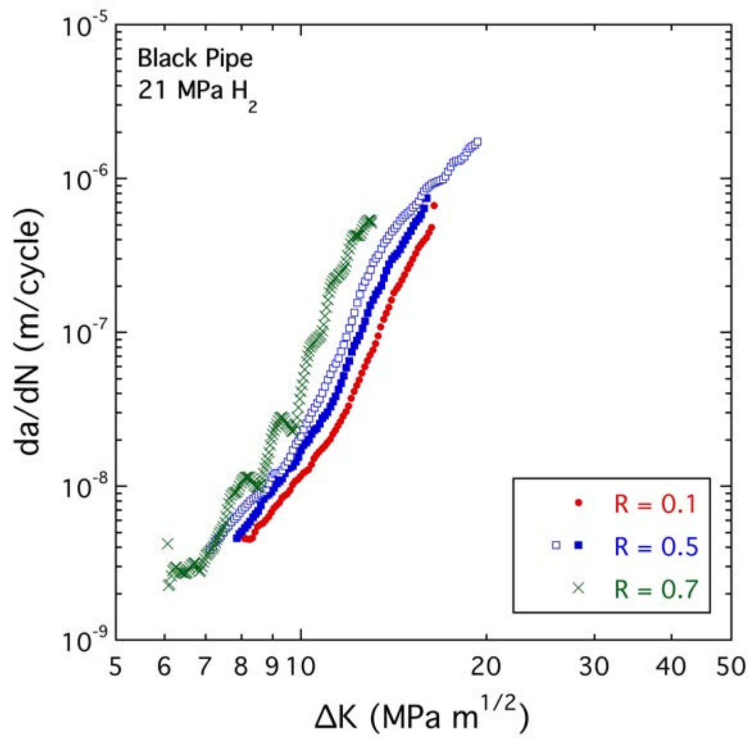


† thermodynamically, pressure should be replaced with fugacity, see PVP2021-62045

Fatigue crack growth of black pipe is similar to API X52

Material Evaluation: distribution piping

- ***Material***: **ASTM A53 Grade A (black pipe)**
  - **polygonal ferrite, pearlite**
  - **YS = 390 MPa, TS = 495 MPa**
- ***Environment***:
  - **21 MPa pressure: pure H_2**
- ***Stress***:
  - **Fatigue crack growth rate measured consistent with ASTM E647**
    - **Multiple R-values on same specimen**
  - **Elastic-plastic fracture resistance evaluated consistent with ASTM E1820 (rising load J_{IC} value)**

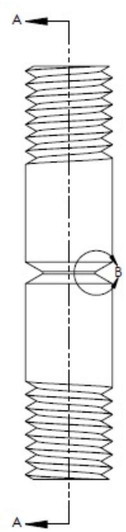


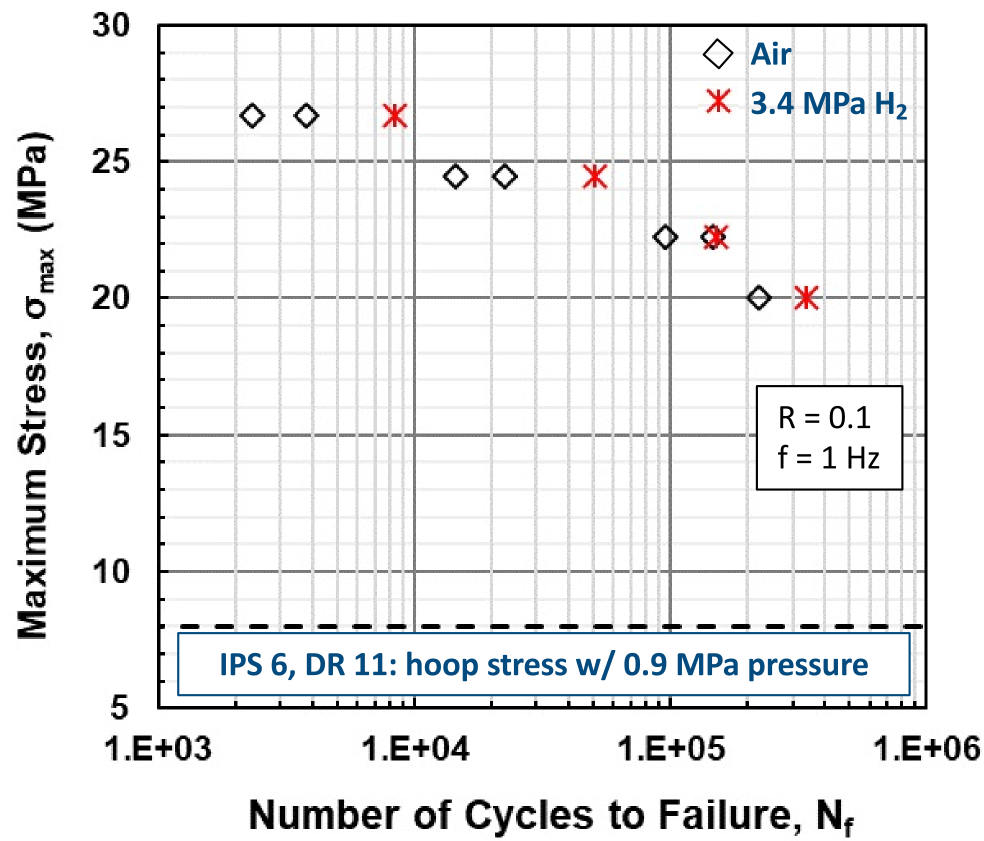
- **Fatigue crack growth rates are similar to X52**
- **Fracture resistance ~ 100 MPa $m^{1/2}$**

Fatigue life testing of yellow pipe in gaseous hydrogen shows no short-term degradation

Material Evaluation: distribution piping

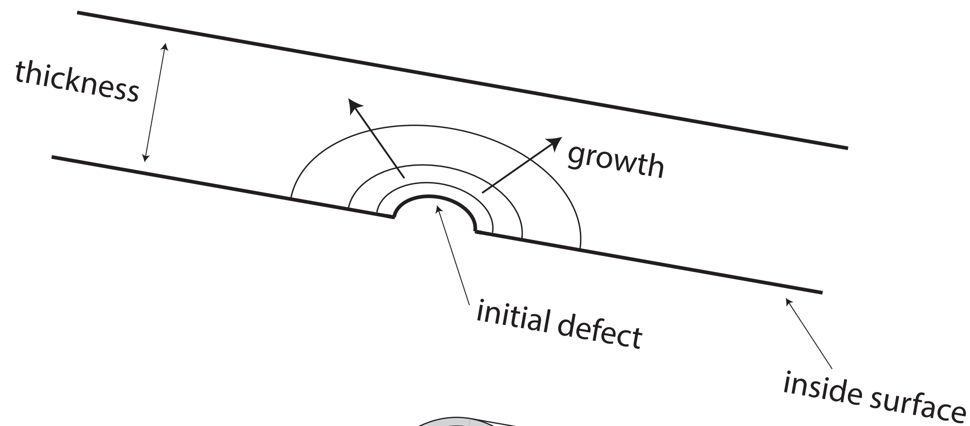
- ***Material***: **ASTM D2513, PE2708 (yellow pipe)**
  - **Medium density polyethylene (MDPE)**
  - **IPS 6, DR 11 (standard size designation)**
- ***Environment***: **pure H_2**
  - **3.4 MPa pressure (500 psi)**
- ***Stress***:
  - **Fatigue life testing consistent with ASTM E466**
    - **Tension-tension configuration (R = 0.1)**
    - **Notched axial geometry**



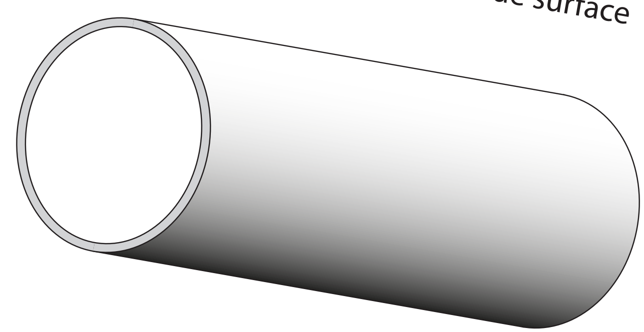


Analysis of transmission pipe structure

Structural Evaluation: transmission pipeline



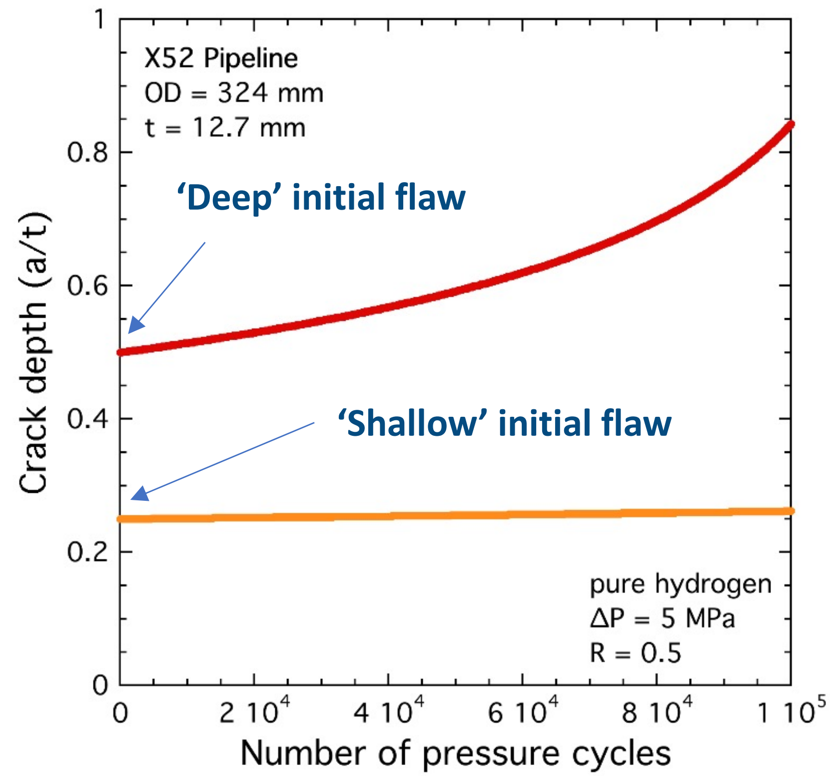
- ***Material***:
  - **API grade X52 pipe**
  - **OD = 324 mm**
  - **t = 12.7 mm**
- ***Environment***:
  - **Pure hydrogen at pressure of 10 MPa**
  - **Consider aggressive service environment (100% H_2)**
- ***Stress***:
  - **Hoop stress ~ 120 MPa (~35% SMYS)**
  - **Cyclic pressure: ΔP = 5 MPa**
  - **Flaw depth: 25% and 50% of wall thickness propagate with constant aspect ratio of 3:1 (length:depth)**



Analysis of transmission pipe structure

- **Stress is rather modest in this example, where P = 10 MPa, ΔP = 5 MPa**
- **Initial flaw depth (a/t) = 0.25**
  - **$K_{applied}$ = 11.2 MPa $m^{1/2}$**
  - **Crack does not extend significantly after 100,000 cycles with ΔP = 5 MPa**
- **Initial flaw depth = 0.50**
  - **$K_{applied}$ = 16.5 MPa $m^{1/2}$**
  - **Nearly 100,000 cycles required to extend crack to a/t = 0.80**
- **Crack depth = 0.80**
  - **$K_{applied}$ = 22 MPa $m^{1/2}$**
  - **$K_{material}$ > 100 MPa $m^{1/2}$**

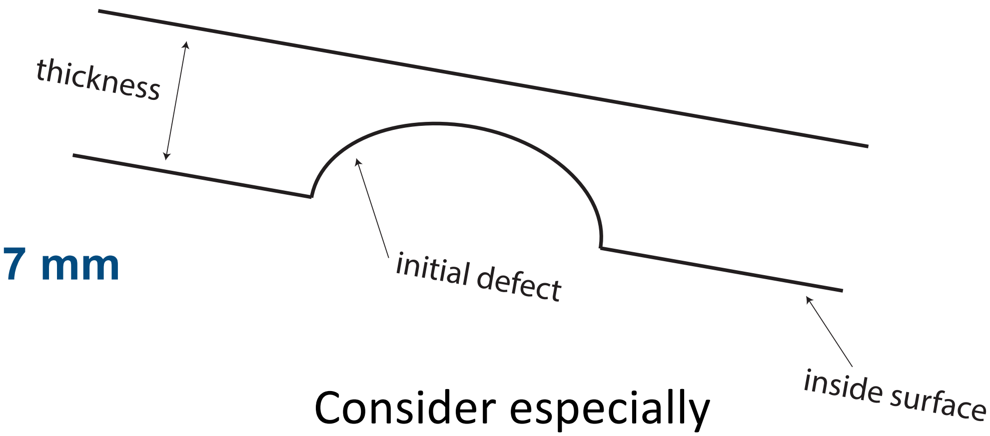
Structural Evaluation:
transmission pipeline



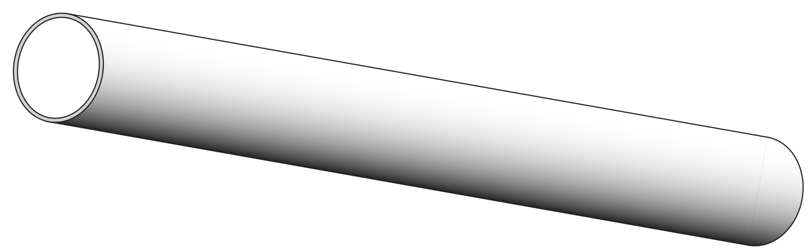
Analysis of distribution piping structure

Structural Evaluation: distribution piping

- ***Material***:
  - ASTM A53 grade A pipe (black pipe)
  - NPS 6, schedule 40: OD = 168 mm, t = 7 mm
- ***Environment***:
  - Pure hydrogen at pressure of 3.4 MPa
  - Consider aggressive service environment: excessively high pressure of 100% H_2
- ***Stress***:
  - Hoop stress ~ 38 MPa (<20% SMYS)
  - Cyclic pressure: ΔP = 3.4 MPa



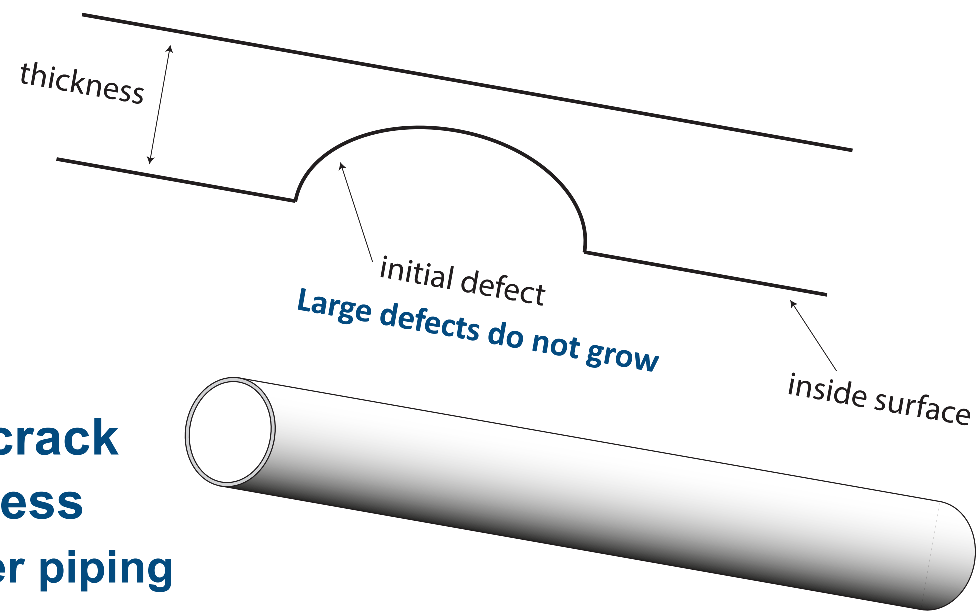
Consider especially large defects: ≥50% of wall thickness



Analysis of distribution piping structure

Structural Evaluation: distribution piping

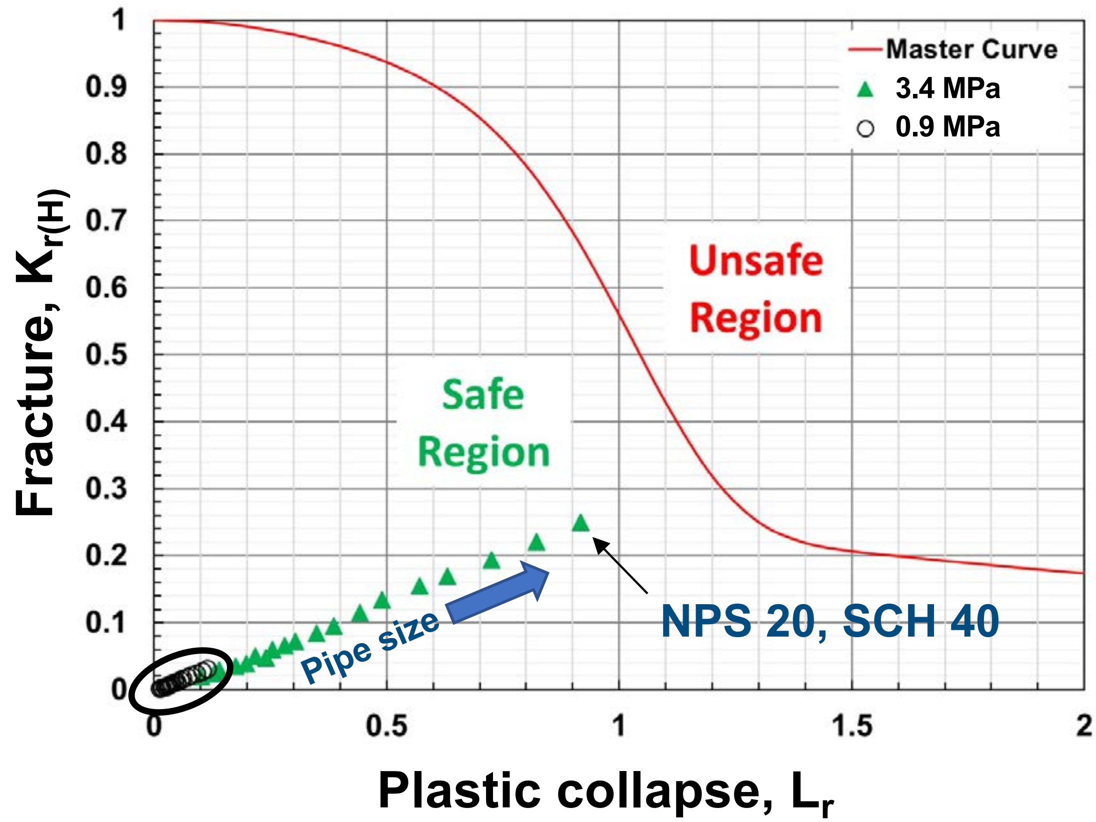
- **Stress is extremely low for standardized piping in distribution system**
  - **In practice, P << 3.4 MPa**
  - **Here, we use P = ΔP = 3.4 MPa**
  - **Defects do not grow**
- **Initial flaw depth (a/t) = 0.50**
  - **$K_{applied}$ < 4 MPa $m^{1/2}$**
- **Initial flaw depth = 0.80**
  - **$K_{applied}$ = 5.2 MPa $m^{1/2}$**
- **In general, the driving forces (K) for crack extension are very low due to low stress**
  - **Relatively thick walled, small-diameter piping**
  - **Low pressure**



Failure Assessment Diagram (FAD) for black pipe shows large margins for failure

- $K_{r(H)}$ characterizes unstable crack growth in hydrogen
- L_r characterizes plastic collapse (%SMYS)
- Idealized example calculations assuming crack depth 80% of wall thickness

Structural Evaluation: distribution piping

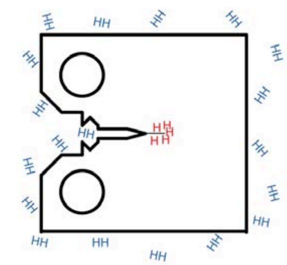


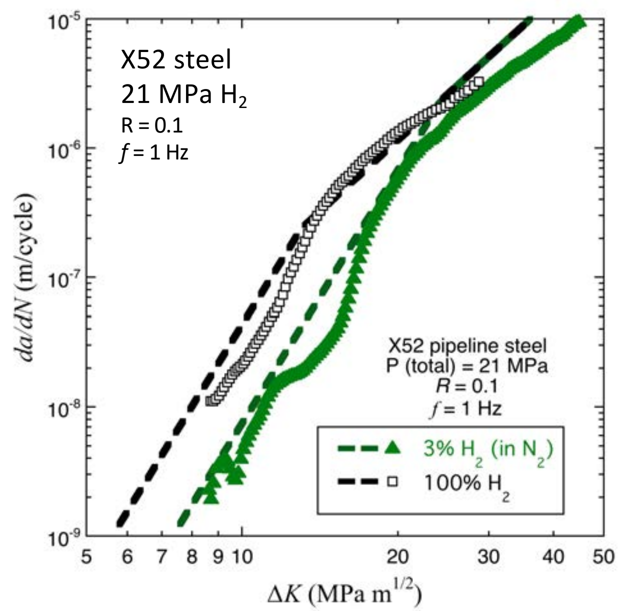
Hydrogen seems very unlikely to induce unstable fracture in distribution piping from quality pipe steels

Summary: Materials Perspective

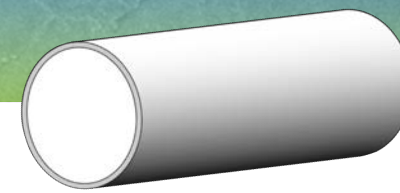
Gaseous hydrogen strongly affects fatigue and fracture properties of steels, even at low pressure

- **Fatigue crack growth**
  - **for small ΔK < 5 MPa m$^{1/2}$, FCG is exceptionally slow (<10^{-9} m/cycle) , even for pure hydrogen**
  - **for intermediate ΔK, FCG depends on square root of hydrogen fugacity**
  - **for large ΔK, FCG >10x faster in hydrogen than air and FCG is independent of pressure**
- **Fracture resistance decreases with pressure, but but remains >100 MPa m$^{1/2}$ in 21 MPa hydrogen**



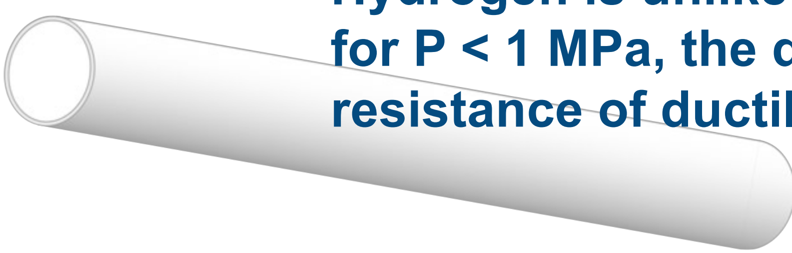


Summary: Structural Integrity Perspective



Gaseous hydrogen will not substantially accelerate fatigue crack growth in fatigue and fracture will not become unstable if the stresses (driving forces) are sufficiently low

- ***Transmission pipeline example***
  - **For realistic conditions, very large flaws are needed to extend a crack and driving forces remain modest relative to hydrogen-assisted fracture resistance of ductile steels**
  - **Actual results will depend on stresses and defect population**
- ***Distribution piping***
  - **Hydrogen is unlikely to be an issue for ductile steels: for P < 1 MPa, the driving force will be >10x less than fracture resistance of ductile steels ($K_{max} < 5$ MPa $m^{1/2}$)**



HyBlend: assessment of technical barriers and value proposition to blending hydrogen in natural gas pipelines

- NREL (lead), SNL, PNNL, ANL, NETL (and ORNL)
- More than 20 partners from industry and academia
- 2-year project
  - >$12 million from DOE-EERE
  - + $3-4 million anticipated from partners
  - Anticipated start summer FY21

HyBlend
U.S. DEPARTMENT OF ENERGY

Three research tasks in HyBlend:

1) Hydrogen compatibility of piping and pipelines
   - Both metals and polymer piping (SNL, PNNL & ORNL)
2) Life-cycle analysis (ANL & NETL)
3) Techno-economic analysis (NREL)

Important pipeline tasks:

- Structural Integrity and Risk Assessment of Hydrogen Pipelines
  - <u>key deliverable</u>: Probabilistic fracture mechanics framework for structural integrity of assessment of natural gas pipelines in hydrogen service
- Degradation of Structural Properties (metals and polymers)
  - <u>key deliverable</u>: fundamental understanding of behavior of materials in natural gas network (emphasis on pipelines and piping)

Thank You!

Joe Ronevich
jaronev@sandia.gov

Chris San Marchi
cwsanma@sandia.gov

https://www.sandia.gov/matlsTechRef/

https://granta-mi.sandia.gov/

Special thanks to James McNair and Brendan Davis for execution of the environmental testing

Sandia National Laboratories